NINTH EDITION

THE IESNA

LIGHTING HANDBOOK

REFERENCE
& APPLICATION

IES
The
LIGHTING
AUTHORITY

ILLUMINATING ENGINEERING
SOCIETY OF NORTH AMERICA

MARK S. REA, Ph.D., FIES, EDITOR-IN-CHIEF

INDEX

01 - Light and Optics
02 - Measurement of Light and Other Radiant Energy
03 - Vision and Perception
04 - Color
05 - Nonvisual Effects of Optical Radiation
06 - Light Sources
07 - Luminaires
08 - Daylighting
09 - Lighting Calculations
10 - Quality of the Visual Environment
11 - Office Lighting
12 - Educational Facility Lighting
13 - Hospitality Facilities and Entertainment Lighting
14 - Lighting for Public Places and Institutions
15 - Theatre,Television and Photographic Lighting
16 - Health Care Facility Lighting
17 - Retail Lighting
18 - Residential Lighting
19 - Industrial Lighting
20 - Sports and Recreational Area Lighting
21 - Exterior Lighting
22 - Roadway Lighting
23 - Transportation Lighting
24 - Underwater Lighting
25 - Lighting Economics
26 - Energy Management
27 - Lighting Controls
28 - Lighting Maintenance
29 - Emergency, Safety, and Security Lighting
30 - Appendix
31 - Glossary of Lighting Terminology

IESNA

Illuminating Engineering Society of North America

The IESNA is the recognized technical authority on illumination. For over ninety years its objective has been to communicate information on all aspects of good lighting practice to its members, to the lighting community, and to consumers through a variety of programs, publications, and services. The strength of the IESNA is its diversified membership: engineers, architects, designers, educators, students, contractors, distributors, utility personnel, manufacturers, and scientists, all *contributing to* the mission of the Society: to advance knowledge and disseminate information for the improvement of the lighted environment to the benefit of society.

The IESNA is a forum for the exchange of ideas and information and a vehicle for its members' professional development and recognition. Through its technical committees, with hundreds of qualified members from the lighting and user communities, the IESNA correlates research, investigations, and discussions to guide lighting experts and laypersons via consensus-based lighting recommendations.

The Society publishes nearly 100 varied publications including recommended practices on a variety of applications, design guides, technical memoranda, and publications on energy management and lighting measurement. The Society, in addition, works cooperatively with related organizations on a variety of programs and in the production of jointly published documents and standards.

In addition, the Society publishes *Lighting Design + Application (LD+A)* and the *Journal of the Illuminating Engineering Society (JIES). LD+A* is a popular application-oriented monthly magazine. Every issue contains special feature articles and news of practical and innovative lighting layouts, systems, equipment and economics, and news of the industry. The *Journal* contains technical papers, most of which are presented at the Society's Annual Conference. IESNA has a strong education program with basic and intermediate level courses and seminars offered through its Sections.

The Society has two types of membership: individual and sustaining. Applications and current dues schedules are available upon request from the Membership Department. IESNA local, regional, and international meetings, conferences, symposia, seminars, workshops, and lighting exhibitions (LIGHTFAIR INTERNATIONAL) provide current information on the latest developments in illumination.

For additional information on the IESNA, consult the Society's Web site: <www.iesna.org>.

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Preface

Many of us believe that the ninth edition of the *IESNA Lighting Handbook* represents a watershed in lighting practice. Over the past twenty years there has been a movement in lighting practice from illuminating engineering to lighting design, a movement from calculations of illuminance to judgments of aesthetics, a movement from quantity to quality. For the first time, the IESNA has, through this edition, formalized recommendations of lighting quality, reflecting this movement in lighting practice.

These formal recommendations are provided in a matrix entitled the IESNA Lighting Design Guide. The Guide includes recommendations on important lighting design criteria such as eye-source-task geometry, flicker, color, and glare. They are provided alongside the traditional recommendations of illuminance for a wide variety of applications. The intent of the Guide is to broaden the perspective of lighting practitioners and to direct them to specify higher quality lighting.

The idea for the IESNA Lighting Design Guide was born beside Lake George in upstate New York at the retreat for editing the eighth edition of this *Handbook*. During a break in editing, some of the editing team took a walk along the edge of the lake. Feeling a bit tired, we lamented that most people would probably never read what we were editing because they would only consult the illuminance selection table. We repeated the standard joke: If the *Handbook* in most architectural-engineering offices is placed on its spine, it will fall open to the illuminance selection table because that is the only section ever consulted. We mused that it be nice if users *had* to consider the many other important lighting design criteria found throughout the text. Building on that idea, we sketched out the basic framework of the matrix. Through hard work and review by several committees, the IESNA Lighting Design Guide in Chapter 10 of this edition of the *Handbook* was produced. Of course we all still hope that users will read the entire text of the ninth edition of the *Handbook*, but if it must fall open to any one section, it will now fall open to a section that describes more than one lighting design criterion.

Actually the genesis of the IESNA Lighting Design Guide goes back several years before our walk along Lake George. One of the first lighting people I met as a graduate student at Ohio State University was Steve Squillace, engineer, teacher, past president of the IESNA, and recipient of its highest technical award. Steve's passion for lighting and life set him apart from his contemporaries. In every conversation I had with Steve he insisted that every lighting designer and illuminating engineer should *think* about lighting. As a passionate radical, he argued that the IESNA should do away with illuminance recommendations altogether because they were substitutes for thinking. Many disagreed with Steve, believing that the majority of practitioners in the building industry were not lighting specialists. These people needed to quickly find practical guidance and then move on to other decisions. The problem had been that illuminance became the only criterion these practitioners considered before moving on. In this edition, the single focus on illuminance is no longer possible.

Steve might argue that we are moving in the wrong direction, however. There are more formal recommendations in this edition of the *Handbook* than ever before. Perhaps people who are now doing good lighting will stop thinking, but we doubt that. Rather, we believe that thinking is required to follow these recommendations. The lighting practitioner who needs to hurry to the next decision can no longer rely upon an illuminance calculation and consider the lighting job completed. Often illuminance is not the primary lighting design criterion in the Guide. With the recommendations put forward in this edition, the practitioner must take some time to study the application and decide among several important lighting design criteria. The thinking time invested by the lighting practitioner is worthwhile because that investment will improve the quality of lighting throughout North America.

Many people deserve a great deal of credit in developing, writing, and producing this edition of the *IESNA Lighting Handbook*. I have tried to acknowledge everyone who contributed, but no acknowledgment can do justice to the long-standing commitment these people have made to lighting. Their contributions to this edition are only a small part of their life-long commitment to improving the quality of life through better lighting. It is my sincerest wish that the ninth edition of the *IESNA Lighting Handbook* does honor to these contributors and helps them continue to improve the quality of lighting throughout North America.

Mark S. Rea, Ph.D., FIES
Editor-in-chief

Foreword

The Illuminating Engineering Society was founded in 1906, but it was not until 1947 that the first edition of the *Handbook* appeared, thus representing the accumulation of 41 years of lighting progress since the Society's founding. In each subsequent edition, IESNA has provided information on an ever-broadening range of technologies, procedures, and design issues. In the ninth edition, the editorial team has continued the trend of securing knowledge on all phases of lighting from IESNA committees and individual experts to ensure that this *Handbook* is *the lighting reference source* for the beginning of the next century.

The emphasis in the ninth edition is on quality. Previous editions have discussed important criteria for assessing and designing the visual environment, but a formal system for considering these issues had not been developed. IESNA has, however, always recommended quantity of light for specific applications or visual tasks. As a result, many practitioners often mistook the IESNA system of recommended illuminances (quantity) as the primary, or even the sole criterion, for lighting design. This *Handbook* introduces a new, formal system of addressing quality issues in the Lighting Design Guide in Chapter 10, Quality of the Visual Environment.

There are changes, too, in the illluminance categories, reduced from nine to seven and organized into three sets of visual tasks (simple, common, and special). Every application in the Lighting Design Guide has a specific (single number) recommended illuminance representing best practice for a typical application.

Through the Lighting Design Guide and other information in Chapter 10, IESNA is recognizing and emphasizing that illuminance is not the sole lighting design criterion. Other criteria may be more important, and, given the complexity and diversity of design goals for a specific application, the designer now has the opportunity to evaluate among the quantity and quality choices. This approach has been described as "a bridge to the 21st century," when it is expected that the tenth edition of the *Handbook* will provide a more precise method of measuring quality factors and their impact on the visual environment.

Other chapters in the book are new, or have been rewritten or updated. There are new application chapters on outdoor lighting, security lighting, parking facilities, retail, shopping mall and industrial lighting, and significant revisions to chapters on measurement of light, vision and perception, photobiology, aviation, and transportation.

This Handbook could not have been produced without the IESNA committees and individual specialists, those willing volunteers who give countless hours to the process of sharing their expertise. The Society thanks each and every contributor.

The professional editorial team brought talent and discipline to the project. Dr. Mark Rea, Judith Block, John Bullough, and Mariana Figueiro of Rensselaer Polytechnic Institute together with four Topic Editors, Michael Ouellette, David DiLaura, Roger Knott, and Nancy Clanton, have earned our appreciation for their contributions in evaluating, editing and, when necessary, developing material.

The IESNA Lighting Handbook represents the most important reference document in the lighting profession. It is one means by which the Society accomplishes its mission: to advance knowledge and disseminate information for the improvement of the lighted environment to the benefit of society. We hope that, you, the reader, will find the ninth edition your principal reference source for lighting information.

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1

Light and Optics

The quest to understand the nature of light has led curious human beings down into the innermost secrets of the atom and out to the farthest reaches of the starry universe.

--*Ben Bova*

FUNDAMENTALS

For illuminating engineering purposes, the Illuminating Engineering Society of North America (IESNA) defines light as radiant energy that is capable of exciting the human retina and creating a visual sensation.

As a physical quantity, light is defined in terms of its relative efficiency throughout the electromagnetic spectrum lying between approximately 380 and 780 nm. Visually, there is some individual variation in efficiency within these limits.

Theories

One of the earliest theories to describe light involved the notion that light was emitted from the eyes, and that they were rendered visible when they were struck by the emissions. Aristotle rejected this theory when questioning why we could not see in the dark. Since then, many alternative theories have been advanced. From a physical point of view, these theories generally regarded light as an energy transfer from one location to another. Some theories[1-4] are briefly discussed below.

Corpuscular Theory. This theory follows from the observation that moving particles, or corpuscles, possess kinetic energy. This position was advocated by Sir Isaac Newton (1642-1727). It is based on three premises:

1. Luminous bodies emit radiant energy in particles.

2. The particles are intermittently ejected in straight lines.

3. The particles act on the retina, stimulating a response that produces a visual sensation.

Wave Theory. This theory follows from the observation that waves can transfer energy even though the medium itself does not travel. This position was advocated by Christiaan Huygens (1629-1695). It too is based on three premises:

1. Light results from the molecular vibration in the luminous material.

2. The vibrations are transmitted through an "ether" as wavelike movements (comparable to ripples in water), and the vibrations slow down upon entering denser media.

3. The transmitted vibrations act on the retina, stimulating a response that produces a visual sensation.

Electromagnetic Theory.[5] The theory was advanced by James Clerk Maxwell (1831-1879), and is based on three premises:

1. Luminous bodies emit light in the form of radiant energy.

2. Radiant energy is propagated in the form of electromagnetic waves.

3. The electromagnetic waves act upon the retina, stimulating a response that produces a visual sensation.

Quantum Theory. A modern form of the corpuscular theory was advanced by Max Planck, and is based on two premises:

1. Energy is emitted and absorbed in discrete quanta (photons).

2. The magnitude of each quantum, Q, is determined by the product of h and ν, where h is 6.626×10^{-34} J·s (Planck's constant), ν is the frequency of the photon vibration in Hz, and Q is energy in Joules.

This theory provides a means of determining the amount of energy in each quantum. It follows from this theory that energy increases with frequency.

Unified Theory. The theory proposed by Louis de Broglie and Werner Heisenberg is based on two premises:

1. Every moving element of mass has associated with it a wave whose length is given by the equation

$$\lambda = \frac{h}{mv} \qquad (1\text{-}1)$$

where

λ = wavelength of the wave motion,
h = Planck's constant,
m = mass of the particle,
v = velocity of the particle.

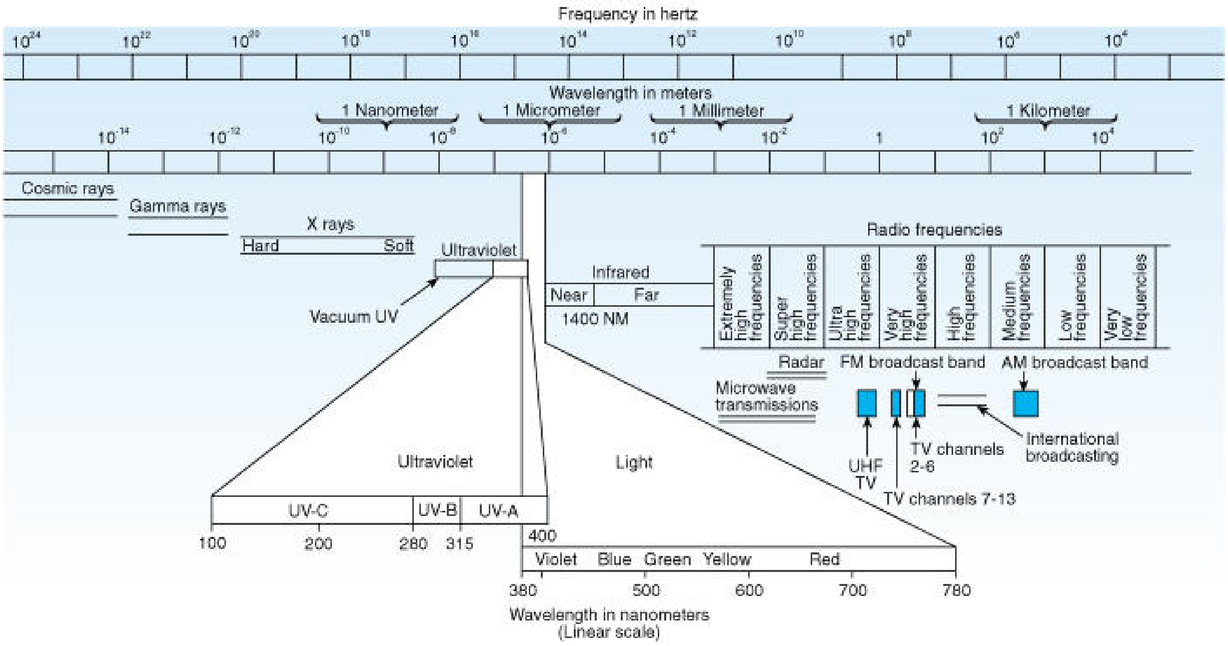


Figure 1-1. The radiant energy (electromagnetic) spectrum.

2. It is impossible to simultaneously determine all of the properties that are distinctive of a wave or a corpuscle.

The quantum and electromagnetic wave theories provide an explanation of those characteristics of radiant energy of concern to the illuminating engineer. Whether light is considered as a wave or a photon, it is radiation that is produced by electronic processes in the most exact sense of the term. It is produced in an incandescent body, a gas discharge, or a solid-state device by excited electrons just having reverted to more stable positions in their atoms, releasing energy.

Light and the Energy Spectrum [6]

The wave theory permits a convenient graphical representation of radiant energy in an orderly arrangement according to its wavelength or frequency. This arrangement is called a spectrum (Figure 1-1). It is useful in indicating the relationship between various radiant energy wavelength regions. Such a graphical representation should not be construed to indicate that each region of the spectrum is divided from the others in any physical way; there is a gradual transition from one region to another. The radiant energy spectrum extends over a range of wavelengths from 10^{-16} to 10^{5} m. The Angstrom unit (Å), the nanometer (nm), and the micrometer (μm), which are respectively 10^{-10}, 10^{-9}, and 10^{-6} m, are commonly used units of length in the visible spectrum region. The nanometer is the preferred unit of wavelength in the ultraviolet (UV) and visible regions of the spectrum. The micrometer is normally used in the infrared (IR) region.

Of particular importance to illuminating engineering are three regions of the electromagnetic spectrum: UV, visible, and IR. On the basis of practical applications and the effect obtained, the UV region is divided into the following bands (for engineering purposes, the "black light" region extends slightly into the visible portion of the spectrum):

Ozone-producing	180 to 220 nm
Bactericidal (germicidal)	220 to 300 nm
Erythemal	280 to 320 nm
Black light	300 to 400 nm

Another division of the UV spectrum, often used by photobiologists, is given by the Commission Internationale de l'Éclairage (CIE):

UVA	315 to 400 nm
UVB	280 to 315 nm
UVC	100 to 280 nm

Radiant energy in the visible spectrum lies between 380 and 780 nm. For practical purposes, infrared radiant energy is within the wavelength range of 0.78 to 10^3 µm. This band is arbitrarily divided as follows:

Near (short wavelength) infrared	0.78 to 1.4 µm
Mid (medium wavelength) infrared	1.4 to 3.0 µm
Far (long wavelength) infrared	3.0 to 10^3 µm

In general, unlike UV energy, IR energy is not evaluated on a wavelength basis but rather in terms of all such energy incident upon a surface. Examples of these applications are industrial heating, drying, baking, and photoreproduction. However, some applications, such as IR viewing devices, involve detectors sensitive to a restricted range of wavelengths; in such cases the spectral characteristics of the source and receiver are of importance.

Medium	Speed (meters per second)
Vacuum	2.99793×10^8
Air (760 mm at 0°C)	2.99724×10^8
Crown Glass	1.98223×10^8
Water	2.24915×10^8

Figure 1-2. Speed of Light for a Wavelength of 589 nm (Na D-lines)

All forms of radiant energy are transmitted at the same speed in vacuum (299,793 km/s, or 186,282 mi/s). However, each form differs in wavelength and thus in frequency. The wavelength and velocity may be altered by the medium through which it passes, but the frequency remains constant, independent of the medium. Thus, through the equation

$$\text{velocity} = \frac{\lambda \nu}{n} \tag{1-2}$$

where

n = index of refraction of the medium,
λ = wavelength in a vacuum,
ν = frequency in Hz,

it is possible to determine the velocity of radiant energy and also to indicate the relationship between frequency and wavelength. Figure 1-2 gives the speed of light in different media for a frequency corresponding to a wavelength of 589 nm in air.

Light is . . . a certain motion or an action, conceived in a very subtle manner, which fills the pores of all other bodies. . . .

--*René Descartes, in La Dioptrique, 1637*

Blackbody Radiation

The intensity and spectral properties of a blackbody radiator are dependent solely upon its temperature. A blackbody radiator may be closely approximated by the radiant power emitted from a small aperture in an enclosure, the walls of which are maintained at a uniform temperature (Figure 1-3).

Emitted light from a practical light source, particularly from an incandescent lamp, is often described by comparison with that from a blackbody radiator. In theory, all of the energy emitted by the walls of the blackbody radiator is eventually reabsorbed by the walls; that is, none escapes from the enclosure. Thus, a blackbody will, for the same area, radiate more total power and more power at a given wavelength than any other light source operating at the same temperature.

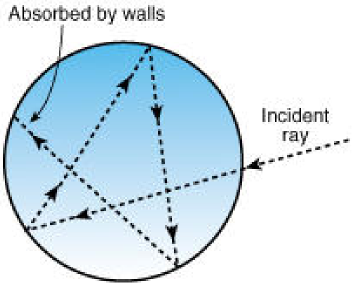


Figure 1-3. Small aperture in an enclosure exhibits blackbody characteristics.

From 1948 to 1979, the luminance of a blackbody, operated at the temperature of freezing platinum (2042 K), was used as an international reference standard to define the unit of luminous intensity. Specifically, it has a luminance of 60 cd/m^2. Since operating and maintaining a blackbody radiator at the freezing point of platinum is a major undertaking, a new definition of the candela was adopted in 1979. The candela is now, essentially, the luminous intensity of a 555.016 nm source whose radiant intensity is 1/683 W/sr. The new photometric unit is based on an electrical unit, the watt, which can be accurately and conveniently measured with an electrically calibrated radiometer. A further advantage of this definition is that the magnitude of the unit is independent of the international temperature scale, which occasionally changes.

Planck Radiation Law. Data describing blackbody radiation curves were obtained by Lummer and Pringsheim using a specially constructed and uniformly heated tube as the source. Planck, introducing the concept of discrete quanta of energy, developed an equation depicting these curves. It gives the spectral radiance of a blackbody as a function of wavelength and temperature. See the definition of Planck's radiation law in the Glossary.

Figure 1-4 shows the spectral radiance of a blackbody, on a logarithmic scale, as a function of wavelength for several absolute temperatures.

Wien Radiation Law. In the temperature range of incandescent filament lamps (2000 to 3400 K) and in the visible wavelength region (380 to 780 nm), a simplification of the Planck equation, known as the Wien radiation law, gives a good representation of the blackbody distribution of spectral radiance (see the Glossary).

Wien Displacement Law. This gives the relationship between the peak wavelength of blackbody radiation at different temperatures (see line AB in Figure 1-4, and the Glossary).

Stefan-Boltzmann Law. This law, obtained by integrating Planck's expression for L_λ from zero to infinity, states that the total radiant power per unit area of a blackbody varies as the fourth power of the absolute temperature (see the Glossary). It should be noted that this law applies to the total power, that is, the whole spectrum. It cannot be used to estimate the power in the visible portion of the spectrum alone.

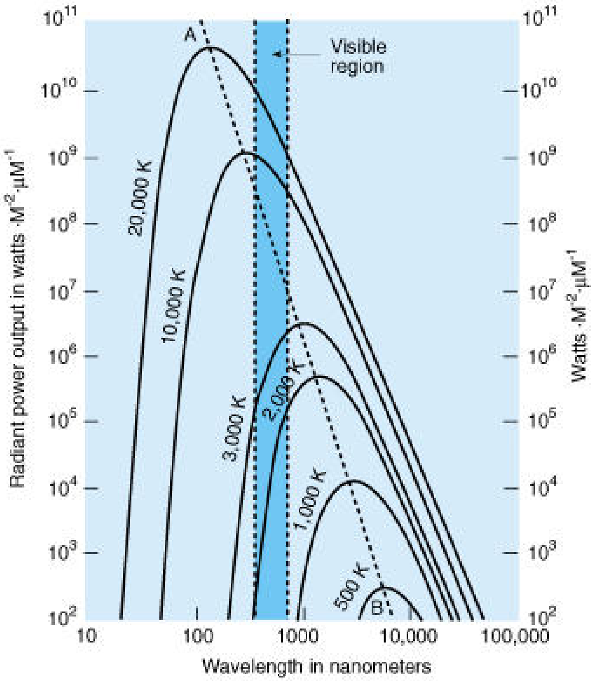


Figure 1-4. Blackbody radiation curves for operating temperatures between 500 and 20,000 K, showing Wein displacement of peaks. The shaded area is the region of visible wavelengths.

Spectral Emissivity

No known radiator has the same emissive power as a blackbody. The ratio of the output of a radiator at any wavelength to that of a blackbody at the same temperature and the same wavelength is known as the spectral emissivity, ε(λ), of the radiator.

Graybody Radiation

When the spectral emissivity is constant for all wavelengths, the radiator is known as a graybody. No known radiator has a constant spectral emissivity for all visible, IR, and UV wavelengths, but in the visible region a carbon filament exhibits nearly uniform emissivity; that is, a carbon filament is nearly a graybody for this region of the electromagnetic spectrum.

Selective Radiators

When the emissivity of all known material varies with wavelength, the radiator is called a selective radiator. In Figure 1-5, the radiation curves for a blackbody, a graybody, and a selective radiator (tungsten), all operating at 3000 K, are plotted on the same logarithmic scale to show the characteristic differences in radiant power.

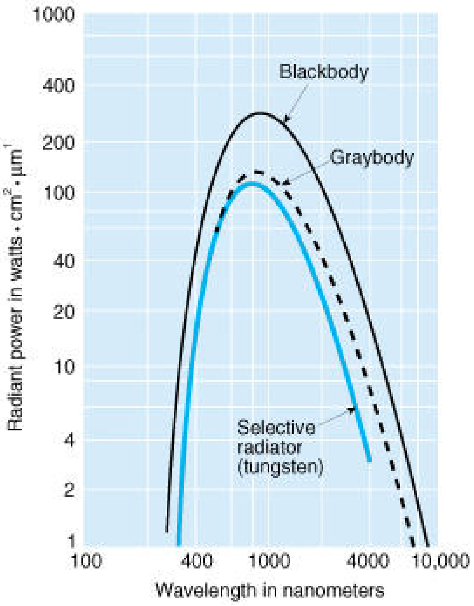


Figure 1-5. Radiation curves for blackbody, graybody, and selective radiators operating at 3000 K.

Color Temperature and Distribution Temperature

The radiation characteristics of a blackbody of unknown area may be specified with the aid of the Planck's equation by fixing only two quantities: the magnitude of the radiation at any given wavelength, and the absolute temperature. The same type of specification may be used with reasonable accuracy in the visible region of the spectrum for tungsten filaments and other incandescent sources. However, the temperature used in the case of selective radiators is not that of the filament but a value called the color temperature.

The color temperature of a selective radiator is that temperature at which a blackbody would have to be operated to produce the same color as that of the selective radiator. Color temperature is calculated from the chromaticity coordinates (u,v) of the source; small differences between chromaticities of a blackbody and an incandescent filament lamp are not of practical importance. This is true because the interreflections that occur at the inner surfaces of the helix formed by the coils used in many tungsten lamps act somewhat like a blackbody radiator. Thus, the spectral power distributions from coiled filaments exhibit combined characteristics of a straight filament and of a blackbody operating at the same temperature.

Distribution temperature is the temperature of a blackbody whose relative spectral power distribution is the closest to that of the given selective radiator. Distribution temperature is defined from the spectral power distribution of the source.[7]

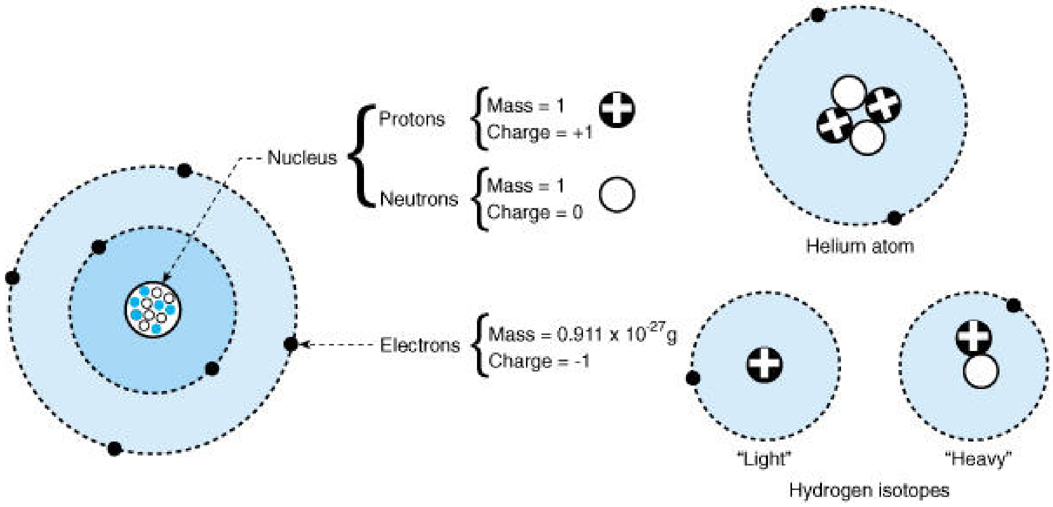


Figure 1-6. Schematic structure of the atom, showing electron orbits around a central nucleus. Hydrogen and helium atoms are the simplest of all atomic structures.

Color temperature and distribution temperature apply only to incandescent sources. Correlated color temperatures are used to describe the light emitted from other types of sources. Color is discussed in greater detail in Chapter 4, Color.

Atomic Structure and Radiation

The atomic theories first proposed by Rutherford and Bohr in 1913 have since been expanded upon and confirmed by an overwhelming amount of experimental evidence. They hypothesize that each atom resembles a minute solar system, such as that shown in Figure 1-6.

The atom consists of a central nucleus possessing a positive charge $+n$, about which revolve n negatively charged electrons. In the normal state these electrons remain in particular orbits, or energy levels, and radiation is not emitted by the atom.

The orbit described by a particular electron rotating about the nucleus is determined by the energy of that electron. In other words, there is a particular energy associated with each orbit. The system of orbits or energy levels is characteristic of each element and remains stable unless disturbed by external forces.

The electrons of an atom can be divided into two classes. The first class includes the inner shell electrons, which are not readily removed or excited except by high-energy radiation. The second class includes the outer shell (valence) electrons, which cause chemical bonding into molecules. Valence electrons are readily excited by UV or visible radiation or by electron impact and can be removed with relative ease. The valence electrons of an atom in a solid, when removed from their associated nuclei, enter the so-called conduction band and confer on the solid the property of electrical conductivity.

Upon the absorption of sufficient energy by an atom in the gaseous state, the valence electron is pushed to a higher energy level further from the nucleus. Eventually, the electron returns to the normal orbit, or an intermediate one, and in so doing the energy that the atom loses is emitted as a quantum of radiation. The wavelength of the radiation is determined by Planck's formula:

$$E_2 - E_1 = h\nu_{21} \qquad (1\text{-}3)$$

where

E_2 = energy associated with the excited orbit,
E_1 = energy associated with the normal orbit,
h = Planck's constant,
ν_{21} = frequency of the emitted radiation as the electron moves from level 2 to level 1.

This formula can be converted to a more usable form:

$$\text{wavelength} = \frac{1239.76}{V_d}\ \text{nm} \qquad (1\text{-}4)$$

where

V_d = potential difference in volts between two energy levels through which the displaced electron has fallen in one transition.

Luminous Flux and the Lumen[8,9]

Of particular importance to illuminating engineering is the lumen. The goal of this section is to show how electric power of radiant flux (in watts) is converted into luminous flux (in lumens), and to describe the underlying rationale for this process. The lumen is, in fact, a unit relating radiant flux (in watts) to visually effective radiation (i.e., light) for a standard human observer.

There are two classes of photoreceptors in the human eye, rods and cones. The photopic function V_λ describes the spectral luminous efficiency function for photopic (cone) vision, and the scotopic function V'_λ describes the spectral luminous efficiency for scotopic (rod) vision (Figure 1-7).[10]

The photopic luminous efficiency function V_λ was established in 1924 by Commission Internationale de l'Éclairage (CIE) and is based on data from several experimenters using different techniques. The two primary techniques used were flicker photometry and step-by-step heterochromatic brightness matching.

Flicker photometry is the least variable technique for determining the photopic efficiency function. With this technique, two lights are seen alternately in rapid succession. The radiance of one light, called the reference light, is held constant while the radiance of the other light, called the test light, which is monochromatic, is varied to the point where minimum flicker is perceived. At this point the luminances of both lights are defined to be the equal. Each test light wavelength is compared with the reference light in this way. The wavelength associated with the reciprocal of the minimum radiance needed to match the reference light is defined as the unit value of the photopic spectral luminous function ($V_\lambda = 1$).

In heterochromatic brightness matching, the reference light of constant radiance is juxtaposed with the test wavelength of variable radiance. The subject simply adjusts the radiance of each test wavelength until it appears to be equal in brightness to the reference. This technique is highly variable and produces results very different from flicker photometry unless the spectral difference between the test wavelength and the reference light is small. To obtain useful results, then, the reference light must be different for different regions of the spectrum. Since the reference light changes across the spectrum, this method is known as the step-by-step heterochromatic brightness matching technique. Again, the wavelength associated with the minimum value needed to match the reference light(s) is defined as the unit value of the photopic function.

Several consistent experimental conditions were used in these early experiments. The test fields were small, usually less than 2° across; the luminance was fairly low due to light source limitations, and a natural pupil was used by the subjects during testing. Gibson and Tyndall[11] pieced together results from several experiments and recommended a particular spectral luminous efficiency function for the photopic (cone) system, which was approved by a committee of the CIE in 1924.

Modification to the CIE 1924 curve followed, based on work by Judd in 1951. The 1924 curve was shown to be inadequate in describing visual sensitivity in the short-wavelength region of the visible spectrum. This modified curve was later published by the CIE.[12] Since not all test fields of interest to experimentalists were 2° or less, a standard function for a 10° field was devised in 1964, which shows a still greater sensitivity to short wavelengths on the photopic curve. This is likely due to the macula lutea screening pigment (see Chapter 3, Vision and Perception).

In 1951 the CIE also established a scotopic luminous efficiency function (Figure 1-7) based on the heterochromatic brightness matching technique (not step-by-step). Test wavelengths were compared with a large, approximately 20°, "white" test field with a luminance of approximately 0.00003 cd/m^2. The field was viewed by subjects using natural pupils after an extended period in darkness (see also Figure 3-8).

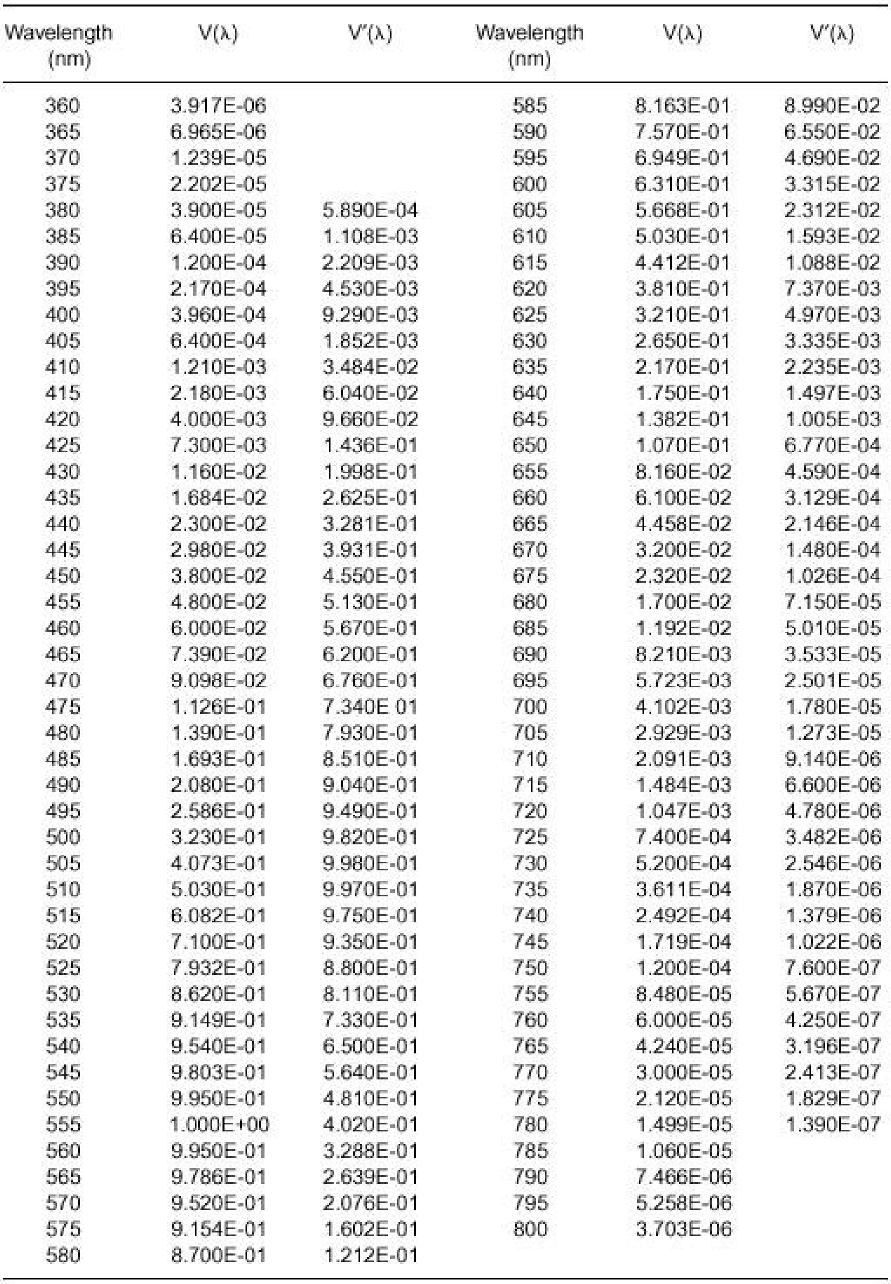
It is important to point out that everyone in the previous studies was color normal. A small percentage of the population (approximately 8%, mostly males) do not have all three cone photopigments or do not have the same ones as color-normal people. The photopic luminous efficiency curves will be different for these people because the cone photopigments determine the shapes of these curves.

The photopic luminous efficiency function applies to visual stimuli to the fovea and at luminance levels higher than approximately 3 cd/m^2. The scotopic luminous efficiency function applies to visual stimuli in regions outside the fovea and to luminances below approximately 0.001 cd/m^2. A family of mesopic luminous efficiency functions is required for application to luminous stimuli between approximately 0.001 and 3 cd/m^2. Research in this area is on-going.[13,14] Presently, mesopic luminous efficiency functions remain to be defined officially.[15] With the exception of special measurements for research purposes, almost all photometric quantities are measured photopically, even at luminances below 3 cd/m^2 and for peripheral vision. See Chapter 3, Vision and Perception, for additional discussion on photopic, scotopic, and mesopic vision.

Luminous Efficacy of Light Sources

The luminous efficacy of a light source is defined as the ratio of the total luminous flux (in lumens) to the total power input (in watts).

There are 683 lumens/watt at 555 nm. Since the scotopic luminous efficiency function peaks at a different wavelength (507 nm), it is necessary to establish different scaling factors for the photopic and for the scotopic luminous efficiency functions. Therefore, the photopic lumens, F, and the scotopic lumens, F', must be determined from the spectral power distribution of the light source:



Wavelength (nm)	V(λ)	V′(λ)	Wavelength (nm)	V(λ)	V′(λ)
360	3.917E-06		585	8.163E-01	8.990E-02
365	6.965E-06		590	7.570E-01	6.550E-02
370	1.239E-05		595	6.949E-01	4.690E-02
375	2.202E-05		600	6.310E-01	3.315E-02
380	3.900E-05	5.890E-04	605	5.668E-01	2.312E-02
385	6.400E-05	1.108E-03	610	5.030E-01	1.593E-02
390	1.200E-04	2.209E-03	615	4.412E-01	1.088E-02
395	2.170E-04	4.530E-03	620	3.810E-01	7.370E-03
400	3.960E-04	9.290E-03	625	3.210E-01	4.970E-03
405	6.400E-04	1.852E-03	630	2.650E-01	3.335E-03
410	1.210E-03	3.484E-02	635	2.170E-01	2.235E-03
415	2.180E-03	6.040E-02	640	1.750E-01	1.497E-03
420	4.000E-03	9.660E-02	645	1.382E-01	1.005E-03
425	7.300E-03	1.436E-01	650	1.070E-01	6.770E-04
430	1.160E-02	1.998E-01	655	8.160E-02	4.590E-04
435	1.684E-02	2.625E-01	660	6.100E-02	3.129E-04
440	2.300E-02	3.281E-01	665	4.458E-02	2.146E-04
445	2.980E-02	3.931E-01	670	3.200E-02	1.480E-04
450	3.800E-02	4.550E-01	675	2.320E-02	1.026E-04
455	4.800E-02	5.130E-01	680	1.700E-02	7.150E-05
460	6.000E-02	5.670E-01	685	1.192E-02	5.010E-05
465	7.390E-02	6.200E-01	690	8.210E-03	3.533E-05
470	9.098E-02	6.760E-01	695	5.723E-03	2.501E-05
475	1.126E-01	7.340E 01	700	4.102E-03	1.780E-05
480	1.390E-01	7.930E-01	705	2.929E-03	1.273E-05
485	1.693E-01	8.510E-01	710	2.091E-03	9.140E-06
490	2.080E-01	9.040E-01	715	1.484E-03	6.600E-06
495	2.586E-01	9.490E-01	720	1.047E-03	4.780E-06
500	3.230E-01	9.820E-01	725	7.400E-04	3.482E-06
505	4.073E-01	9.980E-01	730	5.200E-04	2.546E-06
510	5.030E-01	9.970E-01	735	3.611E-04	1.870E-06
515	6.082E-01	9.750E-01	740	2.492E-04	1.379E-06
520	7.100E-01	9.350E-01	745	1.719E-04	1.022E-06
525	7.932E-01	8.800E-01	750	1.200E-04	7.600E-07
530	8.620E-01	8.110E-01	755	8.480E-05	5.670E-07
535	9.149E-01	7.330E-01	760	6.000E-05	4.250E-07
540	9.540E-01	6.500E-01	765	4.240E-05	3.196E-07
545	9.803E-01	5.640E-01	770	3.000E-05	2.413E-07
550	9.950E-01	4.810E-01	775	2.120E-05	1.829E-07
555	1.000E+00	4.020E-01	780	1.499E-05	1.390E-07
560	9.950E-01	3.288E-01	785	1.060E-05	
565	9.786E-01	2.639E-01	790	7.466E-06	
570	9.520E-01	2.076E-01	795	5.258E-06	
575	9.154E-01	1.602E-01	800	3.703E-06	
580	8.700E-01	1.212E-01			

Figure 1-7. Photopic Luminous Efficiency, V (*λ*), and Scotopic Luminous Efficiency, V'(*λ*) Functions

$$F = 683 \sum_{360}^{800} P_\lambda V_\lambda \, \Delta\lambda \qquad (1\text{-}5)$$

where

P_λ = spectral power, in watts, of the source at the wavelength λ,
V_λ = photopic luminous efficiency function value at λ,
$\Delta\lambda$ = interval over which values of the spectral power were measured,

and

$$F' = 1700 \sum_{380}^{780} P_\lambda V_\lambda' \, \Delta\lambda \qquad (1\text{-}6)$$

where

V_{λ}' = scotopic luminous efficiency function value at λ.

The maximum luminous efficacy of an ideal white source, defined as a radiator with constant output over the visible part of the spectrum and no radiation in other parts, is approximately 220 lm/W.

LIGHT GENERATION

Natural Phenomena

Sunlight. Energy with a color temperature of approximately 6500 K is received from the sun just outside the earth's atmosphere at an average rate of about 1350 W/m^2. About 75% of this energy reaches the earth's surface at sea level (on the equator) on a clear day.

The average luminance of the sun is approximately 1600 Mcd/m^2 viewed from sea level. The illuminance on the earth's surface by the sun may exceed 100 klx (10,000 fc); on cloudy days the illuminance drops to less than 10 klx (1000 fc). Formulas to calculate these values are in Chapter 8, Daylighting.

Sky Light. A considerable amount of light is scattered by the earth's atmosphere. The investigations of Rayleigh first showed that this was a true scattering effect. On theoretical grounds the scattering should vary inversely as the fourth power of the wavelength when the size of the scattering particles is small compared to the wavelength of light, as in the case of the air molecules themselves. The blue color of a clear sky and the reddish appearance of the rising or setting sun are common examples of this scattering effect. If the scattering particles are relatively large (the water droplets in a cloud, for example), scattering is essentially the same for all wavelengths (clouds appear white). The scattered light from parts of the sky is partially polarized, up to 50%.

Moonlight. The moon shines solely by reflection of sunlight. Since the reflectance of its surface is rather low, its luminance is only on the order of 2500 cd/m^2. The correlated color temperature of moonlight is around 4100 K but will vary widely depending on material suspended in the atmosphere. Illumination of the earth's surface by the moon can be as high as 0.1 lx (0.01 fc).

Lightning. Lightning is a meteorological phenomenon arising from the accumulation, in the formation of clouds, of tremendous electrical charges, usually positive, which are suddenly released in a spark discharge. The lightning spectrum corresponds closely to that of an ordinary spark in air, consisting principally of nitrogen bands, although hydrogen lines sometimes appear owing to dissociation of water vapor.

Aurora Borealis (Northern Lights) and Aurora Australis (Southern Lights). These hazy patches or bands of greenish light, on which white, pink, or red streamers sometimes are superposed, appear 100 to 200 km (60 to 120 mi) above the earth. They are caused by electron streams spiraling into the atmosphere, primarily at polar latitudes. Some of the lines in their spectra have been identified with transitions of valence electrons from metastable states of oxygen and nitrogen atoms.

Bioluminescence. "Living light" is a form of chemiluminescence in which special compounds manufactured by plants and animals are oxidized, producing light. The light-producing compounds are not always required to be in a living organism. Many bioluminescent compounds can be dried and stored many years and then, in response to exposure to oxygen or some other catalyst, emit light.

Fabricated Sources

Historically, light sources have been divided into two types, incandescent and luminescent. Fundamentally, the cause of light emission is the same: electronic transitions from higher to lower energy states. The mode of electron excitation and the resultant spectral distribution of the radiation are different, however. Incandescent solid substances emit a continuous spectrum, while gaseous discharges radiate mainly in discrete spectral lines. There is some overlap, however. Incandescent rare-earth elements can emit discrete spectra, whereas high-pressure discharges produce a continuous spectrum.

The two classic types, with subdivisions showing associated devices or processes, are listed as follows (see also Chapter 6, Light Sources, for discussion on some of the following):

I. Incandescence

A. Filament lamps
B. Pyroluminescence (flames)
C. Candoluminescence (gas mantle)
D. Carbon arc radiation

II. Luminescence

A. Photoluminescence

1. Gaseous discharges
2. Fluorescence
3. Phosphorescence
4. Lasers

B. Electroluminescence

1. Electroluminescent lamps (ac capacitive)
2. Light-emitting diodes
3. Cathodoluminescence (electron excitation)

C. Miscellaneous luminescence phenomena

1. Galvanoluminescence (chemical)
2. Crystalloluminescence (crystallization)
3. Chemiluminescence (oxidation)
4. Thermoluminescence (heat)
5. Triboluminescence (friction or fracture)
6. Sonoluminescence (ultrasonics)
7. Radioluminescence (α, β, γ, and X rays)

INCANDESCENCE

Incandescent Filament Lamps

All familiar physical objects are combinations of chemically identifiable molecules, which in turn are made up of atoms. In solid materials the molecules are packed together, and the substances hold their shape over a wide range of physical conditions. In contrast, the molecules of a gas are highly mobile and occupy only a small part of the space filled by the gas.

Molecules of both gases and solids are constantly in motion at temperatures above absolute zero (0 K or 273°C), and their movement is a function of temperature. If the solid or gas is hot, the molecules move rapidly; if it is cold, they move more slowly.

At temperatures below approximately 873 K (600°C), only IR energy (heat) is emitted by a body, for example, a coal stove or an electric iron. Electronic transitions in atoms and molecules at temperatures above approximately 600°C result in the release of visible radiation along with the heat.

The incandescence of a lamp filament is caused by the heating action of an electric current. This heating action raises the filament temperature substantially above 600°C, producing light.

Pyroluminescence (Flame Luminescence)

A flame is the most often noted visible evidence of combustion. Flame light may be due to recombination of ions to form molecules, reflection from solid particles in the flame, incandescence of carbon or other solid particles, or any combination of these.

The combustion process is a high-temperature energy exchange between highly excited molecules and atoms. The process releases and radiates energy, some of which is in that portion of the electromagnetic spectrum called light. The quality and the amount of light generated depend on the material undergoing combustion. For example, a flashbulb containing zirconium yields the equivalent of 56 lm/W, whereas an acetylene flame yields 0.2 lm/W.

Candoluminescence (Gas Mantle)

Incandescence is exhibited by heated bodies which give off shorter wavelength radiation than would be expected according to the radiation laws, because of fluorescence excited by incandescent radiation. Materials producing such emission include zinc oxide, as well as rare-earth elements (cerium, thorium) used in the Welsbach gas mantle.

Carbon Arc Radiation

A carbon arc source radiates because of incandescence of the electrodes and because of luminescence of vaporized electrode material and other constituents of the surrounding gaseous atmosphere. Considerable spread in the luminance, total radiation, and spectral power distribution may be achieved by varying the electrode materials.

LUMINESCENCE [16-20]

Radiation from luminescent sources results from the excitation of single valence electrons of an atom, either in a gaseous state, where each atom is free from interference from its neighbors, or in a crystalline solid or organic molecule, where the action of its neighbors exerts a marked effect. In the first case, line spectra result, such as those of mercury or sodium arcs. In the second case, narrow emission bands result, which cover a portion of the spectrum (usually in the visible region). Both cases contrast with the radiation from incandescent sources, where the irregular excitation at high temperature of the free electrons of innumerable atoms gives rise to all wavelengths of radiation to form a continuous spectrum of radiation, as discussed in "Blackbody Radiation" above.

Photoluminescence

Gaseous Discharge. Radiation, including light, can be produced by gaseous discharges as discussed previously under "Atomic Structure and Radiation." A typical mechanism for generating light (photons) from a gaseous discharge (such as in a fluorescent lamp) is described below (Figure 1-8).

1. A free electron emitted from the cathode collides with one of the two valence electrons of a mercury atom and excites it by imparting to it part of the kinetic energy of the moving electron, thus raising the valence electron from its normal energy level to a higher one.

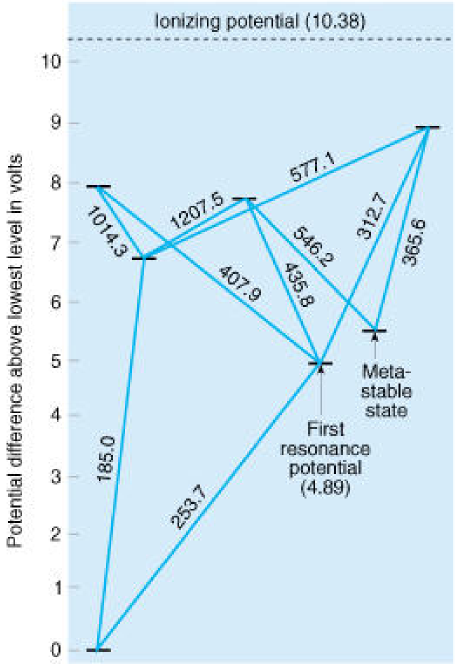


Figure 1-8. Simplified energy diagram for mercury, showing a few of the characteristic spectral lines.

2. The conduction electron loses speed in the impact and changes direction, but continues along the tube to excite or ionize one or more additional atoms before losing its energy stepwise and completing its path. It generally ends at the wall of the tube, where it recombines with an ionized atom. A part of the electron current is collected at the anode.

3. Conduction electrons, either from the cathode or formed by collision processes, gain energy from the electric field, thus maintaining the discharge along the length of the tube.

4. After a short delay the valence electron returns to its normal energy level, either in a single transition or by a series of steps from one excited level to a lower level. At each of these steps a photon (quantum of radiant energy) is emitted. If the electron returns to its normal energy level in a single transition, the emitted radiation is called resonance radiation (Figure 1-9).

5. In some cases (as in the high-pressure sodium lamp) a portion of the resonance radiation is self-absorbed by the gas of the discharge before it leaves the discharge envelope. The absorbed energy is then re-radiated as a continuum on either side of the resonant wavelength, leaving a depressed or dark region at that point in the spectrum.

Fluorescence. In the fluorescent lamp, UV radiation resulting from luminescence of the mercury vapor due to a gas discharge is converted into light by a phosphor coating on the inside of the tube or outer jacket. If this emission continues only during the excitation, it is called fluorescence. Figure 1-9 shows schematically a greatly magnified section of a part of a fluorescent lamp.

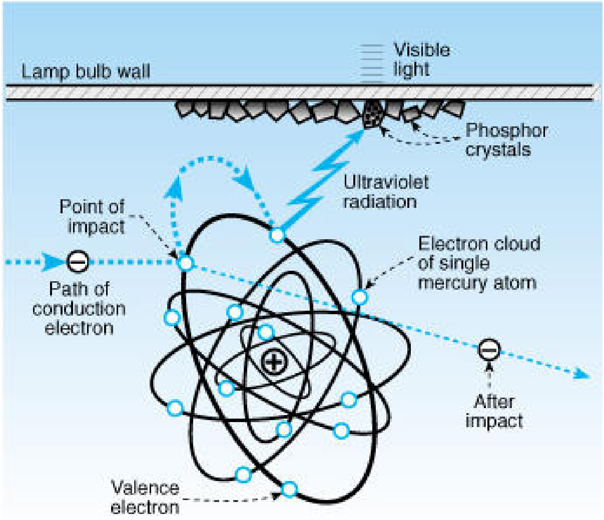


Figure 1-9. Magnified cross section of a fluorescent lamp, schematically showing progressive steps in the luminescent process, which finally result in in the release of visible radiation.

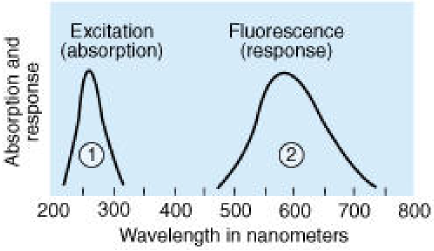


Figure 1-10. Fluorescence curve of a typical phosphor, showing initial excitation by ultraviolet rays and subsequent release of visible radiation.

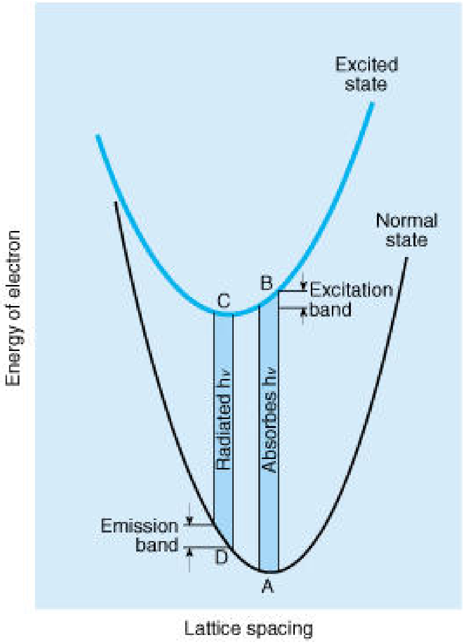
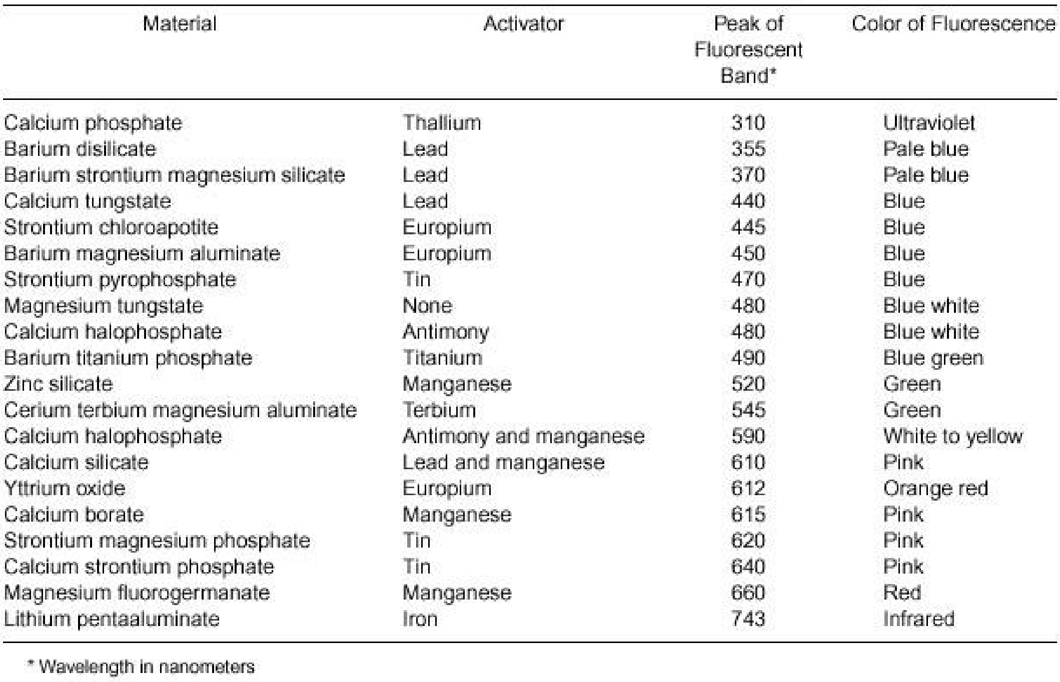


Figure 1-11. Simplified energy diagram for a typical phosphor.



Material	Activator	Peak of Fluorescent Band*	Color of Fluorescence
Calcium phosphate	Thallium	310	Ultraviolet
Barium disilicate	Lead	355	Pale blue
Barium strontium magnesium silicate	Lead	370	Pale blue
Calcium tungstate	Lead	440	Blue
Strontium chloroapotite	Europium	445	Blue
Barium magnesium aluminate	Europium	450	Blue
Strontium pyrophosphate	Tin	470	Blue
Magnesium tungstate	None	480	Blue white
Calcium halophosphate	Antimony	480	Blue white
Barium titanium phosphate	Titanium	490	Blue green
Zinc silicate	Manganese	520	Green
Cerium terbium magnesium aluminate	Terbium	545	Green
Calcium halophosphate	Antimony and manganese	590	White to yellow
Calcium silicate	Lead and manganese	610	Pink
Yttrium oxide	Europium	612	Orange red
Calcium borate	Manganese	615	Pink
Strontium magnesium phosphate	Tin	620	Pink
Calcium strontium phosphate	Tin	640	Pink
Magnesium fluorogermanate	Manganese	660	Red
Lithium pentaaluminate	Iron	743	Infrared

* Wavelength in nanometers

Figure 1-12. Color Characteristics of Important Fluorescent Lamp Phosphors

The phosphors used in fluorescent lamps are crystalline inorganic compounds of exceptionally high chemical purity and of controlled composition to which small quantities of other substances (the activators) have been added to convert them into efficient fluorescent materials. With the right combination of activators and inorganic compounds, the color of the emission can be controlled. A typical schematic model for a phosphor is given in Figure 1-10, and an energy diagram for a typical phosphor is shown in Figure 1-11. In the normal state the electron oscillates about position A on the energy curve in Figure 1-11, as the lattice expands and contracts due to thermal vibration. For the phosphor to emit light it must first absorb radiation. In the fluorescent lamp this is chiefly at 253.7 nm. The absorbed energy transfers the electron to an excited state at position B. After loss of excess energy to the lattice as vibrational energy (heat), the electron again oscillates around a stable position C for a very short time, after which it returns to position D on the normal energy curve, with simultaneous emission of a photon of radiation. Stokes' law, stating that the radiation emitted must be of longer wavelength than that absorbed, is readily explained by this model. It then returns to A with a further loss of energy as heat and is ready for another cycle of excitation and emission.

Because of the oscillation around both stable positions A and C, the excitation and emission processes cover ranges of wavelength, commonly referred to as bands.

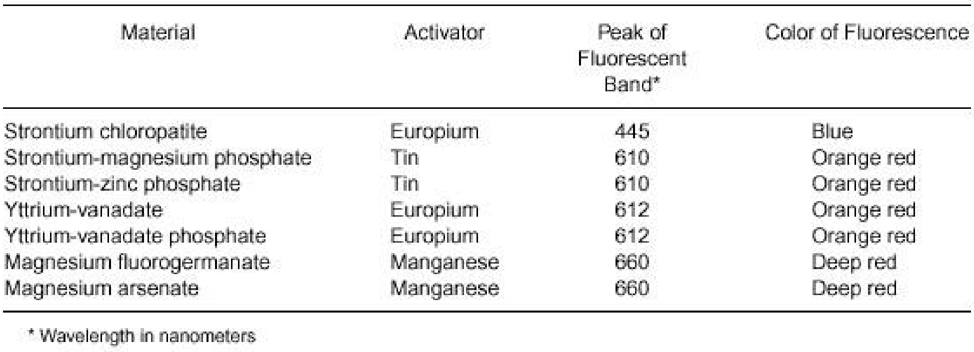
In some phosphors two activators are present. One of these, the primary activator, determines the absorption characteristics and can be used alone, as it also gives emission. The other, the secondary activator, does not enter into the absorption mechanism but receives its energy by transfer within the crystal from a neighboring primary activator. The emitted light from the secondary activator is longer in wavelength than that from the primary activator. The relative amount of emission from the two activators is determined by the concentration of the secondary activator. The phosphors now used in most "white" fluorescent lamps are doubly activated calcium halophosphate phosphors in combination with rare-earth-activated phosphors.

Figure 1-12 shows the characteristic colors and uses of phosphors currently employed in the manufacture of fluorescent lamps. Figure 1-13 gives the characteristics of some phosphors useful with mercury and metal halide lamps. Impurities other than activators and excessive amounts of activators have a serious deleterious effect on the efficiency of a phosphor.[20]

Phosphorescence. In some fluorescent materials, electrons can be trapped in metastable excited states for a time varying from milliseconds to days. After release from these states they emit light. This phenomenon is called phosphorescence. The metastable states lie slightly below the usual excited states responsible for fluorescence, and energy usually derived from heat is required to transfer the electron from the metastable state to the emitting state. Since the same emitting state is usually involved, the color of fluorescence and phosphorescence is generally the same for a given phosphor. In doubly activated phosphors the secondary activator phosphoresces longer than the primary activator, so the color changes with time. Short-duration phosphorescence is important in fluorescent lamps in reducing flicker in alternating current (ac) operation.

Phosphors activated by IR radiation have an unusual type of phosphorescence. After excitation they show phosphorescence, which becomes invisible in a few seconds. However, they retain a considerable amount of energy trapped in metastable states, which can be released as light by IR radiation of the proper wavelength.

Solid Laser.[21-23] Lasers (light amplification by stimulated emission of radiation) are of major interest to illuminating engineers (see Chapter 6, Light Sources). In addition to amplifying light, lasers produce intense, highly monochromatic, well-collimated, coherent light.



Material	Activator	Peak of Fluorescent Band*	Color of Fluorescence
Strontium chloropatite	Europium	445	Blue
Strontium-magnesium phosphate	Tin	610	Orange red
Strontium-zinc phosphate	Tin	610	Orange red
Yttrium-vanadate	Europium	612	Orange red
Yttrium-vanadate phosphate	Europium	612	Orange red
Magnesium fluorogermanate	Manganese	660	Deep red
Magnesium arsenate	Manganese	660	Deep red

* Wavelength in nanometers

Figure 1-13. Color Characteristics of Some Phosphors for Mercury and Metal Halide Lamps

Coherent light consists of radiation whose waves are in phase with regard to time and space. Ordinary light, although it may contain a finite proportion of coherent light, is incoherent because the atomic processes that cause its emission occur in a random fashion. In a laser, however, electronic transitions are triggered (stimulated) by a wave of the same frequency as the emitted light. As a consequence, a beam of light is emitted, all of whose waves are in phase and of the same frequency.

A prerequisite to laser action is a pumping process whereby an upper and a lower electron level in the active material undergo a population inversion. The pumping source may be a light, as in a ruby laser, or electronic excitation, as in a gas laser.

The choice of laser materials is quite limited. First, it must be possible to highly populate an upper electronic level; second, there must be a light-emitting transition from this upper level with a long lifetime; third, a lower level must exist that can be depopulated either spontaneously or through pumping.

Laser construction is as important to laser action, as is the source material. Since light wavelengths are too short to allow building a resonant cavity, long multi-nodal chambers are made with parallel reflectors at each end to feed back radiation until lasing takes place. The effect is to produce well-collimated light that is highly directional.

Consider as an example the pink ruby laser, whose electronic transitions are shown in Figure 1-14, and whose mechanical construction is indicated in Figure 1-15. This laser is pumped by a flash tube (a), and electrons in the ruby (b) are raised from level E_1 to E_3. The electrons decay rapidly and spontaneously from E_3 to E_2. They can then spontaneously move from E_2 to E_1 and slowly emit fluorescent light, $h\nu_{21}$ (see Equation 1-3), or they can be stimulated to emit coherent light, $h\nu_{21}$. The full reflector (c) and the partial reflector (d) channel the coherent radiation, $h\nu_{21}$, until it has built up enough to emit coherent light $h\nu_{21}$ through (d). The fact that this light has been reflected many times by parallel mirrors ensures that it is well collimated. The electrons are then available for further pumping (Figure 1-16).

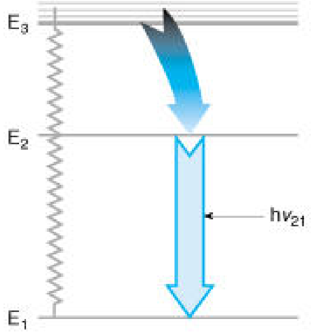


Figure 1-14. Simplified diagrammatic representation of electronic transitions in a ruby laser.

Gas Laser. In a solid laser there are three requirements: a material that reacts energetically to light, a population inversion generated by pumping in energy at the correct level and a growth of the internal energy caused by the reflection of photons within the solid. While the same requirements are met in a gas laser, two other characteristics are available, namely strong, narrow spectral lines and unequal emission at different energy levels. An example of such a gas laser is that containing a mixture of helium and neon (Figure 1-17). Helium is used as the energizing gas because it has a level from which it can lose energy only by collision. This level corresponds to the one at which neon radiates energy in the form of red light. On energizing helium in a gas discharge inside a cavity whose ends are reflecting and that contains both helium and neon, the helium transfers energy by collision with neon. The excited neon emits photons, which begin to amplify by cascading between the two reflecting surfaces until the internal energy is so large that the losses through the partially transmitting mirror become equal to the internal gains and the laser becomes saturated.

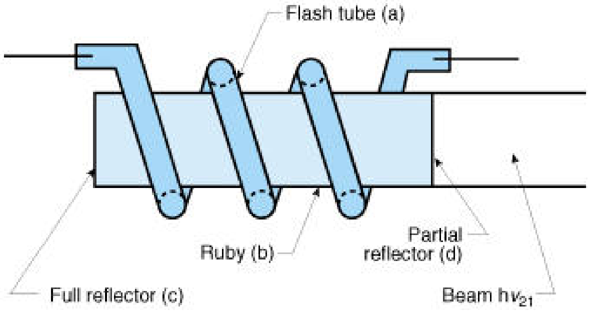


Figure 1-15. Simplified diagram of a ruby laser.

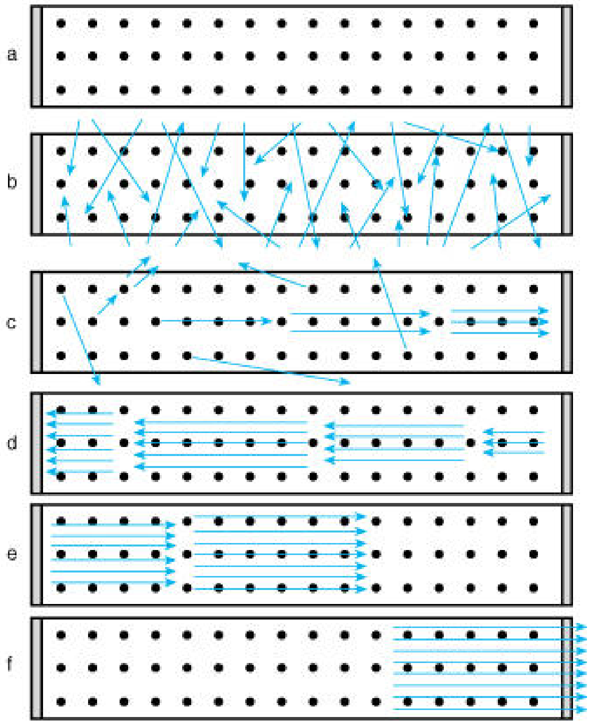


Figure 1-16. Photon cascade in a solid laser. Before the buildup begins, atoms in the laser crystal are in the ground state (a). Pumping light [arrows in (b)] raises most of the atoms to the excited state. The cascade (c) begins when an excited atom spontaneously emits a photon parallel to the axis of the crystal (photons emitted in other directions pass out of the crystal). The buildup continues in (d) and (e) through thousands of reflections back and forth from the silvered surfaces at the ends of the crystal). When amplification is great enough, light passes out at (f).

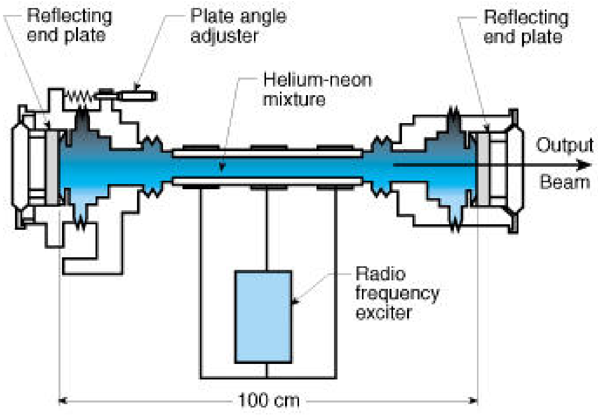


Figure 1-17. Structure of helium-neon gas laser, showing essential parts. Operation of the laser depends on the right mixture of helium and neon to provide an active medium. A radio-frequency exciter puts energy into the medium. The output beam is built up by repeated passes back and forth between reflecting end plates.

Semiconductor Laser. A third type of laser uses a semiconducting solid material where the electron current flowing across a junction between p-type (electron-deficient) and n-type (electron-rich) material produces extra electrons in the conduction band (Figure 1-18). These radiate upon their transition back to the valence band or lower-energy states. If the junction current is large enough, there will be more electrons near the edge of the conduction band than there are at the edge of the valence band, and a population inversion may occur. To use this effect, the semiconductor crystal is polished with two parallel faces perpendicular to the junction plane. The amplified waves can then propagate along the plane of the junction and are reflected back and forth at the surfaces.

Electroluminescence[24]

Certain phosphors convert ac energy directly into light, without using an intermediate step as in a gas discharge, by utilizing the phenomenon of electroluminescence.

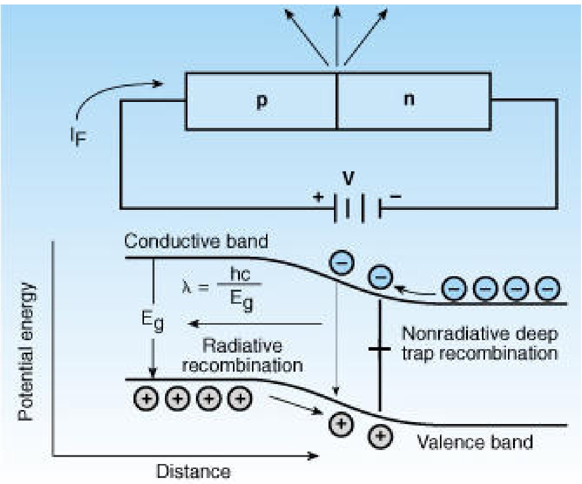


Figure 1-18. Diagram of an LED p-n junction.

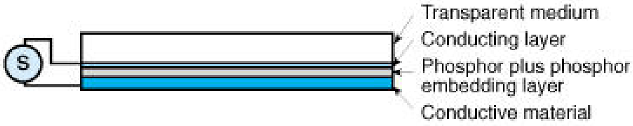


Figure 1-19. Diagrammatic cross section of an electroluminescent lamp.

Electroluminescent Lamps (ac capacitive). An electroluminescent lamp is composed of a two-dimensional area conductor (transparent or opaque) on which a dielectric-phosphor layer is deposited. A second two-dimensional area conductor of transparent material is deposited over the dielectric-phosphor mixture.

An alternating electric field is established between the two conductors with the application of a voltage across the two-dimensional (area) conductors. Under the influence of this field, some electrons in the electroluminescent phosphor are excited. During the return of these electrons to their ground or normal state the excess energy is radiated as light.

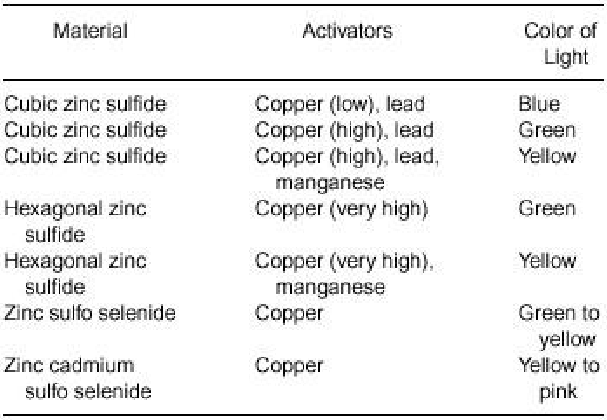
Figure 1-19 shows a cross-sectional view of an electroluminescent lamp. Figure 1-20 gives the properties of some electroluminescent phosphors.

The color of the light emitted by an electroluminescent lamp is dependent on frequency, while the luminance is dependent on frequency and voltage. These effects vary from phosphor to phosphor.

The efficacy of electroluminescent devices is low compared to incandescent lamps. It is of the order of a few lumens per watt.

Light-Emitting Diodes. Light-emitting diodes (LEDs) produce light by electroluminescence when low-voltage direct current is applied to a suitably doped crystal containing a p-n junction (Figure 1-18). The doping is typically carried out with elements from column III and V of the periodic table of elements. When activated by a forward biased current, I_f, the p-n junction emits light at a wavelength defined by the active region energy gap, E_g.

The phenomenon was observed as early as 1923 in naturally occurring junctions, but was not considered practical due to its low luminous efficacy in converting electric energy to light. Efficacy has increased considerably since then such that LEDs are used for signals, indicators, signs, and displays.



Material	Activators	Color of Light
Cubic zinc sulfide	Copper (low), lead	Blue
Cubic zinc sulfide	Copper (high), lead	Green
Cubic zinc sulfide	Copper (high), lead, manganese	Yellow
Hexagonal zinc sulfide	Copper (very high)	Green
Hexagonal zinc sulfide	Copper (very high), manganese	Yellow
Zinc sulfo selenide	Copper	Green to yellow
Zinc cadmium sulfo selenide	Copper	Yellow to pink

Figure 1-20. Properties of Some Electroluminescent Phosphors

When the forward biased current I_f is applied, minority carrier electrons are injected into the p-region and corresponding minority carrier electrons are injected into the n-region. Photon emission occurs as a result of electron-hole recombination in the p-region. Electron energy transitions across the energy gap, called radiative recombinations, produce photons (i.e., light), while shunt energy transitions, called nonradiative recombinations, produce phonons (i.e., heat).

The energy band gap E_g, shown in Figure 1-18, is the separation between the conduction energy band and the valence energy band in the semiconductor crystal. The characteristics of the energy band gap determine the quantum efficiency and the radiative wavelengths of the LED device. For example, the radiative energy wavelength, λ, is given by

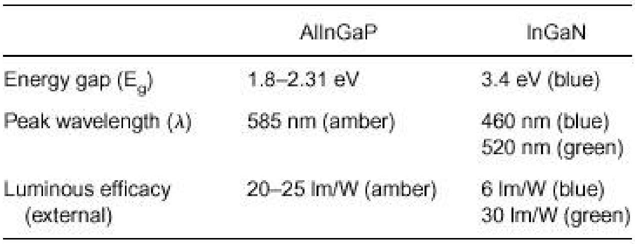
$$\lambda = \frac{hc}{E_g}$$

where *h* is Planck's constant and *c* is the speed of light.

The luminous efficacies of typical AlInGaP LEDs and InGaN LEDs for different peak wavelengths are shown in Figure 1-21.

The efficacy is dependent on the visible energy generated at the junction and losses due to reabsorption when light tries to escape through the crystal. Due to the high index of refraction of most semiconductors, light is reflected back from the surface into the crystal and highly attenuated before finally exiting. The efficacy expressed in terms of this ultimate measurable visible energy is called the external efficacy. The external efficacies are moderate, though the internal efficacies are calculated to be very high. For more information see Chapter 6, Light Sources.

Cathodoluminescence. Cathodoluminescence is light emitted when a substance is bombarded by an electron beam from a cathode, as in cathode-ray and television picture tubes.



	AlInGaP	InGaN
Energy gap (E_g)	1.8–2.31 eV	3.4 eV (blue)
Peak wavelength (λ)	585 nm (amber)	460 nm (blue) 520 nm (green)
Luminous efficacy (external)	20–25 lm/W (amber)	6 lm/W (blue) 30 lm/W (green)

Figure 1-21. Properties of AlInGaP and InGaN LEDs

Miscellaneous Luminescence Phenomena

Galvanoluminescence. Galvanoluminescence is light that appears at either the anode or the cathode when solutions are electrolyzed.

Crystalloluminescence. Crystalloluminescence (lyoluminescence) is observed when solutions crystallize; it is believed to be due to rapid reformation of molecules from ions. The intensity increases upon stirring, perhaps on account of triboluminescence (see below).

Chemiluminescence. Chemiluminescence (oxyluminescence) is the production of light during a chemical reaction at room temperatures. True chemiluminescences are oxidation reactions involving valence changes.

Thermoluminescence. Thermoluminescence is luminescence exhibited by some materials when slightly heated. In all cases of thermoluminescence, the effect is dependent on some previous illumination or radiation of the crystal. Diamonds, marble apatite, quartz, and fluorspar are thermoluminescent.

Triboluminescence. Triboluminescence (piezoluminescence) is light produced by shaking, rubbing, or crushing crystals. Triboluminescent light may result from unstable light centers previously exposed to some source or radiation, such as light, X rays, radium emissions, and cathode rays; centers not exposed to previous radiation but characteristic of the crystal itself; or electrical discharges from fracturing crystals.

Sonoluminescence. Sonoluminescence is light that is observed when sound waves are passed through fluids. It occurs when the fluids are completely shielded from an electrical field and is always connected with cavitation (the formation of gas or vapor cavities in a liquid). It is believed the minute gas bubbles of cavitated gas develop a considerable charge as their surface increases. When they collapse, their capacitance decreases and their voltage rises until a discharge takes place in the gas, causing a faint luminescence.

Radioluminescence. Radioluminescence is light emitted from a material under bombardment from α rays, β rays, δ rays, or X rays.

LIGHT DETECTION

Historically, the eye was used for most photometric assessments. Today, physical detectors have all but eliminated visual assessment for photometric purposes. Two common physical detector types in use today are photodiodes and photomultiplier tubes. Thermal detectors and photoconductive detectors are used for IR measurements.

Photodiodes

Photodiodes are the most commonly used photodetectors for photometry and radiometry. Because of their excellent linearity and stability (freedom from fatigue), they replaced selenium cells, which had been widely used. Photodiodes are based on solid-state p-n junctions that react to external stimuli such as light. Rather than emitting light for the LED p-n junction, photons are absorbed in the p-n junction (Figure 1-18). Detectors are made of specific solid-state materials such as silicon, germanium, and indium-gallium-arsenide (InGaAs). Silicon photodiodes have sensitivity from the UV to near-IR region of the spectrum, and their spectral responsivity generally increases approximately linearly with wavelength throughout the visible region of the spectrum. Combined with a filter for photopic spectral response, silicon photodiodes are commonly employed in photometers. Recent high-quality silicon photodiodes have a dynamic range of eight orders of magnitude or larger and can also be used with special electronics for very low levels where photomultipliers had been required.

Based on the quantum physics of photodiodes, some types of high-quality silicon photodiodes can be used as high-accuracy radiometric standards. This method, called the silicon photodiode self-calibration technique, was introduced during the late 1970s.[25,26] Today, the highest-accuracy radiometric standards employ cryogenic radiometers, but silicon photodiodes are widely used as the most stable transfer standards in radiometry in the visible and near-IR region of the electromagnetic spectrum.

Photomultiplier Tubes

Photomultiplier tubes (PMTs) are widely used as detectors for photometric and radiometric applications requiring high sensitivity (Figure 1-22). A PMT is a vacuum tube with a photocathode, a number of dynodes (i.e., a series of electrodes), and an anode. High voltages are applied between photocathode and dynodes and anode. The first element, the photocathode, is negatively biased and will eject photons (called photoelectrons) in response to radiant energy, due to the photoelectric effect. The photoelectrons hit the next dynodes with higher energy, creating more electrons (secondary electrons), which flow to the next dynode where even more electrons are emitted, eventually causing a cascade effect that multiplies the original number of photoelectrons by several orders of magnitude. Thus, photomultipliers have very high sensitivity. Spectral response ranges depend on the photocathode and the type of glass in the outer envelope, but they generally cover the visible region. Some others extend to the UV and near-IR regions of the spectrum. The stability of the voltage supply to PMT is especially critical to accurate measurements. Silicon photodiodes generally are more stable than PMTs. Photometers employing a PMT generally require an internal calibration source.

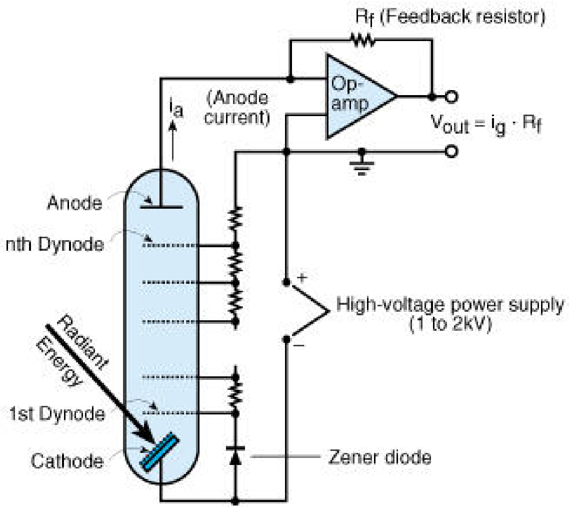


Figure 1-22. Schematic diagram of a photomultiplier and its electric circuit. *From:* G. Wyszecki, and W. Stiles, *Color science.* Copyright © 1982. Reprinted with permission of John Wiley & Sons, Inc.

Thermal Detectors

Thermopiles and bolometers are known as thermal detectors. Thermal detectors have a light-receiving surface coated with black material such as carbon black and gold black. When light is incident on the black surface, it causes the surface temperature to rise due to absorbed radiation. The increase in temperature is proportional to the power of the absorbed radiation. Thermopiles employ a series of thermocouples to measure temperature. Bolometers employ metal or semiconductor materials having temperature-dependent resistance.

Thermal detectors are seldom used in photometry due to their low sensitivity (several orders of magnitude lower than silicon photodiodes) and slow response time. An advantage of thermal detectors, however, is that they have generally nonselective spectral response, and are consequently well suited for radiant power measurements. Thermal detectors are often used in the IR region of the spectrum where other quantum detectors are not available.

Photoconductive Detectors

Photoconductive detectors are semiconductors whose resistance changes directly as a result of photon absorption. These detectors use materials such as lead sulfide (PbS), lead selenide (PbSe), mercury cadmium telluride (HgCdTe), cadmium sulfide (CdS), and cadmium selenide (CdSe). Photoconductive detectors are widely used for IR measurements.

OPTICAL CONTROL[27-29]

Optical control may be provided in a number of ways. All are applications of one or more of the following phenomena: reflection, refraction, polarization, interference, diffraction, diffusion, and absorption.

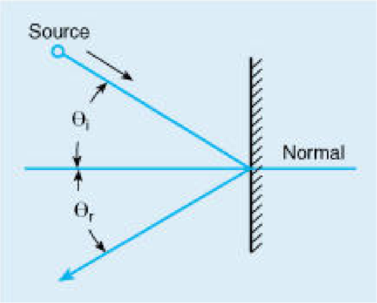


Figure 1-23. The law of reflection states that the angle of incidence, θ_i, equals the angle of reflection, θ_r.

Reflection and Reflectors

Reflection is the process by which a part of the light falling on a medium leaves that medium from the incident side. Reflection may be specular, spread, diffuse or compound, and selective or nonselective. Reflection from the front of a transparent plate is called first-surface reflection, and that from the back is called second-surface reflection. Refraction and absorption by supporting media are avoided in first-surface reflection.

Specular Reflection. If a surface is polished, it reflects specularly; that is, the angle between the reflected ray and the normal to the surface will equal the angle between the incident ray and the normal, as shown in Figure 1-23. If two or more rays are reflected, they may produce a virtual, erect, or inverted image of the source.

Specular Reflectors. Examples of specular reflectors are:

1. Smooth polished metal and aluminized or silvered smooth glass or plastic surfaces. Reflector lamps use first-surface reflection when the bulb interior is coated with a thin metal reflecting mirror surface, as shown in Figure 1-24b. Light reflected from the upper surface of a transparent medium, such as glass plate, as in Figure 1-24a and c, also is an example of first-surface reflection. As shown in Figure 1-25, less than 5% of the incident light is reflected at the first surface unless it strikes the surface at wide angles from the normal. The sheen of silk and the shine from smooth or coated paper are images of light sources reflected in the first surface.

2. Rear-surface mirrors. Some light, the quantity depending on the incident angle, is reflected by the first surface. The rest goes through the transparent medium to a rear-surface mirror coating, where it is reflected as shown in Figure 1-24c.

Reflection from Curved Surfaces. Figure 1-26 shows the reflection of a beam of light by a concave surface and by a convex surface. A ray of light striking the surface at point T obeys the law of reflection (Figure 1-25), and by taking each ray separately, the paths of various reflected rays may be constructed.

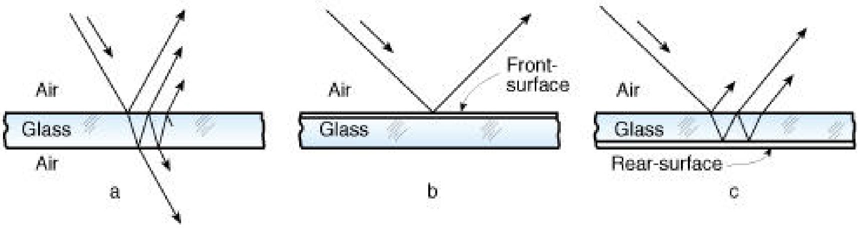


Figure 1-24. Reflections from (a) a transparent medium, such as clear plate glass, and from (b) front-surface and (c) rear-surface mirrors.

In the case of parallel rays reflected from a concave surface, all the rays can be directed through a common point F by properly designing the curvature of the surface. This is called the focal point. The focal length FA is denoted by *f*.

Spread Reflection. If a reflecting surface is not smooth (that is, corrugated, etched, or hammered), it spreads parallel rays into a cone of reflected rays, as shown in Figure 1-27b.

Spread Reflectors. Slightly textured or hammered surfaces reflect individual rays at slightly different angles, but all in the same general direction. These are used to smooth beam irregularities and where moderate control or minimum beam spread is desired.

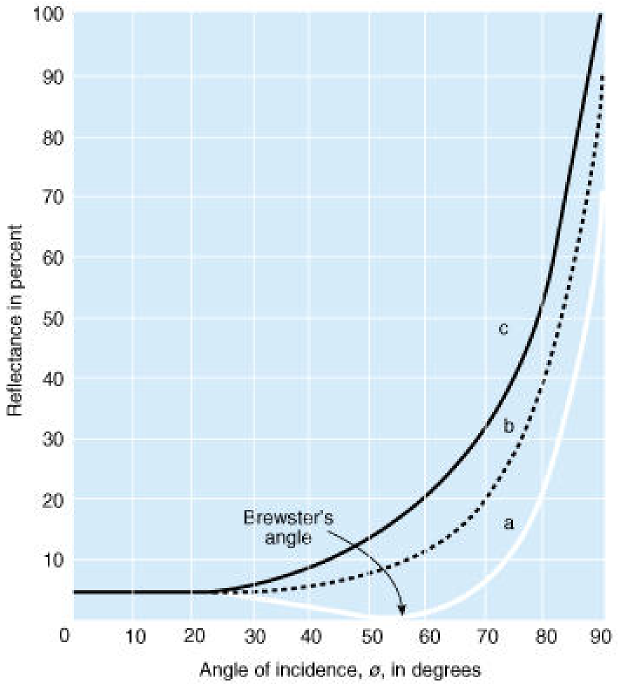


Figure 1-25. Effect of angle of incidence and state of polarization on the percentage of light reflected at an air-glass surface: (a) Light that is polarized in the plane of incidence; (b) unpolarized light; (c) light that is polarized in a plane perpendicular to the plane of incidence.

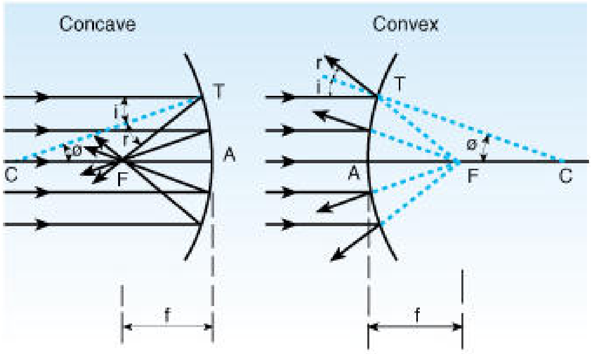


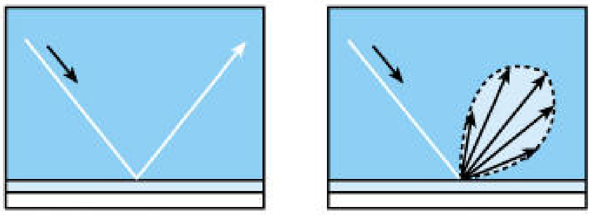
Figure 1-26. Focal point and focal length of curved surfaces.

Corrugated, brushed, dimpled, etched, or pebbled surfaces consist of small specular surfaces in irregular planes. Brushing the surface spreads the image at right angles to the brushing. Pebbled, peened, or etched surfaces produce a random patch of highlights. These are used where wide beams free from striations and filament images are required.

The angle through which reflections are spread can be controlled by proper peening, for which equations describing peen radius and depth are available. Shot- or sandblasting and etching may cause serious losses in efficiency as a result of multiple reflections in random directions.

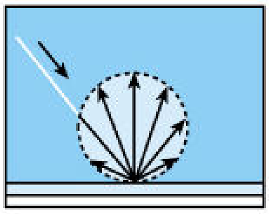
Diffuse Reflection. If a material has a rough surface or is composed of minute crystals or pigment particles, the reflection is diffuse. Each ray falling on an infinitesimal particle obeys the law of reflection, but as the surfaces of the particle are in different planes, they reflect the light at many angles, as shown in Figure 1-27c.

Diffuse Reflectors. Flat paints and other matte finishes and materials reflect at all angles and exhibit little directional control. These are used where wide distribution of light is desired.



a Polished surface, specular

b Rough surface, spread

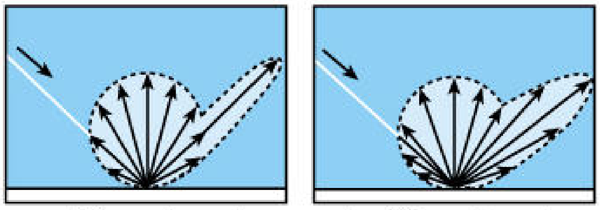


c Matte surface, diffuse

Figure 1-27. The type of reflection depends on the surface: (a) polished surface (specular); (b) rough surface (spread); (c) matte surface (diffuse).

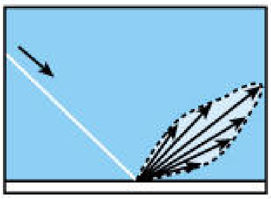
Compound Reflection. Most common materials are compound reflectors and exhibit all three reflection components (specular, spread, and diffuse) to varying degrees. In some, one or two components predominate, as shown in Figure 1-28. Specular and narrowly spread reflections (usually surface reflections) cause the sheen on etched aluminum and semigloss paint.

Diffuse-Specular Reflectors. Porcelain enamel, glossy synthetic finishes, and other surfaces with a shiny transparent finish over a matte base exhibit no directional control except for a specularly reflected ray as shown in Figure 1-28a, with an intensity of approximately 5 to 15% of the incident light.



a Diffuse and specular

b Diffuse and spread



c Specular and spread

Figure 1-28. Examples of compound reflection: (a) diffuse and specular; (b) diffuse and spread; (c) specular and spread.

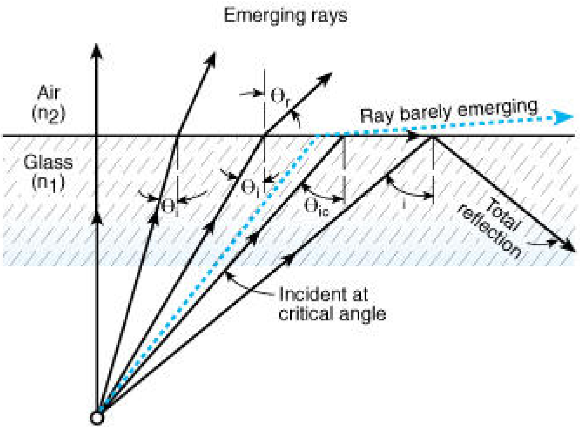


Figure 1-29. Total reflection occurs when sin $r = 1$. The critical angle i_c varies with the medium.

Total Reflection. Total reflection of a light ray at a surface of a transmitting medium (Figure 1-29) occurs when the angle of incidence (θ_i) exceeds a certain value whose sine equals n_2/n_1, the ratio of indices of refraction. If the index of refraction of the first medium (n_1) is greater than that of the second medium (n_2), sin θ_r will become unity when sin θ_i is equal to n_2/n_1. At angles of incidence greater than this critical angle, the incident rays are reflected totally (Figure 1-30). In most glass total reflection occurs whenever sin θ_i is greater than 0.66, that is, for all angles of incidence greater than 41.8° (glass to air). Light piping by edge lighting and light transmission through rods and tubes are examples of total (internal) reflection.

When light, passing through air, strikes a piece of ordinary glass ($n_2/n_1 \approx 1.5$) normal to its surface, approximately 4% is reflected from the upper surface and 4% from the lower surface. Approximately 92% of the light is transmitted. The proportion of reflected light increases as the angle of incidence is increased (Figure 1-25).

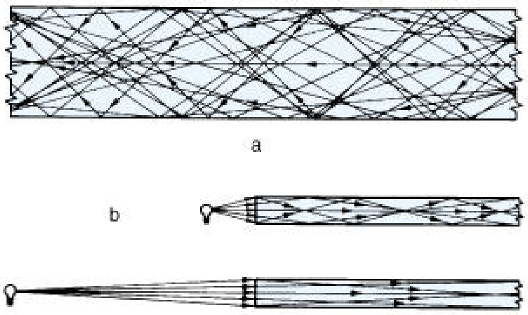


Figure 1-30. Representation of light transmission through a single fiber of a fiber-optics system, showing (a) internal reflections and (b) the effect of light source location on collimation of light.

Fiber Optics. Fiber optics is the branch of optical science concerned with thin, cylindrical glass or plastic fibers of optical quality. Light entering one end of the fiber is transmitted to the other end through the process of total internal reflection (Figure 1-30). In order to prevent light leaking from a fiber, it is coated with a lower-refractive-index material. Large numbers of fibers (from 100 to 1,000,000) can be clustered together to form a bundle. Fiber bundles are of two major types: coherent and noncoherent. The first are used for transmitting images, and each individual fiber is carefully oriented with respect to its neighbors in the entire bundle. Noncoherent bundles have random fiber locations in the bundle, but are suitable for transmitting light between points.

Refraction and Refractors

A change in the velocity of light (speed of propagation, not frequency) occurs when a ray leaves one material and enters another of greater or lower optical density. The speed will be reduced if the medium entered is denser, and increased if it is less dense.

Except when light enters at an angle normal to the surface of the new medium, the change in speed always is accompanied by a bending of the light from its original path at the point of entrance, as shown in Figure 1-31. This is known as refraction. The degree of bending depends on the relative densities of the two substances, on the wavelength of the light, and on the angle of incidence, being greater for large differences in density than for small. The light is bent toward the normal to the surface when it enters a denser medium, and away from the normal when it enters a less dense material.

When light is transmitted from one medium to another, each ray follows the law of refraction. When rays strike or enter a new medium, they may also be scattered in many directions because of irregularities of the surface, such as fine cracks, mold marks, scratches or changes in contour, or because of foreign deposits of dirt, grease, or moisture.

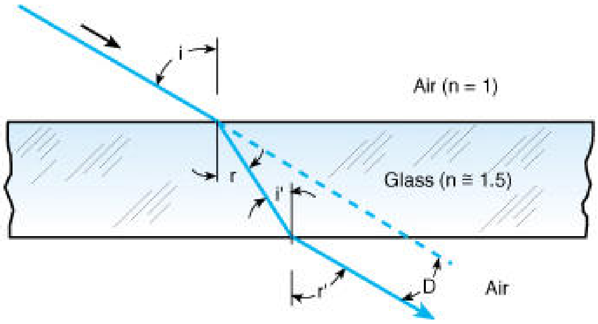


Figure 1-31. Refraction of light rays at a plane surface causes bending of the incident rays and displacement of the emergent rays. A ray passing from a rare to a denser medium is bent toward the normal to the interface, while a ray passing from a dense to a rarer medium is bent away from the normal.

Snell's Law. The law of refraction (Snell's law) is expressed as follows:

$$n_1 \sin \theta_i = n_2 \sin \theta_r \tag{1-7}$$

where

n_1 = index of refraction of the first medium,
θ_i = angle the incident light ray forms with the normal to the surface,
n_2 = index of refraction of the second medium,
θ_r = angle the refracted light ray forms with the normal to the surface.

When the first medium is air, of which the index of refraction usually is taken as 1 (the vacuum value; this approximation is correct to three decimal places), the formula becomes

$$\sin \theta_i = n_2 \sin \theta_r \tag{1-8}$$

The two interfaces of the glass plate shown in Figure 1-31 are parallel, and therefore the entering and emerging rays also are parallel. The rays are displaced from each other (a distance *D*) because of refraction.

Examples of Refraction. A common example of refraction is the apparent bending of a straw at the point where it enters the water in a drinking glass. Although the straw is straight, light rays coming from that part of the straw under water are refracted when they pass from the water into the air and appear to come from higher points.

Prismatic light directors, such as shown in Figure 1-32a and b, may be designed to provide a variety of light distributions using the principles of refraction. Lens systems controlling light by refraction are used in automobile headlights and in beacon, floodlight, and spotlight Fresnel lenses.

Prisms. Consider Snell's law:

$$n_2 = \frac{\sin \theta_i}{\sin \theta_r} = \frac{\text{velocity of light in air}}{\text{velocity of light in a prism}} \tag{1-9}$$

This equation suggests, since the velocity of light is a function of the indices of refraction of the media involved and also of wavelength, that the exit path from a prism will be different for each wavelength of incident light and for each angle of incidence (Figure 1-33). This orderly separation of incident light into its spectrum of component wavelengths is called dispersion.

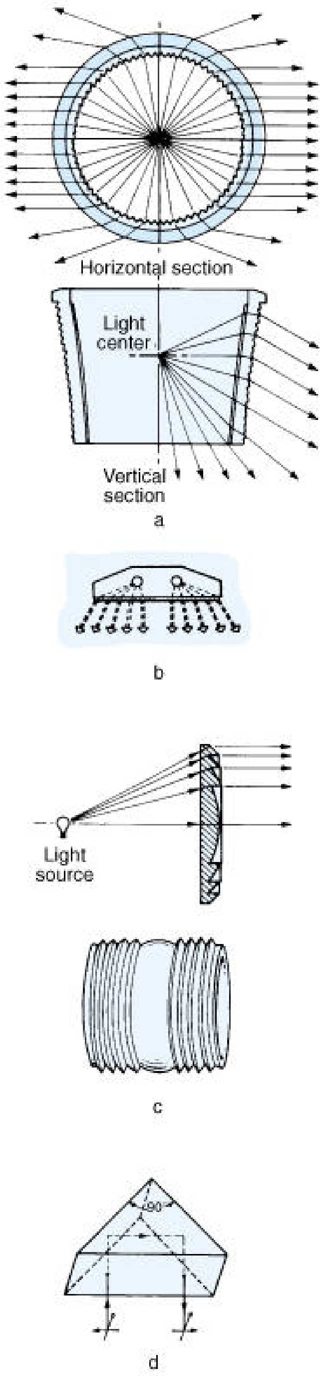


Figure 1-32. Optical systems utilizing the refractive properties of prisms and lenses: (a) Street lighting unit in which the outer piece controls the light in vertical directions (concentrating the rays into a narrow beam at about 75°from the vertical) and the inner piece redirects the light in the horizontal plane. The result is a "two-way" type of intensity distribution. (b) Prismatic lens for a fluorescent lamp luminaire intercepts as much light as possible, redirecting part from the glare zone to more useful directions (c) Cylindrical and flat Fresnel lenses. (d) Reflecting prism.

Refracting Prisms. The degree of bending of light at each prism surface is a function of the refractive indices of the media and the prism angle (A in Figure 1-33). Light can be directed accurately within certain angles by having the proper angle between the prism faces.

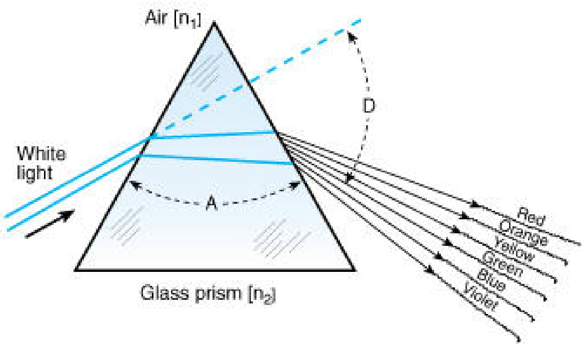


Figure 1-33. White light is dispersed into its component colors by refraction when passed through a prism. The angle of deviation D (illustrated for green light) varies with wavelength.

Refracting prisms are used in such devices as headlight lenses and refracting luminaires. In the design of refracting equipment, the same general considerations of proper flux distribution hold true as for the design of reflectors. Following Snell's law of refraction, the prism angles can be computed to provide the proper deviation of the light rays from the source. For most commercially available transparent materials like glasses and plastics, the index of refraction lies between 1.4 and 1.6.

Often, by proper placement of the prisms, it is possible to limit the prismatic structure to one surface of the refractor, leaving the other surfaces smooth for easy maintenance. The number and the sizes of prisms used are governed by several considerations. Among them are ease of manufacture and convenient maintenance of lighting equipment in service. Use of a large number of small prisms may magnify the effect of rounding of prisms that occurs in manufacture; on the other hand, small prisms produce greater accuracy of light control.

Ribbed and Prismed Surfaces. These can be designed to spread rays in one plane or scatter them in all directions. Such surfaces are used in lenses, luminous elements, glass blocks, windows, and skylights.

Reflecting Prisms. These reflect light internally, as shown in Figure 1-32d, and are used in luminaires and retro-directive markers. Their performance quality depends on the flatness of reflecting surfaces, accuracy of prism angles, elimination of dirt in optical contact with the surface, and elimination (in manufacturing) of prismatic error.

Lenses. Positive lenses form convergent beams and real inverted images as in Figure 1-34a. Negative lenses form divergent beams and virtual, inverted images as in Figure 1-34b.

Stepped and Fresnel Lenses. The weight and cost of glass in large lenses used in illumination equipment can be reduced by making cylindrical steps in the flat surface. The hollow, stepped back surface reduces the total quantity of glass used in the lens. In a method developed by Fresnel, as shown in Figure 1-33c, the curved face of the stepped lens becomes curved rings and the back is flat. Both the stepped and Fresnel lenses reduce the lens thickness, and the optical action is approximately the same. Although outside prisms are slightly more efficient, they are likely to collect more dust. Therefore, prismatic faces are often formed on the inside.

Figure 1-34. Ray path races through lenses: (a) positive; (b) negative.

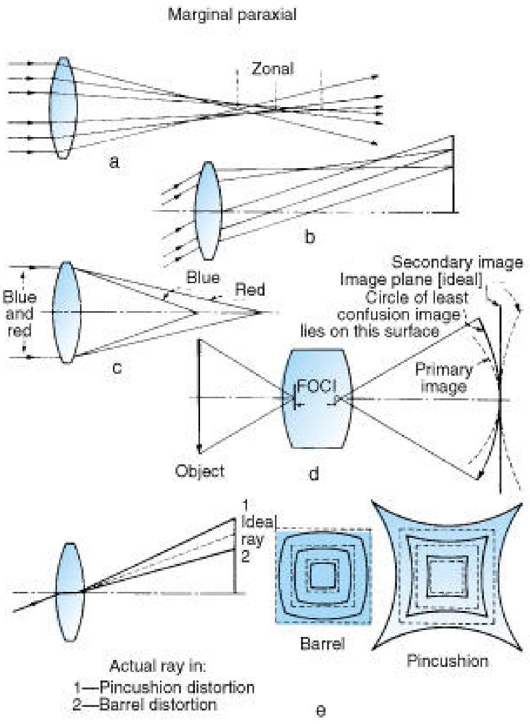


Figure 1-35. Lens aberrations. (a) Spherical aberration: convergence of parallel rays at different focal points at different distances from the axis of a lens. (b) Coma: difference in the lateral magnification of rays passing through different zones of a lens. (c) Chromatism: a difference in focal length for rays of different wavelengths. (d) Astigmatism and curvature: existence in two parallel planes of two mutually perpendicular line foci and a curved image plane. (e) Distortion: a difference in the magnification of rays passing through a lens at different angles.

Lens Aberrations. There are, in all, seven principal lens aberrations: spherical aberration, coma, axial and lateral chromatism, astigmatism, curvature, and distortion (Figure 1-35). Usually they are of little importance in lenses used in common types of lighting equipment. The simpler the lens system, the more difficult it is to correct the aberrations.

Transmission and Transmitting Materials

Transmission is a characteristic of many materials: glass, plastics, textiles, crystals, and so forth. The luminous transmittance τ of a material is the ratio of the total emitted light to the total incident light; it is affected by reflections at each surface of the material, as explained in Figure 1-24, and by absorption within the material. Figure 1-36 lists characteristics of several materials.

Bouguer's or Lambert's Law. Absorption in a clear transmitting medium is an exponential function of the thickness of the medium traversed:

$$I = I_0 e^{-\alpha d} \qquad (1\text{-}10a)$$

$$I = I_0 \tau^d \qquad (1\text{-}10b)$$

where

I = intensity of transmitted light,
I_0 = intensity of light entering the medium after surface reflection,
α = absorption coefficient that characterizes the absorbing properties of a unit thickness of the medium,
τ = transmittance of a unit thickness,
d = thickness of the medium traversed. The optical density D is the common logarithm of the reciprocal of the transmittance:

$$D = \log_{10}(1/\tau) \qquad (1\text{-}11)$$

Spread Transmission. Spread transmission materials offer a wide range of textures. They are used for brightness control, as in frosted lamp bulbs, in luminous elements where accents of brilliance and sparkle are desired, and in moderately uniform brightness luminaire-enclosing globes. Care should be used in placing lamps to avoid glare and spotty appearance.

Figure 1-37a shows a beam of light striking the smooth side of a piece of etched glass. In Figure 1-37b, the frosted side is toward the source, a condition that with many ground or otherwise roughened glasses results in appreciably higher transmittance. For outdoor use, the rough surface usually must be enclosed to avoid excessive dirt collection.

Diffuse Transmission. Diffusing materials scatter light in all directions, as shown in Figure 1-37c. White, opal, and prismatic plastics and glass are widely used where uniform brightness is desired.

Mixed Transmission. Mixed transmission is a result of a spectrally selective diffusion characteristic exhibited by certain materials such as fine opal glass, which permits the regular transmission of certain colors (wavelengths) while diffusing other wavelengths. This characteristic in glass varies greatly, depending on such factors as its heat treatment, composition, thickness, and the wavelengths of the incident light.

Material	Reflectance* or transmittance† (percent)	Characteristics
	Reflecting	
Specular		
Mirrored and optical coated glass	80 to 99	Provide directional control of light and brightness at specific viewing angles. Effective as efficient reflectors and for special decorative lighting effects.
Metallized and optical coated plastic	75 to 97	
Processed anodized and optical coated aluminum	75 to 95	
Polished aluminum	60 to 70	
Chromium	60 to 65	
Stainless steel	55 to 65	
Black structural glass	5	
Spread		
Processed aluminum (diffuse)	70 to 80	General diffuse reflection with a high specular surface reflection of from 5 to 10 per cent of the light.
Etched aluminum	70 to 85	
Satin chromium	50 to 55	
Brushed aluminum	55 to 58	
Aluminum paint	60 to 70	
Diffuse		
White plaster	90 to 92	Diffuse reflection results in uniform surface brightness at all viewing angles. Materials of this type are good reflecting backgrounds for coves and luminous forms.
White paint‡	75 to 90	
Porcelain enamel‡	65 to 90	
White terra-cotta‡	65 to 80	
White structural glass	75 to 80	
Limestone	35 to 65	
	Transmitting	
Glass		
Clear and optical coated	80 to 99	Low absorption; no diffusion; high concentrated transmission. Used as protective cover plates for concealed light sources.
Configurated, obscure, etched, ground, sandblasted, and frosted	70 to 85	Low absorption; high transmission; poor diffusion. Used only when backed by good diffusing glass or when light sources are placed at edges of panel to light the background.
Opalescent and alabaster	55 to 80	Lower transmission than above glasses; fair diffusion. Used for favorable appearance when indirectly lighted.
Flashed (cased) opal	30 to 65	Low absorption; excellent diffusion. Used for panels of uniform brightness with good efficiency.
Solid opal glass	15 to 40	Higher absorption than flashed opal glass; excellent diffusion. Used in place of flashed opal where a white appearance is required.
Plastics		
Clear prismatic lens	70 to 92	Low absorption; no diffusion; high concentrated transmission. Used as shielding for fluorescent luminaires, outdoor signs and luminaires.
White	30 to 70	High absorption; excellent diffusion. Used to diffuse lamp images and provide even appearance in fluorescent luminaires.
Colors	0 to 90	Available in any color for special color rendering lighting requirements or aesthetic reasons.
Marble (impregnated)	5 to 30	High absorption; excellent diffusion; used for panels of low brightness. Seldom used in producing general illumination because of the low efficiency.
Alabaster	20 to 50	High absorption; good diffusion. Used for favorable appearance when directly lighted.

Figure 1-36. Reflecting and Transmitting Materials

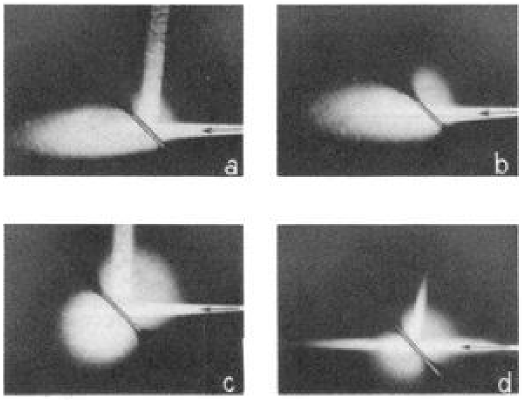


Figure 1-37. (a) Spread transmission of light incident on the smooth surface of figured, etched, ground, and hammered glass samples. (b) Spread transmission of light incident on the rough surface of the same samples. (c) Diffuse transmission of light incident on solid opal and on flashed opal glass, white plastic or marble sheet. (d) Mixed transmission through opalescent glass.

Polarization

Unpolarized light consists of visible electromagnetic waves having transverse vibrations of equal magnitude in an infinite number of planes, all of which oscillate about the line representing the direction of propagation (Figure 1-38). In explaining the properties of polarized light, it is common to resolve the amplitude of the vibrations of any light ray into components vibrating in two orthogonal planes each containing the light ray. These two principal directions are usually referred to as the horizontal and vertical vibrations. The horizontal component of light is the summation of the horizontal components of the infinite number of vibrations making up the light ray. When the horizontal and vertical components are equal, the light is unpolarized. When these two components are not equal, the light is partially or totally polarized as shown in Figure 1-38.

The percentage polarization of light from a source or luminaire at a given angle is defined by the following relation:[29]

$$\text{percent vertical polarization} = \frac{(I_v - I_h)}{(I_v + I_h)} \times 100 \qquad (1\text{-}12)$$

where I_v and I_h are the intensities of the vertical and horizontal components of light, respectively, at the given angle.

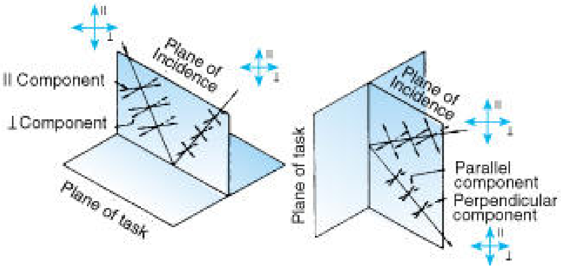


Figure 1-38. Graphical representations of polarized and unpolarized light.

Reference to vertically polarized light or horizontally polarized light can be misleading in that it suggests that all light waves vibrate either horizontally or vertically. A better terminology would be to refer to light at a given instant as consisting of one component vibrating in a horizontal plane and another component vibrating in a vertical plane. A general terminology would identify the light components in terms of two reference planes as shown in Figure 1-39. One plane is the plane of the task at the point of the incident light ray, and the second plane is the plane of incidence: the plane perpendicular to the plane of the task and containing the incident light ray. Then the two components of light would be referred to as the parallel component, or the component in the plane of incidence, and the perpendicular component. This terminology would apply to any task position and would be free of ambiguity with respect to spatial orientation. Polarized light can be produced in four ways: (1) scattering, (2) birefringence, (3) absorption, and (4) reflection and refraction.

Scattering is the mechanism of polarization in daylighting; that is, light from a clear blue sky is partially polarized due to the scattering of light by particles in the air.

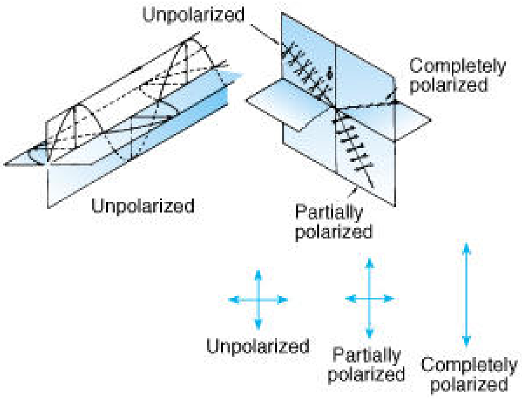


Figure 1-39. Reference planes of a task.

The birefringence, or double refraction property, of certain crystals can be used to achieve polarization. However, the size of these crystals limits this technique to scientific applications; it is not suitable for general lighting.

Polarization by absorption can be achieved by using dichroic polarizers. These polarizers absorb all of the light that is in one particular plane and transmit a high percentage of the light polarized in a perpendicular plane. A high percentage of polarization can be obtained by this method, but with a loss of total luminous transmittance. This type of polarizer is commonly used in sunglasses, where it is oriented to transmit the vertical component of light while suppressing the horizontal (typically reflected) component.

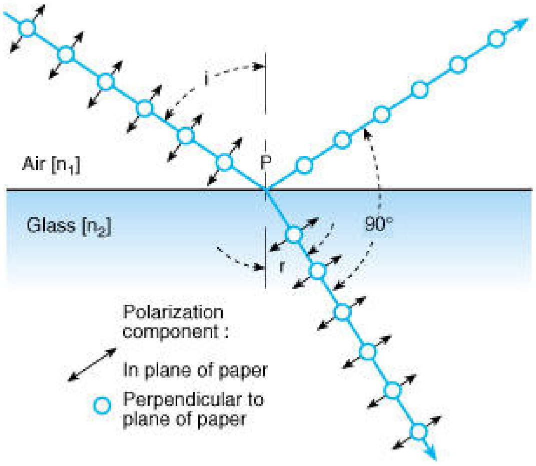


Figure 1-40. Polarization by reflection at a glass-air surface is at a maximum when the angle of incidence *i* plus the angle of refraction *r* equals 90°.

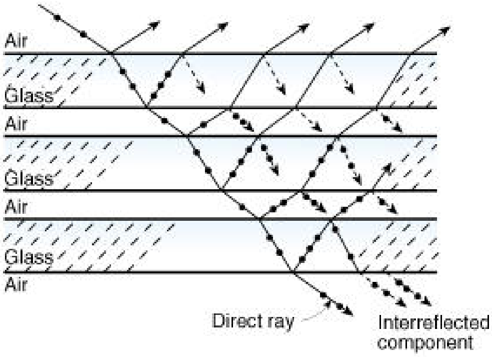


Figure 1-41. Principle of multilayer polarizers.

Light may be polarized by utilizing the reflection characteristics of dielectric materials. When light is reflected from a glass surface, it is partially polarized; a larger percentage of the horizontal component is reflected than of the vertical component. At approximately 57° (Brewster's angle), the reflected light contains only the horizontal component (Figure

1-25). For this one surface, however, only 15% of the incident horizontal component is reflected. The light transmitted through a plate at this angle is made up of the remaining portion of the horizontal component and all the vertical component of the original beam. The resulting light is partially polarized (Figure 1-40). As additional glass plates are added to the system, more and more of the horizontal component is reflected and the transmitted light is more completely vertically polarized. A stack of glass plates, as shown in Figure 1-41, thus becomes a method of producing polarization, and the polarizing effect is greatest at Brewster's angle. The percentage polarization is less at all other angles and is zero for a light ray at normal incidence. Polarization by this method can be obtained by arranging glass or plastic flakes in a suitable material.

Interference

When two light waves of the same wavelength come together at different phases of their vibration, they combine to make up a single wave whose amplitude is between the difference and the sum of the amplitudes of the two, depending on their relative phase. Figure 1-42 illustrates this concept for waves of water in a pool. The waves tend to cancel each other at the node lines. Figure 1-43 shows the resulting interference when light refracts and reflects from thin films. Part of the incident light *ab* is first reflected as *bc*. Part is refracted as *bd*, which again reflects as *de*, and finally emerges as *ef*. If waves *bc* and *ef* have wavefronts of appreciable width, they will overlap and interfere. Optical interference coatings have been used for many years in cameras, projectors, and other optical instruments and can reduce reflection from transmitting surfaces, separate heat from light, transmit or reflect light according to color, increase reflections from reflectors, or perform other light control functions. Naturally occurring examples of interference are soap bubbles and oil slicks. Also, many birds, insects, and fish get their iridescent colors from interference films. The application of interference coatings can significantly increase the reflectance of reflectors and the transmittance of luminaire glass or plastic enclosures.

Low-Reflectance Films. Dielectric optical interference films are applied to surfaces to reduce reflectance, increase transmittance, and consequently improve contrast relationships. Films that are one-quarter wavelength thick with an index of refraction between that of the medium surrounding the glass and that of the glass are used. The hardest and most permanent films are those of magnesium fluoride condensed on the transmitting surface after thermal evaporation in vacuum.

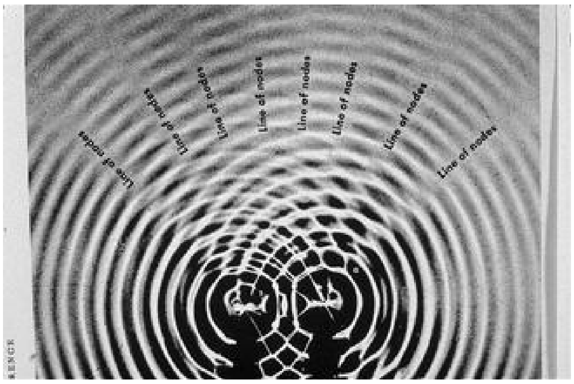


Figure 1-42. Interference.

The usual 4% reflection at uncoated air-to-glass surfaces may be reduced to less than 0.5% at each filmed surface at normal incidence, as a result of the canceling interference between the waves reflected at the air-to-film and film-to-glass surfaces. Dielectric coatings can be made very specific to one reflected wavelength or, by varying the layer's thickness or index of refraction, spread over a wide wavelength interval.

Dichroic (Dielectric) Coating. A multilayer coating that selectively transmits or reflects portions of the spectrum can be added to optical materials. Often called hot or cold mirrors, such coatings are efficient in their selective reflection and transmission, respectively, of IR energy. The coatings are typically designed for incident radiation at 45° or 90° to the coated surface. Deviations from the design angle will change the reflected and the transmitted energy. Undesirable results occur when dichroic filters are used in wide beams of light, since the color varies across the resulting beam.

Hot-mirror lamp envelopes, which reflect IR back to a filament, are used with special tungsten-halogen lamps to increase their efficacy without increasing their wattage and reducing their life.

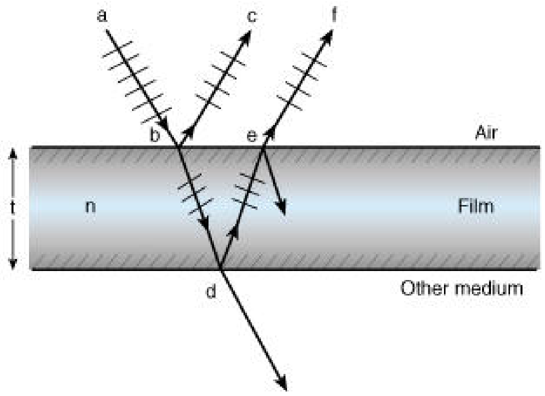


Figure 1-43. Constructive and destructive interference.

Diffraction

Due to its wave nature, light will be redirected as it passes by an opaque edge or through a small slit. The wavefront broadens as it passes by an obstruction, producing an indistinct, rather than sharp, shadow of the edge. The intensity and spatial extent of the shadow depends on the geometric characteristics of the edge, the physical extent (size and shape) of the source, and the spectral properties of the light. Light passing through a small slit will produce alternating light and dark bars as the wavefronts created by the two edges of the slit interfere with one another.

Diffusion

Diffusion is the breaking up of a beam of light and the spreading of its rays in many directions by irregular reflection and refraction from microscopic crystalline particles, droplets or bubbles within a transmitting medium, or from microscopic irregularities of a reflecting surface. Perfect diffusion seldom is attained in practice but sometimes is assumed in calculations in order to simplify the mathematics (Figures 1-27c).

Absorption

Absorption occurs when a light beam passes through a transparent or translucent medium or meets a dense body such as an opaque reflector surface. If the intensity of all wavelengths of the light passing through a transparent body is reduced by nearly the same amount, the substance is said to show general absorption. The absorption of certain wavelengths of light in preference to others is called selective absorption. Most colored objects owe their color to selective absorption in some part of the visible spectrum, with resulting reflection and transmission in other selected parts of the spectrum.

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2

Measurement of Light and Other Radiant Energy

PRINCIPLES OF PHOTOMETRY AND RADIOMETRY

Introduction

Progress in a branch of science or engineering is very much dependent on the ability to measure the associated quantities. Lord Kelvin (1824-1907) expressed this most bluntly:

> *When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.*

The earliest instruments for measuring luminous quantities depended on visual appraisal. Such methods lacked both precision and accuracy, largely because the results were dependent on the individual observers making the measurement. Even for a particular observer, measurement reproducibility was poor because a number of variables influencing the measurements could not be controlled or explained. These visual methods are now rarely used. Today measurements usually are made using calibrated physical instruments that respond to radiant energy.

The human visual system responds only to radiation in a very narrow band of the electromagnetic spectrum. This range of wavelengths is approximately from 380 to 780 nm, depending on the individual observer. It should be kept in mind that for any source of illumination, the radiant energy produced is rarely limited to wavelengths within these boundaries. Although the primary concern in this chapter is the measurement of radiation that results in visual sensation, measurements of radiant quantities outside the visible spectrum are also important because of the nonvisual effects that this radiation produces (see Chapter 5, Nonvisual Effects of Optical Radiation).

Optical radiation generally refers to all radiation that can be measured using certain techniques and equipment (mirrors, lenses, filters, diffraction gratings, prisms). Thus visible, ultraviolet (UV), and infrared (IR) radiation are collectively considered as optical radiation. The measurement of optical radiation is called radiometry. Radiometry is the science of measuring radiant quantities without regard for the visual effects of the radiation. Light almost always refers to wavelengths visible to humans, although sometimes invisible radiation is also called light when describing radiation on plants or on skin.

Photometry, a special branch of radiometry, is the measurement of radiation in terms of human visual response. The Commission Internationale de l'Éclairage (CIE) has established a standard observer response curve (also known as the photopic luminous efficiency function), denoted by $V(\lambda)$ (see Chapter 1, Light and Optics). This standard observer response curve, with its peak at approximately 555 nm, is used as a standard weighting function that, when applied to a spectral power distribution (SPD) of the light being measured, is an approximation of the perceived brightness of that light.

The standardization of the eye spectral sensitivity function is the key to photometry, removing the influence of the observer from the measurements. However, despite the industry-wide acceptance of this function, one should recognize that it represents a compromise in assuming a predictable correlation of physical measurements with visual response, and that there are some circumstances where the system works poorly (see Chapter 3, Vision and Perception).[1]

Photopic, Mesopic, and Scotopic Vision. Vision can be categorized with reference to the adaptive state of the rod and cone photoreceptors of the retina. At very low luminance levels, below approximately 0.01 cd/m^2--the scotopic region--the light energy is insufficient to energize the cone photoreceptor system, but is adequate to stimulate the rod photoreceptor system. The standard luminous efficiency function for scotopic vision is represented by the function $V'(\lambda)$, with its peak near 507 nm (see Chapter 1, Light and Optics).

At luminance levels greater than approximately 3 cd/m^2--the photopic region--colors can be distinguished, and objects having fine detail can be readily seen in the central visual field, where the density of the cone population of the retina is highest, that is, in the fovea. Strictly speaking, the photopic luminous efficiency function applies to visual fields of size 2° or less.

At intermediate luminance levels, between approximately 0.01 and 3 cd/m^2--the mesopic region--both rod and cone photoreceptors contribute to vision. Because of methodological difficulties, there is presently no standard luminous efficiency function for this range of adaptation luminance, although it is of practical importance for roadway, security, and other exterior nighttime conditions (see "mesopic vision" in Chapter 3, Vision and Perception).

Basic Concepts

Units of Measurement. The International System of Units, abbreviated SI, is accepted worldwide as a standard system of units of measurement. In that system, the fundamental photometric quantity, luminous intensity, is expressed in candelas (cd). The magnitude of the candela has a historical basis. At one time called the candlepower, it was defined in terms of flame or filament standards. For practical purposes the terms candela and candlepower are equivalent and, although no longer standard, the latter term is still occasionally used. The current definition of the candela is[2]

> . . . the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 × 10^{12} Hz and that has a radiant intensity in that direction of 1/683 W/sr.

The candela is now formally defined on this radiometric basis because of advances that have been made in this area of metrology. The definition expresses the candela in terms of the watt and the steradian. The steradian is defined as the solid angle subtending an area on the surface of a sphere equal to the square of the sphere's radius. The steradian is an SI supplementary unit. The unit of power, the watt, is likewise not a base SI unit but can be defined as 1 J/s (energy per unit time) or, in base units, 1 $m^2 \times kg \times s^{-3}$. Since the formal definition of the candela is at a single wavelength (at the peak of the photopic luminous efficiency function), $V(\lambda)$ must be applied to measurements of radiant power produced by real sources in order to reduce them to candelas.

In casual discussions, the terms "energy" and "power" often are used interchangeably; in general discussions on measurements of optical radiation, the term "radiant energy" is most commonly used (as in the title of this chapter). However, it should be kept in mind that it is radiant power (that is, the transfer of energy per unit of time) weighted in terms of an eye sensitivity curve, and not radiant energy, that acts as the visual stimulus. The terms "radiant power" and "radiant flux" are used synonymously. There is no photopic weighting inherent in the concept of radiant flux; it is strictly a radiometric quantity. The unit of radiant flux is the watt.

Two important derived units based on the candela are those of luminous flux and illuminance. To understand how these two quantities are related to the luminous intensity, consider a hypothetical model, illustrated in Figure 2-1. An isotropic point source of radiation (that is, one that radiates energy uniformly in all directions) is located at the geometric center of an ideal sphere of zero reflectance (all incident radiation is absorbed). Any portion of the inner sphere's surface receives only direct radiation from the point source itself and no reflected radiation from other parts of the sphere's surface. For a sphere having a radius of one unit, a one-square-unit area on the sphere's surface represents a solid angle of one steradian. (The two-dimensional shape of this area is irrelevant; it might be a circle, in which case the steradian would be represented by a cone. This becomes clearer when the strict definition of luminous intensity is given in terms of a limit.) The luminous intensity of the source in this model is the same in all directions and assumed to be 1 cd. The radiant flux falling on a unit area of the sphere's surface can now be defined to be the luminous flux.

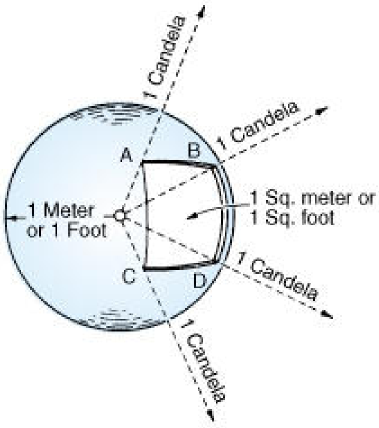


Figure 2-1. Relationship between candelas, lumens, lux, and footcandles. A point source (luminous intensity = 1 cd) is shown at the center of a sphere of unit radius whose surface has a reflectance of zero. The illuminance at any point on the sphere is 1 lx if the radius is 1 m, or 1 fc if the radius is 1 ft. The solid angle subtended by the area ABCD is 1 sr. The flux density is therefore 1 lm /sr, which corresponds to a luminous intensity of 1 cd as originally assumed. The sphere has a total area of 4π m^2 or ft^2, and there is a luminous flux of 1 lm falling on each unit area. Thus, the source provides a total of 4π lm.

The unit of luminous flux is the lumen (lm); the quantity of luminous flux falling on one square unit of the sphere's surface is defined as 1 lm. Note that the unit itself is arbitrary, since the total quantity of flux that will be incident on this area is independent of the size of the sphere. For a sphere of unit radius, it can be shown by simple geometry that the area of the sphere's surface is equal to 4π square units; thus the isotropic source having a luminous intensity of 1 cd produces a total luminous flux of 4π lm.

The concentration of luminous flux falling on a surface, that is, the incident flux per unit area, is called illuminance. To define a unit of illuminance, the sphere must now be given real dimensions because the flux density diminishes with increasing distance from the source. If the sphere's radius is 1 m, the illuminance on the sphere's wall is 1 lm/m^2, or 1 lux (lx). If the radius is 1 ft, the illuminance is 1 lm/ft^2, or 1 footcandle (fc).

Another important luminous quantity is luminance. This quantity is more difficult to grasp, and the sphere model is not useful for that purpose. Luminance relates directly to perceived brightness, that is, the visual effect that illumination produces. Luminance depends not only on the illuminance on an object and its reflective properties, but also on its projected area on a plane perpendicular to the direction of view. There is a direct relationship between the luminance of a viewed object and the illuminance of the resulting image on the retina of the eye. This is analogous to the exposure requirements in photography. The unit of luminance is the candela per square meter (cd/m^2).

Photometric quantities, along with their radiometric counterparts, are discussed and defined in the Glossary.

Radiometric and photometric measurements frequently involve a consideration of the inverse square law (which is strictly applicable only for point sources) and the cosine law.

Inverse Square Law. The inverse square law (Figure 2-2a) states that the illumination E at a point on a surface varies directly with the luminous intensity I of the source, and inversely as the square of the distance d between the source and the point. If the surface at the point is normal to the direction of the incident light, the law may be expressed as follows:

$$E = \frac{I}{d^2} \qquad (2\text{-}1)$$

This equation holds true within 1% when *d* is at least five times the maximum dimension of the source (or luminaire) as viewed from the point on the surface. For a further discussion of this "five-times rule," see Chapter 9, Lighting Calculations.

Cosine Law. The cosine law (Figure 2-2b), also known as Lambert's law, states that the illuminance on any surface varies as the cosine of the angle of incidence. The angle of incidence, θ, is the angle between the normal to the surface and the direction of the incident light. The inverse square law and the cosine law can be combined as follows:

$$E = \frac{I}{d^2}\cos\theta \qquad (2\text{-}2)$$

Cosine-Cubed Law. A useful extension of the cosine law is the cosine-cubed equation (Figure 2-2c). By substituting h/cosθ for d, the above equation may be written

$$E = \frac{I\cos^3\theta}{h^2} \qquad (2\text{-}3)$$

Other Measurable Quantities. The principal photometric quantities have been discussed. These and other quantities of interest are summarized in Figure 2-3 and in the Glossary.

PHOTOMETRY IN PRACTICE: GENERAL REQUIREMENTS

Traceability and Accreditation

Contractual agreements often require that measurements made by laboratories be traceable to national and international measurement standards and that the laboratories be able to support claims of traceability with appropriate documentation and records of equipment used in the measurement process. Such agreements are becoming more common with increasing awareness and adoption of documented quality management systems based on the ISO 9000 series of standards, which states that:

> 4.11.2b [The supplier shall:] identify all inspection, measuring, and test equipment that can affect product quality, and calibrate and adjust them at prescribed intervals, or prior to use, against certified equipment having a known valid relationship to internationally or nationally recognized standards. Where no such standards exist, the basis for calibration shall be documented.

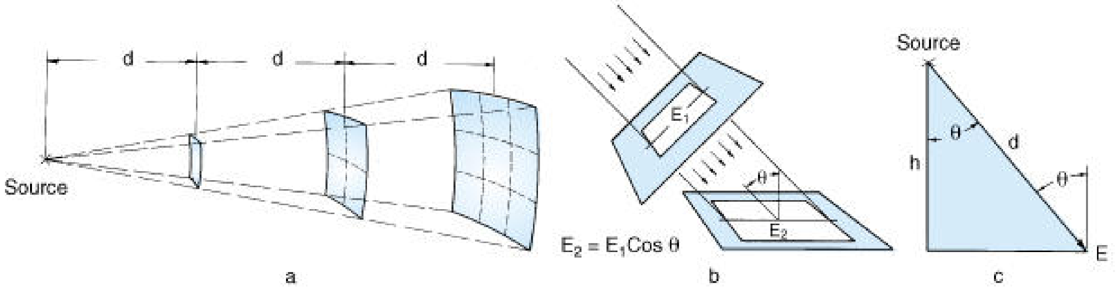
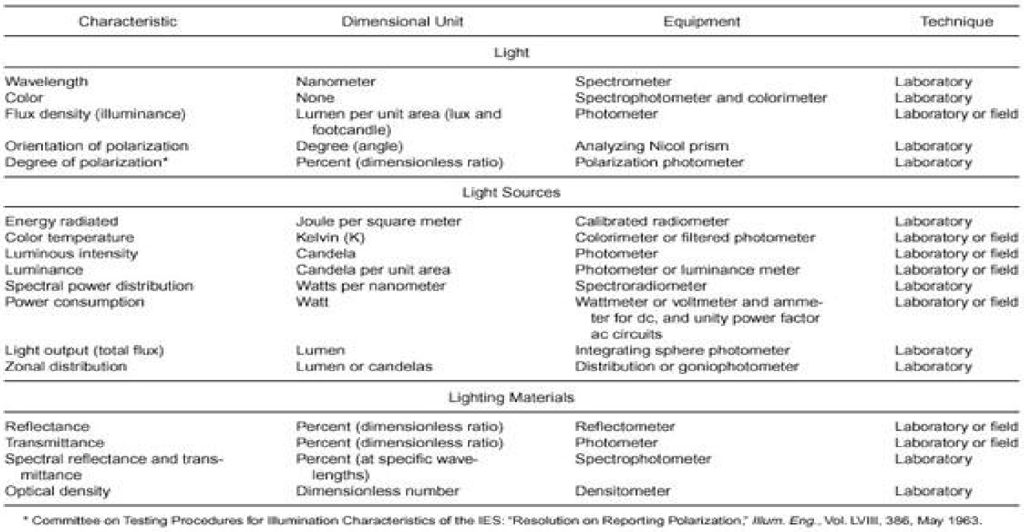


Figure 2-2. (a) The inverse-square law illustrating how the same quantity of light flux is distributed over a greater area, as the distance from source to surface is increased. (b) The Lambert cosine law showing that light flux striking a surface at angles other than normal is distributed over a greater area. (c) The cosine-cubed law explaining the transformation of the formula.

The requirement for traceability[3] involves the ability to relate individual measurement results, with a stated uncertainty, through an unbroken chain of comparisons to a stated reference source. In this way, the reference source is transferred from the national standards through to the end user of the national measurement system.



Characteristic	Dimensional Unit	Equipment	Technique
		Light	
Wavelength	Nanometer	Spectrometer	Laboratory
Color	None	Spectrophotometer and colorimeter	Laboratory
Flux density (illuminance)	Lumen per unit area (lux and footcandle)	Photometer	Laboratory or field
Orientation of polarization	Degree (angle)	Analyzing Nicol prism	Laboratory
Degree of polarization*	Percent (dimensionless ratio)	Polarization photometer	Laboratory
		Light Sources	
Energy radiated	Joule per square meter	Calibrated radiometer	Laboratory
Color temperature	Kelvin (K)	Colorimeter or filtered photometer	Laboratory or field
Luminous intensity	Candela	Photometer	Laboratory or field
Luminance	Candela per unit area	Photometer or luminance meter	Laboratory or field
Spectral power distribution	Watts per nanometer	Spectroradiometer	Laboratory
Power consumption	Watt	Wattmeter or voltmeter and ammeter for dc, and unity power factor ac circuits	Laboratory or field
Light output (total flux)	Lumen	Integrating sphere photometer	Laboratory
Zonal distribution	Lumen or candelas	Distribution or goniophotometer	Laboratory
		Lighting Materials	
Reflectance	Percent (dimensionless ratio)	Reflectometer	Laboratory or field
Transmittance	Percent (dimensionless ratio)	Photometer	Laboratory or field
Spectral reflectance and transmittance	Percent (at specific wavelengths)	Spectrophotometer	Laboratory
Optical density	Dimensionless number	Densitometer	Laboratory

* Committee on Testing Procedures for Illumination Characteristics of the IES: "Resolution on Reporting Polarization," *Illum. Eng.*, Vol. LVIII, 386, May 1963.

Figure 2-3. Some Measurable Characteristics of Light, Light Sources, and Lighting Materials

To assure the end user of traceability and competence throughout the chain, laboratories may seek recognition through assessment and accreditation by a recognized accreditation body. The assessments are discussed in Reference 49, which sets out the general management and technical requirements for calibration or testing laboratories. Laboratories that comply with this guide also comply, by definition, with the requirements of ISO 9002 for the scope of the testing and calibration services covered by their quality management system. The reverse is not true since ISO 9002 registration gives no recognition of the quality of the laboratory's specific measurements. In the United States, a number of federal and private agencies offer calibration laboratory assessment and accreditation services. Contact the National Institute of Standards and Technology (NIST) for additional information. In Canada, contact the National Research Council of Canada (NRC).

Standards[4,5]

Primary Standards. A primary standard is a standard that is designated or widely acknowledged as having the highest metrological quantities and whose value is accepted without reference to other standards of the same quantity. The candela, maintained by the Bureau International des Poids et Mesures (BIPM), is a primary standard.

National (Measurement) Standards. National standards that define radiometric and photometric quantities are maintained by national standard laboratories.[2] These standards typically are developed from international standards through a specified, usually complex, experimental procedure. In North America, measurement standards for lighting, including the candela, are maintained by NIST and NRC. National measurement standards are not directly accessible by other laboratories.

Transfer Standards. Transfer standards are necessary to link the measurement systems of one laboratory (e.g., a national measurement laboratory) to another. They are defined simply as intermediaries used to compare standards. They can be called travelling standards when intended for transport between different locations.

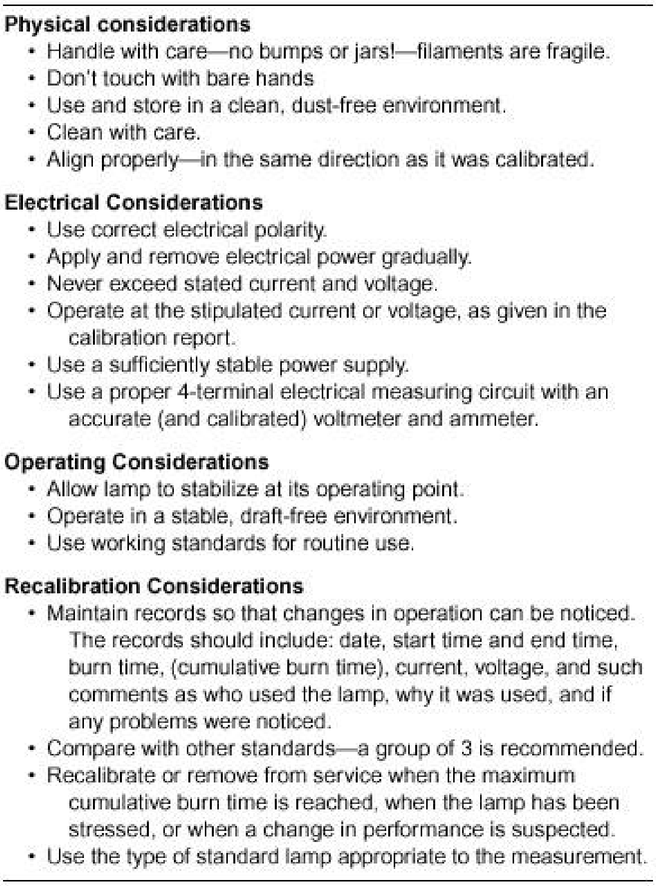
Reference Standards. Reference standards are standards having the highest metrological quantity available at a given location or in a given organization, from which the measurements made there are derived. Reference standards can be derived directly from a national measurement standard or from the reference standards of other laboratories in the calibration chain. They usually are prepared with precise electrical and radiometric measurement equipment.

Working Standards. Working standards are used for routine measurements in a laboratory and usually are prepared and calibrated by that same laboratory from its own reference standard.

The preceding classification of standards is based on the 1993 International Vocabulary of Basic and General Terms in Metrology published by the BIPM. Other nomenclatures have evolved from historical usage. They do not represent the internationally accepted BIPM definitions, and they are not all consistent. For example, the term "primary standard" often is used to designate a standard source that was obtained from a national standards laboratory and that is used only to make other working standards for everyday use in that laboratory. Sometimes, a primary standard is called a "master standard." The term "secondary standard" is also commonly used in private laboratories to distinguish a standard from the one called primary, and sometimes the terms "secondary standard" and "working standard" are used interchangeably. The term "tertiary standard" is used if there are three levels of standards deployed. To avoid confusion, the BIPM definitions should be used.

Documentation of Standards. It is most important to document the lineage of all standards back to the national measurement standards. The documentation should define the calibration procedure and also the state of any influencing environmental conditions. Measurement uncertainty should be documented in accordance with the ISO Guide to the Expression of Uncertainty in Measurement (1995). It should include the uncertainty due to random and systematic error. Without such documentation, measurements cannot be properly compared.

Types of Standards. Incandescent lamps of various wattages are commonly used to establish a traceability chain for photometric quantities outside NIST and NRC. Alternative standards are calibrated detectors from which sources themselves can be calibrated. Such detectors can also be used to calibrate other photometric detectors. Ideal standard lamps and detectors have two principal characteristics: they both are accessible and invariant. In the United States, lamp and detector standards can be purchased from NIST. In Canada, consult NRC. Photometric standards can also be purchased from private laboratories. This adds one or more steps in the calibration chain and increases the uncertainties in the measured quantities. If the supplier of photometric standards is not accredited to ISO/IEC Guide 25 for calibration of the specific type of standard, it is the responsibility of the user of those standards to verify that the supplier has the management and technical procedures in place to carry out the calibrations competently.



Physical considerations
- Handle with care—no bumps or jars!—filaments are fragile.
- Don't touch with bare hands
- Use and store in a clean, dust-free environment.
- Clean with care.
- Align properly—in the same direction as it was calibrated.

Electrical Considerations
- Use correct electrical polarity.
- Apply and remove electrical power gradually.
- Never exceed stated current and voltage.
- Operate at the stipulated current or voltage, as given in the calibration report.
- Use a sufficiently stable power supply.
- Use a proper 4-terminal electrical measuring circuit with an accurate (and calibrated) voltmeter and ammeter.

Operating Considerations
- Allow lamp to stabilize at its operating point.
- Operate in a stable, draft-free environment.
- Use working standards for routine use.

Recalibration Considerations
- Maintain records so that changes in operation can be noticed. The records should include: date, start time and end time, burn time, (cumulative burn time), current, voltage, and such comments as who used the lamp, why it was used, and if any problems were noticed.
- Compare with other standards—a group of 3 is recommended.
- Recalibrate or remove from service when the maximum cumulative burn time is reached, when the lamp has been stressed, or when a change in performance is suspected.
- Use the type of standard lamp appropriate to the measurement.

Figure 2-4. How Does One Treat a Standard Lamp?

Handling, Operation, and Storage of Calibrated Lamps. Calibrated lamps, as with all measurement standards, should be handled, operated, and stored with special care. Figure 2-4 summarizes key considerations in this regard.[6] Additional information for specific measurement applications is available in the IESNA Lighting Measurements Testing and Calculation Guides (LM-5 through to LM-61).

Other Radiometric Standards. Spectral standards are calibrated in terms of radiometric units. These are usually tungsten-halogen lamps, most often calibrated for spectral irradiance. The calibration typically includes portions of the UV and IR regions of the spectrum. Deuterium standards provide greater flux than tungsten-halogen lamps in the UV and extend the calibration range to below 250 nm.

General Methods

Photometric measurements, in general, make use of the basic laws of photometry previously described. Three types of photometric measurement procedures are:

Direct Photometry. Direct photometry consists of the simultaneous comparison of a standard lamp and an unknown light source.

Substitution Photometry. Substitution photometry consists in the sequential evaluation of the desired photometric characteristics of a standard lamp and an unknown light source in terms of an arbitrary reference.

Relative Photometry. To avoid the use of standard lamps, the relative method is widely applied. It consists of the evaluation of the photometric characteristic of a lamp by comparison with the assumed lumen or spectral output of a test lamp.

MEASURING EQUIPMENT

Radiometric measurement instrumentation consists of a detector, a means of conditioning or amplifying the output of the detector, a method of displaying or storing the measurement, and possibly an optical element or system of elements to collect the radiant quantity to be measured. Depending on the geometric relationship between the source and detector, the quantity measured is radiance, irradiance, or radiant intensity (or the corresponding photometric quantities: luminance, illuminance, or luminous intensity).

A radiometer measures radiant power over a wide range of wavelengths that can include the UV, visible, and IR regions of the spectrum. It can employ a detector that is nonselective in wavelength response or one that gives adequate response in a specific wavelength band. Optical filtering can be used to level (flatten) the radiometer's response over a particular range of wavelengths or to approximate a desired function. For example, a number of useful action functions have been defined in the UV range, to which detector responses can be matched. Examples are industrial polymerization functions used for photoresist exposures and for UV curing. Another example is the erythemal effectiveness function (action spectrum) (see Chapter 5, Nonvisual Effects of Optical Radiation). The filtering must compensate not only for the spectral selectivity of the detector but also for the transmission characteristics of any optical components incorporated into the radiometer. Filtering also can be used to suppress the detector's response to radiant power outside the desired range.

A radiometer that has been optically or electronically filtered to approximate a spectral sensitivity function of the fovea is called a photometer. The spectral response characteristic of a photometer is typically designed to match the CIE photopic standard observer. Photometers can also be filtered to provide a response similar to the CIE scotopic standard observer.

A more elaborate radiometer is the colorimeter, which incorporates multiple detectors corrected to respond according to the CIE tristimulus functions. See Chapter 4, Color, for information on the CIE tristimulus functions. Filter colorimeters are used extensively to measure the color characteristics of visible radiation.

Detectors

There is a broad range of detector options available. Choosing the correct detector will depend on the application in terms of spectral response, geometry, and quality. The characteristics of the signal, such as signal-to-noise ratio, amplitude, time response, and frequency bandwidth, all influence the choice of detector. The detector system's linearity range, field of view, noise equivalent power, and window transmission, as well as other factors, affect the measurement.

Thermal Detectors. Thermal detectors include thermopiles, bolometers, and pyroelectric detectors. They produce a voltage proportional to the absorbed radiant power. The absorbing surface of the detector is usually blackened, making it nonselective over a wide range of wavelengths. The signal levels of these detectors are very low, and the detectors are very sensitive to ambient temperature changes. Once used extensively, they are now largely confined to laser light measurements.

Phototubes. A phototube is a vacuum- or gas-filled glass tube containing a photoemissive surface as the source of electrical current. Photons striking the photoemissive surface release electrons by the photoelectric effect, and those electrons are collected by an anode having a higher voltage. The smallness of the resulting current limits the usefulness of vacuum phototubes to applications with high levels of radiant power.

Adding a gas to a phototube and impressing a high voltage on the anode produces an avalanche amplification of the current. Gas-filled phototubes can measure lower levels of radiant power; however, their nonlinear response to power makes them a poor choice for measurement purposes.

The most useful form of phototube is the photomultiplier tube (PMT). PMTs employ a photocathode, which emits electrons when irradiated. The spectral sensitivity of a photomultiplier tube depends on the entrance window and photocathode material, for which many choices are available. Generally the photocathode has either a side-on or a head-on (or end-on) configuration. The side-on type is commonly used in spectroscopy applications and general photometric systems. The head-on type is commonly used for high-energy physics and scintillation counting. When photons strike the photocathode, electrons are emitted and then accelerated through a series of electron multipliers (dynodes), where the signal is greatly multiplied. The electrons are collected by an anode, where the output current is measured. A voltage divider chain connects the elements in the PMT in such a way that electrons are accelerated from one stage to the next. Typical PMT designs employ several to 15 stages of dynodes and produce signal gains from several thousand to hundreds of millions. The voltage required to operate the PMT can vary from 500 to 2000 V, depending on the tube construction and number of dynodes. The overall gain of the PMT is controlled by the voltage applied between elements. A high degree of voltage regulation is required for accurate operation.

PMT detectors differ from solid-state devices in that they produce an output signal (dark current) in the absence of light, due to thermionic emission. The dark current can be reduced by lowering the temperature of the PMT. Most PMTs exhibit gain differences when exposed to magnetic fields or when their orientation in the earth's magnetic field is changed. Magnetic shielding is required in most applications. Most PMTs are shock sensitive, and rough handling can cause failure or loss of previous calibration. All phototubes have highly selective spectral response characteristics. Depending on the photoemissive cathode material used, a phototube can be used for UV, visible, or near-IR measurement; however, a single phototube cannot cover this entire spectral range.

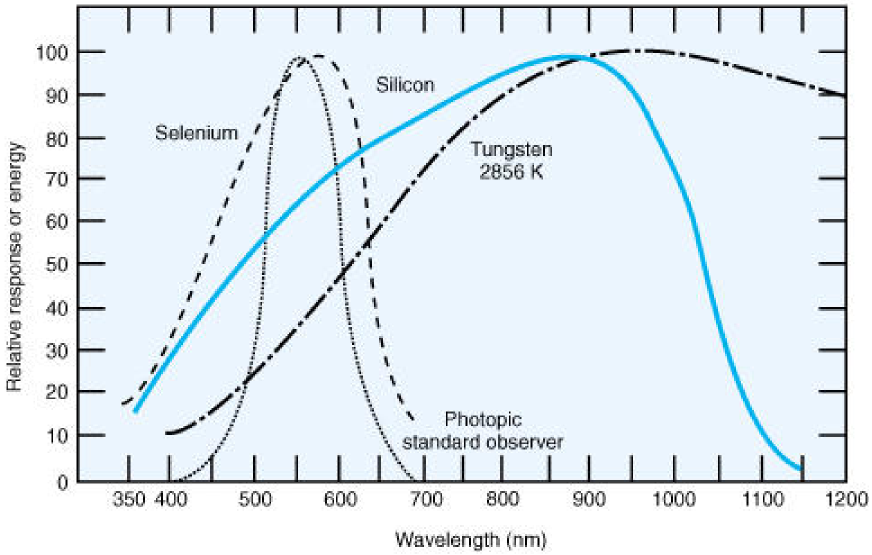


Figure 2-5. The relative spectral sensitivity of selenium and silicon photovoltaic cells, the spectral distribution of tungsten radiation at 2856 K, and the spectral sensitivities assigned to the photopic standard observer. From A. Stimson, *Photometry and radiometry for engineers*. Copyright © 1974. Reprinted by permission of John Wiley & Sons, Inc.

Solid-State Detectors. Solid-state detectors comprise a very large category of detectors incorporating semiconducting materials. All exhibit similar spectral response characteristics; their sensitivity to longer wavelengths increases up to a photon energy limit, where the detector response drops to zero. The useful spectral ranges of solid-state detectors extend from the UV to the far IR region. Some detectors are used in the photovoltaic mode, where the short-circuit current is measured; others are used as photoconductors, that is, a reverse bias voltage is applied and the device is treated as a radiation-sensitive variable resistor. Examples of photoconductive detectors include cadmium sulfide and cadmium selenide cells.

The photovoltaic mode is most frequently used for radiant power measurements because of its inherent linearity of current as a function of incident radiant power level. The quantum nature of photovoltaic detectors makes them ideal for instruments that must perform over a wide range of radiation levels. The selenium barrier-layer cell, an early type of photovoltaic solid-state detector, was widely used in laboratory photometers but is now not recommended in photometers due to nonlinearity, fatigue, and instability. Today silicon photodiodes are commonly used in laboratory and commercial photometers. They offer a broader spectral range than the older selenium-based detectors (Figure 2-

5) and the ability to measure lower levels of radiant power. The silicon photodiode can be combined with a glass filter to match its spectral responsivity to the CIE photopic luminous efficiency curve. Silicon detectors are also used in self-scanning linear arrays, facsimile (fax) machines, spectral measuring instruments, and two-dimensional charge-coupled devices (CCDs). For more information see "Imaging Photometers" below.

Photodiodes perform best when operated as current sources into "zero-impedance" amplifier circuitry. The linearity of silicon photodiodes has been shown to extend over 10 decades with appropriate amplification. Because very small currents are involved (typically 10^{-13} to 10^{-3} A), proper amplifier design is essential for the performance of these photometric instruments. Test methods, classes, and performance characteristics are discussed in more depth in Reference 18.

General Considerations

Spectral Response. The detector is the primary component affecting the spectral response of a radiant-power-measuring instrument. Photomultiplier tubes (PMTs) and silicon photodiodes are the most commonly used detectors in radiometers and photometers. As previously noted, these detectors respond differently to different regions of the spectrum. The spectral range of the detector should be matched to the spectral region to be measured. This can significantly improve sensitivity or relieve the burden of filtering. Photometers require good suppression of both UV and IR and good correction to the CIE luminous efficiency function. The CIE f_1' parameter is the only internationally agreed, illuminant-independent designation for the spectral error of photometers. Contrary to other designations in use, this one does not allow positive departures from $V(\lambda)$ to cancel negative ones and is dependent of the spectral distribution of illuminant A.

Transient Effects. Selenium photovoltaic cells, when suddenly exposed to constant illumination, require a short rise time to reach a stable output and thereafter can decrease slightly over a longer time due to fatigue. By contrast, silicon photodiodes typically exhibit microsecond rise times and no fatigue. The rise and fall times for most photometers employing silicon photodiodes are usually limited by the amplification circuitry. PMTs have nanosecond rise times but exhibit hysteresis, requiring from seconds to minutes to adapt to light-level changes. Precision radiometers and photometers usually employ PMTs with minimum hysteresis.

Temperature Effects. Temperature variations affect the performance of all photodetectors. Selenium photovoltaic cells exhibit significant changes in shunt resistance with temperature, which can interact with external circuit impedance and produce gain changes. In addition, selenium cells can be permanently damaged by temperatures above 50°C (120°F). Silicon photodiodes are considerably less affected by temperature; however, problems can arise from the effects of temperature on detector response. The transmission of the spectral correction filters can also be affected by temperature. Correction factors can be employed when using photovoltaic detectors at temperatures other than their calibrated temperature (typically 25°C), or means can be provided to maintain the instrument temperature near the calibration temperature. Hermetically sealed detectors provide protection against the effects of humidity and some insulation against temperature cycling. Care should be taken that the effects of high temperature or temperature cycling do not damage cemented layers of the detector filter.

PMTs are quite temperature sensitive. Both dark current and noise increase at higher temperatures. Also, the spectral response can vary significantly with temperature changes. Thermoelectric temperature control is frequently used to control the dark current, noise, and spectral characteristics of PMTs.

Effect of Pulsed or Cyclical Variation of Light.[7-13] Electric discharge sources flicker when operated on alternating-current (ac) power supplies (see "Flicker and Stroboscopic Effect" below). Precautions should be taken with regard to the effects of frequency, pulse rate, and pulse width when measuring the luminous properties of lamps.[4,14-17] It cannot be assumed that an instrument will treat modulation of a light source in the same way as the human eye. The internal capacitance of the detector, the response time of the amplifier, and the response of the readout device (whether analog or digital) to pulsating signals must be considered. Special metering circuitry for the integration of pulsed light is available for the measurement of flashing incandescent and pulsed xenon sources.

Instrument Zeroing. It is important to check the photometer or radiometer zeroing prior to taking measurements. For any type of equipment using an amplifier, it might be necessary to zero both the amplifier and the dark current. Where possible, it should be verified that the instrument remains correctly zeroed when the range is changed. Alternatively, any deviation from zero under dark current conditions should be measured and subtracted from the measurements.

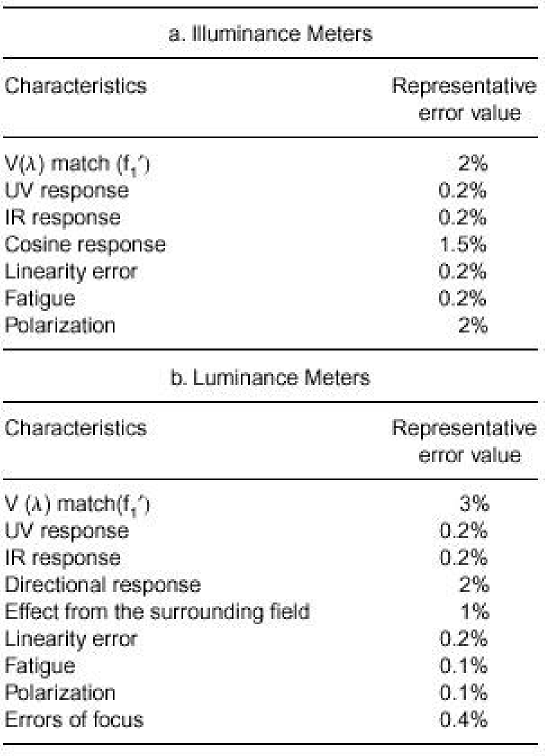
Electrical Interference. With electronic instrumentation, electrical interference can be induced in the leads between the detector and the instrumentation. This effect can be minimized by using filter networks, shielding, grounding, or combinations of the above.

Magnetic Fields. As previously noted, radiometers and photometers containing PMTs can be affected by strong magnetic fields. Commercial instruments containing PMTs use magnetic shielding adequate to protect them from most ambient magnetic fields; however, it is advisable to keep them away from heavy-duty electrical machinery.

Signal Conditioning. The current produced by photovoltaic detectors usually requires amplification and other kinds of signal conditioning. The most common signal conditioning method uses an operational amplifier in a current follower configuration. This configuration provides low input impedance, and the output voltage is the product of the detector current and the feedback resistance. Although PMTs provide much higher signal currents, they are frequently used with a similar circuit to assure linearity. The output of the operational amplifier can drive most displays, whether analog or digital. Frequently, commercial instrumentation provides other kinds of signal conditioning. If signal currents are very low, integration can be used to increase the signal level and to improve the signal-to-noise ratio. Analog-to-digital conversion can be introduced in order to provide an interface to digital computing or a means of signal averaging. Memory may also be provided for data logging. Computing can be done inside the instrument by a microprocessor or by an external computer by means of a data link.

Measuring Instruments

Instruments for photometric measurement are defined by their application. A photometric instrument can be used as a stand-alone system such as an illuminance or luminance meter, or combined with auxiliary equipment such as an integrating sphere to form a lamp measurement photometer system. CIE Publication 69[18] serves as a guide for characterizing the performance parameters of photometers for luminance and illuminance (Figure 2-6a and 2-6b). Digital instrumentation for display and computer data acquisition further enhance the utility of modern photometric systems.



a. Illuminance Meters

Characteristics	Representative error value
V(λ) match (f_1')	2%
UV response	0.2%
IR response	0.2%
Cosine response	1.5%
Linearity error	0.2%
Fatigue	0.2%
Polarization	2%

b. Luminance Meters

Characteristics	Representative error value
V (λ) match(f_1')	3%
UV response	0.2%
IR response	0.2%
Directional response	2%
Effect from the surrounding field	1%
Linearity error	0.2%
Fatigue	0.1%
Polarization	0.1%
Errors of focus	0.4%

Figure 2-6, a and b, is exerpted from CIE Publication No. 69 (1987) and contains a summary of the expected errors of an illuminance meter and a luminance meter, respectively. Representative error values for best available commercial instruments have been estimated for several parameters. For all photometers the V(λ) match is of special importance, and should be as small as possible.

Illuminance Meters

Typical Configurations. The simplest illuminance meters consist of a photodiode with a photopic correction filter. The photodiode is connected to an operational amplifier with a display. These can be bench top, rack mountable, or portable. They can be enclosed in one case, or, as is more common with laboratory photometers, the detector and filter can be in one module that is connected by a cable to a console, at a convenient distance, containing the amplifier and display. The electrical scheme can be anything from a simple amplifier with manual controls to a programmed microprocessor with routines for calibration, measurement, and conversion of display units. Some meters include communication ports for remote operation and data manipulation. Various commercial instruments are shown in Figure 2-7.

Effect of Angle of Incidence (Cosine Effect). Illuminance meters are frequently used to measure the luminous flux density incident on a surface such as a table top, a wall, or a road surface. Part of the light reaching the detector at high angles of incidence is reflected by the cell surface or the filter or cover glass in front of it, and some may be obstructed by the rim of the case surrounding the detector. The resultant error increases with angle of incidence; where an appreciable portion of the flux comes at large angles, values as much as 25% below the true illuminance value can be obtained.

Figure 2-7. Various commercial illuminance meters. (a) Portable illuminance meter with small integrating sphere; (b) laboratory grade system that includes a photometer, a radiometer, and a fiber-optic power meter; (c) multifunction portable illuminance meter with detachable receptor head.

The component of illuminance contributed by single sources at large angles of incidence can be determined by orienting the plane of the detector perpendicular to the direction of the light, and multiplying the reading thus obtained by the cosine of the angle of incidence. Detectors used in most illuminance photometers now have diffusing covers or some means of correcting the readings to a true cosine response. Solutions to the cosine problem include placing over the detector a flashed opal glass, diffusing acrylic disk, or an integrating sphere with a knife edge entrance port. With flashed opal glass and the diffusing acrylic disk at high angles of incidence, however, light will reflect specularly, so that the readings remain too low. This can be compensated by allowing light to enter through the edges of the diffuser. The readings at very high angles will then be too high but can be corrected by using a screening ring. The addition of auxiliary optics to improve cosine response can affect the photometric and directional response. CIE Publication 69 suggests correction methods for these errors.[18]

Leveling. Particularly during photometry of lighting systems where light is received from one or a small number of discrete sources, such as in roadway lighting, accurate leveling of the illuminance meter head is important. Instruments are available in which the detector is gimbal mounted and self-leveling. This removes problems when trying to measure horizontal illuminance on uneven or sloping surfaces.

Figure 2-8. Luminance meter with data processor.

Luminance Meters (Telephotometers)

Luminance meters are essentially illuminance meters with the addition of suitable optics to image an object onto the detector (Figure 2-8). A means of viewing the object is usually provided so that the user can see the area that is being measured as well as the surrounding field. Because of the similarity of this optical system to a telescope, these instruments are also called telephotometers.

Changing the focal length of the objective lens changes the field of view and thus the size of the measurement field. Some systems have apertures of various sizes to further define the measured area. Angular measurement fields from seconds of arc to several degrees can be selected.

Typically, modern luminance meters use silicon photodiodes or PMTs. The amplifier sensitivity may be either manually selected or automatic. Color filters can be incorporated for color measurements, and neutral density filters to extend the dynamic range.

Photodetectors are typically silicon for portable and low-sensitivity instruments and PMT for high-sensitivity instruments. Most instruments have at least a sensitivity dynamic range of four, and many incorporate attenuation screens or neutral-density filters for additional range. Most instruments in current manufacture incorporate digital displays. The electrical scheme can be anything from a simple amplifier with manual controls to a programmed microprocessor with routines for calibration, measurement, and conversion of display units. Some meters include communication ports for remote operation and data manipulation.

Beamsplitter Spot Meters. This type of photometer employs, behind the objective lens, a beamsplitter, which divides the incoming radiation into two paths. Approximately half of the radiation passes through the beamsplitter and is focused on an aperture defining the measurement field. The radiation passing through the aperture can be measured with either a PMT or a solid-state detector. The radiation reflected from the beamsplitter is focused on a reticle having an etched pattern with the same dimensions as the measurement aperture. A viewing system with an eyepiece allows the user to see the field of view and an outline of the area being measured. The reticle must be carefully aligned with the measuring field. Readings are usually in cd/m^2 or cd/ft^2. Some instruments may include colorimetric filter options. Field-of-view capabilities may range from 0.25° to 10°, with sensitivity ranging from 10^{-2} to 10^6 cd/m^2.

Although good measurements can be made with this type of instrument, it does have some noteworthy disadvantages. Among these are loss of illumination to both the detector and the viewer; introduction of polarization, which affects the measurement of polarized sources (see Chapter 1, Light and Optics); and the difficulty of changing apertures and reticles for different measurement fields. In general, a low-cost instrument using a beamsplitter will provide adequate but not exact location of the measured spot.

Aperture Mirror Photometers. Most of the problems of the beamsplitter spot meter are addressed by the aperture mirror photometer. There is no beamsplitter to introduce polarization error or reduce the brightness at either the measuring aperture or the viewed image. The image formed by the objective lens falls on an angled first surface mirror with a through hole for the measuring aperture. The viewing optics are focused on the aperture, which appears as a black circle. The field around the measurement aperture is clearly seen in the eyepiece. This arrangement allows apertures to be changed without the need to change precisely aligned reticles as well. A disadvantage of the aperture mirror photometer is that if a small source is imaged within the measuring aperture, it cannot be seen in the viewing optics. Instruments of this class usually employ high-quality detectors, one or more neutral-density range-multiplying filters, lens options, and some degree of colorimetric capability. They are available with internal microprocessor control and direct reading capability for luminance in several units, for color chromaticity coordinates, and for color temperature. The full-scale sensitivity for the best laboratory instruments ranges from 10^{-4} to 10^8 cd/m^2.

Imaging Photometers.
Recent developments in imaging devices have provided a powerful tool for luminance measurements of complete scenes. Cameras equipped with a charge-coupled device (CCD) array are able to capture and digitize electronic images of visual scenes.[19,20] Providing the proper controls are applied, the digital image can be used to determine the luminance at every point in the scene, corresponding to the pixels of the camera's CCD array. See Figure 2-9.

A complete photometric capture can be carried out and saved in seconds. As the information is provided in digital form, complicated functions of luminance images can be analyzed and reported quickly for uniformity, contrast, spatial characteristics, and other photometric values. Some systems also provide chromaticity values.

This form of photometry requires many factors to be controlled in the instrument and software if accurate results are to be obtained. The CCD and optical attachments must be of high quality. "Field flattening" adjustments are required for all lenses that spatially distort the image to at least some degree. To measure the complete dynamic range of luminances in most interior scenes, earlier 8-bit systems required capture of multiple images at different exposure settings. Today, 16-bit systems are available that cover a dynamic range of over 65,000 : 1. For low luminance capability, cooling of the CCD array is required to reduce noise, to increase the detection limit, and to minimize susceptibility to changes in ambient temperature.

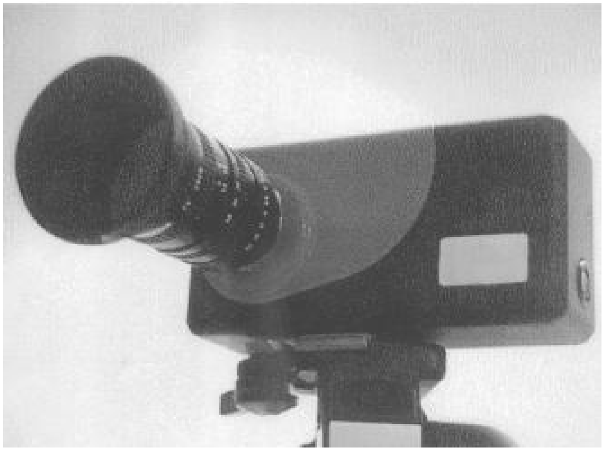


Figure 2-9. The battery-powered 496×288 pixel camera of a commercially available imaging photometric system with zoom lens and dynamic range of 0.05 to 500,000 cd/m^2. The camera connects to a laptop computer by a parallel printer cable. The system can measure the luminances in an entire scene and automatically analyze, archive, and report the results.

Applications for imaging photometers include the energy distribution of lamps (e.g., floodlamps and automobile headlights), production line quality control, luminance uniformity of a projected scene, and complicated analyses of scene illumination.

Reflectometers

Reflectometers are reflectance measurement photometers. Reflectance measurements typically fall under three categories: diffuse, specular, and a mix of specular and diffuse reflectances. The design of the reflectometer and the method of measurement depend on the reflectance properties of the sample material and what part of the reflectance one desires to measure. ASTM [21] provides over seventy standards on color and appearance measurements, some of which employ reflectometers.

Reflectance, the ratio of reflected light to incident light, is not simply a property of a material. Rather, it also depends on the measurement geometry, that is, the spatial relationship between the source and the detector.

The fraction of the incident light reflected is very difficult to determine directly, particularly for diffuse reflection. To bring some order into what could be a chaotic measurement situation, reflectance is usually expressed as a reflectance factor, the ratio of the reflectance of a sample to that of a reflectance standard under the same measurement geometry. Three commonly used reflectance standards are a polished front surface mirror, a polished black glass having a specified index of refraction, and a total diffuse reflector (e.g., $BaSO_4$).

In one method commonly used for measuring total reflectance, the sample is illuminated by a narrow cone of light from a given angle, typically 10° or less from the normal to the sample surface, and the reflected light is collected over the entire hemisphere surrounding the sample. Instruments of this type are said to employ a conical-hemispherical geometry. The hemispherical flux collection is often accomplished by means of an integrating sphere with a detector, arranged so that it does not receive light reflected directly from the sample, but rather views the sphere wall. In this way the signal is proportional to the total flux reflected from the sample.

The same type of instrument also can be used to measure only that part of the light that is diffusely reflected. One example of a sample that one might measure in this way is one with a very smooth dielectric surface that reflects strongly by scattering from pigments or other inclusions beneath the surface. In this case, light specularly reflected from the sample is allowed to escape through an specular subtraction port in the sphere wall, where a light trap can be positioned to absorb the specular reflected beam.

For measuring color, a 45/0 reflectometer is often used to evaluate the spectral character of diffusely reflected light. Figure 2-10a illustrates a typical mechanical layout. The source and the detector are mounted in a fixed relationship in the same housing. Light is incident on the surface from an angle of 45°, and the detector is positioned above and normal to the sample surface.

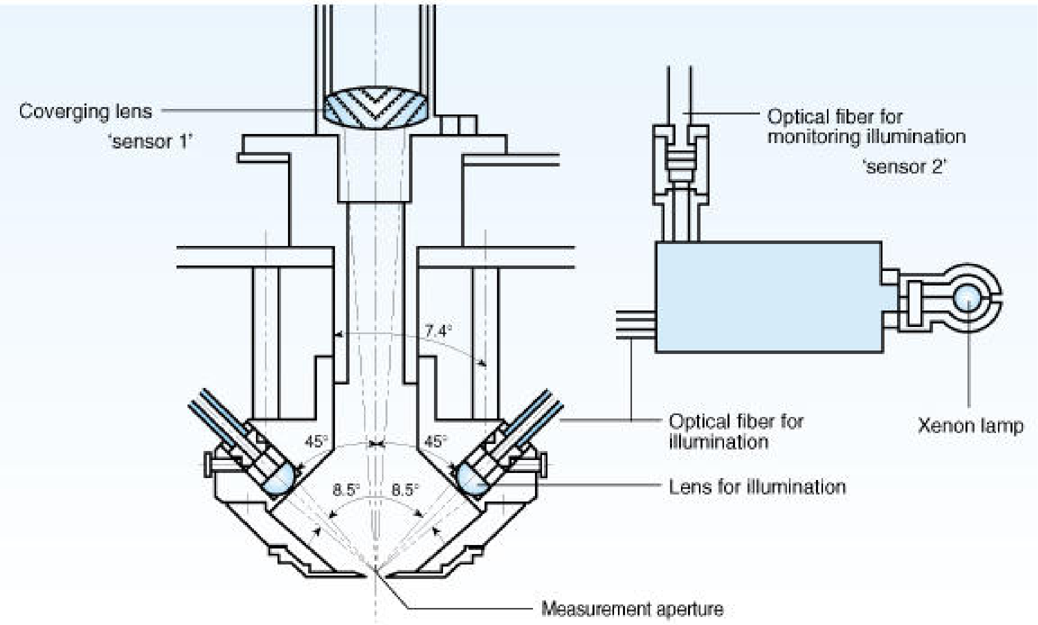


Figure 2-10a. A 45/0 reflectometry geometry.

Reflectances from plane samples can be measured in many ways. One method employs a reflectometer that compares, with the aid of an auxiliary mirror, the incident flux with the flux after two reflections from the sample. Such a reflectometer is often available as an accessory to commercial spectrophotometers. Another method employs a goniophotometer that allows the user to position the light source and detector at any known angle. In some models, the sample holder can also be repositioned. Applications of the goniophotometer include measurements of gloss, luster, and haze.

Another type[22,23] of instrument, a Taylor Baumgartner sphere reflectometer, shown in Figure 2-10b, measures total reflectance. It consists of an integrating sphere, light source, and a photodiode. The sample is placed at the sample port of the integrating sphere. A collimated beam of light is directed onto the sample from approximately 30° to the normal, and the total reflected light, integrated by the sphere, is measured by the photodiode mounted in the sphere wall. The collimated light source is then rotated so that the light is incident on the sphere wall, and a second reading is taken. The sample is in place during both measurements, so that the effect on both readings of the small area of the sphere surface it occupies is the same.[24] The ratio of the first reading to the second is the reflectance of the sample for the conditions of the test. Samples of translucent materials should be backed by a light trap.

Various other instruments are available for measuring reflectance characteristics of materials.[25-29] For any reflectance measurements, the reflectometer geometry employed should be specified, and for reflectance factor measurements the ideal reflector should also be specified.

Spectral Measuring Systems[30]

General Principles. The spectral response of a particular detector can be modified using optical or electronic filters to approximate some desired spectral response function (such as photopic correction). The detector itself, of course, must have adequate sensitivity over the spectral range being measured. Measurements with instruments that use corrected detectors are often called broadband or heterochromic radiometric measurements.

Good-quality detectors are stable over time, and once they are calibrated, accurate measurements can be made without frequent corrections. Broadband instruments are very practical because they are inexpensive and simple to use.

A disadvantage to broadband measurement is that it is difficult to design a filter correction to fit a desired function exactly, and although corrections can be applied, these corrections are usually themselves approximations. This can be a problem for the most critical measurements that demand the highest accuracy. In some circumstances, measurement errors can be very large if the corrections are not appropriately applied or if there is a wide departure in filter correction from the ideal response function at wavelengths where a test source produces significant energy.[3] Sometimes, as in the case of a photopically corrected detector, a very accurate fit can be achieved only at substantial cost, and even if the fit is initially satisfactory, the response of the detector or the filter can, at least theoretically, change over time. Commercial instruments usually provide an approximate correction, stating in their specification how closely their detector conforms to an ideal function. The only meaningful specification, however, is f_1' (Figures 2-6a and b and CIE[18]), the only internationally accepted specification that does not allow negative departures from $V(\lambda)$ to cancel positive departures.

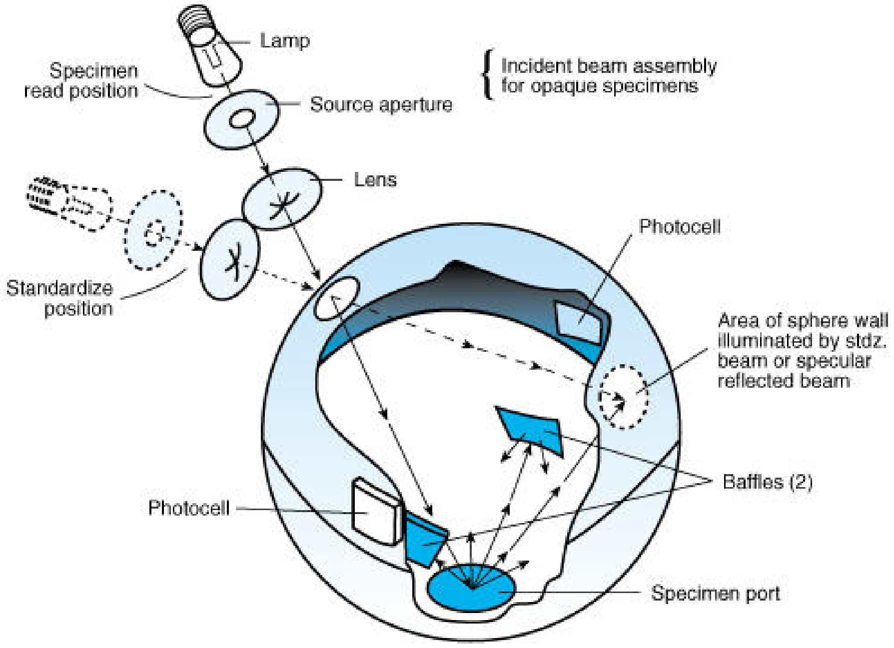


Figure 2-10b. A Taylor Baumgartner sphere reflectometer. From R.S. Hunter, and R.W. Harold, *The measurement of appearance*, 2nd ed. Copyright © 1987. Reprinted by permission of John Wiley & Sons, Inc.

Methods have been developed for correcting measurement errors due to imperfect filter design. For measurements on light sources, errors can be minimized by calibrating a detector with sources that have a known output and a spectral power distribution similar to that of the test source. There are also methods for characterizing a given detector and providing an analytical correction to the measurements.[18]

Perhaps the most important disadvantage of broadband measurement is the loss of specific wavelength information, resulting from the integration of radiation by the detector. Although detailed spectral information is not always needed, for some purposes the complete spectral power distribution (SPD) of a source, that is, the radiant power per unit wavelength as a function of wavelength, must be known.

Spectral measurement systems are capable of determining the SPD in a very small band of wavelengths. The measurement of an SPD is considered fundamental; from these data, absolute radiometric, photometric, and colorimetric properties of a source can be determined.

In comparison with broadband measuring systems, spectral measuring systems are complex and costly. The measurements also are generally more difficult and time consuming to make, often requiring a trained operator.

There are different types of spectral measuring systems to suit specific applications, but they all generally incorporate the following elements: collection optics to receive and limit the radiation to be measured, a monochromator, a detector or detector array, electronics to process the detector or array signal, and some kind of readout or display. The monochromator houses a dispersing element such as a prism or diffraction grating that separates the various wavelengths of the spectrum. The monochromator has an entrance aperture, usually in the form of a rectangular slit, through which the collected radiation enters; maybe some optical elements that image the entrance slit onto the dispersing element(s); and an exit slit through which selected wavelengths of the dispersed radiation pass. A suitable detector or array is positioned at the exit slit to measure the SPD at the source. To make the many measurements necessary for a complete SPD, an automated system is recommended. There are many variations, on the automation scheme, but typical scanning spectrometers incorporate a drive system to scan through a range of wavelengths (such as a means of rotating the monochromator grating) and a means of reading and storing the detector output for each sample, performing the necessary calculations and reporting the results (in printouts or graphs). This entire process is usually carried out using a computer. Detector array spectrometers acquire spectral data simultaneously without mechanical moving parts. Only a computer is needed for data processing.

Types of Systems. A spectroradiometer is used to measure the SPD of light sources and relative spectral responsivities of detectors. Two methods are usually employed. For the first method, the collection fore-optics of a spectroradiometer system directs the radiation into a small integrating sphere or diffuser plate positioned in front of the entrance slit of the monochromator. This geometry is typically used to measure the spectral irradiance of a light source. For the second method, fore-optics of a spectroradiometer system directs radiance from a uniform source integrating sphere, an irradiated highly reflecting diffuse target, or a diffusely emitting lamp into the entrance slit of the monochromator. For the case of calibrating a detector, an appropriate lamp is chosen for its known spectral distribution.

A spectrophotometer is used to determine spectral reflectance and transmittance properties of materials. Measurement results provide a means of examining the color of a material for analysis, standardization, and specification. In addition, it is the only means of color standardization that is independent of material color standards (always of questionable permanence) and independent of the differences in color vision existing among even so-called normal observers. Although called a spectrophotometer because of its principal application to measurements in the visible spectrum, this type of instrument is often designed for measuring UV and near-IR radiation. Some spectrophotometers are, in fact, designed specifically for UV or IR measurements.

Spectroradiometers and spectrophotometers are closely related instruments in that they involve similar dispersion methods, detectors, and automation requirements. The principal difference is that a spectroradiometer performs measurements with the source(s) external to the system itself, whereas a spectrophotometer incorporates internal sources and an integrating sphere or chamber in which test samples are placed. It should be kept in mind that in using spectrophotometers for color standardization, it is really the reflectance properties of the test sample that are being measured and that the actual color appearance is dependent on the SPD of the source being used to evaluate the sample.

Both of these instruments can be used in a spectrograph configuration. In this type of instrument, the exit slit is replaced by photographic film. Because there is no restrictive aperture, the dispersed radiation falls on the film plane and consequently the various wavelengths are spread out simultaneously. The exposed film provides a qualitative "picture" of the spectral components present. This is particularly useful in studying line emission sources, where the lines provide a "signature" of the source or material present. A means of measuring the optical density of the photographic emulsion where the various lines appear can provide quantitative information as to the intensity of the lines. This type of system obviates for mechanical scanning through the spectrum. In the form of a spectroradiometer, the instrument is used as an astronomical tool to evaluate the chemical composition of stellar objects.

In modern instruments, the spectrograph employs diode arrays in the place of a photographic emulsion. Each diode detects incident radiation in a narrow wavelength band. Many modern spectroradiometers and spectrophotometers use this approach. Electronically scanned silicon photodiode arrays provide nearly instantaneous determination of a spectral power distribution. For many applications, array radiometry has replaced scanning systems, with the advantage of much greater measurement speed and the elimination of complex moving parts. For routine work, this reduced measurement time allows many more measurements to be taken, and changes in the SPD of a nonstable test source over time can be monitored. The disadvantages of array systems are that they inherently have more stray light, which is usually the limiting factor, and they do not have the absolute accuracy and sensitivity of the best scanning systems.

Another very simple spectral measuring instrument, used to examine a spectrum visually rather than with a photodetector, is a spectroscope.

Special Considerations. The ranges of spectral response in spectral measurement systems generally depend on the nature of the detector. Scanning spectroradiometers usually employ PMTs because of their high sensitivity. The response of PMTs extends from 125 to 1100 nm.[31] Various types of silicon photodiodes cover the range from 200 to 1200 nm.[31] For IR measurements several compounds can be used: intrinsic germanium (900 to 1500 nm), lead sulfide (1000 to 4000 nm), indium arsenide (1000 to 3600 nm), indium antinomide (2000 to 5400 nm), various types of doped germanium (zinc-doped, 2000 to 40,000 nm), and mercury cadmium telluride (1000 to 13,000 nm).[32-33] The response of nonselective detectors spans a range from the near UV to beyond 30,000 nm.[32,33] Where monochromators utilize diffraction gratings, the grating itself also influences the system response, so gratings must be carefully selected for the range of wavelengths being measured.

For accurate quantitative measurements, the electrical output of the detector must be known as a function of the input radiation to a spectral measuring system. Thus, for processing the electrical output of detectors (voltage, current, or charge), the instrumentation and the measurement method must be carefully selected with regard to a number of parameters, such as signal level (saturation), signal-to-noise ratios, fatigue, linearity, and response times (for rapidly varying signals). Photon counting and charge integration techniques are sometimes used for extremely low radiation levels.[34,35]

The influence of stray radiation on the measurement results must be minimized. This can be accomplished by designing an optical system to prevent unwanted wavelengths from reaching the detector. In all radiometric work there are two types of unwanted radiation: out-of-band radiation (radiation that is not completely dispersed) and higher-order radiation coming from diffraction gratings. Out-of-band radiation can usually be minimized by using a double monochromator (dispersing the radiation twice) or a single monochromator with appropriate filters. This type of unwanted radiation limits the use of diode-array spectroradiometers. It arises primarily from the properties of diffraction, so it cannot be eliminated entirely. Higher-order radiation can also be effectively limited by appropriate filters or by using a double monochromator employing a prism as one of the dispersing elements.

Radiated flux of some wavelengths (mainly UV below 200 nm) is dispersed or absorbed by a layer of air between the radiator and the detector. In this case consideration must be given to the placement of the source and the detector, and to the surrounding medium.

All observed spectroradiometric data (sometimes called raw data) are a function not only of the SPD of the light source but also of the spectral throughput of the optical system, the spectral bandwidth of the monochromator, and the spectral responsivity of the detector. Collectively, these define the system responsivity, which is determined by measuring at each wavelength the output of a calibration or standard source having a known output. Once this function is known, the test-source observed data can be corrected by multiplying each value by the known output of the standard source divided by its observed value at that wavelength.

Photometric Measuring Systems: Basic Equipment Types

Optical Bench Photometers. Optical bench photometers are used for the calibration of instruments for illuminance measurement. They provide a means for mounting sources and detectors in proper alignment and a means for easily determining these relative distances between them. If the source is of known luminous intensity in a specified direction and is distant enough from the detector so that its radiation can be treated spatially as if it were emanating from a point, the inverse square law (Equation 2-1) can be used to compute illuminance.

Distribution Photometers. For characterizing the spatial distribution of illumination from a source, a series of luminous intensity measurements are made on a distribution photometer, which can be one of the following types:

- Goniometer and single detector
- Fixed multiple detector
- Moving detector
- Moving mirror

All types of distribution photometers have advantages and disadvantages. The significance attached to each advantage or disadvantage is dependent on other factors, such as available space and facilities, polarization requirements, and economic considerations.

Goniometer and Single Detector. The light source is mounted on a goniometer, which allows it to be rotated about both horizontal and vertical axes. The luminous intensity is measured by a single fixed detector.

There are several different versions of goniometers. Each is related to the type of source or luminaire being measured and the facilities in which it is located. With the use of computers, the coordinate system of a goniometer system can be easily transformed to another coordinate system;[36] thus consistent data-reporting formats become practical. Figures 2-11a, 2-11b, and 2-11c show three types of goniometer systems, known as Type A, B, and C. Details are provided in LM-35-1989.[37] Types B and C are most commonly used for outdoor and indoor sources, respectively. Note that these designations differ from the Types A, B, and C photometry defined by the CIE.

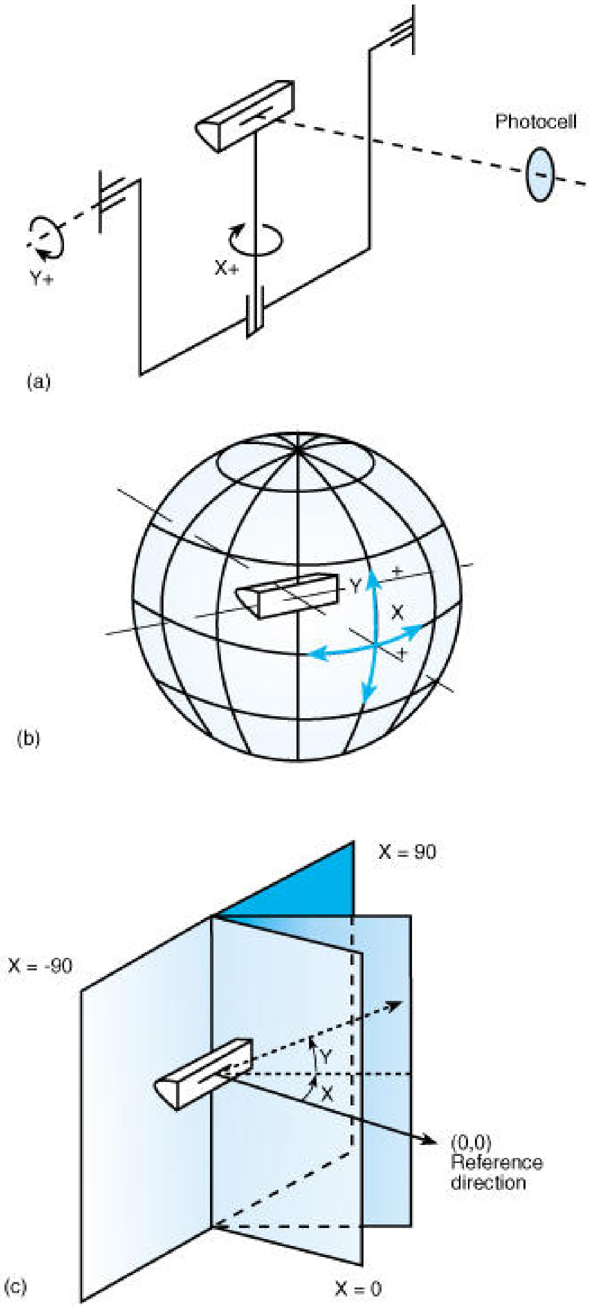


Figure 2-11a. Type A goniometer with fixed horizontal axis: (a) related coordinate systems; (b) representation on a sphere of the *X*-*Y* coordinate system; and (c) *X*-*Y* coordinate system.

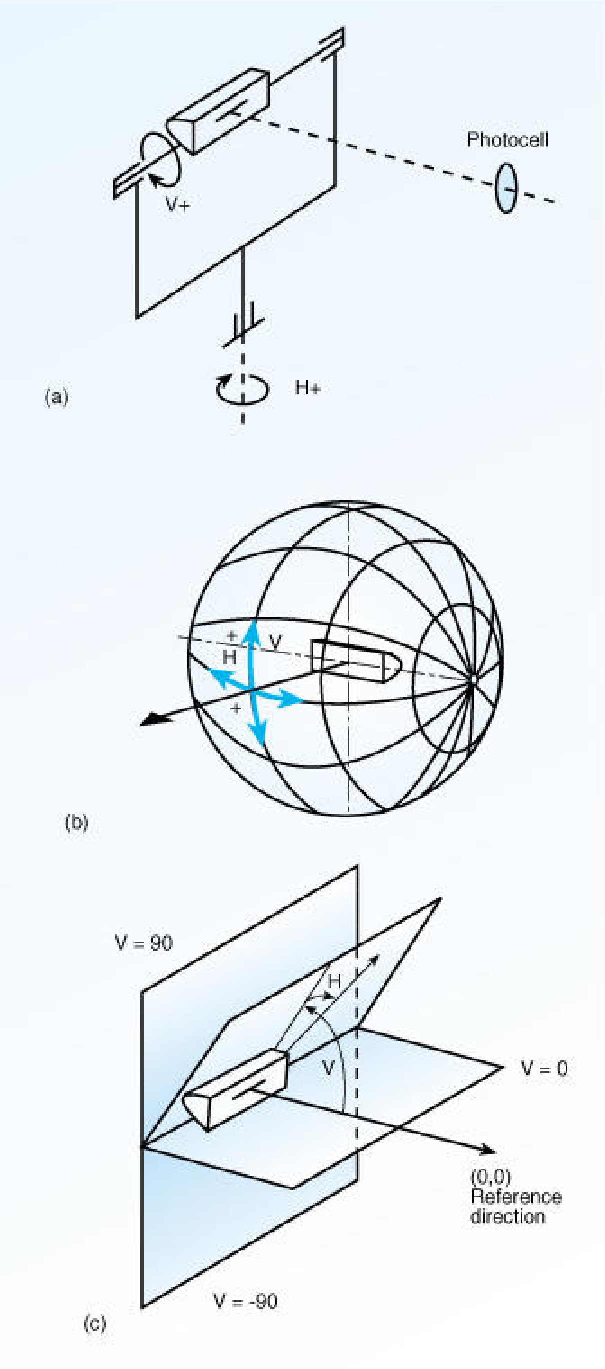


Figure 2-11b. Type B goniometer with fixed vertical axis: (a) related coordinate system; (b) representation on a sphere of the *V-H* coordinate system; and (c) *V-H* coordinate system.

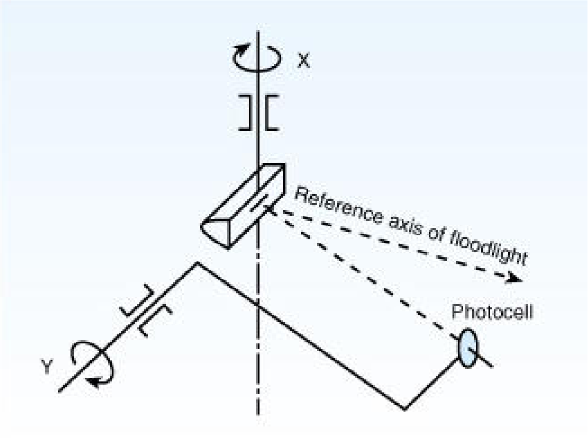


Figure 2-11c. Type C goniometer with a photocell or mirror movable around a horizontal axis.

Fixed-Multiple-Detector Photometer. Numerous individual detectors are positioned at various angles around the light source under test. Readings are taken on each detector to determine the intensity distribution. See Figure 2-12.

Moving-Detector Photometer. This device consists of a detector that rides on a rotating boom or arc-shaped track; the light source is centered in the arc traced by the detector. Readings are collected with the detector positioned at the desired angular settings. Sometimes a mirror is placed on a boom to extend the test distance. See Figure 2-13.

Moving-Mirror Photometer. This is a Type C photometer in which the mirror rotates around the light source, reflecting the light to a single detector. Readings are taken at each desired angle as the mirror moves to that location. See Figure 2-14.

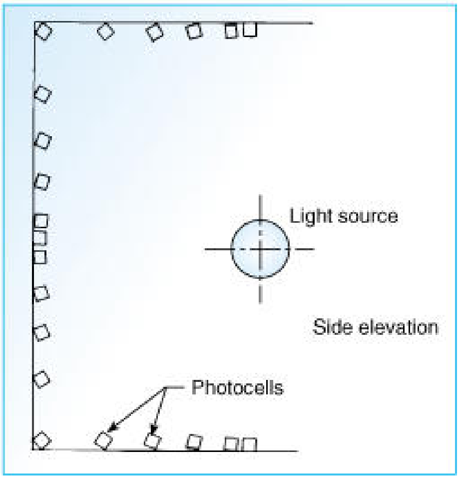


Figure 2-12. Schematic side elevation of a fixed multiple cell photometer.

Integrating-Sphere Photometer. The integrating-sphere photometer is used to measure the total luminous flux from a source (lamp or luminaire). The most common type is the Ulbricht[38] sphere. The theory of the integrating sphere assumes an empty sphere whose inner surface is perfectly diffusing and of uniform nonselective reflectance. Every point on the inner surface then reflects to every other point, and the illuminance at any point is therefore made up of two components: the flux coming directly from the source and that reflected from other parts of the sphere wall. With these assumptions, it follows that the illuminance, and hence the luminance, of any part of the wall due to reflected light only is proportional to the total flux from the source, regardless of its distribution. The luminance of a small area of the wall, or the luminance of the outer surface of a uniformly diffuse transmitting window in the wall, when carefully screened from direct light from the source but receiving light from other portions of the sphere, is therefore a relative measurement of the total luminous flux from the source. Figure 2-15 shows the Ulbricht-type integrating sphere with a high-reflectance, diffuse white interior. Diffuse coatings of lower reflectance are also used. There are advantages as well as disadvantages to the level of reflectance of the sphere coating or material used. An integrating sphere coated with an 80% diffuse reflectance coating is less susceptible to spectral errors due to surface contamination than that from a sphere coated with a diffuse high-reflectance coating. The compromise is reduced efficiency. If a reference source of known output (in terms of luminous flux) is measured in the integrating sphere, a calibration constant can be determined, and thus the luminous flux of a source of unknown output can be determined.

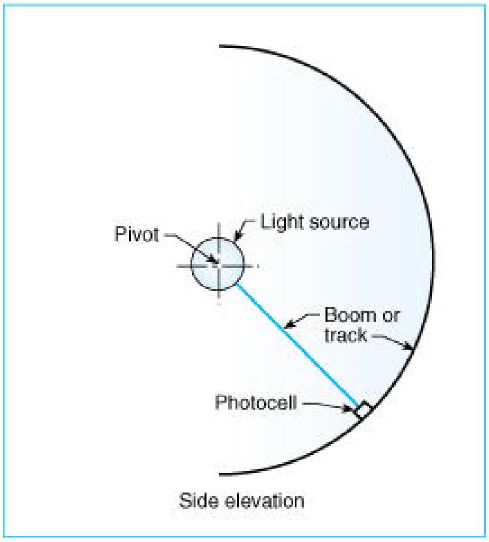


Figure 2-13. Schematic diagram of a moving cell photometer.

The presence of a source having finite dimensions, its supports and electrical connections, the necessary baffles or shields, auxiliary accessories, and the exit window or ports are all departures from the basic assumptions of the integrating-sphere theory. While durable high-reflectance diffuse material (Figure 2-15) and coatings are now available for sphere interiors, none exhibits the ideal properties of perfect diffusivity and spectral nonselectivity. Despite these limitations, if the reference source and the test source are similar in shape, size, surface reflectance characteristics, and light distribution patterns, the errors introduced by a imperfect integration can be small. For accurate measurements of sources dissimilar from the reference source, corrections must be applied for self absorption, spectral mismatch, and spatial nonuniformity, which are inherent with integrating sphere lamp measurement photometry.[4,39-43]

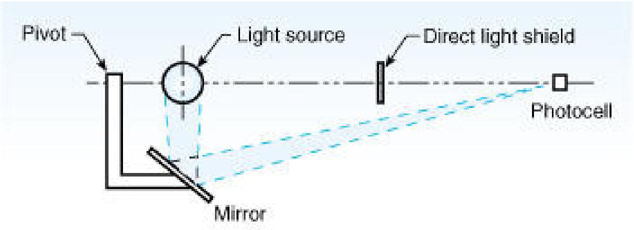


Figure 2-14. Schematic diagram of a moving mirror photometer.

Figure 2-15. Ulbricht-type integrating sphere with diffuse high-reflectance coating, shown here at the National Institute of Standards and Technology (NIST).

Alternatives to the Ulbricht-type integrating sphere exist.[44] Recently, an alternative integrating-sphere method using an external source has been developed at the National Institute of Standards and Technology (NIST) (Figure 2-16).[5] In this geometry the total luminous flux $\varphi_{v,i}$ of a source in the integrating sphere is calibrated against an external reference source calibrated for illuminance, at an aperture outside the integrating sphere. The total luminous flux $\varphi_{v,e}$ of the external source can be determined from *Ea* and aperture area *A*.

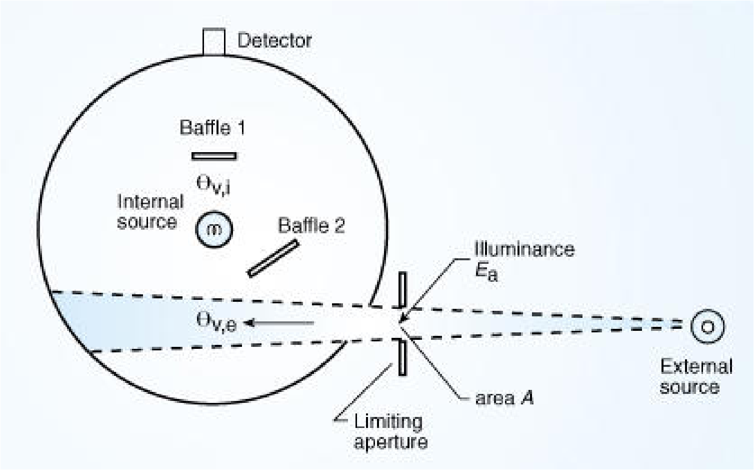


Figure 2-16. Alternative geometry for luminous flux measurements.

Despite its shortcomings, the integrating sphere is an important tool for photometric measurements. It can produce results quickly with a single measurement, and suitable accuracy can be achieved if good instrumentation and proper procedures are employed.

LABORATORY MEASUREMENTS[4,45-48]

Precision and accuracy of laboratory measurements can be consistently attained by correctly following a set of standard procedures and using good equipment. Such procedures are prepared and published by standardizing committees or consensus organizations to serve as a common basis for measurements. IESNA guides provide detailed procedures for the many required electrical and photometric tests for different lamp types. These should be consulted when testing or calibration is being performed. The following information is a general overview of good laboratory practices.

Important elements that standard procedures embody are:

- Controlling the electrical supply characteristics
- Ensuring electrical stability of reference and working standards
- Securely mounting the source
- Minimizing the influence of stray light
- Frequently checking instrument readings
- Stabilizing sources and auxiliaries by operating and maintaining them for a sufficient period of time before measurements are taken
- Compensating for the inherent nonsymmetry of sources and luminaires[48]
- Using instruments that have adequate precision and accuracy to meet the requirements of the test
- Understanding the limitations of instruments used with respect to sensitivity, linearity, and dynamic range
- Ensuring that the instruments are suitably calibrated and maintained

The laboratory must provide an adequate test distance for sealed beam, floodlight, and projector lamp measurements. Space can be conserved by using mirrors to fold the effective test distance. Large integrating spheres can require extending the ceiling height. There must be adequate space surrounding the sphere to gain access to the sphere interior. Temperature and air circulation control are critical requirements for discharge lamp photometry. Cleanliness, provision of suitable electric power, and storage space for lamps, luminaires, and instruments are also important requirements in any photometric laboratory, as are the provision of suitable training and the maintenance of records of the response or output of instruments and reference standards. These and other general guidelines are described in ISO/IEC Guide 25, General Requirements for the Competence of Calibration and Testing Laboratories.[49] See "Traceability and Accreditation," earlier in this chapter.

Electrical Measurements

Photometric results depend on the electrical operating characteristics of the source being tested. For this reason, electrical and photometric measurements are almost always made concurrently, and both sets of data are included in the report.

Electrical measuring instruments should be selected to have current and voltage ratings corresponding to the circuit conditions to be encountered and should give indications of the desired precision and accuracy. Digital instrumentation has replaced analog instruments in most cases, and their use is highly recommended. A comprehensive discussion on instrumentation requirements is given in the IES guide "Selection, Care, and Use of Electrical Instruments in the Photometric Laboratory."[50] If analog instruments are used, it is especially important to consult this reference so that appropriate instrument corrections can be applied for the type of measurement being performed.

Test lamps must be stable before attempting any accurate electrical measurement. It is necessary to season the test lamps in accordance with established procedures.[51]

Instrumentation

Direct-Current Circuits

CURRENT. Current-measuring instruments, or ammeters, are inserted in series with the source and have low impedance, thus adding little to the load on the power supply. They can be self-contained, but this type of instrument might not have sufficient range to directly measure the current through high-wattage sources. When current exceeds several amperes, it is usually determined using an accurate digital voltmeter (DVM) in combination with a calibrated current shunt. The shunt resistance should be sufficient to produce a voltage drop that can be measured accurately, although too high a resistance will lower the current appreciably. For most lamp types, an appropriate shunt resistance is between 0.1 and 1 Ω.

VOLTAGE. The voltage applied to the light source is measured by means of a voltmeter connected in parallel with the source. It should have the highest impedance possible so as not to disturb the circuit. To avoid corrections to compensate for a voltage drop in the ammeter or across the current shunt, the voltmeter is usually connected directly across the load. Often, separate voltage leads are connected to the base of the lamp through special lampholders (kelvin sockets) to avoid voltage drop errors resulting from socket-to-lamp connections.

POWER. Power can be computed as the product of current and voltage.

Alternating-Current Circuits. Instruments that measure alternating current must be compatible with the waveform and frequency of the voltage or current being measured. They should have a frequency response comparable to the supply frequency. For measurements of sinusoidal waveforms, instruments that indicate rms values are satisfactory. For accurate measurements of distorted waveforms that contain harmonics, true rms instruments with frequency response capabilities well above the fundamental frequency are required.

In some ac circuits, a dc component can also be present. In this case a true rms instrument that measures ac and dc must be used; otherwise a separate dc measurement is necessary to determine the true rms value of the voltage or current. Many measuring instruments do not include the dc component in the measurement, and this feature needs to be verified.

As described for dc instruments, ac instruments are connected to the test circuit, and the same impedance considerations apply.

In electrical measurements with high-intensity discharge lamps, some instruments require protection from transient voltages (on the order of 1500 to 4500 V) that occur when lamps are turned on and off. This is usually accomplished by providing switches to connect the instruments into the circuit only after the lamp is operating.

CURRENT. Ammeters for use in ac circuits can be self-contained; however, as with dc circuits, the rating of many meters is too low. A transformer or ac current shunt can be used in combination with a digital meter to achieve a more extensive measuring range. The shunt should be noninductive to avoid current waveform distortion and phase shifting. For this reason, dc current shunts are generally unsuitable.

VOLTAGE. As with dc circuits, voltage can be measured directly across the load using an ac voltmeter. The measuring range can be extended using a potential transformer or voltage divider.

POWER. In a resistive circuit (e.g., an incandescent filament lamp) the ac power load can be either computed as the volt-ampere product or measured directly with a wattmeter. In reactive circuits (e.g., a circuit with a magnetic ballast or where distorted waveforms are present), power is measured with a wattmeter, which measures or computes the real power by averaging all the instantaneous volt-ampere products over one cycle of lamp operation. Such an instrument should be capable of responding to harmonics well above that of the fundamental. Older analog wattmeters require corrections to achieve high accuracy. Modern digital power-measuring instruments are often capable of performing all the necessary electrical measurements and seldom require corrections. The specification of the instrument should be checked to ensure the instrument is capable of accurately measuring the specific waveforms.

Electrical Measurements of Incandescent Lamp Circuits

Incandescent filament lamps usually are measured on a dc circuit where accurate measurement results can be obtained using inexpensive dc power sources and measuring instruments. High-accuracy electrical measurements of incandescent lamps are especially desirable because lamp output is very sensitive to small changes in electrical settings. For example, a 1% change in current through a typical filament lamp results in a 5 to 7% change in light output.

Some incandescent sources have integral electronic components such as diodes and are designed to operate only on ac circuits. True rms instruments that also measure the dc component of a waveform should be used for measurements on this type of source.

Electrical Measurements on Discharge Lamp Circuits. All electric discharge lamps have negative volt-ampere characteristics and must therefore be operated in conjunction with internal or external current-limiting devices, such as resistors or reactors. These are described in Chapter 6, Light Sources. Because of the presence of distorted waveforms, true rms measuring instruments must be used for any measurements on discharge lamp circuits.

Such measurements may involve lamps or ballasts. In some cases the two are inseparable and measurements are made on the combination as a single device. Because of normal manufacturing tolerances, commercial ballasts supply lamps with some variation in voltage and current characteristics, which affect the electrical input and the light output of lamps. To promote uniformity of testing, the International Electrotechnical Commission (IEC), working through the American National Standards Institute (ANSI), the Canadian Standards Association (CSA), and similar national standardizing bodies throughout the world, has established or is establishing standardized testing procedures for determining the electrical characteristics for most of the common types of discharge lamps. These standard tests are performed using reference circuits and reference ballasts that comply with specified electrical requirements.

Where international standards have not been established, national standards are used.

Lamp Testing. Lamp parameters are influenced by many factors. Detailed, accepted testing procedures where these factors are controlled or specified are described in the appropriate IESNA guides.[52-54] Some of the more important conditions affecting lamp test results are listed below:

- Ambient temperature
- Drafts
- Lamp position
- Lamp connections
- Lamp stabilization
- Power-supply characteristics
- Ballast characteristics
- Lamp circuit characteristics

Ballast Testing. Ballast parameters are influenced by many factors. Detailed accepted testing procedures are described in the appropriate ANSI standards.[55-60] Ballast testing requires consideration of some or all of the following.

VOLTAGE RANGE. For most tests, ballasts should be operated at their rated primary voltage.

REFERENCE LAMPS. Some tests on ballasts specify that the ballast shall be operating a reference lamp. Reference lamps are seasoned lamps that, when operated under stated conditions with the specified reference ballast, operate within specified tolerances of electrical values established by the appropriate existing or proposed specifications.

OPEN-CIRCUIT VOLTAGE. This measurement is necessary only for ballasts containing a transformer.

ELECTRODE HEATING VOLTAGE. On ballasts for use with lamps having continuously heated electrodes, the electrode heating voltages are measured with the electrode windings loaded with a specified dummy load.

SHORT-CIRCUIT CURRENT (ballasts for high-intensity discharge lamps). An ammeter is inserted in the circuit in place of the lamp, and the short-circuit current of the ballast is measured.

STARTING CURRENT. Ballasts for instant-start fluorescent lamps, a resistor and ammeter, in series, with a total resistance equivalent to the value specified in the appropriate standard,[55-61] is used instead of the lamp. For ballasts used with high-intensity discharge lamps, the secondary circuit is short-circuited.

ELECTRODE PREHEATING CURRENT (preheat ballasts for fluorescent lamps). This measurement is made with an ammeter connected in series with the lamp electrodes while the lamp is maintained in the preheat condition.

BALLAST OUTPUT FOR FLUORESCENT LAMPS. For preheat and instant start ballasts, specifications are in terms of the power delivered to a reference lamp operated by the ballast under test, as compared with the power delivered to the same lamp by the appropriate reference ballast.

With continuously heated electrodes, specifications are in terms of the light output of a reference lamp operated with the ballast under test, as compared with the light output of the same reference lamp when operated with the appropriate reference ballast.

BALLAST REGULATION FOR FLUORESCENT LAMPS. Relative lamp power input and light output are measured at 90% and 110% of rated ballast input voltage.

FLUORESCENT LAMP CURRENT. The current of a reference lamp should be measured on both the ballast under test and the reference ballast.

For lamps with continuously heated electrodes,[61] unless the internal connections of the ballasts are accessible, measurement of lamp current requires special instrumentation to supply the vector summation of currents in the two leads to an electrode.

Photometric Measurements

Incandescent Filament Lamps.[62] In determining the photometric characteristics of bare incandescent filament lamps, the requirements for electrical measurements previously described should be observed. Test lamps (except series types) are usually measured at rated voltage.

Reference lamps[63-65] can be purchased from or recalibrated by NIST, NRC, or other established national or commercial laboratories. Reference lamps are usually rated for lumens at a current or voltage a little below their nominal rating in order to extend the burning time. The correct color temperature and lamp filament temperature should be maintained. Nickel-plated bases are used on these standards to reduce corrosion and high-resistance problems over their life.

Working standards usually are calibrated against reference standards. They should have the loops of filament supports closed firmly around the filament to avoid the possibility of random short-circuiting of a portion of the filament by the support. They should be adequately seasoned and selected by successive comparisons with reference standards for stability. All standards should be handled carefully to avoid exposure to electrical and mechanical shocks. Exposure to current or voltage above the standard value may alter lamp ratings. For a more in-depth discussion on photometric standards see Reference 42. It is recommended that the voltage applied to the test lamp be ramped up slowly to its final setting (Figure 2-4).

Intensity Measurements. Sources can be measured on an optical bench photometer if either the luminous intensity in a particular direction or a mean horizontal luminous intensity is desired. Lamps standardized for unidirectional measurements are usually marked to indicate the orientation. A common practice is to inscribe a circle and a vertical line on opposite sides of the bulb. The standardized direction is from the circle toward the line, when they are centered on each other, looking toward the receiver.

Total Flux Measurements. Most routine photometric measurements on incandescent filament lamps are for total light output or total luminous flux and are made in a sphere (Figure 2-15). Best results are obtained when the standard lamp has approximately the same physical size, lumen output, color temperature, and location in the sphere as the test lamp.

Lamp depreciation measurements usually are taken at 70% of rated lamp life. By this time, some blackening of the bulb is likely. This blackening can lead to errors in photometric measurements taken with an integrating sphere because the blackened area of the lamp absorbs some of the interreflected light. To overcome these errors, a third lamp, commonly called the "absorption," "comparison," or "auxiliary" lamp, should be installed in the sphere so that it is shielded from both the integrating sphere detector and the test lamps. Successive readings should be taken with the absorption lamp operating: first with the reference (known) lamp installed but not operating, then with the blackened (aged) lamp installed but not operating. The difference between these readings represents the light absorbed by the blackened lamp and can be used to correct the values given by the integrating sphere. The same general procedure can be followed in most cases where the characteristics of the integrator are altered during the test by the introduction of light-absorbing elements (see the above discussion on "Integrating-Sphere Photometer").

Photometry of Discharge Lamps.[66-68] As with incandescent lamp measurements, the photometric characteristics of discharge lamps usually are determined in conjunction with electrical measurements, whose general requirements have been given. The substitution method is normally employed for photometric measurements. Complete, detailed photometry procedures can be found in IESNA test guides.[52-54]

Equipment

BALLASTS. When a lamp is measured for rating purposes, it should be operated on the appropriate reference ballast. If no standard exists, the ballast should comply with the general lamp requirements. In general practice, photometric measurements of fluorescent lamps burning on commercial ballasts should be made with the ballast operating at rated input voltage, and measurements on high-intensity discharge lamps should be made with the lamp operating at rated wattage. The ballast should be operated long enough to reach thermal equilibrium. The use of commercial ballasts should conform to the procedures given in the appropriate standards.[47]

DETECTORS. Detectors should be selected according to the criteria given in "Illuminance Meters" above. Additional corrections may have to be applied to the measured data.

STANDARD LAMPS. These lamps should have characteristics similar to the lamp under test with respect to light output, physical size, shape, and spectral distribution.

INTEGRATING SPHERES.[38,44] The integrating sphere to be used should comply with the requirements described in the previous discussion of integrating-sphere photometers. To provide acceptable performance, integrating spheres should be of adequate size for the lamp being tested. Direct substitution is not always possible, and generally the larger the integrator with respect to the test lamp dimensions, the smaller any necessary corrections will be. Also, the ambient temperature in a larger sphere is less affected by heat generated by the test lamp. The sphere diameter should be at least 1.5 m for high-intensity discharge lamps and at least 1.2 times the length of the lamp for straight lamps; the area of the light source should not exceed 2% of the interior surface of the sphere. If direct substitution is used, these requirements are less stringent.

DISTRIBUTION PHOTOMETER.[69-71] The lamp is mounted in open air with the distance between receiver and lamp at least five times the lamp length or 3 m, whichever is greater. Except as stipulated below, the lamp should be operated in the same burning position as associated with the luminaire for which it is intended, and it should be held stationary during measurement. Movement can disturb its stabilization.[52-54] The total light output can be computed if the lumen-candlepower ratio is known, or if strict substitution is practiced. The measured luminous intensity values for a lamp are established by multiplying the test readings by the photometric calibration constant. The total light output is the sum of products of these values with the appropriate zonal lumen constants. Measures should be taken to exclude stray light, to control ambient temperature and drafts, and to reduce the effects of light-absorbing or -reflecting materials. For fluorescent lamp measurements the lamp is mounted in a horizontal position and measurements taken normal to the axis of the lamp. To provide the greatest accuracy, these measurements must be taken at several angular positions by rotating the lamp around its axis between sets of measurements. For measurements of high-intensity discharge lamps, especially metal halide lamps, the lamp should be placed in its designed operating position. If this is vertical, measurements can be made while the lamp is rotating slowly on its longitudinal axis. Holding the lamp stationary is desirable for stabilization and accuracy. If the lamp is to be operated in any other position, it must be held stationary during measurement, since the light distribution from a high-intensity discharge lamp is a function of arc position, which is influenced by gravity.

Reflector-Type Lamps.[72] For purposes of identification, a reflector-type lamp is defined as a lamp having a reflective coating applied to part of the bulb, this reflector being specifically contoured for control of the luminous distribution. Included are pressed or blown lamps such as PAR and ER lamps, as well as other lamps with optically contoured reflectors. Excluded are lamps of standard bulb shape to which an integral reflector is added, such as silvered-bowl and silvered-neck lamps; lamps designated for special applications, such as automotive headlamps and picture projection lamps, for which special test procedures are already established; lamps having translucent coatings, such as partially phosphor-coated mercury lamps; and reflector fluorescent lamps.

Intensity Distribution. Several methods for measuring intensity distribution are available, depending on the type of lamp and the purpose of the test. The photometric center of the lamp is usually taken as the center of the bulb face, disregarding any protuberances or recesses in the face. The test distance should be great enough so that the inverse square law applies (Equation 2-1).

The intensity distribution of a circular beam is commonly represented by an average curve in a plane along the beam axis. (The beam axis is that axis around which the average distribution is substantially symmetrical; the beam axis and photometric axis are adjusted to coincide.) The curve is obtained either by taking measurements with the lamp rotating about the beam axis, or by averaging a number of curves (at least eight) taken in planes at equally spaced azimuthal intervals about the axis.

The intensity distribution of a lamp whose beam is oval or rectangular in cross section is not adequately represented by one average curve. For some lamps, two curves through the beam axis, one in the plane of each axis of symmetry, can supply sufficient information. The necessary number of traverses, their distribution within the beam, and the intervals between individual readings vary considerably with the type of lamp; sufficient measurements should be made to describe the average distribution pattern adequately.

When reflector-type lamps are considered for a specific application, test results will be most readily comparable when in the same form as that for equipment used for the same application. For example, when a direct performance comparison of a reflector lamp with floodlighting luminaires is desired, the lamp should be tested according to approved floodlight testing procedures.[37] The same is true for indoor luminaire applications.

Total Luminous Flux Measurements.[4] The total luminous flux can be obtained by direct measurement in an integrating sphere or by calculation from intensity distribution data. Because of the high-intensity spot produced by most reflector-type lamps, special precautions should be taken when using an integrating sphere. One possible position for the test lamp in the sphere is with its base close to the sphere wall and the beam aimed through the sphere center, thus distributing the flux over as large an area of the sphere as possible. An appropriate baffle should be placed between the light source and the detector.

When reflector-type standards are available, the calibration of the sphere follows the usual substitution procedure, and for maximum accuracy the standard lamp should be of the same type as the test lamps.

Beam and Field Flux. The beam and field flux can be calculated from an average intensity distribution curve or from an isocandela diagram. Of particular interest is the flux contained within the limits of 50% and 10%, respectively, of the maximum intensity. The beam angle is defined as the total angular spread of the cone intercepting the 50%-of-maximum intensity. The field angle is defined as the total angular spread of the cone intercepting the 10%-of-maximum intensity.

Flicker and Stroboscopic Effect.[73] All light sources operated on alternating current will flicker. The degree to which flicker is perceived, if at all, depends on the frequency of the alternating current, the persistence of light generated by the source, and the viewing conditions.

Flicker has special significance for objects moving within the field of view. Objects may appear to move discretely rather than continuously under flickering illumination; this is known as the stroboscopic effect. The magnitude of the effect depends on the rate and amplitude of the flicker, the rate of object motion, and the viewing conditions.

The flicker index[73] has been established as a reliable relative measure of the cyclic variation in output of various sources at a given power frequency. It takes into account the waveform of the light output as well as its amplitude. It is calculated by dividing the area above the line of average light output by the total area under the light output curve for a single curve (Figure 2-17). Area 2 in Figure 2-17 may be close to zero if light output varies as periodic spikes.

The flicker index assumes values from 0 to 1.0, with 0 for steady light output. Higher values indicate in increased possibility of noticeable stroboscopic effect, as well as lamp flicker.

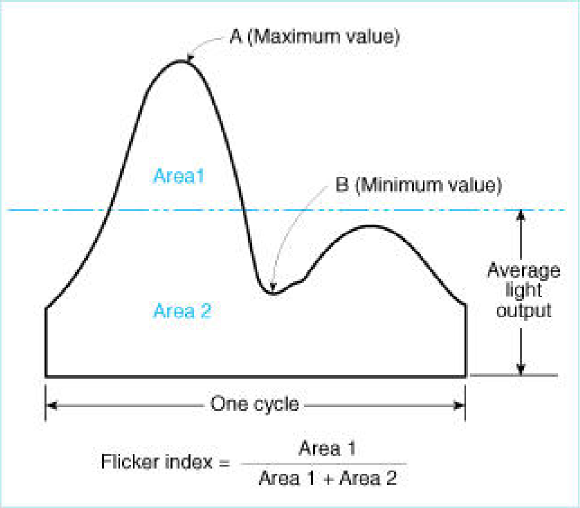


Figure 2-17. Curve of the light output variation from a lamp during each cycle, showing the method of calculating the flicker index.

Spectroradiometric Measurements of Light Sources[30,74]

Spectroradiometric measurements of light sources can be reported in relative terms or as absolute values. The units of the latter are generally watts per unit area as a function of specified wavelength bands for spectral irradiance, and watts within the wavelength bands for spectral flux. Extended light sources typically are measured for their spectral radiance in units of watts per unit area per solid angle per unit wavelength. Spectroradiometric measurements provide the fundamental data for the determination of radiant quantities; all other quantities can be computed from these measurements.

Measurement Methods. Spectroradiometric measurement involves the comparison of two light sources: a reference source of known SPD and a test source whose SPD is to be determined. The two sources can be compared wavelength by wavelength with a scanning monochrometer, or they can be measured sequentially by completely scanning each source throughout the spectrum.

When the sources are compared wavelength by wavelength, the two sources are operated simultaneously. This approach necessitates discontinuous wavelength scanning, pausing at each measurement point. It also requires that the reference and test source not drift over the lengthy measurement period. The advantage of this method is the minimizing of errors due to short-term drift in the instrument's response.

When the sources are measured sequentially, either continuous or discontinuous wavelength scanning can be adopted. When this method is used, the spectral response of the measuring system must remain constant throughout the measurement period. Instrument drift can be checked by remeasuring the standard source.

With discontinuous measurements, several readings at each wavelength can be taken and averaged, or other filtering methods can be employed to minimize the effect of electrical noise on the measurement.

With continuous measurements, the spectrum is scanned from one end to the other at a uniform rate, and the signal from the detector is integrated over discrete intervals within the scanning period. This approach effectively converts the spectral power distribution into a histogram, the height of a segment being proportional to the power emitted by the source over that interval. In principle, this method does not require that the scanning intervals and the monochromator bandwidths be perfectly correlated, but the best resolution is obtained when they are. An advantage of this method is excellent rejection of electrical noise, which is integrated out of the measurement in the signal averaging that takes place over each interval. It is also efficient, as there is no stopping and starting of the wavelength drive. When this method is adopted, the timing requirements are critical and the system response time must be adequate to capture the rapidly changing signal levels encountered during the scanning process. This is especially important when strong spectral lines are present.

Modern spectroradiometers incorporate a means of automating both the operation of the system and the data collection process.[75,76] Some form of immediate presentation of the data, such as a graph on a chart recorder, is desirable to aid in the recognition of malfunctions in the measurement system or instability in the test source.

The final presentation of the data is usually in the form of a series of values that describe the SPD of the light source over a particular spectral range. Typically, an SPD curve accompanies the report of numerical data on output versus wavelength.

A suitable wavelength interval for a particular test is chosen by considering the type of spectra being measured. Excessively small intervals are wasteful, requiring the collection of unnecessary data. Excessively large intervals can result in missed information. For optimum results, the sample interval and the bandwidth of the instrument are the same. The SPD from an incandescent lamp can be adequately represented by a series of measurements at 10-nm intervals across the spectrum, since the intensity changes gradually with wavelength. For measurements on discharge lamps, whose spectra include a number of emission lines, a smaller interval is required. For the calculation of chromaticity, which is one of the most important applications of spectroradiometric data, a 2-nm sample interval and bandwidth gives values of the chromaticity coordinates x and y accurate to ±0.001 for almost any type of source, and this is adequate for most purposes.

Color Appearance of Light Sources

For measurement of the color appearance of a light source, see Chapter 4, Color.

Life Performance Testing of Lamps

Life tests are performed on a very small portion of the products under consideration. Under such conditions, test program planning, sampling techniques, and data evaluation become especially important.[77-79]

It is not practical to test lamps under all of the many variables that occur in service; hence specific reproducible procedures must be included in the test experiment plan.

Incandescent Lamp Life Testing.[80-83] Life tests of incandescent filament lamps can be divided into two classes: rated-voltage and overvoltage tests.

Rated Voltage. Lamps are operated in the specified burning position at a voltage or current held within ±0.25% of rated value. Sockets should be designed to assure good contact with lamp bases, and the racks should not be subjected to excessive shocks or vibration. If lamps are removed for interim photometric readings, care should be taken to avoid accidental filament breakage. Sockets should be lubricated, because vibration can break a filament that has been rendered brittle by burning.

Overvoltage (Accelerated) Tests. Lamp life is shortened by voltages in excess of rated. Extreme overvoltage life testing, sometimes called "high forced testing," exponentially shortens lamp life so that lamps can be tested in less time. The exponents are empirical and require many comparison tests at rated voltages to determine them.

Electric Discharge Lamp Life Testing.[84-86] Tests generally are made using ac supply. The power supply should have a voltage waveform in which the harmonic content does not exceed 3% of the fundamental. The line voltage should be regulated. There is no widely accepted method of accelerated life testing of discharge lamps.

Auxiliaries. Since an electric discharge lamp must be operated with auxiliaries, which often affect lamp life, they must be selected to conform to the requirements of the appropriate guides, test methods, and specifications.

Test Cycles. An on-off cycle is normally employed to simulate field conditions. The commonly accepted cycles are 3 h on and 20 min off for fluorescent lamps, and 11 h on and 1 h off for high-intensity discharge lamps, although others are in use. It is known that more rapid cycling (that is, shorter off-times) shortens lamp life, but the correlation with the standard cycle is not sufficiently accurate to predict the life on the standard cycle.

Environment. Vibration, shock, room temperature, and drafts should be controlled to minimize their effect on measurement results.

Orientation. Lamps should be tested in an orientation recommended by the lamp manufacturer. See the IESNA guides for testing specific lamp types.[37,52-54,62]

Luminaire Photometry

The purpose of making photometric measurements of a luminaire is to determine its light distribution and characteristics in a way that will most adequately describe its performance. Characteristics such as intensity distribution, zonal lumens, efficiency, luminances, beam widths, and typing are necessary in designing, specifying, and selecting lighting equipment. Photometric data are essential in deriving and developing additional application information.

The information that follows is only a rudimentary guide to the photometry of luminaires. Specific photometric guides and practices are referenced below and should be consulted to obtain the detailed testing procedure for each type of luminaire. The IES Practical Guide to Photometry[47] provides information covering general photometric practices, equipment, and related matters. Each specific type of luminaire (indoor lighting, task lighting, floodlighting, or streetlighting) requires different testing procedures. However, there are several general requirements that should be met in all tests. The luminaire to be tested should be (1) typical of the unit it is to represent, (2) clean and free of defects (unless it is the purpose of the test to determine the effects of such conditions), (3) equipped with lamps of the size and type recommended for use in service, and (4) installed with the light source in the recommended operating position for service. If the location of the source in a beam-producing luminaire is adjustable, it should be positioned as recommended to obtain such a beam as is desired in service.

To provide an accurate description of the characteristics of the materials used in the manufacture of a luminaire, measurements should be made of the reflectances of reflecting surfaces where applicable.

Luminaires should be tested in a controlled environment under controlled conditions. The photometric laboratory temperature should be held steady. Typically, for fluorescent photometry, where lamps are sensitive to temperature variations, the room temperature should be held to 25 ± 1°C. Power supplies should be regulated and free of distortion to minimize any effects of line voltage variations. Test rooms should be painted black or provided with sufficient baffling to minimize or eliminate extraneous and reflected light during testing.

For accurate measurements, the distance between the luminaire and the light sensor should be great enough that the inverse square law applies (Equation 2-1). The minimum test distance is governed by the dimensions of the luminaire. This distance should not be less than 3 m (10 ft) and at least five times the maximum dimension of the luminous area of the luminaire. For best accuracy the test distance should be measured from the center of the apparent source to the surface of the detector. However, from a practical standpoint, the following rules should suffice: (1) for recessed, coffered, and totally direct luminaires, the test distance should be measured to the plane of the light opening (plane of the ceiling); (2) for luminous-sided luminaires the test distance should be measured to the geometric center of the lamps; (3) for suspended luminaires, (a) if the light center of the lamp(s) is within the bounds of the reflector and there is no refractor, the test distance should be measured to the plane of the light opening, (b) if the light center of the lamp(s) does not fall within the bounds of the reflector and there is no refractor, the test distance should be measured to the light center of the lamp(s), and (c) if a refractor is attached, then the test distance should be measured to the geometric center of the refractor.

General-Lighting Luminaires

Intensity Distribution. See the following IESNA guides for specific information on testing general-lighting luminaires: Photometric Testing of Indoor Fluorescent Luminaires,[87] Photometric Testing of Indoor Luminaires Using High Intensity Discharge or Incandescent Filament Lamps,[88] and Reporting General Lighting Equipment Engineering Data.[89,90]

The basic measurement made in a photometric test of a luminaire is the luminous intensity in specified planes and angles. The resulting intensity distribution is used to determine zonal lumens, efficiency, and average luminances. It is therefore essential that sufficient data be taken to adequately describe the intensity distribution and the luminaire's total luminous flux.

Luminaires having a symmetric distribution can be measured in five to twelve equally spaced planes and the results averaged. Most fluorescent luminaires are measured in five planes per quadrant in opposite quadrants, and the results for the two quadrants averaged to give the five-plane data. To adequately describe a highly asymmetric luminaire it might be necessary to measure in planes at 10° (or smaller) intervals.

The distribution in each vertical plane is determined by taking readings at 10° (or smaller) intervals. If the luminaire is of the beam-forming type, the intensity measurements should be made at smaller intervals within the beam-forming area. If visual comfort probability calculations are to be made, it is recommended that intensity measurements be made at least at every 5° in the vertical plane, and preferably every 2 ½°.

Most luminaires are measured using the relative method, similar to that for lamps. From these readings, total luminous flux can be estimated using the zonal lumen method. The lumen rating of the lamp is divided by this value to give the constant factor for that lamp on that photometer. By multiplying by that constant, the readings taken on the luminaire can be converted to luminous intensity for the lamps operating as rated.

The intensity distribution data generally are presented in tabular form on the test report sheet. Data for a lens or indoor luminaire are given in five planes. Three distributions (parallel to the lamps, 45° to parallel, perpendicular to the lamps) usually are presented in the form of polar distribution curves.

Luminance. Either before or after the photometric test, while the lamps are still installed and stabilized, the maximum luminance of the luminaire should be measured at the angles specified in the appropriate guide and at the shielding angles. The readings should be taken both crosswise and lengthwise in the case of fluorescent luminaires or luminaires giving asymmetric distributions. The projection of the measurement field should be circular and of 6.45 cm^2 (1 in.^{2}) area. The luminance photometer must be calibrated for the SPD of the test lamps.

If average luminance values are desired, they can be calculated by using the intensity measurements obtained from the test data. By definition, luminance is the luminous intensity (candlepower) of any surface in a given direction per unit of projected area of the surface viewed from that direction.[91]

Total Luminous Flux. The total luminous flux from of the luminaire, needed to establish its efficiency in terms of the total luminous flux of the installed lamps(s), can be determined in an integrating-sphere photometer or by computations from the intensity distribution data.

If it is to be measured in a sphere, the efficiency can be determined by the relative method (Figure 2-18). First, lamps are mounted at the center of the sphere and a reading taken. A reading is then taken on an auxiliary lamp mounted at another point in the sphere. The luminaire is then mounted at the center of the sphere, and a reading is taken. Another reading is then taken with the auxiliary lamp mounted in the sphere. The efficiency is then calculated as follows:

$$\text{efficiency} = \frac{R_3 R_2}{R_1 R_4} \times 100\% \qquad (2\text{-}4)$$

where

R_1 = reading of lamp(s) at the center of the sphere,
R_2 = auxiliary lamp reading,
R_3 = luminaire reading,
R_4 = auxiliary lamp reading with luminaire in the sphere.

Only one lamp (or one luminaire) should be operated whenever a reading is being taken. The sphere method is not considered to be as accurate as the method using luminous intensity distribution data.

Intensity distribution data are used to compute the luminous flux in any angular zone from nadir to 180°. The product of the midzone intensity and the zonal constant gives the zonal lumens. The summation of the zonal lumens multiplied by 100 and divided by the nominal lamp lumens gives the efficiency in percent.

Constants useful in calculating luminous flux from intensity data are given in Figures 2-19 and 2-20. For computing the luminous flux, the average luminous intensity at the center of each zone should be multiplied by the zonal constant (Figure 2-19) equal to $2\pi (\cos \theta_1 - \cos \theta_2)$. In Figure 2-18, the zone limits represent θ_1 and θ_2. The measurements should be made at the midpoint of this interval.

The constants in Figure 2-20 are computed for intensity measurements on projector-type luminaires made on a goniometer of the type shown in Figure 2-11b. In this figure, the vertical spacing is φ and the horizontal angle and setting represents the midpoint between θ_1 and θ_2. If the measurements have been made with the type shown in Figure 2-11a, the same constants can be used by interchanging the vertical and horizontal angular arguments, that is, by substituting the word "vertical" wherever "horizontal" appears, and vice versa. The zonal constants for Figure 2-20 were computed as $\varphi\pi (\sin \theta_2 - \sin \theta_1)/180$, where φ is the vertical interval and θ_1 and θ_2 are the limits of the horizontal interval. If a goniometer of the type in Figure 2-11a is used, the constant is equal to $\theta\pi (\sin \varphi_2 - \sin \varphi_1)/180$, where θ is the horizontal interval and φ_1 and φ_2 are the limits of the vertical interval. See Reference 91 for additional zonal constants.

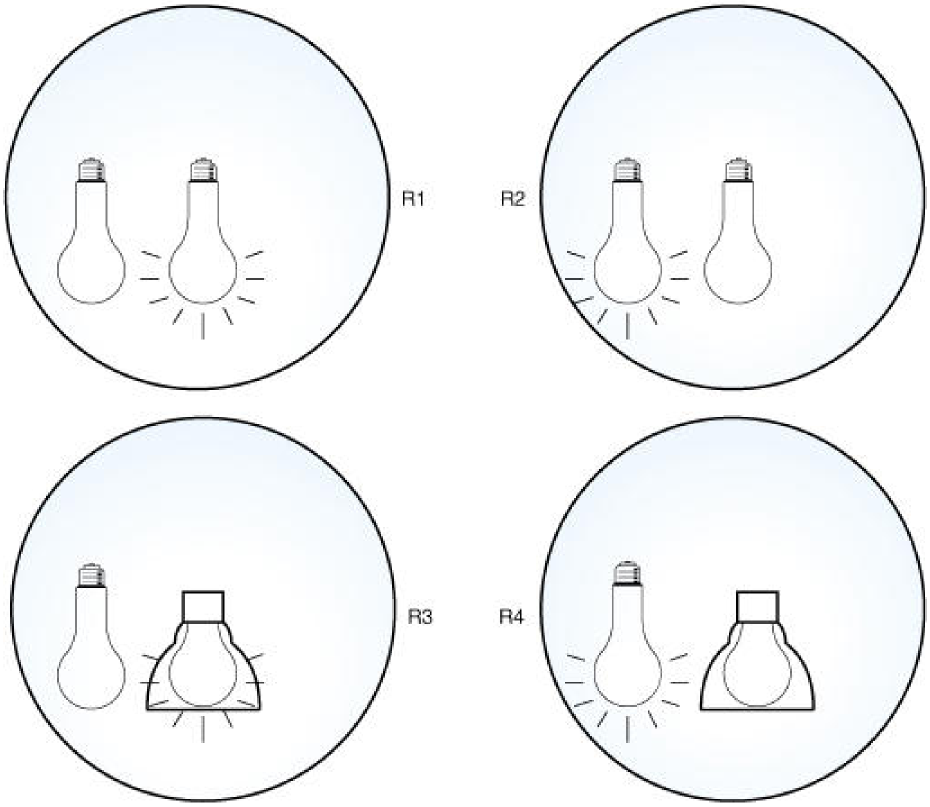
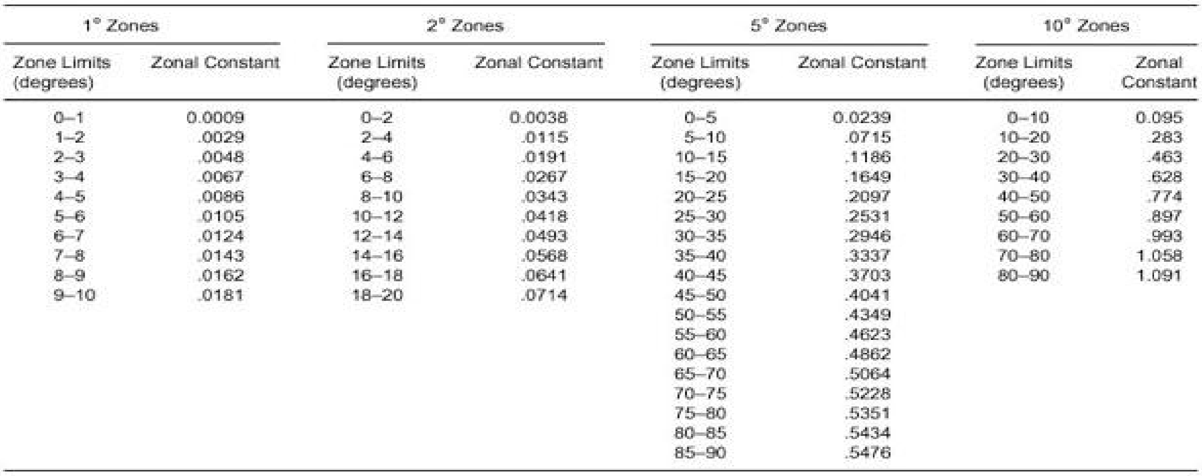
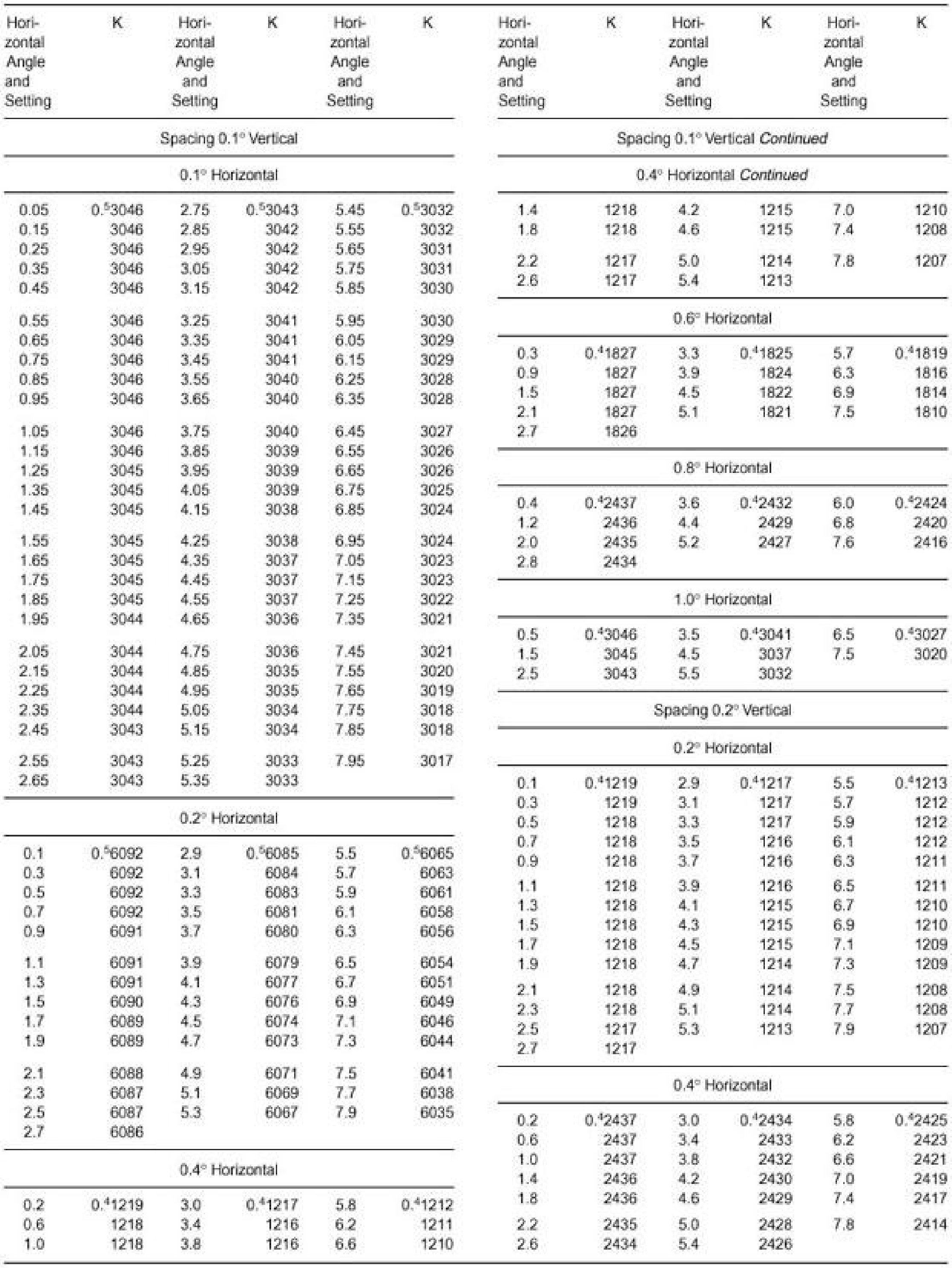


Figure 2-18. Luminaire and lamp positions within an integrating sphere for the relative method of determining luminaire efficiency. The diameter of the sphere should be at least twice the maximum dimension of the luminaire to be measured.



1° Zones		2° Zones		5° Zones		10° Zones	
Zone Limits (degrees)	Zonal Constant	Zone Limits (degrees)	Zonal Constant	Zone Limits (degrees)	Zonal Constant	Zone Limits (degrees)	Zonal Constant
0–1	0.0009	0–2	0.0038	0–5	0.0239	0–10	0.095
1–2	.0029	2–4	.0115	5–10	.0715	10–20	.283
2–3	.0048	4–6	.0191	10–15	.1186	20–30	.463
3–4	.0067	6–8	.0267	15–20	.1649	30–40	.628
4–5	.0086	8–10	.0343	20–25	.2097	40–50	.774
5–6	.0105	10–12	.0418	25–30	.2531	50–60	.897
6–7	.0124	12–14	.0493	30–35	.2946	60–70	.993
7–8	.0143	14–16	.0568	35–40	.3337	70–80	1.058
8–9	.0162	16–18	.0641	40–45	.3703	80–90	1.091
9–10	.0181	18–20	.0714	45–50	.4041		
				50–55	.4349		
				55–60	.4623		
				60–65	.4862		
				65–70	.5064		
				70–75	.5228		
				75–80	.5351		
				80–85	.5434		
				85–90	.5476		

Figure 2-19. Constants for Use in the Zonal Method of Computing Luminous Flux from Intensity Data



Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 0.1° Vertical					
0.1° Horizontal					
0.05	$0.^{5}3046$	2.75	$0.^{5}3043$	5.45	$0.^{5}3032$
0.15	3046	2.85	3042	5.55	3032
0.25	3046	2.95	3042	5.65	3031
0.35	3046	3.05	3042	5.75	3031
0.45	3046	3.15	3042	5.85	3030
0.55	3046	3.25	3041	5.95	3030
0.65	3046	3.35	3041	6.05	3029
0.75	3046	3.45	3041	6.15	3029
0.85	3046	3.55	3040	6.25	3028
0.95	3046	3.65	3040	6.35	3028
1.05	3046	3.75	3040	6.45	3027
1.15	3046	3.85	3039	6.55	3026
1.25	3045	3.95	3039	6.65	3026
1.35	3045	4.05	3039	6.75	3025
1.45	3045	4.15	3038	6.85	3024
1.55	3045	4.25	3038	6.95	3024
1.65	3045	4.35	3037	7.05	3023
1.75	3045	4.45	3037	7.15	3023
1.85	3045	4.55	3037	7.25	3022
1.95	3044	4.65	3036	7.35	3021
2.05	3044	4.75	3036	7.45	3021
2.15	3044	4.85	3035	7.55	3020
2.25	3044	4.95	3035	7.65	3019
2.35	3044	5.05	3034	7.75	3018
2.45	3043	5.15	3034	7.85	3018
2.55	3043	5.25	3033	7.95	3017
2.65	3043	5.35	3033		
0.2° Horizontal					
0.1	$0.^{5}6092$	2.9	$0.^{5}6085$	5.5	$0.^{5}6065$
0.3	6092	3.1	6084	5.7	6063
0.5	6092	3.3	6083	5.9	6061
0.7	6092	3.5	6081	6.1	6058
0.9	6091	3.7	6080	6.3	6056
1.1	6091	3.9	6079	6.5	6054
1.3	6091	4.1	6077	6.7	6051
1.5	6090	4.3	6076	6.9	6049
1.7	6089	4.5	6074	7.1	6046
1.9	6089	4.7	6073	7.3	6044
2.1	6088	4.9	6071	7.5	6041
2.3	6087	5.1	6069	7.7	6038
2.5	6087	5.3	6067	7.9	6035
2.7	6086				
0.4° Horizontal					
0.2	$0.^{4}1219$	3.0	$0.^{4}1217$	5.8	$0.^{4}1212$
0.6	1218	3.4	1216	6.2	1211
1.0	1218	3.8	1216	6.6	1210

Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 0.1° Vertical *Continued*					
0.4° Horizontal *Continued*					
1.4	1218	4.2	1215	7.0	1210
1.8	1218	4.6	1215	7.4	1208
2.2	1217	5.0	1214	7.8	1207
2.6	1217	5.4	1213		
0.6° Horizontal					
0.3	$0.^{4}1827$	3.3	$0.^{4}1825$	5.7	$0.^{4}1819$
0.9	1827	3.9	1824	6.3	1816
1.5	1827	4.5	1822	6.9	1814
2.1	1827	5.1	1821	7.5	1810
2.7	1826				
0.8° Horizontal					
0.4	$0.^{4}2437$	3.6	$0.^{4}2432$	6.0	$0.^{4}2424$
1.2	2436	4.4	2429	6.8	2420
2.0	2435	5.2	2427	7.6	2416
2.8	2434				
1.0° Horizontal					
0.5	$0.^{4}3046$	3.5	$0.^{4}3041$	6.5	$0.^{4}3027$
1.5	3045	4.5	3037	7.5	3020
2.5	3043	5.5	3032		
Spacing 0.2° Vertical					
0.2° Horizontal					
0.1	$0.^{4}1219$	2.9	$0.^{4}1217$	5.5	$0.^{4}1213$
0.3	1219	3.1	1217	5.7	1212
0.5	1218	3.3	1217	5.9	1212
0.7	1218	3.5	1216	6.1	1212
0.9	1218	3.7	1216	6.3	1211
1.1	1218	3.9	1216	6.5	1211
1.3	1218	4.1	1215	6.7	1210
1.5	1218	4.3	1215	6.9	1210
1.7	1218	4.5	1215	7.1	1209
1.9	1218	4.7	1214	7.3	1209
2.1	1218	4.9	1214	7.5	1208
2.3	1218	5.1	1214	7.7	1208
2.5	1217	5.3	1213	7.9	1207
2.7	1217				
0.4° Horizontal					
0.2	$0.^{4}2437$	3.0	$0.^{4}2434$	5.8	$0.^{4}2425$
0.6	2437	3.4	2433	6.2	2423
1.0	2437	3.8	2432	6.6	2421
1.4	2436	4.2	2430	7.0	2419
1.8	2436	4.6	2429	7.4	2417
2.2	2435	5.0	2428	7.8	2414
2.6	2434	5.4	2426		

Figure 2-20. *Continued*

Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 0.2° Vertical *Continued*					
0.6° Horizontal					
0.3	0.^{4}3655	3.3	0.^{4}3649	5.7	0.^{4}3637
0.9	3655	3.9	3647	6.3	3633
1.5	3654	4.5	3644	6.9	3629
2.1	3653	5.1	3641	7.5	3624
2.7	3651				
0.8° Horizontal					
0.4	0.^{4}4874	3.6	0.^{4}4864	6.0	0.^{4}4848
1.2	4872	4.4	4858	6.8	4840
2.0	4870	5.2	4854	7.6	4832
2.8	4868				
1.0° Horizontal					
0.5	0.^{4}6092	3.5	0.^{4}6082	6.5	0.^{4}6054
1.5	6090	4.5	6074	7.5	6040
2.5	6086	5.5	6064		
Spacing 0.4° Vertical					
0.2° Horizontal					
0.1	0.^{4}2437	2.9	0.^{4}2434	5.5	0.^{4}2426
0.3	2437	3.1	2434	5.7	2425
0.5	2437	3.3	2433	5.9	2424
0.7	2437	3.5	2432	6.1	2423
0.9	2437	3.7	2432	6.3	2422
1.1	2437	3.9	2431	6.5	2421
1.3	2436	4.1	2431	6.7	2420
1.5	2436	4.3	2430	6.9	2419
1.7	2436	4.5	2430	7.1	2418
1.9	2436	4.7	2429	7.3	2417
2.1	2435	4.9	2428	7.5	2416
2.3	2435	5.1	2427	7.7	2415
2.5	2434	5.3	2426	7.9	2414
2.7	2434				
0.4° Horizontal					
0.2	0.^{4}4874	3.0	0.^{4}4867	5.8	0.^{4}4849
0.6	4874	3.4	4865	6.2	4846
1.0	4874	3.8	4863	6.6	4842
1.4	4872	4.2	4861	7.0	4838
1.8	4872	4.6	4858	7.4	4834
2.2	4870	5.0	4855	7.8	4829
2.6	4869	5.4	4852		
0.6° Horizontal					
0.3	0.^{4}7310	3.3	0.^{4}7299	5.7	0.^{4}7274
0.9	7310	3.9	7294	6.3	7267
1.5	7308	4.5	7288	6.9	7258

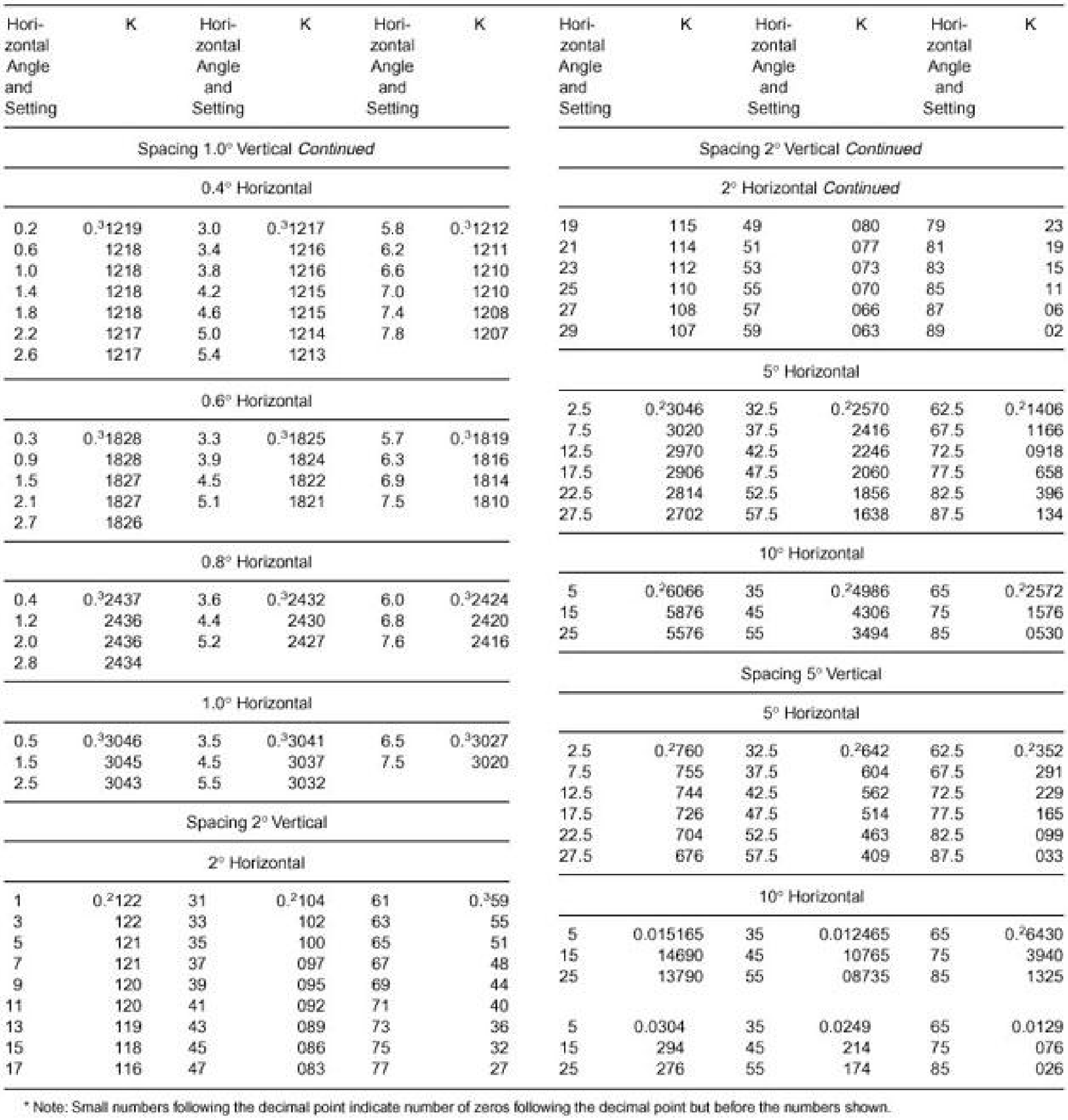
Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 0.4° Vertical *Continued*					
0.6° Horizontal *Continued*					
2.1	7306	5.1	7282	7.5	7248
2.7	7302				
0.8° Horizontal					
0.4	0.^{4}9747	3.6	0.^{4}9728	6.0	0.^{4}9694
1.2	9746	4.4	9719	6.8	9679
2.0	9742	5.2	9707	7.6	9662
2.8	9736				
1.0° Horizontal					
0.5	0.^{3}1218	3.5	0.^{3}1216	6.5	0.^{3}1211
1.5	1218	4.5	1215	7.5	1208
2.5	1217	5.5	1212		
Spacing 0.6° Vertical					
0.2° Horizontal					
0.1	0.^{4}3655	2.9	0.^{4}3650	5.5	0.^{4}3638
0.3	3655	3.1	3650	5.7	3637
0.5	3655	3.3	3649	5.9	3636
0.7	3655	3.5	3649	6.1	3635
0.9	3655	3.7	3648	6.3	3634
1.1	3655	3.9	3647	6.5	3632
1.3	3654	4.1	3646	6.7	3631
1.5	3654	4.3	3645	6.9	3629
1.7	3654	4.5	3644	7.1	3628
1.9	3653	4.7	3643	7.3	3626
2.1	3653	4.9	3642	7.5	3625
2.3	3653	5.1	3641	7.7	3622
2.5	3652	5.3	3640	7.9	3621
2.7	3652				
0.4° Horizontal					
0.2	0.^{4}7310	3.0	0.^{4}7301	5.8	0.^{4}7273
0.6	7310	3.4	7299	6.2	7268
1.0	7310	3.8	7295	6.6	7262
1.4	7308	4.2	7292	7.0	7256
1.8	7307	4.6	7288	7.4	7250
2.2	7306	5.0	7283	7.8	7243
2.6	7303	5.4	7278		
0.6° Horizontal					
0.3	0.^{3}1097	3.3	0.^{3}1095	5.7	0.^{3}1091
0.9	1097	3.9	1094	6.3	1090
1.5	1096	4.5	1093	6.9	1089
2.1	1096	5.1	1092	7.5	1087
2.7	1095				

Figure 2-20. *Continued*

Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 0.6° Vertical *Continued*					
0.8° Horizontal					
0.4	$0.^{3}1462$	3.6	$0.^{3}1459$	6.0	$0.^{3}1454$
1.2	1462	4.4	1458	6.8	1452
2.0	1461	5.2	1456	7.6	1449
2.8	1460				
1.0° Horizontal					
0.5	$0.^{3}1828$	3.5	$0.^{3}1824$	6.5	$0.^{3}1816$
1.5	1827	4.5	1822	7.5	1812
2.5	1826	5.5	1819		
Spacing 0.8° Vertical					
0.2° Horizontal					
0.1	$0.^{4}4874$	2.9	$0.^{4}4867$	5.5	$0.^{4}4851$
0.3	4874	3.1	4867	4.7	4850
0.5	4874	3.3	4866	5.9	4848
0.7	4874	3.5	4865	6.1	4846
0.9	4874	3.7	4864	6.3	4845
1.1	4874	3.9	4862	6.5	4842
1.3	4872	4.1	4862	6.7	4841
1.5	4872	4.3	4860	6.9	4838
1.7	4872	4.5	4859	7.1	4837
1.9	4871	4.7	4858	7.3	4834
2.1	4870	4.9	4856	7.5	4833
2.3	4870	5.1	4854	7.7	4830
2.5	4869	5.3	4853	7.9	4828
2.7	4869				
0.4° Horizontal					
0.2	$0.^{4}9747$	3.0	$0.^{4}9734$	5.8	$0.^{4}9698$
0.6	9747	3.4	9730	6.2	9691
1.0	9747	3.8	9726	6.6	9683
1.4	9744	4.2	9722	7.0	9675
1.8	9743	4.6	9717	7.4	9667
2.2	9741	5.0	9710	7.8	9658
2.6	9738	5.4	9704		
0.6° Horizontal					
0.3	$0.^{3}1462$	3.3	$0.^{3}1460$	5.7	$0.^{3}1455$
0.9	1462	3.9	1459	6.3	1453
1.5	1462	4.5	1458	6.9	1452
2.1	1461	5.1	1456	7.5	1450
2.7	1460				
0.8° Horizontal					
0.4	$0.^{3}1949$	3.6	$0.^{3}1946$	6.0	$0.^{3}1939$
1.2	1949	4.4	1944	6.8	1936
2.0	1948	5.2	1941	7.6	1932
2.8	1947				

Horizontal Angle- and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 0.8° Vertical *Continued*					
1.0° Horizontal					
0.5	$0.^{3}2437$	3.5	$0.^{3}2432$	6.5	$0.^{3}2421$
1.5	2436	4.5	2429	7.5	2416
2.5	2435	5.5	2426		
Spacing 1.0° Vertical					
0.1° Horizontal					
0.05	$0.^{4}3046$	2.75	$0.^{4}3043$	5.45	$0.^{4}3032$
0.15	3046	2.85	3042	5.55	3032
0.25	3046	2.95	3042	5.65	3031
0.35	3046	3.05	3042	5.75	3031
0.45	3046	3.15	3042	5.85	3030
0.55	3046	3.25	3041	5.95	3030
0.65	3046	3.35	3041	6.05	3029
0.75	3046	3.45	3041	6.15	3029
0.85	3046	3.55	3040	6.25	3028
0.95	3046	3.65	3040	6.35	3028
1.05	3046	3.75	3040	6.45	3027
1.15	3046	3.85	3039	6.55	3026
1.25	3045	3.95	3039	6.65	3026
1.35	3045	4.05	3039	6.75	3025
1.45	3045	4.15	3038	6.85	3024
1.55	3045	4.25	3038	6.95	3024
1.65	3045	4.35	3037	7.05	3023
1.75	3045	4.45	3037	7.15	3023
1.85	3045	4.55	3037	7.25	3022
1.95	3044	4.65	3036	7.35	3021
2.05	3044	4.75	3036	7.45	3021
2.15	3044	4.85	3035	7.55	3020
2.25	3044	4.95	3035	7.65	3019
2.35	3044	5.05	3034	7.75	3018
2.45	3043	5.15	3034	7.85	3018
2.55	3043	5.25	3033	7.95	3017
2.65	3043	5.35	3033		
0.2° Horizontal					
0.1	$0.^{4}6092$	2.9	$0.^{4}6085$	5.5	$0.^{4}6065$
0.3	6092	3.1	6084	5.7	6063
0.5	6092	3.3	6083	5.9	6061
0.7	6092	3.5	6081	6.1	6058
0.9	6092	3.7	6080	6.3	6056
1.1	6092	3.9	6079	6.5	6054
1.3	6090	4.1	6077	6.7	6051
1.5	6090	4.3	6076	6.9	6049
1.7	6089	4.5	6074	7.1	6046
1.9	6089	4.7	6073	7.3	6044
2.1	6088	4.9	6071	7.5	6041
2.3	6087	5.1	6069	7.7	6038
2.5	6087	5.3	6067	7.9	6035
2.7	6086				

Figure 2-20. *Continued*



Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 1.0° Vertical *Continued*					
0.4° Horizontal					
0.2	$0.^{3}1219$	3.0	$0.^{3}1217$	5.8	$0.^{3}1212$
0.6	1218	3.4	1216	6.2	1211
1.0	1218	3.8	1216	6.6	1210
1.4	1218	4.2	1215	7.0	1210
1.8	1218	4.6	1215	7.4	1208
2.2	1217	5.0	1214	7.8	1207
2.6	1217	5.4	1213		
0.6° Horizontal					
0.3	$0.^{3}1828$	3.3	$0.^{3}1825$	5.7	$0.^{3}1819$
0.9	1828	3.9	1824	6.3	1816
1.5	1827	4.5	1822	6.9	1814
2.1	1827	5.1	1821	7.5	1810
2.7	1826				
0.8° Horizontal					
0.4	$0.^{3}2437$	3.6	$0.^{3}2432$	6.0	$0.^{3}2424$
1.2	2436	4.4	2430	6.8	2420
2.0	2436	5.2	2427	7.6	2416
2.8	2434				
1.0° Horizontal					
0.5	$0.^{3}3046$	3.5	$0.^{3}3041$	6.5	$0.^{3}3027$
1.5	3045	4.5	3037	7.5	3020
2.5	3043	5.5	3032		
Spacing 2° Vertical					
2° Horizontal					
1	$0.^{2}122$	31	$0.^{2}104$	61	$0.^{3}59$
3	122	33	102	63	55
5	121	35	100	65	51
7	121	37	097	67	48
9	120	39	095	69	44
11	120	41	092	71	40
13	119	43	089	73	36
15	118	45	086	75	32
17	116	47	083	77	27

Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 2° Vertical *Continued*					
2° Horizontal *Continued*					
19	115	49	080	79	23
21	114	51	077	81	19
23	112	53	073	83	15
25	110	55	070	85	11
27	108	57	066	87	06
29	107	59	063	89	02
5° Horizontal					
2.5	$0.^{2}3046$	32.5	$0.^{2}2570$	62.5	$0.^{2}1406$
7.5	3020	37.5	2416	67.5	1166
12.5	2970	42.5	2246	72.5	0918
17.5	2906	47.5	2060	77.5	658
22.5	2814	52.5	1856	82.5	396
27.5	2702	57.5	1638	87.5	134
10° Horizontal					
5	$0.^{2}6066$	35	$0.^{2}4986$	65	$0.^{2}2572$
15	5876	45	4306	75	1576
25	5576	55	3494	85	0530
Spacing 5° Vertical					
5° Horizontal					
2.5	$0.^{2}760$	32.5	$0.^{2}642$	62.5	$0.^{2}352$
7.5	755	37.5	604	67.5	291
12.5	744	42.5	562	72.5	229
17.5	726	47.5	514	77.5	165
22.5	704	52.5	463	82.5	099
27.5	676	57.5	409	87.5	033
10° Horizontal					
5	0.015165	35	0.012465	65	$0.^{2}6430$
15	14690	45	10765	75	3940
25	13790	55	08735	85	1325
5	0.0304	35	0.0249	65	0.0129
15	294	45	214	75	076
25	276	55	174	85	026

* Note: Small numbers following the decimal point indicate number of zeros following the decimal point but before the numbers shown.

Figure 2-20. Constants* (K) for Converting Beam Intensity of Projector-Type Luminaires (Searchlights, Floodlights, and Spotlights) into Luminous Flux

If a number of constants are to be calculated for the same interval, the following shortcut method is useful and accurate. For the first formula above, let θ_m be the midzone angle and let *P* equal one-half the zone interval. The formula becomes

$$4\pi \sin P \sin \theta_m \qquad (2\text{-}5)$$

The zone width is often the same for a series of constants. In these cases, the first factor is simply multiplied successively by the sines of the midzone angles.

For the second formula above, let θ_m be the median angle on the horizontal interval. The formula then becomes

$$2\pi \frac{\theta}{180} \sin P \cos \theta_m \qquad (2\text{-}6)$$

It is commonly assumed that a ballast operated at its rated input voltage delivers rated wattage to a lamp, and that a lamp operated at its rated wattage delivers rated total luminous flux. In many instances, the assumption is invalid. Therefore, a procedure has been developed[92] to provide a factor called the equipment operating factor to be applied to photometric data on luminaires to adjust them to the specific combination of luminaire, lamp type, and ballast used in a system. By repetitive tests, this procedure can be used to determine variations of system performance exclusive of lamp variations. Such a factor can be applied specifically to total luminous flux, intensity, and illuminance as given on photometric data sheets.

Two possibilities are recognized: the first (LLB1) in which the lamp is used in the operating position for which it is rated, and the second (LLB2) in which the lamp is operated in a position other than the one for which it is rated. The factors determined are equipment-specific (luminaire-lamp-ballast combination) under initial conditions unless specified otherwise.

The procedures essentially involve a relative measurement of total luminous flux. The test luminaire is operated at the rated supply voltage, after operating conditions have stabilized. Relative flux measurements are obtained with the test ballast and, without extinguishing the lamp, with the reference ballast operated at its rated input voltage. The equipment operating factor is the ratio of the first to the second measurement of total luminous flux.

Floodlight-Type Luminaires. The following applies to floodlighting equipment having total beam spread (divergence) of more than 10°. For specific information on testing this type of equipment, consult the IES Approved Method for Photometric Testing of Floodlights Using Incandescent Filament or Discharge Lamps.[37] For equipment having a beam spread less than 10°, see the IES Guide for Photometric Testing of Searchlights.[93]

The classification of floodlights is based on horizontal and vertical beam width. The classification is designated by National Electrical Manufacturers Association (NEMA) type numbers.[94] For symmetrical beams the floodlight type is defined by the average of the horizontal and vertical beam spreads. For asymmetrical beams it is defined by the horizontal and vertical beam spreads in that order; for example, a floodlight with a horizontal beam spread of 75° (Type 5) and a vertical beam spread of 35° (Type 3) would be designated as a Type 5 × 3 floodlight.

Stray light is defined as light emitted by the floodlight that is outside the classified beam. In some instances, stray light is useful in illumination. It can also be detrimental, depending on its magnitude and direction. To determine the amount and direction of stray light, it is necessary to make measurements as far horizontally and vertically as the readings have significant values in relation to the measuring system.

If the geometric center of the emitted light is not enclosed by the reflector, the floodlight should be mounted on the goniometer so that the light center of the lamp is at the goniometric center. If the lamp light center is within the reflector, the floodlight should be positioned so that the center of the reflector opening coincides with the goniometric center.

Either the direct or the relative method of photometry can be used for floodlights. The relative method has an advantage in that cumulative errors can be reduced and maintenance of standards of luminous intensity and flux is not necessary. In the latter method, relative intensity readings for the test lamp alone made with a distribution photometer, and for the lamp-floodlight combination made with a floodlight photometer, are taken with the lamp operating under identical electrical conditions in both tests.

The method of taking intensity readings is to traverse the beam with such angular spacings as to give approximately 100 uniformly spaced readings throughout the beam. For the definition of the beam limit, see Reference 95. By interpolating between these readings, an isocandela diagram can be plotted on rectangular coordinates (see Chapter 9, Lighting Calculations). The total luminous flux in the beam can be computed using the constants in Figure 2-20.

The information usually reported for floodlights includes the following: NEMA type, horizontal and vertical beam distribution curves, maximum beam luminous intensity, average maximum beam luminous intensity, beam spread in both horizontal and vertical directions, beam flux, beam efficiency, total floodlight flux, and total efficiency. The report should also indicate whether the data were obtained with a Type A, Type B, or Type C goniometer (Figure 2-11a, b, and c).[96,97]

Roadway Luminaires. A guide has been prepared to provide test procedures and methods of reporting data to promote consistent evaluation of roadway luminaires performance that use incandescent filament or high-intensity discharge lamps.[98]

Luminaires selected for test should be representative of the manufacturer's product. A test distance of 8 to 10 m (25 to 30 ft) should be sufficient for most beam-forming luminaires. The photometric test distance is generally defined as the distance from the light center to the surface of the detector, taking into account the distances to and from any mirrors that might be used.

The number of planes explored during photometric measurements should be determined by the symmetry or irregularity of the distribution and by the purpose of the test. The number of vertical angles at which readings are taken depends on how the readings are to be used. If an isocandela diagram is to be plotted, readings might have to be taken at close intervals, especially if the values change rapidly. Computer acquisition systems provide comprehensive evaluation of luminaires and lighting application designs; readings taken at vertical angle intervals through the beam section do not exceed 2½°.

For luminaires having a distribution that is symmetrical about a vertical axis (IES Type V), readings should be taken in ten or more vertical planes and averaged.

For luminaires having a distribution that is symmetrical about a single vertical plane (IES Types II, III, IV, and II four-way), readings should be taken in vertical planes that are no more than 10° apart. To simplify data processing, it can be advantageous to divide the beam section laterally into 10° zones and measure at the midzone angle. Averages may be taken of the readings at corresponding angles on the opposite sides of the plane of symmetry. Any computations that are to be performed can then be done on one side of the plane of symmetry, using the averaged data.

For luminaires having a distribution that is symmetric about two vertical planes (IES Type I), readings should be taken as above, but the computations may be performed in one quadrant of the sphere.

For luminaires having a distribution that is symmetric about four vertical planes (IES Type I four-way), readings may be taken as above, but the computations may be performed in one octant of the sphere.

For luminaires having an asymmetric distribution, readings should be taken in vertical planes that no more than are 10° apart. Since there is no symmetry, any computations performed should be done without averaging the data obtained from different planes.

Sufficient data should be obtained to allow classification of the light distribution in accordance with recommended practice (see Chapter 22, Roadway Lighting) as well as to provide an isolux (isofootcandle) diagram, the utilization efficiency, and the total and four-quadrant efficiencies.

Projector Luminaires.[99,100] The equipment required for photometric measurements of projectors, searchlights, and beacons is similar in most respects to that required for other types of photometry.

When the projector luminaire is of unusual size and weight, it might be necessary to use its own mounting and goniometric facilities for the photometric work, or to hold the luminaire fixed and traverse the beam by moving the detector.

Since projector luminaires can have a total beam spread of less than 1° and furthermore can be massive, the mechanical requirements on the goniometer are severe (Figure 2-21). Rigidity, freedom from backlash, and accuracy of angular measurements are prime requirements. There should be provision for accurate angular settings of the order of 0.1° or less.

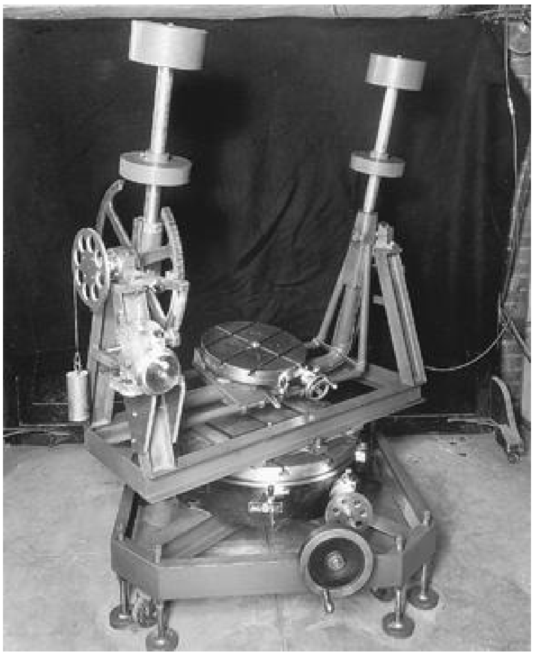


Figure 2-21. Typical goniometer for indoor photometric range. Two rotary tables of the type used in large machine tools are incorporated into the goniometer to provide two of the three rotations available. For horizontal distributions either the rotary table on which the outer frame is mounted or the inner table on which the test equipment is mounted may be used. This makes for flexibility and is especially useful for obtaining polar angle distributions. The inner frame with the test unit mounted can then be balanced with the adjustable counterweights. After balancing, a small constant torque is applied to the inner frame through the use of the pulley and weight at the side, thus eliminating backlash.

Indoor photometric measurements are preferred but frequently impracticable because of the lengths required. For photometry on the relatively short indoor ranges, proper photometric procedures must be followed.[31,43,92,101] Outdoor ranges require much more attention to methods of reducing stray light, minimizing atmospheric disturbances, and correcting for atmospheric transmission. Range sites should be selected where the terrain is flat and uniform. The range should be as high off the ground as practicable. Stray light should be minimized by a suitable system of diaphragms. Any remaining stray light should be measured and subtracted from all readings.

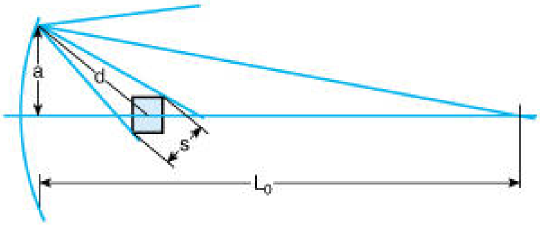


Figure 2-22. Diagram showing distances and dimensions used to determine minimum inverse-square distance.

Ranges should not be located where atmospheric disturbances occur regularly or where dust or moisture are prevalent. The absorption and scattering of light by moisture, smoke, and dust particles, even in an apparently clear atmosphere, can introduce considerable errors in measurements.[102,103] Therefore, it is desirable to measure the atmospheric transmittance before and after the test. A standard reference projector is frequently employed, calibrated either by repeated observations in the clearest weather, when the atmospheric transmittance can be accurately estimated or independently measured, or by laboratory measurement methods.

The illuminance from searchlights, beacons, or other highly collimating luminaires, if measured at distances greater than a certain minimum, obeys the inverse square law (Equation 2-1). The minimum distance is a function of the focal length of the reflector, the diameter of the reflector aperture, and the diameter of the smallest element of the light source (arc stream or filament). This minimum distance is called the beam crossover point and is the distance where the optic is seen to be completely flashed, that is, the minimum distance where the refracting lens or the reflector is seen as completely luminous. Only at distances greater than this does the inverse square law apply. This minimum distance can be calculated by using the following general formula (Figure 2-22):

$$L_0 = \frac{ad}{Ks} \tag{2-7}$$

where

L_0 = minimum distance for optic under consideration,
a = distance from the optical axis to the outermost flashed point when viewed from a distance point on the optical axis,
d = distance from the centroid of the light source to the same outermost flashed point as used to determine a,
s = diameter of the smallest element of the light source (for example, the arc stream width of an arc source, or one coil of a multicoil filament lamp),
K = constant equal to 500 when a, d, and s are in mm and L_0 is in m; and 6 when a, d, and s are in inches and L_0 is in ft.

The above calculation determines the minimum inverse square distance based on ideal light sources and axial measurements, and therefore should be considered approximate. In practice, the range used should be much larger than this calculated distance to ensure conformance. Methods for using shorter ranges and "zero-length photometry" have been devised; however, the full length range gives the highest accuracy. These methods and a fuller discussion of minimum inverse-square-distance calculations can be found in References 92, 100, and 104.

Luminance Measurements[105]

Luminance measurements of lamps and luminaires should be made by either the absolute or the relative method. With the absolute method, reference standards must be available for equipment calibration. In practice the relative method is generally used.

The published luminances of symmetric fluorescent lamps are computed from the rated lumen output of the lamp according to the following formula:[106]

$$L_{avg} = \frac{K \times (\text{total lamp lumens})}{(\text{lamp diameter}) \times (\text{lamp luminous length})} \qquad (2\text{-}8)$$

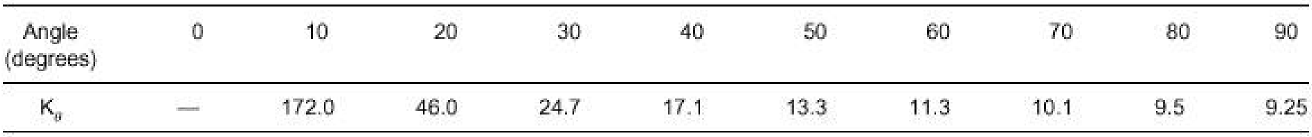
where L_{avg} is the average luminance of the full width of the lamp at its center, in candelas per square meter. The diameter and length are expressed in meters or inches, and K for T-12 lamps is as follows:

Size		
(m)	(in.)	*K*
1.22	48	0.118
1.83	72	0.115
2.44	96	0.113

To compute the approximate luminance L_θ of a fluorescent lamp at any angle to the lamp axis, the following formula is used:

$$L_\theta = \frac{\text{total lamp lumens}}{K_\theta \times (\text{lamp diameter}) \times (\text{lamp luminous length}) \times \sin\theta}$$

where K_θ is as shown in Figure 2-23.



Angle (degrees)	0	10	20	30	40	50	60	70	80	90
K_θ	—	172.0	46.0	24.7	17.1	13.3	11.3	10.1	9.5	9.25

Figure 2-23. Values at Various Angles of the Lamp: Intensity Ratio K_θ for Preheat-Starting Types of Fluorescent Lamps (Average for 15, 20, 30, 40, and 100 W Lamps)

A luminance meter should be used to make direct measurements of the luminaire luminance. The characteristics of the luminance meter should be such that the field of measurement corresponds to a projected area of 645 mm^2 (1 in.^2) normal to its axis at the distance of measurement.[107] This can be achieved with an appropriate lens system and a measurement distance determined from the manufacturer's specifications. This technique has the advantage of the observer being able to view the exact area being measured through the luminance photometer.

Calorimetry of Luminaires

A thermal testing method has been developed for compiling data on air-cooled heat transfer luminaires.[108] The method uses a calorimeter to measure the thermal energy distribution of the luminaires. The entire laboratory room in which the calorimeter is located becomes a part of the calorimetric system. The room must be controlled closely with respect to temperature, air motion, and relative humidity. Varying conditions can affect the results of the calorimetric measurements. The room conditions should be as follows: the temperature should be controlled at 25 ± 0.3°C; the velocity of the air in the space containing the calorimeter should be held constant and not exceed 0.15 m/s (30 ft/min); the relative humidity should be held constant at any convenient value between 20 and 50%; and the room should not be affected by external conditions.

The selection of a calorimeter type is determined by the purpose of the device and the degree to which its conditions can be controlled. Three types of calorimeters are the zero-heat-loss calorimeter, a calorimeter constructed to compensate for the heat transfer through its walls; the calibrated-heat-loss calorimeter (the approved IESNA type), a box in which the heat loss can be determined by dissipating a measured quantity of energy in the plenum; and the continuous-fluid-flow calorimeter, a modification of the zero-heat-loss calorimeter consisting of a heavily insulated heat exchanger installed over the luminaire.

Precision instrumentation is needed to measure temperature (thermometers, thermocouples, thermistors, and resistance elements), pressure (manometers, micromanometers, draft gauges, and swinging-vane gauges), mass flow rate of air and water, electrical quantities, and luminous flux.

Each luminaire that is to be tested for energy distribution should first be measured photometrically in accordance with accepted procedures. During calorimetry, the photometer should be installed at luminaire nadir, not less than 300 mm (1 ft) from the bottom of the enclosure. The distance at which the detector should be mounted below the luminaire is limited by the distance required for the cell to integrate flux over the entire luminous area of the luminaire. It is necessary that precautions be taken to prevent the detector from responding to luminous flux other than that transmitted by the luminaire under test. Its position must not be changed during the test.

The data to be recorded and reported should include the description and size of the luminaire, mode of operation, test conditions (space and plenum temperatures), relative light output from a 25°C base with the luminaire operated in free air outside the calorimeter, energy to space, energy removed by the exhaust air stream, and exhaust air temperature, all as functions of the exhaust flow rate. Energy and relative luminous flux should be reported as a function of the air volume flow rate.

FIELD MEASUREMENTS

In evaluating an actual lighting installation in the field it is necessary to measure or survey the quality and quantity of lighting in the particular environment.

Field measurements apply only to the conditions that exist during the survey. Recognizing this, it is very important to record a complete detailed description of the surveyed area and all factors that might affect results, such as interior surface reflectances, lamp type and age, voltage, and instruments used in the survey.

In measuring illuminance, detectors should be cosine and color corrected (Figure 2-6).[109] They should be used at a temperature above 15°C (60°F) and below 50°C (120°F), if possible. Care should be exercised while taking readings to avoid casting shadows on the detector of the measuring instrument, and also by standing far enough away from the detector, especially when wearing light-colored clothes, to prevent light from the source from being reflected onto it.
A high-intensity discharge or fluorescent system must be lighted for at least 1 h before making measurements. In new lamp installations, at least 100 h of operation of a gaseous source should elapse before measurements are taken. With incandescent lamps, seasoning is accomplished in a shorter time (20 h or less for common sizes).

The IESNA has developed a uniform survey method for measuring and reporting the necessary data for interior applications.[110] The results of the uniform surveys can be used alone or with those of other surveys for comparison purposes, to determine compliance with specifications, and to reveal the need for maintenance, modification, or replacement. The IESNA survey method was compared with other survey methods and with comprehensive illuminance measurements on horizontal working planes in 11 different rooms under actual conditions of use.[110] The rooms varied in room cavity ratio and in luminaire configurations. They included five of the six room types shown in Figure 2-24. The study found that the IESNA method was generally reliable to within an accuracy of 10%. Larger errors can be expected for spaces with unusual room cavity ratios or poor uniformity. It was concluded that, of all the survey methods studied, the IESNA method has the advantage of requiring the smallest number of measurement points and has no problems of coincidence of luminaire and measurement grids because the measurement points are fixed to the luminaires. The rigidity of the method is a disadvantage, however, in spaces that are obstructed, lack orthogonal geometry, or have highly nonuniform illumination. In these cases, a measurement grid can be used.

Interior Measurements

Illuminance Measurements--Average

Determination of Average Illuminance on a Horizontal Plane From General Lighting Only. The measuring instrument should be positioned so that when readings are taken, the surface of the detector is in a horizontal plane and 760 mm (30 in.) above the floor. This can be facilitated by means of a small portable stand to support the detector. Daylight can be excluded during illuminance measurements by taking the readings either at night or with shades, blinds, or other opaque covering on the fenestration. The area should be divided into approximately sized squares, taking a reading in each square and calculating the arithmetic mean. A measurement grid of 0.6 m (2 ft) is suitable for many spaces. For spaces with unusual room cavity ratios or highly nonuniform illumination, as in corridors under emergency lighting conditions, see Chapter 9, Lighting Calculations.

Ouellette et al.[111] have shown that nonuniform lighting, as, for example, in some emergency lighting applications, may require several hundred randomly selected measurement points to obtain a representative value for average illuminance. This study illustrates how difficult it is to obtain an accurate representative value for illuminance in highly nonuniform illuminated spaces.

Regular Area with Symmetrically Spaced Luminaires in Two or More Rows.

See Figure 2-24a.

1. Take readings at stations r-1, r-2, r-3, and r-4 for a typical inner bay. Repeat at stations r-5, r-6, r-7, and r-8 for a typical centrally located bay. Average the eight readings. This is *R* in Equation 2-8.

2. Take readings at stations q-1, q-2, q-3, and q-4 in two typical half bays on each side of the room. Average the four readings. This is *Q* in Equation 2-8.

3. Take readings at stations t-1, t-2, t-3, and t-4 in two typical half bays at each end of the room. Average the four readings. This is *T* in Equation 2-8.

4. Take readings at stations p-1 and p-2 in two typical corner quarter bays. Average the two readings. This is *P* in Equation 2-8.

5. Determine the average illuminance in the area by using the equation

$$\text{average illuminance} = \frac{R(N-1)(M-1) + Q(N-1) + T(M-1) + P}{NM} \qquad (2\text{-}8)$$

where

N = number of luminaires per row,
M = number of rows.

Regular Area with Symmetrically Located Single Luminaire. See Figure 2-24b. Take readings at stations p-1, p-2, p-3, and p-4 in all four quarter bays. Average the four readings. This is *P*, the average illuminance in the area.

Regular Area with Single Row of Individual Luminaires. See Figure 2-24c.

1. Take readings at stations q-1 through q-8 in four typical half bays located two on each side of the area. Average the eight readings. This is *Q* in Equation 2-9.

2. Take readings at stations p-1 and p-2 for two typical corner quarter bays. Average the two readings. This is *P* in Equation 2-9.

3. Determine the average illuminance in the area by using the equation

$$\text{average illuminance} = \frac{Q(N-1) + P}{N} \qquad (2\text{-}9)$$

where

N = number of luminaires.

Regular Area with Two or More Continuous Rows of Luminaires. See Figure 2-24d.

1. Take readings at stations r-1 through r-4 located near the center of the area. Average the four readings. This is *R* in Equation 2-10.
2. Take readings at stations q-1 and q-2 located at each midside of the room and midway between the outside row of luminaires and the wall. Average the two readings. This is *Q* in Equation 2-10.
3. Take readings at stations t-1 through t-4 at each end of the room. Average the four readings. This is *T* in Equation 2-10.
4. Take readings at stations p-1 and p-2 in two typical corners. Average the two readings. This is *P*.
5. Determine the average illuminance in the area by using the equation

$$\text{average illuminance} = \frac{RN(M-1) + QN + T(M-1) + P}{M(N+1)} \qquad (2\text{-}10)$$

where

N = number of luminaires per row,
M = number of rows.

Regular Area with Single Row of Continuous Luminaires. See Figure 2-24e.

1. Take readings at stations q-1 through q-6. Average the six readings. This is *Q* in Equation 2-11.
2. Take readings at stations p-1 and p-2 in typical corners. Average the two readings. This is *P* in Equation 2-11.
3. Determine the average illuminance in the area by using the equation

$$\text{average illuminance} = \frac{QN + P}{N+1} \qquad (2\text{-}11)$$

where

N = number of luminaires.

Regular Area with Luminous or Louvered Ceiling. See Figure 2-24f.

1. Take readings at stations r-1 through r-4 located at random in the central portion of the area. Average the four readings. This is *R* in Equation 2-12.
2. Take readings at stations q-1 and q-2 located 0.6 m (2 ft) from the long walls, at random lengthwise of the room. Average the two readings. This is *Q* in Equation 2-12.
3. Take readings at stations t-1 and t-2 located 0.6 m (2 ft) from the short walls, at random crosswise of the room. Average the two readings. This is *T* in Equation 2-12.
4. Take readings at stations p-1 and p-2 located at diagonally opposite corners 0.6 m (2 ft) from each wall. Average the two readings. This is P in Equation 2-12.
5. Determine the average illuminance in the area by using the equation

$$\text{average illuminance} = \frac{R(L-8)(W-8) + 8Q(L-8) + 8T(W-8) + 64P}{WL} \qquad (2\text{-}12)$$

where

W = number of luminaires per row,
L = number of rows.

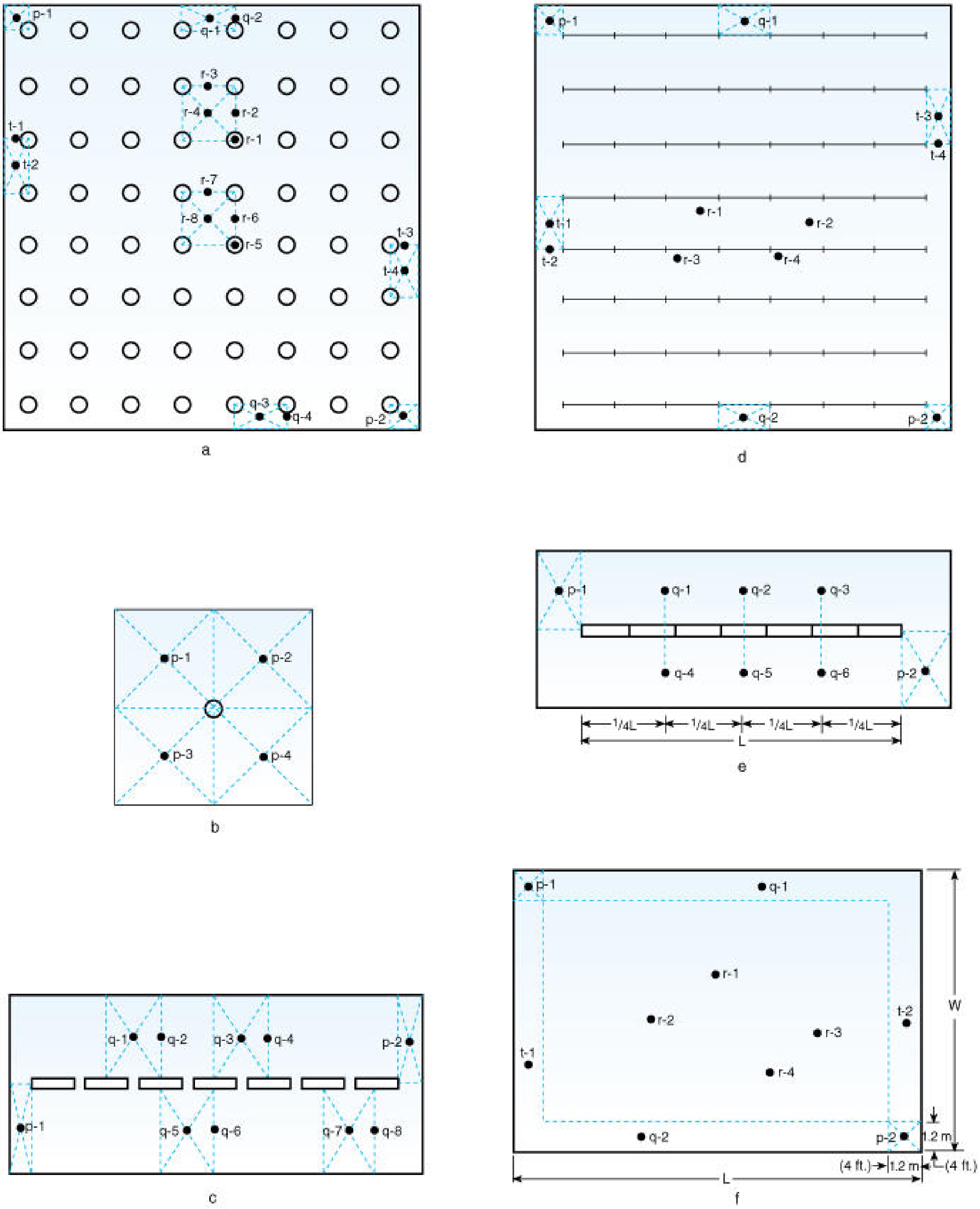
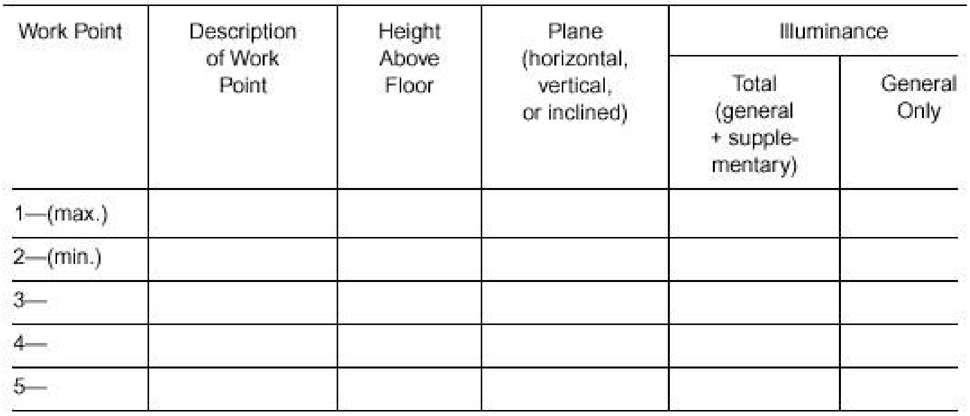


Figure 2-24. Location of illuminance measurement stations in (a) regular area with symmetrically located single luminaire; (b) regular area with symmetrically located single luminaire; (c) regular area with single row of continuous luminaires; (d) regular area with two or more continuous rows of luminaires; (e) regular area with single row of continuous luminaires; (f) regular area with luminous ceiling.

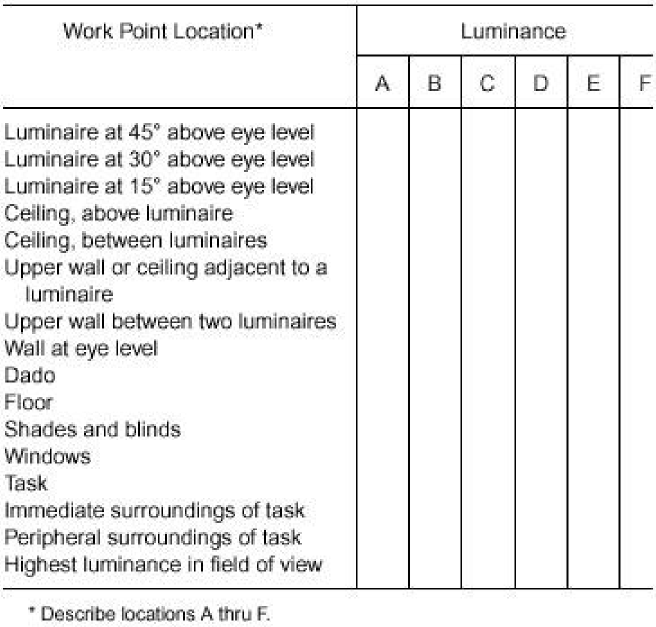


Work Point	Description of Work Point	Height Above Floor	Plane (horizontal, vertical, or inclined)	Illuminance	
				Total (general + supplementary)	General Only
1—(max.)					
2—(min.)					
3—					
4—					
5—					

Figure 2-25. Form for Tabulation of Point Illuminance Measurements

Illuminance Measurements--Point

With task, general, and supplementary lighting in use, the illuminance at the point of work should be measured with the worker in his or her normal working position. The measuring instrument should be located so that when readings are taken, the surface of the light-sensitive cell is in the plane of the visual task or of that portion of the visual task on which the critical visual processing is required--horizontal, vertical, or inclined. Readings should be recorded as shown in Figure 2-25.



Work Point Location*	Luminance					
	A	B	C	D	E	F
Luminaire at 45° above eye level						
Luminaire at 30° above eye level						
Luminaire at 15° above eye level						
Ceiling, above luminaire						
Ceiling, between luminaires						
Upper wall or ceiling adjacent to a luminaire						
Upper wall between two luminaires						
Wall at eye level						
Dado						
Floor						
Shades and blinds						
Windows						
Task						
Immediate surroundings of task						
Peripheral surroundings of task						
Highest luminance in field of view						

* Describe locations A thru F.

Figure 2-26. Form for Tabulation of Luminance Measurements

Luminance Measurements

Luminance surveys should be made under actual working conditions and from a specified work point location with the combinations of daylight and electric lighting facilities available. Consideration should be given to sun position and weather conditions, both of which can have a marked effect on the luminance distribution. All lighting in the area--task, general, and supplementary--should be in normal use. Work areas used only in the daytime should be surveyed in the daytime; work areas used both day and night should be surveyed under both conditions, as the luminance distribution and the possibilities of comfort and discomfort can differ markedly between them. Nighttime surveys should be made at night or with shades drawn. Daytime surveys should be made with shades adjusted to positions actually set by the occupants.

On a floor plan sketch of the area, an indication should be made of which exterior wall or walls, if any, were exposed to direct sunlight during the time of the survey by writing the word "Sun" in the appropriate location. Readings should be taken, successively, from the worker's position at each work point location *A*, *B*, *C*, etc., and luminance readings from each location recorded as shown in Figure 2-26.

Outdoor Measurements

In roadway and many floodlight installations, light is projected to the surface to be lighted, and each luminaire must be adjusted carefully to produce the best utilization and quality of illumination. For an accurate evaluation of this type of installation, illuminance must be measured carefully.

Preparation for the Survey[112-114]

1. Inspect and record the condition of the luminaires (globes, reflectors, refractors, lamp positioning, etc.). In the case of roadway lighting, make sure the luminaires are level and their vertical and lateral placement is as designed. Unless the purpose of the test is to check depreciation or actual in-service performance, all units should be cleaned and new lamps installed. New lamps should be seasoned properly.[95-97] While inoperative lamps are readily noticed in roadway installations, they can easily

be overlooked in large floodlighting systems. If these lamps are not replaced for the field survey, proper consideration must be given when evaluating the results.

2. Measure and record the mounting heights of the luminaires.

3. Measure and record the locations of the poles, the number of luminaires per pole, the wattage of the lamps, and other pertinent data. Check these data against the recommended layout; a small change in the location or adjustment of the luminaires can make a considerable difference in illuminance.

4. Determine and record the burning hours of the installed lamps.

5. Consider the impact of stray light on the measurements. The survey should be made only when the atmosphere is reasonably clear. Extraneous light produced by a store, a service station, or other lights in the vicinity requires careful attention in street lighting tests.

6. Luminaire voltage should be measured because it can affect illuminance. At night, during the hours when the luminaires are normally used, record the voltage at the lamp socket with all of the lamps operating. The voltage at the main switch can be used instead, provided allowance is made for the voltage drop to the individual luminaires. If discharge lamps are used, record the input voltage to the ballast at the ballast terminals. Discharge lamps should be operated at least 60 min to reach normal operating conditions before measurements are made.

Survey Procedures. Measurements should be made with a recently calibrated, color-corrected, and cosine-corrected photometer (Figure 2-6) capable of being leveled for horizontal measurements or positioned accurately for other measurement planes as required. The photometer should be selected for its portability, repeatability, and measurement range.

1. For roadway lighting systems, at least one traffic lane must be closed for substantial periods of time. Because of this difficulty and expense of making field measurements of pavement luminance, it is common to use a computerized design procedure using point calculations of horizontal illuminance level at each of the pavement luminance measurement points recommended. As a check on the computer calculations, it is necessary only to measure the illuminance at a reduced number of points.[112]

2. For roadway signs, the minimum and maximum illuminance levels are determined by scanning the sign face. Additional illuminance measurements are taken at specific locations according to the sign size. Luminance measurements are also made for both externally and internally illuminated signs.[114]

3. For sports installations,[113] the sports area (or the portion of the area under immediate consideration) should be divided into test areas of approximately 5% of the total area, and readings should be taken at the center of each area. Where lighting for color television is involved,[115] horizontal illuminance readings need to be taken at each station. Another set of readings should be made with the detector tilted 15° from vertical in the direction of each camera location and 0.9 m (36 in) above ground level (unless otherwise specified for the particular activity). This will help ensure adequate illumination for the color television cameras.

4. Readings should be made at each test station, with repeat measurements at the first station frequently enough to assure stability of the system and repeatability of results. Readings should be reproducible within 5%. Enough readings should be taken so that additional readings in similar locations will not change the average results significantly.

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3

Vision and Perception

. . . [S]eeing, regarded as a supply for the primary wants of life is in its own right the superior sense

--Aristotle (384-322 BC)

INTRODUCTION

Vision depends on light. Lighting should provide visual conditions in which people can function effectively, efficiently, and comfortably. To predict human behavior as a function of the lighting conditions, it is important to understand the physical, physiological, and perceptual characteristics of the visual system. This chapter highlights some of the basic relationships between light and vision. It provides some fundamental data that the illuminating engineer may find useful, and calls attention to the factors that need to be considered when designing lighting for visual performance and comfort.

VISUAL SYSTEM STRUCTURE

The visual system is an image processing system. It involves the eye and brain working together to interpret the visual environment (Figures 3-1 and 3-2). The optical elements of the eye form an image of the world on the retina. At the retina, photons of light are absorbed by the photoreceptors and converted to electrical signals. These signals are transmitted by the optic nerve to the lateral geniculate nucleus (LGN) and then to the visual cortex for visual processing. In addition to the neural pathways from the eye to the visual cortex, there are a number of other pathways leaving the optic nerve shortly after it exits the eye that control pupil size, eye movements, and circadian rhythms.

The Eye

The structure of the eye can be divided into three distinct parts: the ocularmotor components (the eye muscles), the optical components (the cornea, crystalline lens, pupil, and intraocular humors), and the neurological components (the retina and optic nerve).

Ocularmotor Components. The ocularmotor components of the eye consist of three pairs of muscles (Figure 3-3). These muscles position the lines of sight of the two eyes so that they are both pointed towards the same object of regard (Figures 3-4 and 3-5). The line of sight of the eye passes through the part of the retina used for discriminating fine detail, the fovea. If the image of a target does not fall on the fovea, the resolution of target detail will be reduced. Additionally, if the foveas of both eyes are not aimed at the same target, the target may be seen as double (diplopia).

Eye movements can take several different forms.[1] Among the more important are:

> 1. Saccades. High-velocity movements, usually generated to move the line of sight from one target to another, are called saccades. Velocities may range up to 1000 degrees per second, depending upon the distance moved. Saccadic eye movements have a latency of 150 to 200 ms, which limits how frequently the line of sight can be moved in a given time period; approximately five movements per second is the maximum. Visual functions are substantially limited during saccadic movements. Eye movements during reading characterize a series of alternate fixations and saccades, along a row of print.

2. Pursuit. Smooth eye movements called pursuits are used to follow a smoothly moving target after a saccade has been used to bring the retinal image of the target onto the fovea. The pursuit system cannot follow smoothly moving targets at high velocities, nor can it follow slowly but erratically moving targets. If the eye cannot follow the target, resolution of target details decreases because the target's retinal image is no longer on the fovea. To catch up, binocular pursuit and jump movements are made, which are referred to as version movements when they involve objects in a frontal plane. For these movements, the two eyes make equal movements in the same direction, so there is no change in their angle of convergence (Figure 3-4).

3. Vergence movements. Movements of the two eyes that keep the primary lines of sight converged on a target or that may be used to switch fixation from a target at one distance to a new target at a different distance are called vergence movements (Figure 3-5). These can occur as a jump movement or can smoothly follow a target moving in a fore-and-aft direction. Both types of movement involve a change in the angle between the eyes. When the primary lines of sight drift apart so that they fail to converge at the intended point of fixation, vergence movements play a major role in making the eyes see the target.

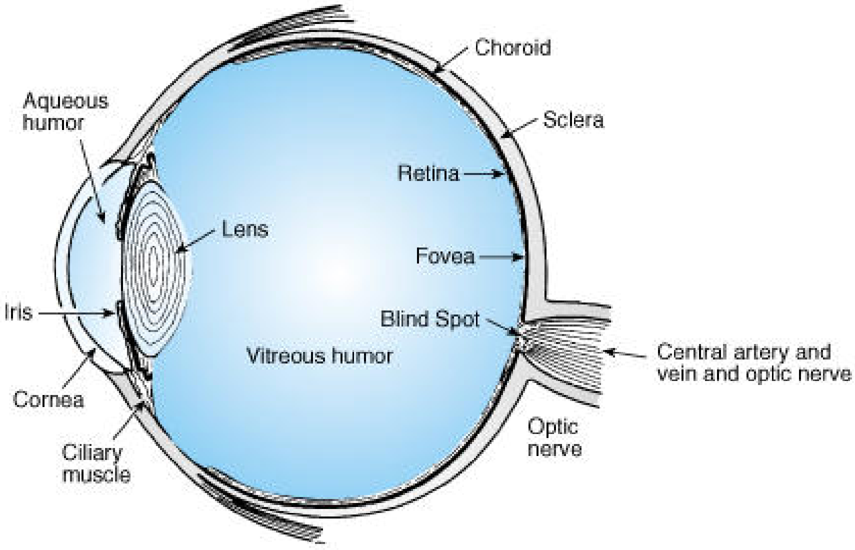


Figure 3-1. A horizontal section through the eye. The approximate length from the cornea to the retina is 24 mm. The thickness of the choroid is about 0.05 mm and the sclera 1.0 mm.

Optical Components. The function of the optical components of the eye is to form an image of the target on the retina. For this to occur, light has to be transmitted through the eye without excessive absorption and scattering, and
the image of the target has to be focused on the retina (Figure 3-1).

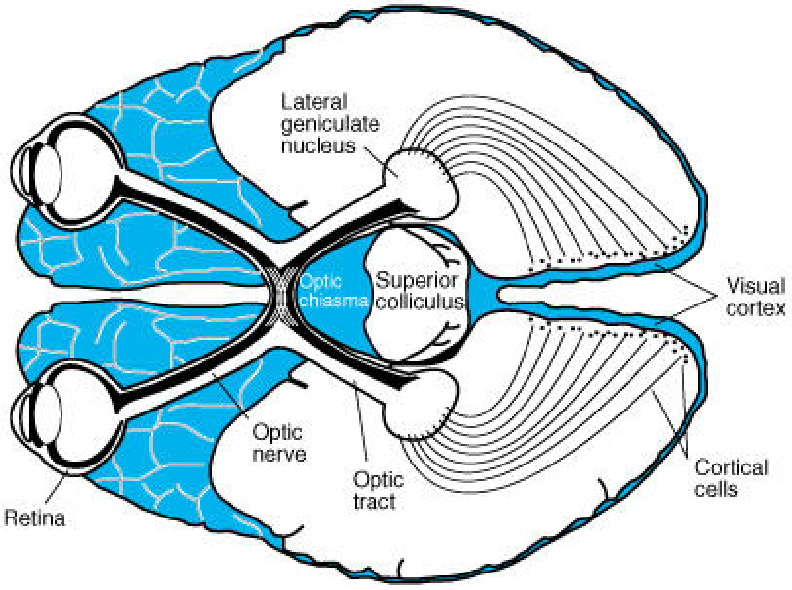


Figure 3-2. A schematic diagram of the structure of the visual system. Used, by permission, from R. Sekuler and R. Blake, *Perception*. © 1994. McGraw-Hill.

The transmittance of the eye varies with wavelength and with age.[2] In young and old eyes, the cornea absorbs most of the incident radiation shorter than 300 nm. In contrast, the human crystalline lens gradually develops a yellow pigmentation as it ages. This pigmentation attenuates the total transmission of radiant energy to the retina, especially in the shorter-wavelength portion of the visible and UV spectrum (Figure 3-6).[3] As shown in more recent work (see Chapter 5, Nonvisual Effects of Optical Radiation, and Figure 5-4), newborn human lenses transmit UV energy.[4] This transmission is greatly reduced but not entirely lost by early adulthood. Later in adulthood the UV transmission is entirely lost, and there are also significant reductions in transmission of short-wavelength portions of the visible spectrum. Accordingly, the retina receives radiation in the range from 380 to 950 nm with limited attenuation. Beyond 950 nm, transmittance is variable, with major absorption in the infrared (IR) water bands. Very little IR radiation beyond 1400 nm reaches the retina.

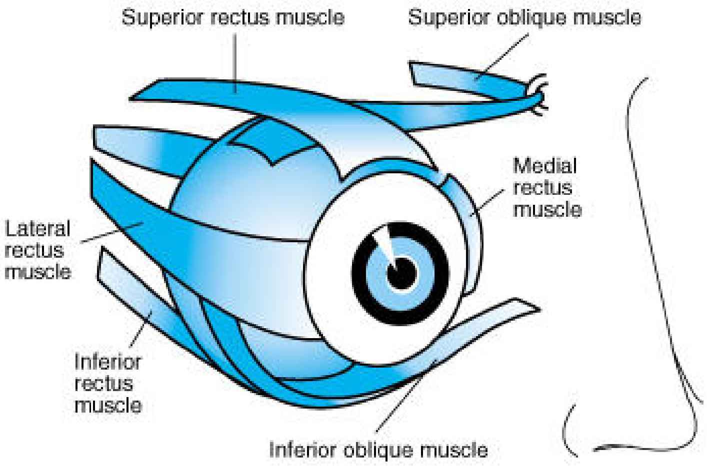


Figure 3-3. An eye and the extraocular muscles used to move it. Used, by permission, from R. Sekuler and R. Blake, *Perception*. © 1994. McGraw-Hill.

In the visible region of the spectrum, the optics of the eye transmit more light at long wavelengths (the red end) than at short wavelengths (the blue end), a tendency that is enhanced at the fovea by the additional short wavelength absorption of the macula lutea, a yellow filter that lies immediately above the fovea and parafovea. On average, some 70 to 85% of the visible spectrum reaches the retina in young eyes.[4] As one ages, there is a general reduction in the transmittance at all wavelengths combined with a marked reduction (greater than 4 times) in short-wavelength transmittance, due primarily to thickening and yellowing of the crystalline lens (Figure 3-7).[5]

While absorption of light reduces the magnitude of the stimulus to the visual system, it does not degrade the quality of the retinal image, that is, it does not blur the retinal image nor reduce its luminance contrast. Such degradation occurs when light is scattered in the eye or additional light is generated within the eye. Scattering within the eye is primarily large-particle scattering, which is not wavelength dependent. In young eyes, some 25% of the scattered light is produced by the cornea,[6] another 25% by the fundus[7-9] (see "Neurological and Supportive Components" below), and the rest by the lens and the vitreous humor. The aqueous humor causes little scattering, if any. The amount of scattered light in the eye increases with age. Consequently, older eyes are more susceptible to disability glare, as discussed later. Almost all of the increased scattering with age is due to changes in the lens.[10] The quality of the retinal image can also be reduced by light generation within the eye, caused by fluorescence in the lens. This phenomenon occurs primarily in the elderly and is produced by absorption of short wavelength visible and ultraviolet radiation in the lens which is then re-emitted at longer wavelengths to which the visual system is more sensitive.[11]

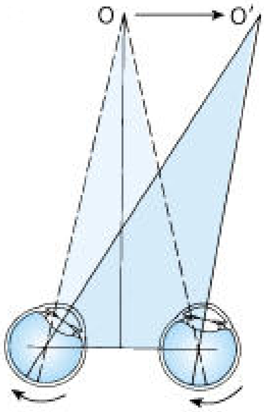


Figure 3-4. In a version movement, as the target moves from point O to point O' the angle between the eyes remains constant.

There are three optical components involved in the ability of the eye to refract or to focus an image on the retina. The first is the thin film of tears on the cornea. This film is important because it cleans the surface of the eye, starts the optical refraction (light bending) process necessary for focusing objects, and smoothes out small imperfections in the surface of the cornea. The second optical component is the cornea. This covers the transparent anterior one-fifth of the eyeball (Figure 3-1). With the tear layer, it forms the major refracting component of the eye and gives the eye about 70% of its refractive power. The crystalline lens provides most of the remaining 30% of the refracting power. The ciliary muscles have the ability to change the curvature of the lens and thereby adjust the power of the eye's optical system, when needed, in response to changing target distances or certain types of refractive errors; this change in power is called accommodation.

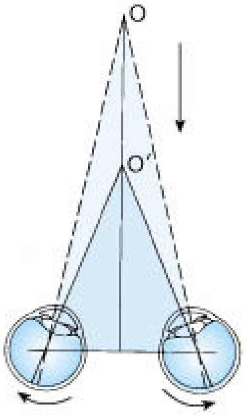


Figure 3-5. In a vergence movement, as the target moves from point O to point O', the angle between the eyes changes.

Accommodation is always a response to an image of the target located on or near the fovea rather than in the periphery. It is used to bring a defocused image into focus or to change focus from one target to another at a different distance. It may be gradually changed to keep in focus a target that is moving in a fore-and-aft direction. Any condition, either physical or physiological, that handicaps the fovea, such as a low light level, will adversely affect accommodative ability. Blurred vision and eyestrain can be consequences of limited accommodative ability.[12]

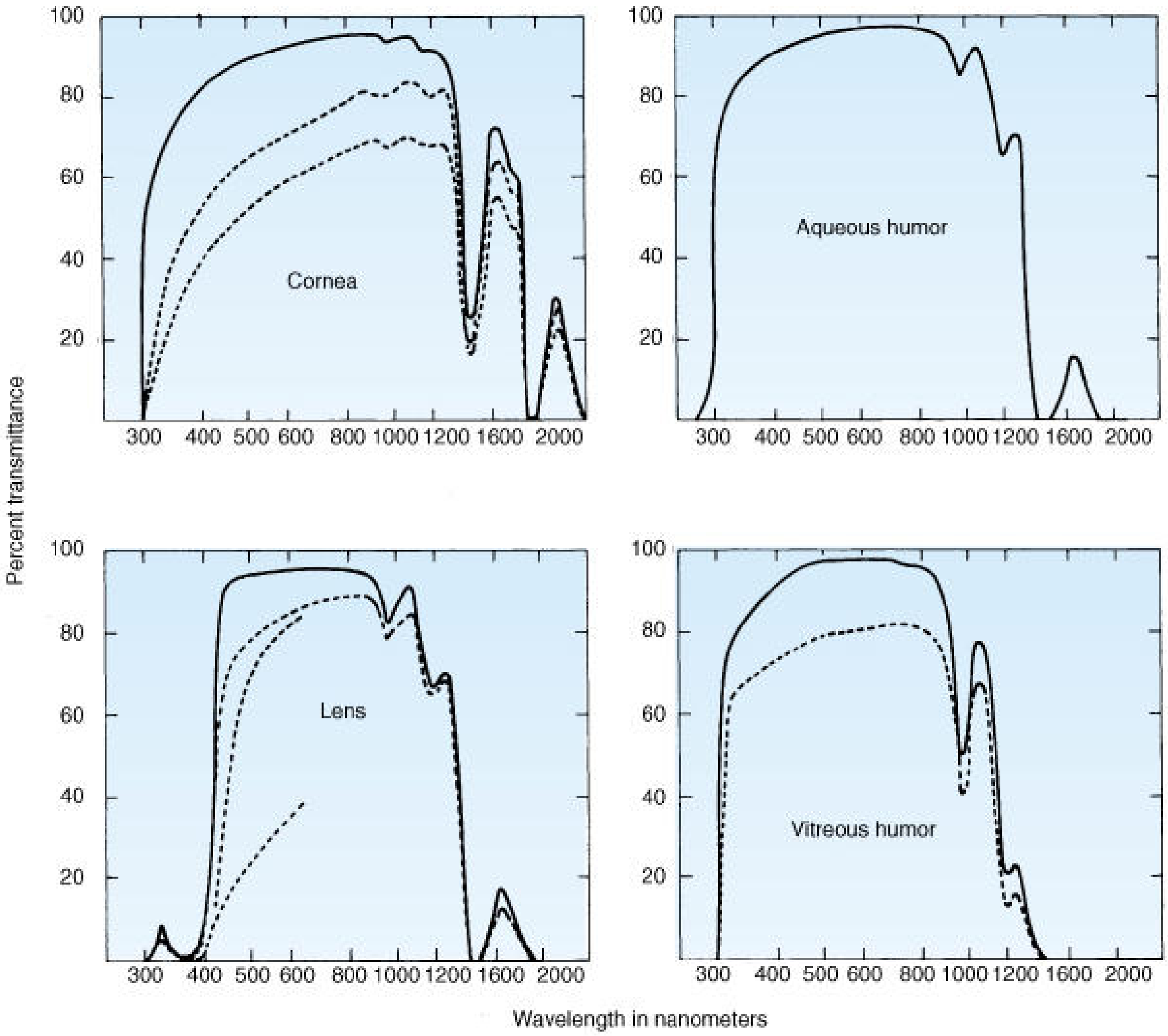


Figure 3-6. Spectral transmission properties of the human ocular media. The solid curves refer to the total light transmittance through the medium. The dashed curves refer to the direct, unscattered components only. The difference between the solid and dashed curve at each wavelength indicates the amount of light that is scattered by transmission through the medium. Where more than one dashed curve is shown the lower ones are for older eyes.

When there is no stimulus for accommodation, as in complete darkness or in a uniform luminance visual field such as occurs in a dense fog, the accommodation system typically accommodates to approximately one meter away.[13]

Neurological and Supportive Components. The posterior 80% of the eye is enclosed by three layers of tissue (Figure 3-1). Collectively, they protect and nourish the eye and transduce light into electrical signals:

1. The sclera. The outermost covering of the globe, which is continuous with the cornea, protects the eye's contents and defines its shape.

2. The choroid. A highly vascular tissue that contains the blood supply to much of the eye.

3. The retina. The innermost layer, which converts radiant energy into electrical signals that are sent to the brain.

Together, the choroid and the retina constitute the fundus.

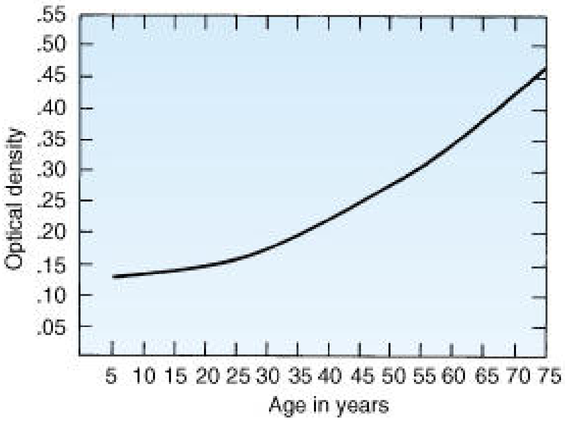


Figure 3-7. The optical density of the human lens at 490nm as a function of age (optical density D = log (1/t) where t = total transmittance).

Photoreceptors. The retina contains two main classes of light-sensitive receptors, rods and cones, which are differentiated by their morphology and by the spectral sensitivity of the photopigments which they contain (Figure 3-8).

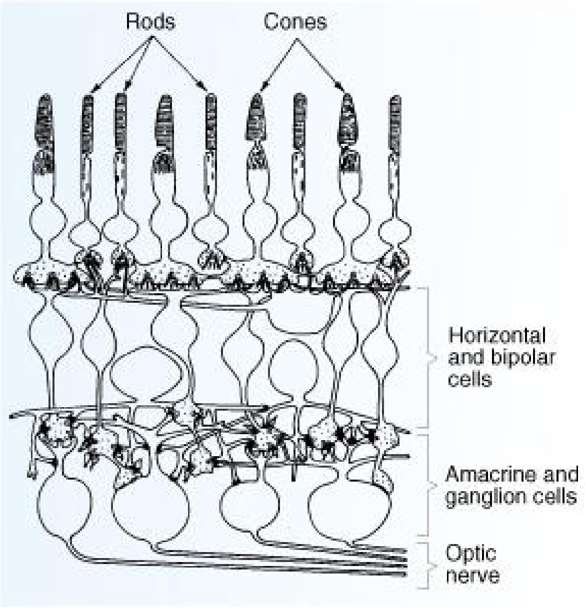


Figure 3-8. A simplified diagram of the connections among the neural elements in the retina. The regions where the cells are contiguous are synapses. The direction of incident light is from the bottom of this diagram.

Rods, which are absent in the fovea, increase in number to a maximum at about 20° of eccentricity and then gradually decrease towards the edges of the retina (Figure 3-9). All rods contain the same photopigment (rhodopsin), which has a peak spectral sensitivity at approximately 507 nm (Figure 3-10).

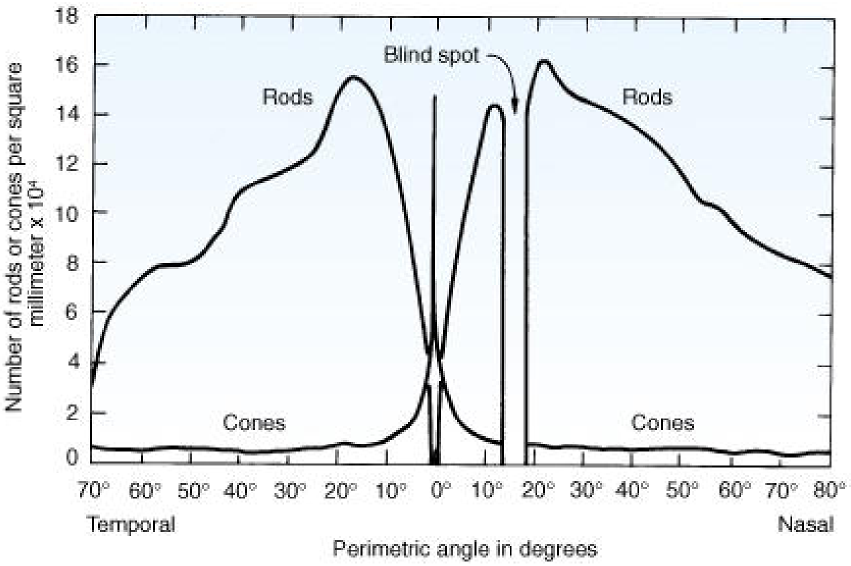


Figure 3-9. The distribution of rod and cone photoreceptors across the retina. The 0° point represents the fovea.

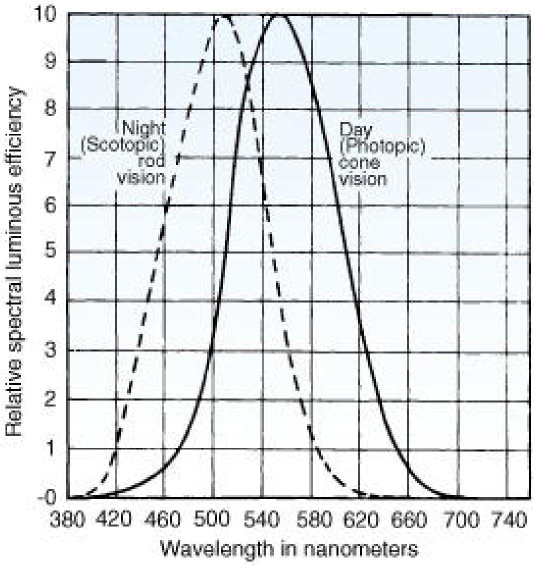


Figure 3-10. The CIE Standard Photopic and Scotopic Observers, representing the relative spectral sensitivity of the cone and rod photoreceptors, respectively.

Cones are divided into three known classes, each characterized by the photopigment that it contains: erythrolabe, chlorolabe, or cyanolabe (also known as L-type, M-type, and S-type or long-, middle-, and short-wavelength type) (Figure 3-11). Cones are concentrated in the fovea, although there are cones in all parts of the retina (Figure 3-9). All three cone types acting together have a peak spectral sensitivity at approximately 555 nm (Figure 3-10). The different photopigments in the cones make color discrimination possible.[14]

Receptive Fields. Photoreceptors do not send their information directly to the brain, but rather to several other cells in the retina, which in turn send them to ganglion cells, whose terminal axons constitute the optic nerve (Figure 3-8). In this way, light received by a number of receptors is "pooled" to provide a signal strong enough to stimulate a ganglion cell. The area of retina that stimulates a ganglion cell is called a receptive field. Although photoreceptors are the primary transducers of light into electrical signals, the receptive fields begin the image processing, which enables the visual system to interpret the visual environment.

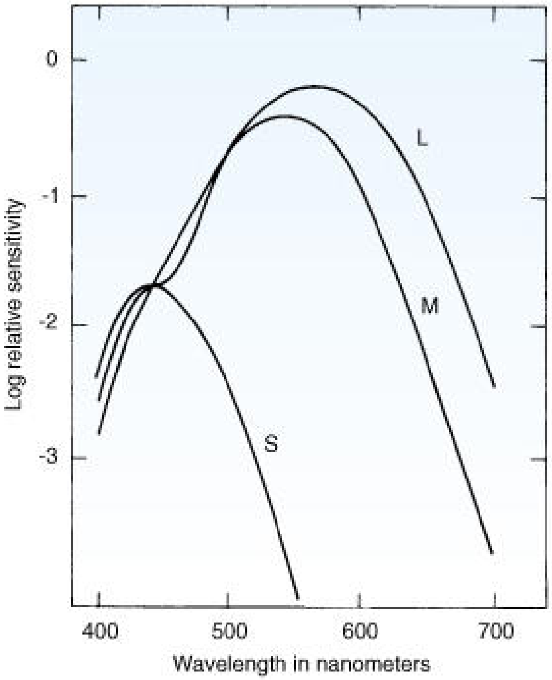


Figure 3-11. The relative spectral sensitivity curves of the three cone photoreceptors: long (L), middle (M), and short (S).

Ganglion cell receptive fields are comprised of two distinct, juxtaposed areas: a circular center and an annular surround. These two areas receive signals from different, individual bipolar cells (Figure 3-8), which have received information from different photoreceptors.

In the fovea, the center area of the receptive field receives neural signals from a single bipolar cell, which itself receives signals from a single cone photoreceptor. At greater eccentricities from the fovea, receptive field centers are larger because they receive input from many photoreceptors, both rods and cones, through the bipolar layer. Receptive field surrounds commonly receive input from several bipolar cells, which are fed not only by direct links to photoreceptors but also from special cells in the retina which laterally connect other bipolar cells. Some of the lateral connections are illustrated in the bipolar layer of Figure 3-8.

These facts reflect the tradeoff in the retina between fine spatial resolution and high sensitivity to light. Large receptive fields, like those found in the periphery, can gather very few photons and sum them to produce a neural signal for "light." Every photon captured within a receptive field produces the same neural response; hence, the location of each photon capture within a receptive field cannot be spatially segregated. Very small receptive fields, like those in the fovea, are needed to precisely locate objects on the retina. Thus, the fovea has excellent spatial resolution but low sensitivity to light, whereas the periphery has high sensitivity to light and poor spatial resolution.

A very important aspect of this center-surround organization is the ability to enhance the contrast of images at the boundary. The eye is a very poor optical system fraught with many types of aberrations and imperfections (see "Focusing Problems"). To overcome its severe optical limitation, the visual system has developed the center-surround receptive field organization to provide a simple, yet elegant, image enhancement system.

The center and surround areas produce opposite neural polarities in the ganglion cell when stimulated by light. Light striking the center of the receptive field will increase the neural firing rate of the ganglion cell, whereas the same light striking the surround will decrease the firing rate. Light striking both the center and surround will produce an intermediary response because the excitation produced by the light stimulating the center area will be counteracted by the inhibitory effect of light stimulating the surround.

Consider then an image of a white disc on a black background focused and precisely covering the center of a receptive field. This configuration will produce the maximum excitation to the ganglion cell because the center is maximally stimulated and the surround is minimally stimulated. The net effect is the strongest possible signal from the ganglion cell and, therefore, the highest possible contrast between the white center and black surround. Larger or smaller discs imaged at the same location will have smaller impact on the ganglion cell; a larger disc will increase the inhibitory response of the surround, and a smaller disc will not stimulate the center as strongly because it does not completely cover the center of the receptive field. With a little thought, the magnitude of contrast enhancement for other image shapes can be surmised on the basis of how their edges are positioned within the receptive field. The common result, however, is that the contrast of juxtaposed light and dark areas of an image will be enhanced if they are focused at the boundary between a receptive field center and its surround.

At any location in the retina there is an equal proportion of receptive fields with excitatory centers and inhibitory centers. Therefore, the contrast of both black discs and white discs will be enhanced. Also at any location in the retina, there is a distribution of receptive field sizes. This enables the retina to enhance the contrast of variously sized images. Nevertheless, there is an optimum target size for any retinal location; smaller images are seen best in the fovea, and larger ones are seen best in the periphery.

It is important to note that receptive field sizes are not constant, but rather they change size with light level. As light level increases, receptive field sizes increase as they collect signals through their lateral connections from more distant locations in the retina. In effect, this greater inhibition from the receptive field surround makes the center of the receptive field functionally smaller. Indeed, the center of a receptive field in the fovea can become smaller than the diameter of single cone at high light levels. This reduction in the size of the receptive field center enables us to improve acuity as light level is increased (Figure 3-27).

Color vision also depends on this organization. Consider a receptive field where L-cones exclusively populate an excitatory center and M-cones populate an inhibitory surround. Consider now two colored lights that cover the entire receptive field. If the L-cones are stimulated more than the M-cones for one of the colored lights this ganglion cell will signal "red" by increasing its neural firing rate. If the other light produces a greater response in the M-cones, the ganglion cell will signal "green" because its firing rate decreases. Because of this receptive field polarity, red and green hues are perceptual opposites; this is why one cannot see, for example, a "reddish green" light. Yellow and blue are also opposed through ganglion cell receptive field organization. Yellow is created by the sum of the input of the L and M cones in opposition to blue, which is produced by the input from the S cone. There are also some spatial implications of this receptive field organization. For example, very small images in the center of the fovea cannot produce perceptions of yellow or blue because there are no S-cones in the center of the fovea. Further information on color vision may be found throughout this chapter and in Chapter 4, Color.

Neural Pathways. Electrical signals from the receptive fields in the retina are transmitted over the optic nerve. Approximately 20% of optic nerve fibers project to the superior colliculus, and 80% to the lateral geniculate nucleus (LGN) and on to the visual cortex (Figure 3-2).

At the optic chiasm, the fibers from each eye divide into two sets; one set remains on the same side of the head as the eye, and the other set crosses over to the other side. The result is two optic tracts, both of which contain nerve fibers from both eyes; one tract transmits the signal from the left side of both eyes to the left side of the visual cortex, and the other transmits the signals from the right side of both eyes to the right side of the visual cortex (Figure 3-2).

The superior colliculus is a phylogenetically older part of the brain and in humans is involved in controlling eye movements. Because the superior colliculus also receives signals from the ears, it is believed that its role is directing eye and head movements towards targets located away from the point of fixation. It is not involved in the detailed image processing.

The LGN contains an orderly representation of the retina. Investigations of its functioning have revealed that it continues processing the retinal image by sorting the information it contains into distinct categories. This is accomplished with two channels of information flow, the magnocellular channel and the parvocellular channel. The magnocellular channel transmits primarily temporal information and is dominant in the periphery of the retina. The parvocellular channel transmits primarily spatial information and is dominant in the fovea. This pattern is consistent with how the periphery of the retina identifies changes in the visual environment and the fovea determines the nature of those changes.

The visual cortex takes the information sorted by the LGN and refines and interprets it in terms of past experience. Approximately 80% of the visual cortex is assigned to analyze and interpret the central 10° of the visual field. This pattern of assignment is called cortical magnification.

Although the components involved in transforming patterns of photons of light into visual perceptions have been discussed separately, it is important to appreciate that there is considerable interaction between them. An example of such interactions is the system of color vision (see Chapter 4, Color, and "Color Discrimination" in this chapter). The ability to discriminate among wavelengths of light is due to a combination of photochemical and neurological processes. Signals from the three cone types are coded in the retina and the lateral geniculate body into chromatic and achromatic information. As a first-order model of color and brightness perception, chromatic information is a result of a subtraction of photoreceptor signals, while achromatic information is a result of the addition of photoreceptor signals. However, many experiments using various testing procedures and stimuli demonstrate that this is an oversimplification of how the visual system processes light signals. Chromatic, achromatic, spatial, and temporal information are combined in complicated ways to give final perceptions of light and color. For example, equal-luminance colored lamps may have different apparent brightnesses because of the interaction between achromatic and chromatic channels.[15] Figure 3-12 is a proposed model of how the visual system combines the information from these various channels to produce human perceptions.[16]

Dark and Light Adaptation

For the visual system to be able to function well, it has to be adapted to the prevailing light condition. The human visual system can process information over an enormous range of luminances (approximately 12 log units), but not all at once. To cope with the wide range of retinal illuminations to which it might be exposed, from a dark night to a sunlit beach, the visual system changes its sensitivity through a process called adaptation. Adaptation involves three distinct processes:

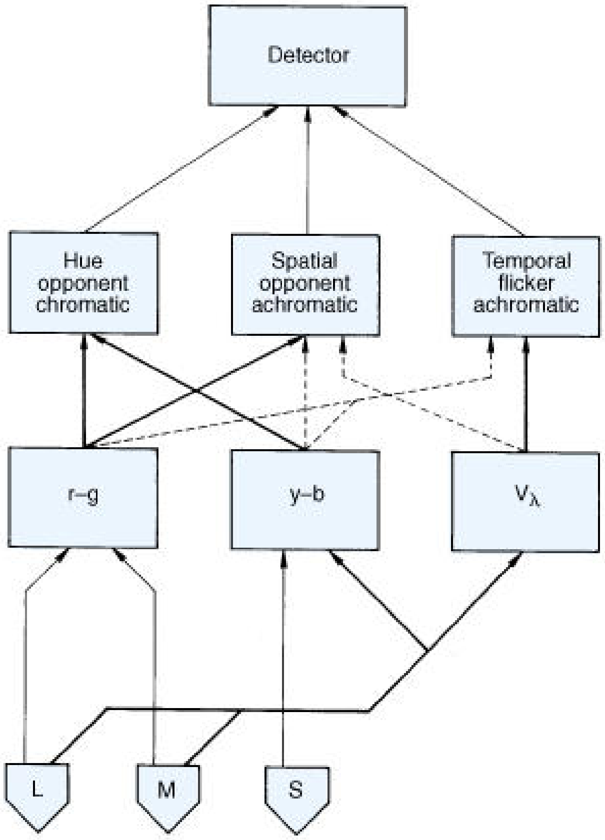


Figure 3-12. A proposed model for the neural connections in the visual system. Information from

the first stage photoreceptors (R,G,B) goes to mechanisms that sum or subtract input to give achromatic and chromatic information, respectively. Subsequent "cortical analysis" mechanisms receive multiple inputs from the second stage. Such a model attempts to qualitatively describe some of the nonlinearities in the visual system that have been discovered using stimuli that vary in several dimensions (spatial, temporal, chromatic and achromatic). The solid lines indicate well-established inputs, while the dashed lines are more speculative.

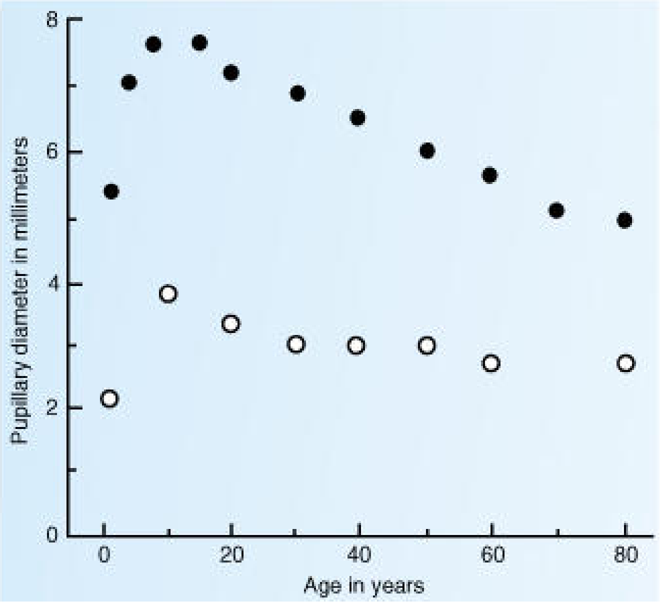


Figure 3-13. Pupil diameter for light-adapted (open circles) and dark-adapted (filled circles) conditions, plotted against the age of the observer. From R.A. Weale, *The senescence of human vision*, © 1992, used by permission of Oxford University Press.

1. Change in Pupil Size. The iris (Figure 3-1) constricts and dilates in response to increased and decreased levels of retinal illumination. Iris constriction has a shorter latency and is faster (approximately 0.3 s) than dilation (approximately 1.5 s).[17] There are wide variations in pupil sizes among individuals and for any particular individual at different times for the same visual stimulus. Pupil size is influenced by emotions, such as fear or elation. Thus, for a given luminous stimulus, some uncertainty is associated with an individual's pupil size until it is measured. The typical range in pupil diameter for young people is from 3 mm for high retinal illuminances to 8 mm for low retinal illuminances.[18] This change in pupil size in response to retinal illumination can only account for a 1.2 log unit change in sensitivity to light. Older people tend to have smaller pupils under comparable conditions (Figure 3-13).

2. Neural Adaptation. This is a fast (less than 200 ms) change in sensitivity produced by synaptic interactions in the visual system.[19] Neural processes account for virtually all the transitory changes in sensitivity of the eye where cone photopigment bleaching has not yet taken place (discussed below), in other words, at luminance values commonly encountered in electrically lighted environments, below approximately 600 cd/m^2. The facts that neural adaptation is fast, is operative at moderate light levels, and is effective over a luminance range of 2 to 3 log units explain why it is possible to look around most lit interiors without being conscious of being misadapted.

3. Photochemical Adaptation. The retinal photoreceptors contain four photopigments. When light is absorbed, the pigment breaks down into an unstable aldehyde of vitamin A and a protein (opsin) and gives off energy that generates electrical signals that are relayed to the brain and interpreted as light. In the dark, the pigment is regenerated and is again available to absorb light. The sensitivity of the eye to light is largely a function of the percentage of unbleached pigment. Under conditions of steady retinal irradiance, the concentration of photopigment is in equilibrium; when the retinal irradiance is changed, pigment is either bleached or regenerated

to reestablish equilibrium. Because the time required to accomplish the photochemical reactions is on the order of minutes, changes in the sensitivity often lag behind the stimulus changes. The cone system adapts much more rapidly than does the rod system; even after exposure to high irradiances, the cones achieve their maximum sensitivity in 10 to 12 min, while the rods require 60 min (or longer) to achieve their maximum sensitivity (Figure 3-14).[20]

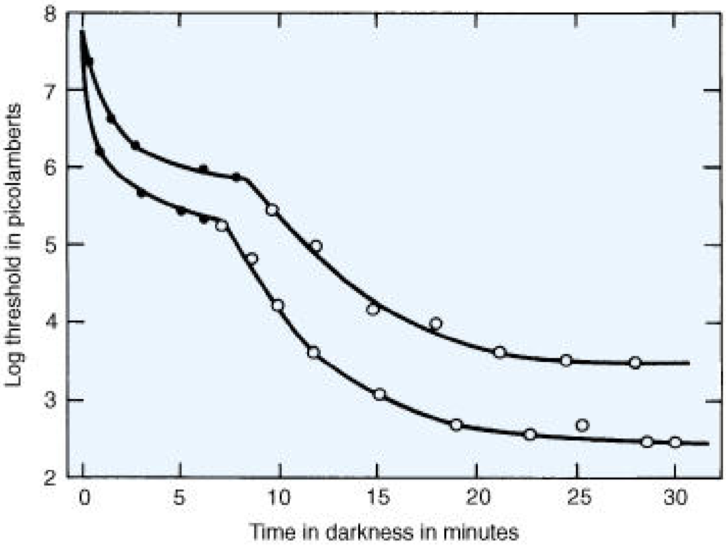


Figure 3-14. The increase in sensitivity to light (decrease in threshold) as a function of time in the dark, after exposure to a bright light. Sensitivity is measured at a point 7°from the fovea. The two curves represent the extremes of the normal range of observers. (1 picolambert = 3.2×10^{-9} cd/m^2)

Exactly how long it takes to adapt to a change in retinal illumination depends on the magnitude of the change, the extent to which it involves different photoreceptors, and the direction of the change. For changes in retinal illumination of approximately 2 to 3 log units, neural adaptation is sufficient, so adaptation is in less than a second. For larger changes, photochemical adaptation is necessary. If the change in retinal illumination lies completely within the range of operation of the cone photoreceptors, a few minutes is sufficient for adaptation to occur. If the change in retinal illumination covers from cone photoreceptor operation to rod photoreceptor operation, tens of minutes can be required. As for the direction of change, once the photochemical processes are involved, changes to a higher retinal illuminance can be achieved much more rapidly than changes to a lower retinal illuminance.

When the visual system is not completely adapted to the prevailing retinal illumination, its capabilities are limited.[21] This state of changing adaptation is called transient adaptation. Transient adaptation is unlikely to be noticeable in interiors in normal conditions but can be significant where sudden changes from high to low retinal illumination occur, such as on entering a long road tunnel on a sunny day or in the event of a power failure in a windowless building.

Photopic, Scotopic, and Mesopic Vision

This process of adaptation takes the visual system through three distinct operating states.

1. Photopic vision. This operating state of the visual system occurs at luminances higher than approximately 3 cd/m^2. For these luminances, the retinal response is dominated by the cone photoreceptors. This means that color is perceived and fine detail can be resolved in the fovea.

2. Scotopic vision. This operating state of the visual system occurs at luminances less than approximately 0.001 cd/m^2. For these luminances only the rod photoreceptors respond to stimulation, so the fovea of the retina is inoperative. There is no perception of color, and what

resolution of detail there is occurs in the periphery within a few degrees of the fovea.

3. Mesopic vision. This operating state of the visual system is intermediate between the photopic and scotopic states. In the mesopic state both cones and rod photoreceptors are active. As luminance declines through the mesopic region, the fovea, which contains only cone photoreceptors, slowly declines in absolute sensitivity without significant change in spectral sensitivity,[22] until vision fails altogether as the scotopic state is reached. In the periphery, the rod photoreceptors gradually come to dominate the cone photoreceptors, resulting in gradual deterioration in color vision and resolution and a shift in spectral sensitivity to shorter wavelengths.

The relevance of these different operating states for lighting practice varies. Scotopic vision is largely irrelevant to lighting practice. Nearly every lighting installation provides enough light to at least move the visual system into the mesopic state. Most interior lighting ensures the visual system is operating in the photopic state. Current practice in exterior lighting ensures the visual system operates near the boundary of the photopic and mesopic states.

The spectral sensitivities of the visual system in the photopic and scotopic states have been defined by the Commission Internationale de l'Éclairage (CIE). Figure 3-10 shows the CIE Standard Photopic and Standard Scotopic Observers. These two luminous efficiency functions are used in the fundamental definition of light, to convert from radiometric quantities to photometric quantities (see Chapter 1, Light and Optics). The mesopic state has been extensively studied but has not been defined officially by the CIE, partly because of problems with additivity.[23-26] Problems with additivity are to be expected for any system based on brightness because brightness perception uses the parvocellular channel, which combines both achromatic and chromatic responses in a complex way. Recently, an alternative approach to mesopic photometry has been proposed, based on measurements of reaction time.[27]

Because scotopic vision is irrelevant and the mesopic state has not officially been defined, virtually all photometric quantities used in lighting practice are measured using the CIE Standard Photopic Observer, even for exterior lighting where the visual system may be operating in the mesopic state. It should be realized that the use of the CIE Photopic Observer can give discrepancies between measured photometric quantities in a space and the perception of brightness in the space. The CIE Standard Photopic Observer is based on the relative amounts of power at each wavelength required to produce a criterion brightness response in a 2° foveal field of view. It is an average response derived from several different experimental techniques, including techniques using direct brightness judgments involving the parvocellular channel and techniques are based on flicker perception involving the magnocellular channel.[8] Studies have shown that, even with the visual system operating in the photopic state, the CIE Standard Photopic Observer slightly underestimates the influence of the short wavelength region of the visible spectrum on brightness, even for a 2° field of view;[28] and the underestimation is greater for a 10° field of view,[8] because this larger field extends beyond the macula lutea. This discrepancy between photometric quantities and brightness perception is slight for light sources with a spectral content distributed over the whole visible spectrum. However, when light sources with a very discrete spectral content are compared, the limitations of the CIE Standard Photopic Observer can become important. This is particularly so for colored signal lights, where the brightness of the light is what matters.[29]

Individual Differences

Although the visual systems of all people have the same basic structure, as in most living things, there are individual differences. For example, Figure 3-15 shows a wide variation in luminous efficiency for 52 individuals.[30] Many of these differences are ignored when considering lighting for use by the general public, but some are sufficiently large and their effects so predictable that they need to be taken into account in some lighting applications. This is especially true when lighting for the aged and partially sighted, as discussed later (see "Aging and Partial Sight").

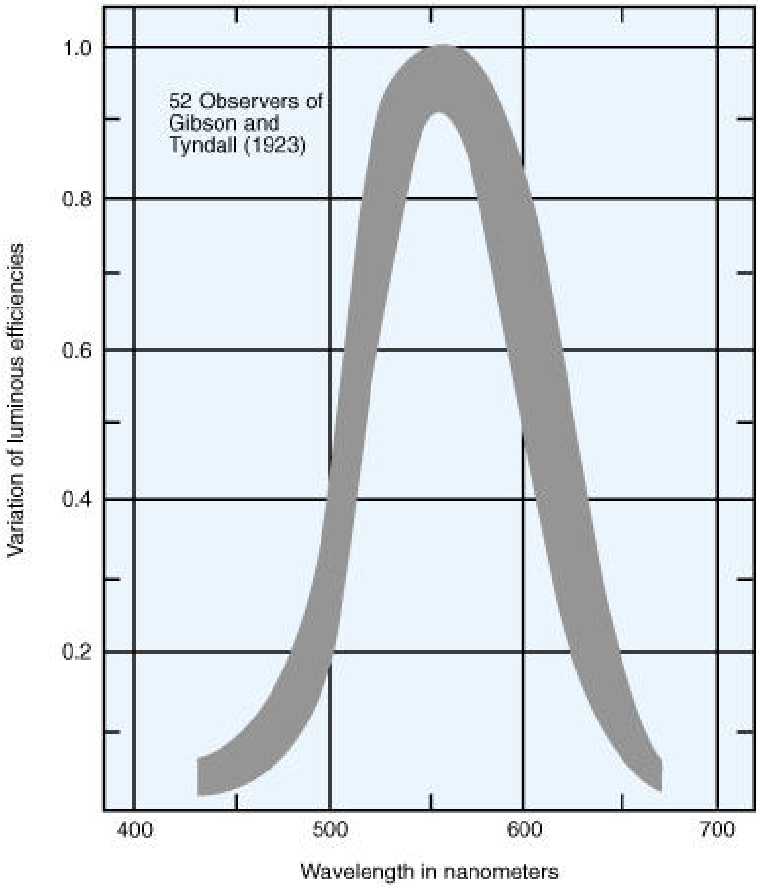


Figure 3-15. The range of luminous efficiency values for 52 observers.

Focusing Problems. As discussed above in "Ocular Components," the eye adjusts its optical power to focus objects at different distances on the retina. This is possible for a wide range of distances when there is a match between the combined optical power of the cornea and lens and the dimensions of the eye. However, when there is a mismatch between the optical power and the distance from the lens to the retina, a sharp image cannot be formed on the retina. This blurred retinal image is called a refractive error. There are several different forms of refractive error. They are:

1. Myopia. The optical power is greater than necessary so objects at a distance are focused in front of the retina (Figure 3-16a).

2. Hyperopia. The optical power is less than necessary so objects at a distance are focused behind the retina (Figure 3-16b).

3. Astigmatism. The optical power is not equal in all planes so objects are focused in front of, behind and on the retina for different planes (Figure 3-16c).

4. Presbyopia. The adjustment of optical power is limited. Typically, near objects are focused behind the retina (Figure 3-16d).

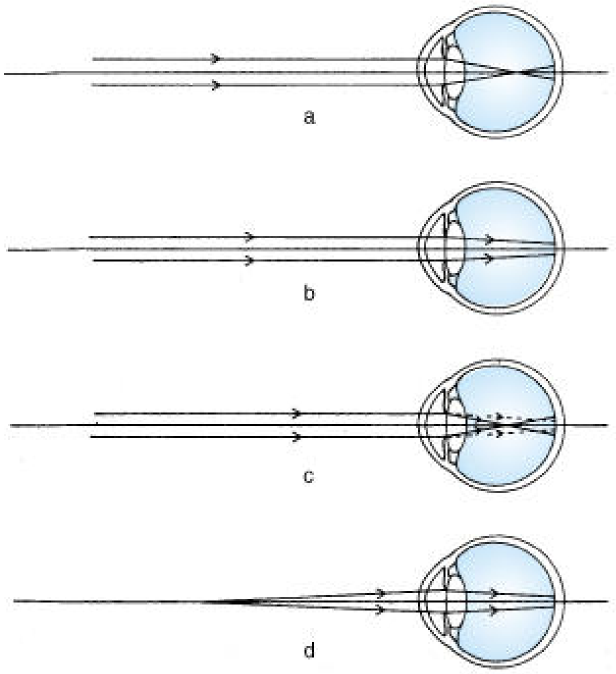


Figure 3-16. The relationship between the image of a point object and the retina in common refractive errors. (a) In myopia, the image forms in front of the retina. (b) In hyperopia, the image forms behind the retina. (c) In astigmatism, multiple foci are formed due to different optical powers occurring in the various meridians of the eye. (d) In presbyopia, accommodation is sufficiently limited that near objects focus behind the retina.

Most of these refractive errors can be corrected by the use of spectacles or contact lenses, although even when the eye is perfectly corrected for refractive errors, a residual blur can remain due to spherical and chromatic aberrations.

1. Spherical aberration. Light rays that enter through the periphery of the cornea are refracted more than those that enter through the central zones (Figure 3-17). Thus, light in the retinal image is partially redistributed over a larger retinal area than would be the case in an aberration-free system. The amount and type of spherical aberration varies with the state of accommodation (Figure 3-18).

2. Chromatic aberration. Shorter wavelengths are refracted more than longer wavelengths (Figure 3-19). As in spherical aberration, the results of the different foci cause blur (Figure 3-20).

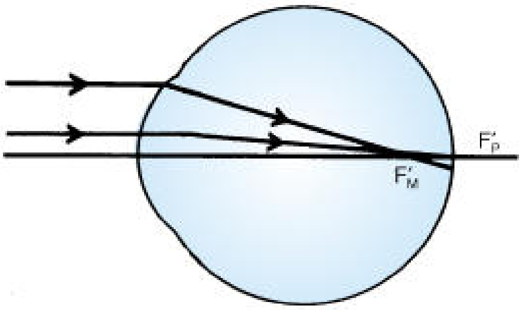


Figure 3-17. Spherical aberration: marginal rays (F'_m) are focused in front of rays entering the eye near the center of the pupil (F'_p).

These aberrations (and others) are mainly of theoretical interest. They are partially compensated by the image processing of the visual system and usually can be neglected in practical lighting design. They may, however, be important in certain specialized applications, such as work under reduced illuminances where pupil sizes can be large.

Abnormal Color Vision. Approximately 8% of males and 0.2% of females have some form of abnormal color vision. Abnormal color vision occurs because of abnormal photoreceptor photopigments. The reason for the preponderance of males is that abnormal color vision is due to a genetic difference on the X-chromosome. Males have only one X-chromosome, but females have two, and for a female to have abnormal color vision, both X-chromosomes must have the same abnormal gene.

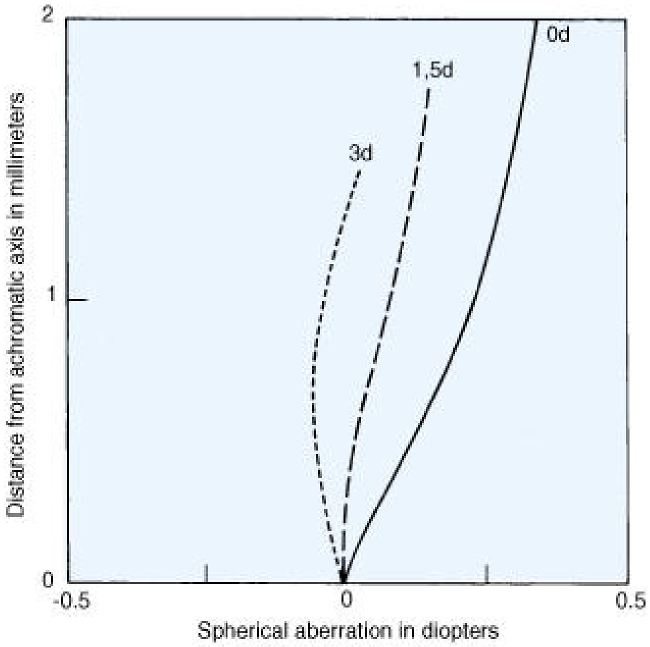


Figure 3-18. Spherical aberration: the amount of spherical aberration (in diopters, D) is on the horizontal axis (positive when undercorrected) and the distance from the achromatic axis is on the vertical axis. The solid line corresponds to the unaccommodated eye; the dashed line corresponds to 1.5 D accommodation; the dotted line corresponds to 3.0 D accommodation.

Figure 3-21 tabulates the different types of abnormal color vision, their causes, and their prevalence. For most activities, abnormal color vision causes few problems, either because the exact identification of color is unnecessary or because there are other cues by which the necessary information can be obtained (e.g., relative location in traffic signals). Abnormal color vision does become a problem when color is the sole or dominant means used to identify objects, for example, in some forms of electrical wiring. People with abnormal color vision have difficulty with such activities.

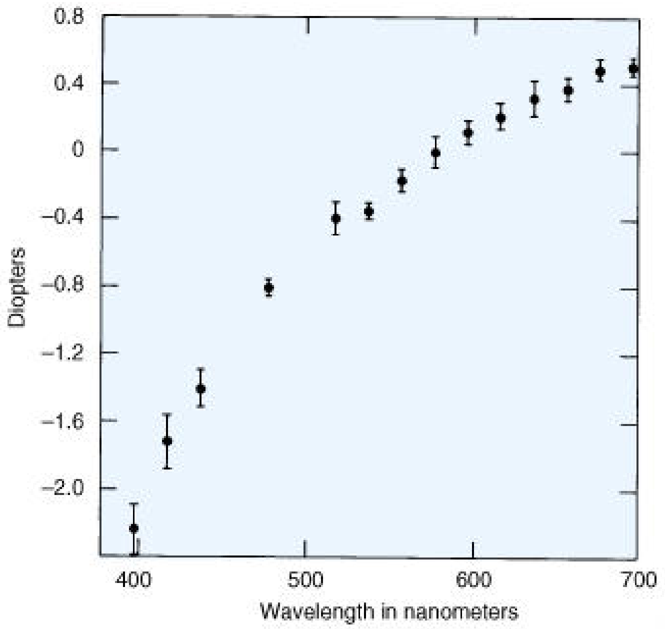


Figure 3-19. Chromatic aberration: the optical power necessary to correct the focus of an eye for differences in refraction at different wavelengths (zero correction is arbitrarily set at 589 nm).

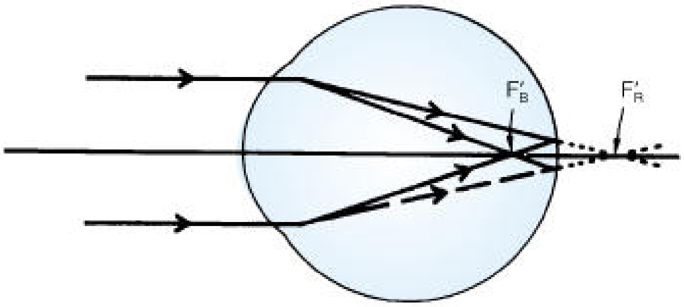
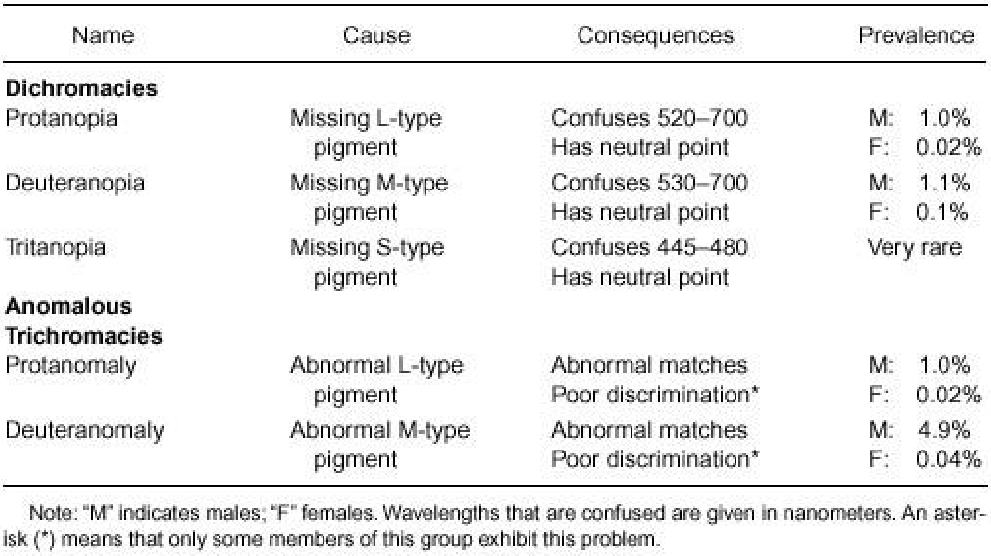


Figure 3-20. Chromatic aberration: because the eye's index of refraction is greater for short wavelengths than for long wavelengths, the eye focuses short wavelengths (F'_B) in front of long wavelengths (F'_R).

Where self-luminous colors are used as signals, colored lights should be restricted to those that can be distinguished by people with the more common forms of color abnormality. The CIE has recently recommended areas on the CIE 1931 Chromaticity Diagram within which red, green, yellow, blue, and white signal lights should lie (see Figure 26-17 in Chapter 26). These areas are designed so that the red signal will be named as red and the green as green, even by dichromats, who are missing either a long or middle-wavelength photoreceptor pigment.[31] It should be noted that for people with the most common form of abnormal color vision, the anomalous trichromats, the ability to discriminate colors shows wide individual differences. Some anomalous trichromats are barely distinguishable for people with normal color vision, whereas others resemble dichromats in their ability to discriminate colors.



Name	Cause	Consequences	Prevalence
Dichromacies			
Protanopia	Missing L-type pigment	Confuses 520–700 Has neutral point	M: 1.0% F: 0.02%
Deuteranopia	Missing M-type pigment	Confuses 530–700 Has neutral point	M: 1.1% F: 0.1%
Tritanopia	Missing S-type pigment	Confuses 445–480 Has neutral point	Very rare
Anomalous Trichromacies			
Protanomaly	Abnormal L-type pigment	Abnormal matches Poor discrimination*	M: 1.0% F: 0.02%
Deuteranomaly	Abnormal M-type pigment	Abnormal matches Poor discrimination*	M: 4.9% F: 0.04%

Note: "M" indicates males; "F" females. Wavelengths that are confused are given in nanometers. An asterisk (*) means that only some members of this group exhibit this problem.

Figure 3-21. The Classification, Characteristics, and Prevalence of Defective Color Vision

Aging. As the visual system ages, a number of changes in its structure and capabilities occur.[18] Usually, the first obvious change is loss of accommodation. Accommodative function decreases rapidly with age, so that by age 45 most people can no longer focus at near-working distances (approximately 40 cm) and might need optical assistance. This is known as presbyopia. By age 60, there is very little accommodative ability remaining in most of the population (Figure 3-22), resulting in a fixed-focus optical system. This lack of focusing ability is compensated somewhat by the physiologically smaller pupils in the elderly (senile myosis) because these increase the depth of field of the eye. However, the smaller pupils in turn increase the requirement for task luminance to maintain the same retinal illuminance as when the pupils were larger.

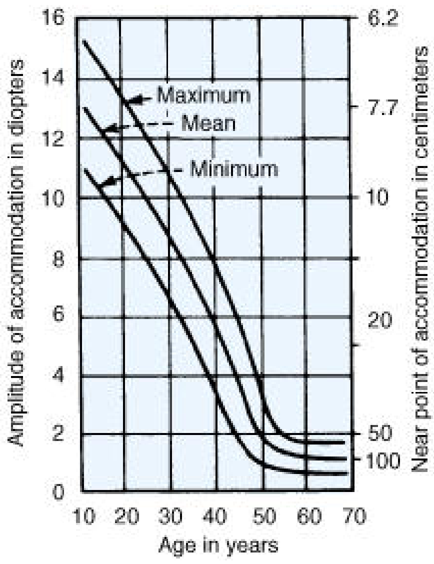


Figure 3.22. The decrease in the amplitude of accommodation with age.

While the increasing rigidity of the lens, as well as many other forms of focusing difficulty, can be compensated by adjusting the optical power of the eye's optical system with spectacles and contact lenses, the other changes that occur in the eye cannot. As the visual system ages, the amount of light reaching the retina is reduced, more of the light entering the eye is scattered, and the spectrum of the light reaching the retina is altered by preferential absorption of the short visible wavelengths. The rate at which these changes occur accelerates after age 60. In addition to these changes in the optical characteristics of the eye, deterioration in the neurological components of the visual system also occurs in later life.[18] The consequences of these changes with age are reduced visual acuity, reduced contrast sensitivity, reduced color discrimination, increased time taken to adapt to large and sudden changes in luminance, and increased sensitivity to glare.[18,32,33]

Lighting can be used to partially compensate for these changes. Specifically, in an extensive long-term field study, the quality of life of the elderly has been shown to be improved by increasing the quality of their lighting.[34] This raises the question of how to improve the quality of lighting for the elderly. Simply providing more light might not be enough. The light must be provided in a way that both disability and discomfort glare are controlled and veiling reflections are avoided. Where elderly people are likely to be moving from a well-lighted area to a dark area, such as a supermarket to a parking lot, a transition zone with a gradually reducing illuminance is desirable. Such a transition zone allows their visual system more time to make the necessary changes in adaptation.

Partial Sight. Partial sight is a state of vision that falls between normal vision and total blindness. While some people are born with partial sight, the majority of people with partial sight are elderly. Among the partially sighted, 20% became partially sighted between birth and 40 years, 21% between 41 and 60 years and 59% after 60 years of age.[32] Surveys in the United States and the United Kingdom suggest that the proportion of the total population who are classified as partially sighted are in the range 0.5 to 1%.[35,36]

The three most common causes of partial sight are cataract, macular degeneration, and glaucoma.[34] These causes involve different parts of the eye and have different implications for how lighting might be used to help people with partial sight.

1. Cataract. This is an opacity developing in the lens. The effect of cataract is to absorb and scatter more of the light passing through the lens. This increased absorption and scattering occurring in the lens results in reduced visual acuity and reduced contrast sensitivity over the entire visual field because the scattered light degrades the contrast of the retinal image. This is known as disability glare, which occurs when light is scattered in the eye. The extent to which more light can help a person with cataract depends on the balance between absorption and scattering. More light will help overcome the increased absorption but if scattering is high, the consequent deterioration in the luminance contrast of the retinal image will reduce visual capabilities. The use of dark backgrounds against which objects are to be seen will also help.[37,38]

2. Macular degeneration. This occurs when the macular photoreceptors and neurons become inoperative due to bleeding or atrophy. The fovea is at the center of the macula lutea, and any loss of vision implies a serious reduction in visual acuity, color vision, and contrast sensitivity at high spatial frequencies. Typically, these changes make reading difficult, if not impossible. However, peripheral vision is largely unaffected so wayfinding is unchanged. Providing more light, usually by way of a task light, will help people in the early stage of macular degeneration to read, although as the deterioration progresses, additional light is less effective. Increasing the visual size of the retinal image by magnification or by getting closer is helpful at all stages, because this can increase the size of the retinal image sufficiently to reach parts of the retina beyond the macula.

3. Glaucoma. Glaucoma is due to an increase in intraocular pressure that damages the retina and the anterior optic nerve. Glaucoma is shown by a progressive narrowing of the visual field, which continues until complete blindness occurs or the intraocular pressure is reduced. As glaucoma develops, in addition to a reduction in visual field size, poor night vision, slowed transient adaptation, and increased sensitivity to glare occur, all due to the destruction of peripheral photoreceptors and neurons. However, the resolution of detail seen on axis is unaffected until the final stage. Lighting has limited value in helping people in the early stages of glaucoma, because where damage has occurred, the retina has been destroyed. However, consideration should be given to providing enough light for exterior lighting at night to enable the fovea to operate. Such lighting will be helpful only if glare is controlled.

While the benefits of additional light depend on the specific cause of partial sight, there is one approach that is generally useful for all those with partial sight. This approach is to simplify the visual environment and to make its salient details more visible. Details can be made more visible by increasing their size, luminance contrast, and color difference. As an example, consider the problem of how to set a table so that a person with partial sight can eat with confidence. The plate holding the food and the associated cutlery can be made more visible by using a contrasting tablecloth, e.g., a dark tablecloth with a white plate and cutlery. The food on the plate can be made easier to identify by using an overlarge plate so that individual food items can be separated from each other. The whole scene can be simplified by using solid colors rather than patterns. This same approach of simplification and enhanced visibility of salient information can be applied to whole rooms, for example, by painting a door frame in a contrasting color to the door so that the door is easily identified. Advice on designing lighting for the partially sighted is given in CIE Technical Report 123.[37]

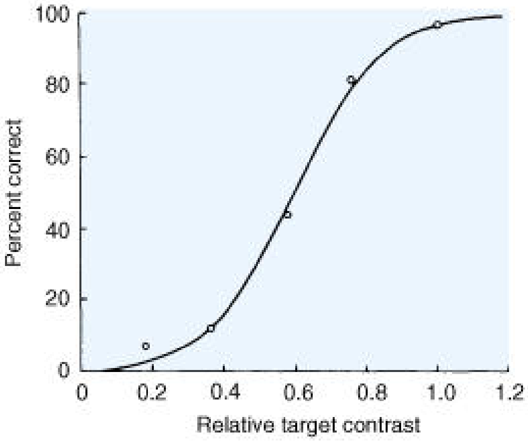


Figure 3-23. A frequency of seeing function. As luminance contrast (see Equation 3-6) is increased, the number of times it is correctly seen relative to the number of times it is presented increases to a maximum of 100%.

THRESHOLD VISUAL PERFORMANCE

Measurements of threshold visual performance are concerned with the limits of the visual system's capabilities. As an example of a threshold, consider the measurement of the minimum difference in luminance that can be detected between a region and an otherwise uniform surround. This function has been studied in great detail[39] and has been used to relate the probability of detecting a small disc test object on a uniform background to the luminance contrast of the disc and the luminance of the background (Figure 3-23). As the luminance contrast of the disc is raised, the probability of seeing increases until, at a certain contrast, it can be detected 100% of the time. The luminance contrast at which the object can be detected 50% of the time is conventionally called the threshold luminance contrast.

Threshold visual performance measurements can be made for the ability to resolve detail, to detect luminance differences and color differences, and to see temporal changes in luminance. All such threshold measurements depend greatly on the characteristics of the lighting, the task, and the visual system of the observer. Among the variables that have been shown to be important are:

- Retinal illumination to which the visual system is adapted
- Spectral content of the illuminant
- Light distribution around the target
- Visual size of target (in units of angle or solid angle)
- Visual size of background (in units of angle or solid angle)
- Luminance of the target
- Luminance of the immediate background
- Luminance contrast of the target
- Color of the target
- Color of the background

- Color difference between the target and the background
- Duration of exposure
- Temporal frequency characteristics
- Location of the target relative to the line of sight
- Movement of the target in the field of view
- Retinal image quality, as determined by the state of accommodation, pupil size, light scatter, and lens fluorescence

Additionally, such cognitive factors as attention, expectation, and habituation affect the measurement of threshold detectability and recognition of targets.

The practitioner can control such variables as the illuminance, the light spectrum, and the light distribution. These variables are sometimes important, per se, and can affect such other important factors as target luminance contrast and color contrast. Occasionally, the practitioner can influence such task variables as target size and duration of exposure. Extensive details of the threshold performance of the visual system are given in Reference 40.

Some Definitions

Retinal Illuminance. For a given individual looking at a given scene, the illuminance on the scene governs the luminances of the surfaces and hence the retinal illuminance. Luminances in object space can be related to retinal illuminance by the following function:

$$E_r = e_t \times \tau \times \left(\frac{\cos\theta}{k^2}\right) \qquad (3\text{-}1)$$

*w*here

E_r = retinal illuminance in lm/m^2,
τ = ocular transmittance,
θ = angular displacement of surface from the line of sight,
k = constant whose value is 15,
e_t = amount of light entering the eye in trolands, and is calculated by

$$e_t = L \times p \qquad (3\text{-}2)$$

where

L = surface luminance in cd/m^2,
p = pupil area in mm^2.

It should be noted that the amount of light entering the eye, e_t, measured in trolands, is often referred to as retinal illumination. This is misleading because it does not take into account the transmittance of the ocular media and therefore does not represent the luminous flux density on the retina.

Visual Size. For a target to be seen, it has to be larger than a minimum size. The relevant size of a target is an angular measure and depends on the physical dimensions, *d*, of the object itself; the angle of inclination, θ, of the target from normal to the line of sight; and the distance from the viewer, *l*. Size can be measured in a plane of two dimensions as a visual angle or in a volume in three dimensions as a solid angle, as shown in Figures 3-24a and 3-24b, respectively.

Visual angle of an object can be approximated by the following equation:

$$\text{Visual angle} = 2 \arctan\left(\frac{d \times \cos\theta}{2l}\right) \qquad (3\text{-}3)$$

For small angles, this can be simplified to:

$$\text{Visual angle} = \arctan\left(\frac{d \times \cos\theta}{l}\right) \qquad (3\text{-}4)$$

Solid angle is given by the following equation:

$$\text{Solid angle} = \frac{d^2 \cos\theta}{l^2} \text{ in steradians} \qquad (3\text{-}5)$$

The choice between visual angle and solid angle as a measure of visual size is largely determined by the symmetry of the object. Where the object is radially symmetrical such as a disc, or symmetrical in one dimension such as a grating, then visual angle is all that is required. Where there is no symmetry in the object, such as a letter F, solid angle is a better measure of visual size. Many times, visual angle or solid angle will be small. In this situation, visual size is measured in minutes of arc (60 minutes equals 1 degree) and solid angle is measured in microsteradians.

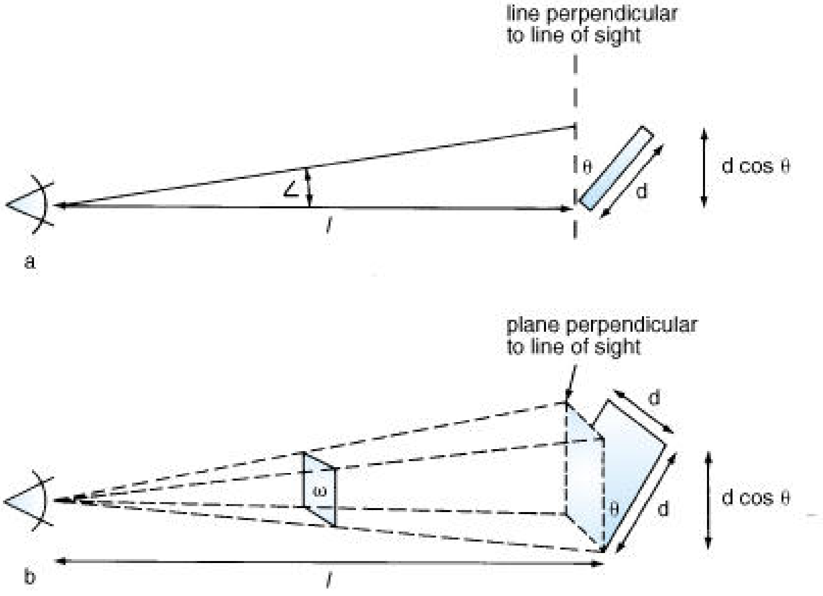


Figure 3-24. Dimensions required for calculating (a) visual angle and (b) solid angle.

Luminance and Luminance Contrast. Given that a target is above the minimum size, it will be visible only if it differs from its immediate background in luminance or color. If it differs in luminance from the immediate background, the target has a luminance contrast.

Luminance contrast is defined in several ways:

$$C = \left| \frac{(L_t - L_b)}{L_b} \right| \qquad (3\text{-}6)$$

where

L_t = luminance of the target,
L_b = luminance of the background.

This equation results in luminance contrasts that range between 0 and 1 for targets that are darker than their backgrounds, and between 0 and infinity for targets that are brighter than their backgrounds. This equation is used most often in the former case, where the background is brighter than the target (e.g., printed text).

$$C = \frac{(L_g - L_l)}{L_g} \qquad (3\text{-}7)$$

where

L_g = greater luminance,
L_l = lesser luminance.

This equation results in contrasts between 0 and 1 for all objects, whether brighter or darker than their backgrounds. It is especially applicable in a situation like a bipartite pattern in which neither of the areas on the two sides of the border can be identified as target or background.

$$C = \frac{(L_{max} - L_{min})}{(L_{max} + L_{min})} \qquad (3\text{-}8)$$

where

L_{max} = maximum luminance,
L_{min} = minimum luminance.

The quantity defined by this equation is often called contrast, or Michelson contrast, but is usually and more properly called modulation. It gives a value between 0 and 1 for all objects. It applies to periodic patterns, such as gratings, which have one maximum and one minimum in each cycle.

Because there are several different definitions of luminance contrast and different definitions have different ranges of possible values, it is important to know which definition is being used when the contrast of a target is specified.

When a target and its background are both diffuse reflectors, the luminance contrast is not affected by changing the illuminance, so the luminance contrast can be calculated from the reflectances. However, if either the object or the background are directional reflectors, luminance must be used to calculate contrast.

It should be noted that for calculating luminance contrast, it does not matter how the luminance is achieved. It makes no difference whether the luminance is produced by reflection from a surface, such as print; from a self-luminous source, such as a VDT screen; or by some combination, such as a display on a VDT screen with a reflected image superimposed.

Color Difference. Visual targets that are larger than the minimum size but have the same luminance as the immediate background, that is, zero luminance contrast, can still be discerned by differences in color. Color difference can be calculated as a distance between the colors of the object and the immediate background using either the CIELAB or the CIELUV color spaces described in Chapter 4, Color, or other approximately uniform color space. It should be noted that one dimension of these color spaces is luminance, so a difference expressed across these color spaces includes both luminance and color difference. To measure only color differences, the separation of the color of the object and its immediate background on a plane of constant lightness in the CIELAB or CIELUV color spaces or the two-dimensional CIE 1976 u',v' diagram can be used.

Spatial Resolution

Spatial Summation. In complete darkness, the smallest amount of light that can be detected varies inversely with the area over which the light occurs. In other words, the total number of photons received in unit time, for detection, is constant. This relationship, which is known as Ricco's Law, takes the form:

$$I \times A = \text{constant} \qquad (3\text{-}9)$$

where

I = threshold luminous flux, measured in photons per unit area per unit time,
A = target area.

Spatial summation is relevant only for very small targets. Above a certain size, spatial summation ceases so that further increases in size make no difference to the smallest amount of light that can be detected. This critical size varies with location on the retina. For foveal vision, it is approximately 6 min of arc, increasing to approximately 0.5° for a target 5° off axis, and 2.0° for a target 35° off axis.

Visual Acuity. The word "acuity" is used to describe the ability to resolve fine details. Several different kinds of acuity are recognized.

1. Resolution acuity. The ability to detect that there are two stimuli, rather than one, in the visual field. It is measured in terms of the smallest angular separation between two stimuli that can still be seen as separate, such as two nighttime stars. Typically, resolution acuity is of the order of 1 min of arc.

2. Recognition acuity. The ability to correctly identify a visual target, as in differentiating between a G and a C. Visual acuity testing performed using letters, as is done clinically, is a form of recognition acuity testing. Typically, recognition acuity is of the order of minutes of arc.

3. Vernier acuity**.** The ability to identify a misalignment between two lines. Vernier acuity is typically of the order of seconds of arc.

Several examples of acuity test objects are shown in Figure 3-25. Gratings, letters, and Landolt rings have all been used as acuity test objects.

As with many other threshold tasks, visual acuity varies with retinal illuminance, size of background field, exposure duration and target motion. It also varies with luminance contrast, but by convention acuity is measured only at high luminance contrast. In general, acuity is finest when the target falls on the fovea (Figure 3-26) and improves as the retinal illuminance increases, because increasing the retinal illuminance decreases receptive field size. As for the size of the background field, Lythgoe[41] has shown that acuity continues to improve with background luminance as long as the background is large; when the background field is small, there is an optimum luminance for visual acuity, above which acuity declines (Figure 3-27).

Visual acuity also increases as the exposure duration increases, up to approximately 500 ms, after which no further improvement occurs (Figure 3-28). Target movement can limit the exposure duration and the ability to keep the retinal image on the fovea. As might be expected, increasing target speed tends to reduce visual acuity (Figure 3-29). The only condition under which the fovea fails to have the best visual acuity is scotopic vision. In this condition, the fovea is inactive and the best visual acuity is found a few degrees off the line of sight.

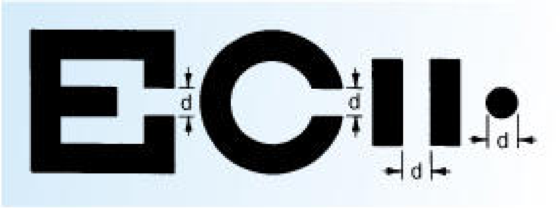


Figure 3-25. Commonly used test objects for determining resolution limits and visual acuity. The critical size is represented by the dimension d.

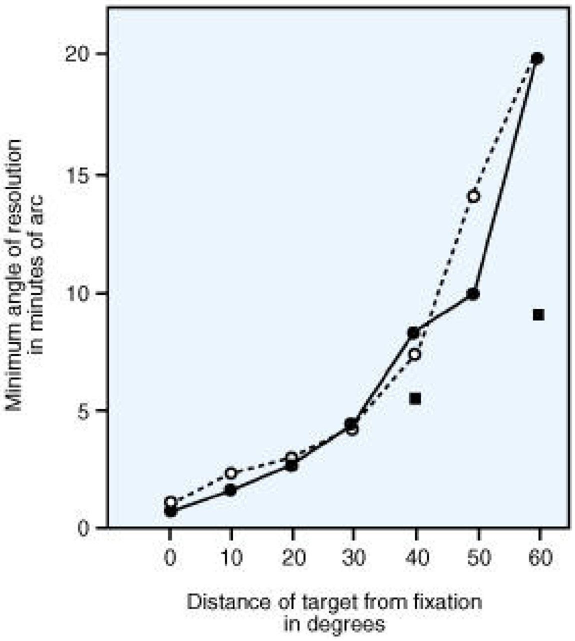


Figure 3-26. Minimum resolution in minutes of arc, as a function of angular separation from the fovea. Three different targets were used: Landolt rings at a background luminance of 2.45 cd/m^2 (open circles); Landolt rings at a background luminance of 245 cd/m^2 (filled circles); sinewave gratings at a background luminance of 1118 cd/m^2 (filled squares).

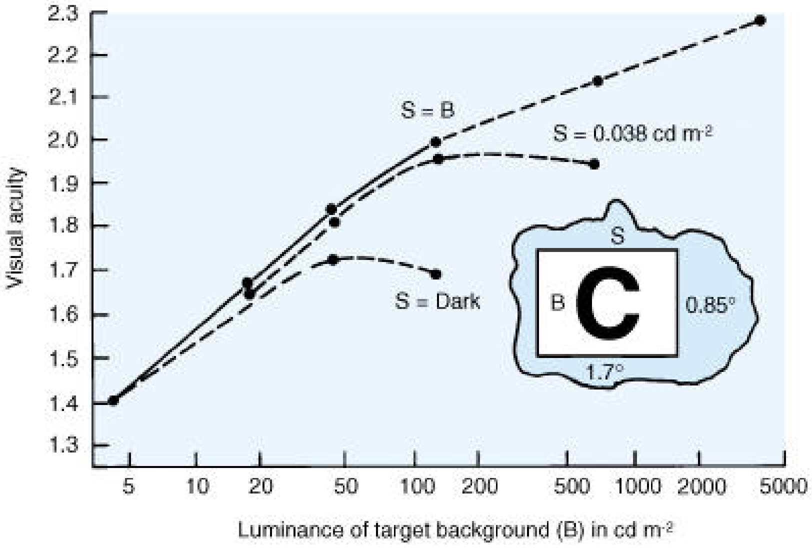


Figure 3-27. Effect of background luminance on visual acuity. The targets are Landolt rings on a background field measuring 0.85° by 1.7°. When the luminance of the surround field (S) equals the luminance of the target background (B) visual acuity continues to improve as background luminance increases.

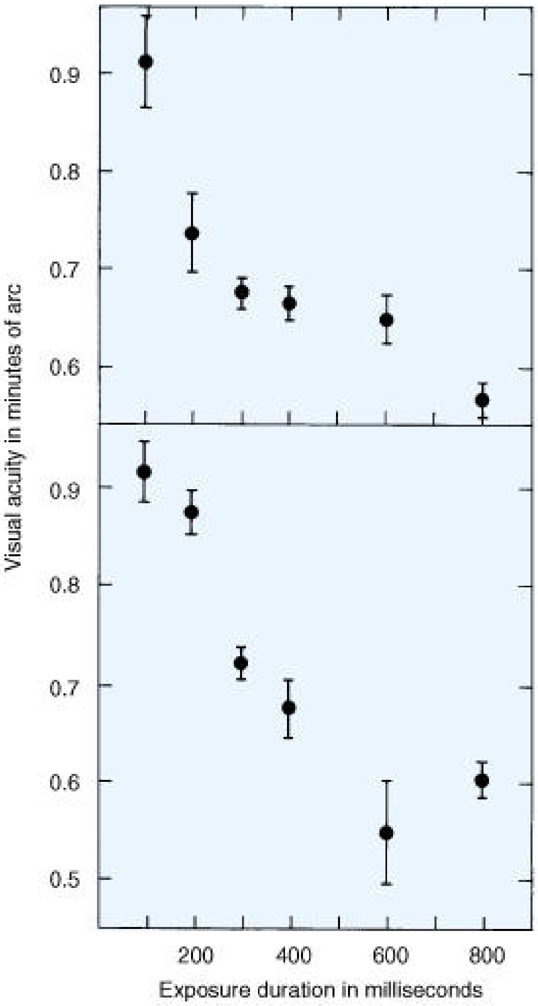


Figure 3-28. Minimum spatial resolution in minutes of arc plotted against target exposure duration. Resolution improves as exposure duration increases up to about 500 ms. Longer exposure durations do not affect minimum resolution.

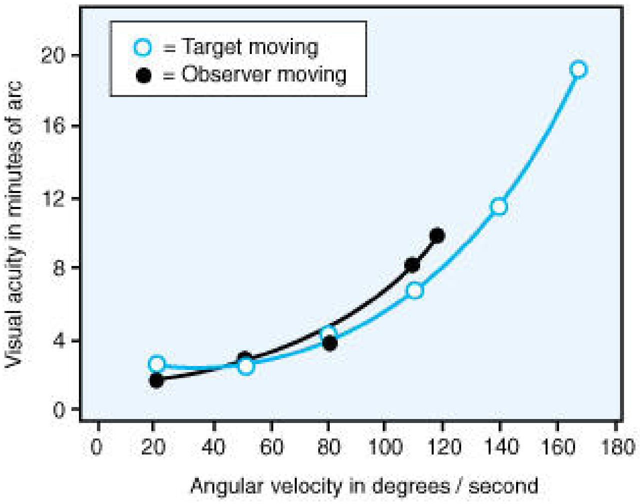


Figure 3-29. Minimum spatial resolution in minutes of arc plotted against angular velocity of target and observer movement.

Contrast Threshold

The visual system gives virtually no useful information when the retina is uniformly illuminated, but is highly specialized to gather information about luminous edges and gradients in the visual field.

The ability to detect a target against a background can be quantified by its threshold contrast. By convention, threshold contrast is the luminance contrast of the target that can be detected on 50% of the occasions it is presented (Figure 3-23). Many factors affect threshold contrast. Among the more important are target size and retinal illuminance. Figure 3-30 shows the change in contrast threshold for a 4 min arc disc displayed for 200 ms plotted against adaptation luminance, for people of two different age groups. It shows that as adaptation luminance increases, the contrast threshold decreases, rapidly at first and then more slowly.[33,42] Targets of different sizes exposed for different times give different absolute values of contrast threshold but all follow the same trend.

Contrast Sensitivity Function

Visual acuity and threshold contrast separately define two aspects of a target that defines its visibility. Visual acuity sets the minimum size for a target to be seen and threshold contrast sets the minimum luminance contrast that is required for a target of a given size to be seen. The contrast sensitivity function combines these two measures by showing the minimum contrast required for targets of different sizes to be seen. Specifically, the contrast sensitivity function is a plot of contrast sensitivity against spatial frequency (Figure 3-31). It is usually based on data collected from grating targets of different spatial frequency. Spatial frequency is the reciprocal of the visual angle of one period of the grating and is measured in cycles / degree. Contrast sensitivity for a given spatial frequency is the reciprocal of the luminance contrast of the grating at threshold. Targets that have a spatial frequency and contrast sensitivity such that they lie above the contrast sensitivity function are invisible (i.e., can be detected on fewer than 50% of the occasions presented) and those that lie below the contrast sensitivity function are visible (i.e., can be detected on more than 50% of occasions presented). For complex targets that contain many different spatial frequencies, the contrast sensitivity function can be used to determine if and how the target will appear by breaking it into its spatial frequency components.[43] The target will be visible only if at least one spatial frequency component has a contrast sensitivity less than the contrast sensitivity function. Exactly how the target will appear will depend on the weighting given to each of its spatial frequency components by the contrast sensitivity function.

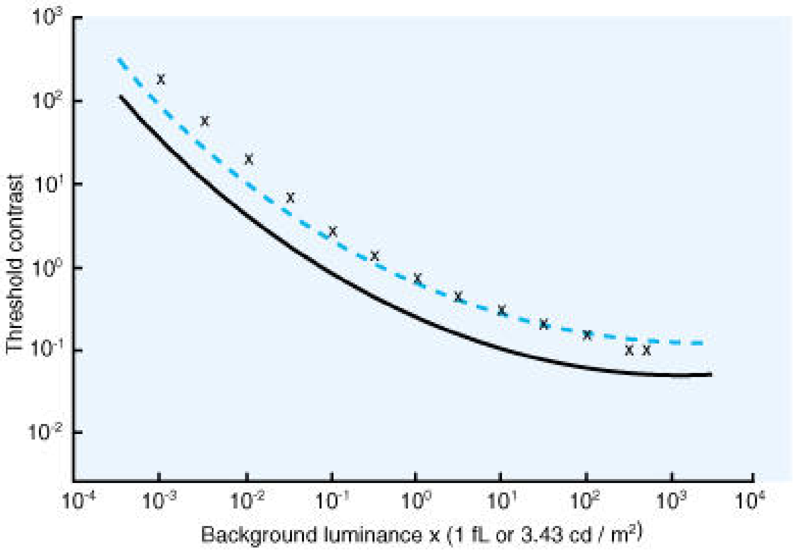


Figure 3-30. Threshold contrast data for a group of 60- to 70-year-olds (x) compared to the threshold contrast curve for a group of 20- to 30-year-olds (solid line), as a function of luminance. The dashed curve is the same as the solid curve but displaced upward by a factor of 2.51. Threshold contrast was calculated according to Equation 3-6.

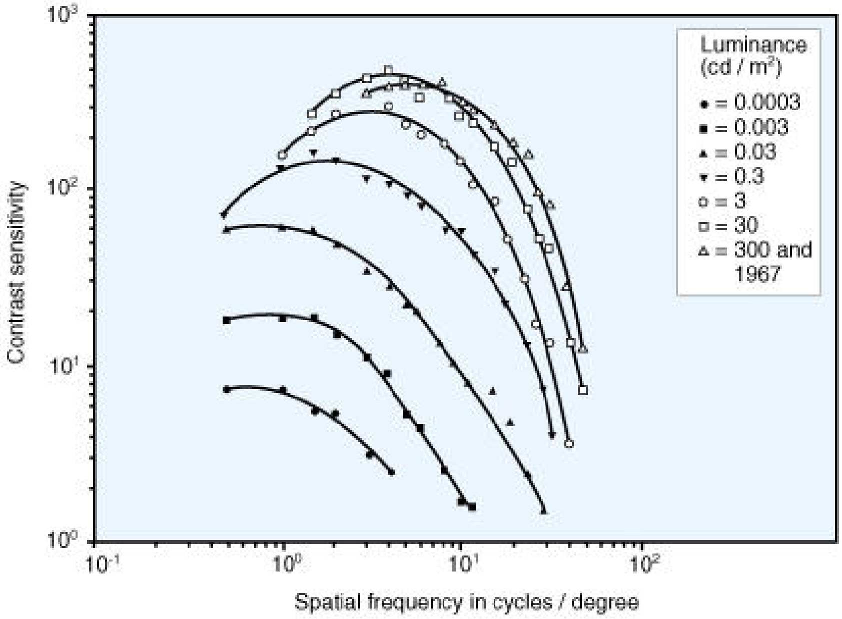


Figure 3-31. The spatial contrast sensitivity function for foveal vision, at different target luminances.

Many factors affect the contrast sensitivity function. Among the most important are the adaptation luminance, the location in the visual field, and the number of cycles of the stimulus. Figure 3-31 shows the variation of contrast sensitivity function with adaptation luminance. As the adaptation luminance changes the operating state of the visual system from scotopic to photopic, the contrast sensitivity increases for all spatial frequencies; the spatial frequency at which the peak contrast sensitivity occurs increases, and the highest spatial frequency that can be detected increases.

As for the effect of the location in the visual field, contrast sensitivity is reduced at all spatial frequencies with increasing eccentricity, but the decrement is greater for high spatial frequencies. More details of the changes in contrast sensitivity functions with different lighting and visual conditions and examples of its diagnostic use can be found in Reference 40.

Temporal Resolution

Just as the visual system responds to variations of luminance in space, it also responds to variations of luminance in time.

Temporal Summation. For single brief flashes of light (less than 100 ms), any combination of luminance (L) and flash duration (t) with the same product produces the same perception. This characteristic is known as Bloch's law:

$$L \times t = \text{constant} \qquad (3\text{-}10)$$

For single brief flashes of light longer than approximately 100 to 200 ms, the perception of the flash is solely a function of stimulus luminance (Figure 3-32).

Flicker. As a repetitive flashing stimulus is increased in frequency, it eventually reaches a point where it is perceived as steady rather than as intermittent; this is the critical flicker frequency (or critical fusion frequency, CFF). The frequency at which the fusion occurs varies with stimulus size, shape, retinal location, adaptation luminance, and modulation depth. Figure 3-33 shows the relationship of CFF to adaptation luminance for centrally fixated test objects of different sizes. The CFF rarely exceeds 60 Hz even for a large visual area with 100% modulation, seen at a high adaptation luminance. This is just as well because all light sources that operate from an ac electrical supply show some fluctuation in light output. The electrical supply frequency in North America is 60 Hz, which means the fundamental frequency of oscillation in light output is 120 Hz although there might be some 60 Hz component present. The fundamental frequency of the light output oscillation (120 Hz) is twice the fundamental frequency of the electrical supply (60 Hz) because of the positive and negative halves of the ac cycle.

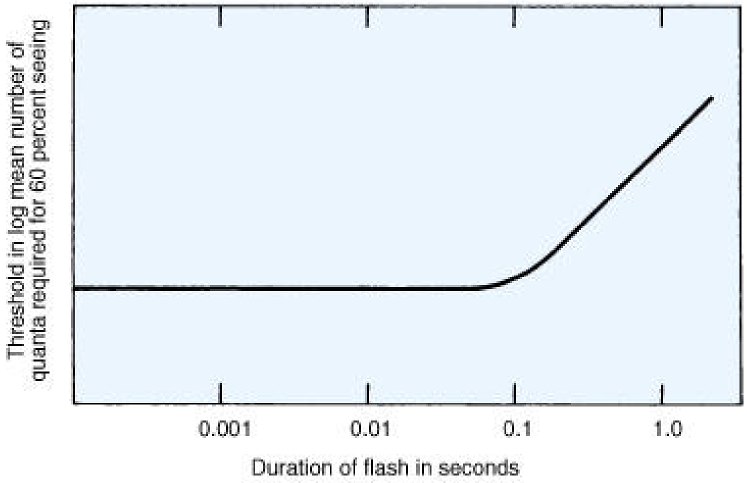


Figure 3-32. Total number of quanta for seeing a flash of light as a function of the duration of the flash.

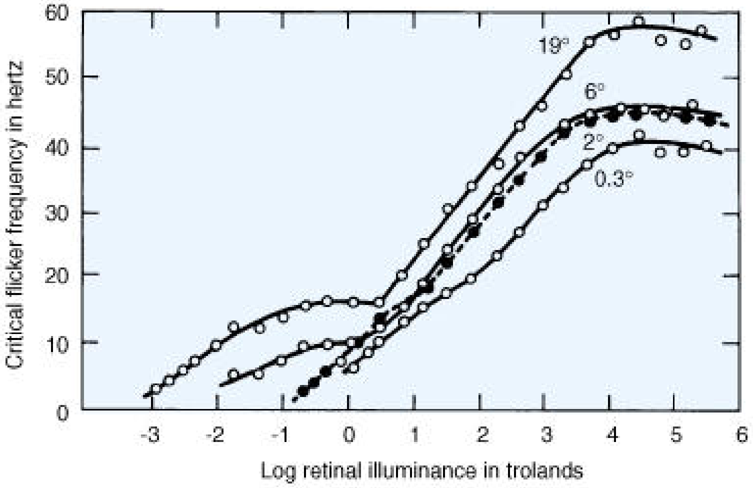


Figure 3-33. Critical flicker frequency (CFF) as a function of source area and retinal illuminance.

Another way of considering the combined effects of temporal modulation and temporal frequency is through the temporal modulation transfer function (MTF). This is the equivalent in time of the spatial contrast sensitivity function (Figure 3-31). Figure 3-34 shows the temporal MTF for different adaptation luminances. The vertical axis is the reciprocal of percent temporal modulation and the horizontal axis is the frequency of fluctuation measured in cycles per second. Figure 3-34 shows that in photopic conditions (i.e., above approximately 3 cd/m^2), the visual system is most sensitive to frequencies in the range 10 to 30 Hz and that as the adaptation luminance decreases, the absolute sensitivity to flicker decreases, the frequency at which the peak sensitivity occurs decreases, and the highest frequency that can be detected decreases. These temporal modulation transfer functions, and others for different conditions, can be used to determine the likelihood that a given fluctuation in light will be perceived as flickering. For a fluctuation with a complex waveform to be seen as flicker, at least one of its frequency components must have a modulation sufficiently high that the modulation sensitivity is below the temporal MTF. Knowledge of the visual system's temporal response is most helpful when considering the detection of flashing signals and the perception of animated signs.

Sensitivity to flicker differs across the retina. The fovea can follow flicker rates up to approximately 60 Hz at moderate luminances, but is relatively insensitive to low frequency modulations. The peripheral retina, on the other hand, can detect flicker rates to approximately 15 Hz, but is very sensitive to small flicker amplitudes. This is why flicker is often detected in the peripheral field but disappears when the light is viewed directly.

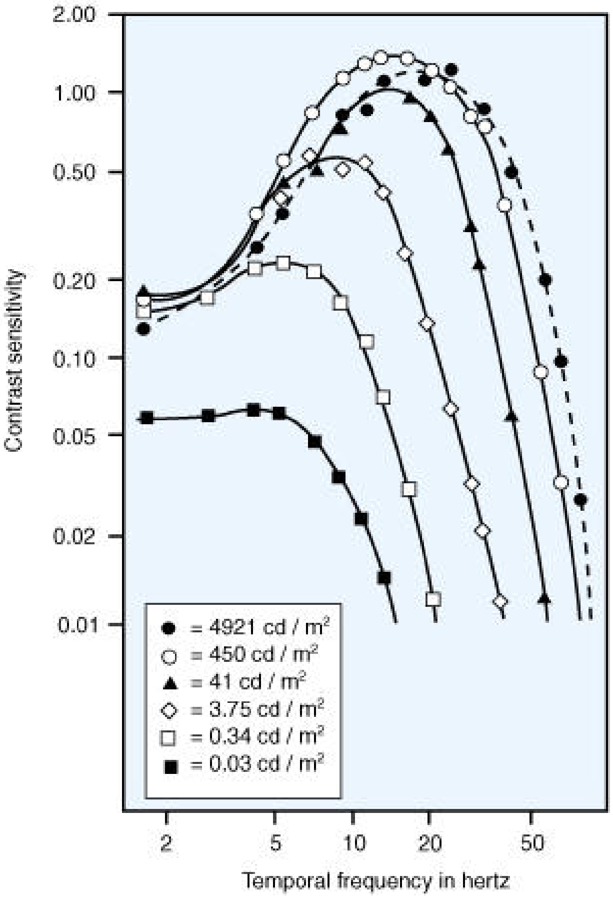


Figure 3-34. Temporal modulation transfer (contrast sensitivity) function for different adaptation luminances for a 68° field of view.

It is widely recognized that visible fluctuations in light occurring over a large area can cause visual discomfort or annoyance. Recently, however, reductions in the prevalence of headaches have been reported when fluorescent lamps were operated on high-frequency electronic ballasts as compared to when they were operated on conventional (British) 50-Hz magnetic ballasts, even though flicker was not visible. This implies that flicker might have subliminal effects on the visual system. This hypothesis is supported by electrophysical recordings under such conditions.[44]

Color Discrimination

The visual system varies in its ability to discriminate among wavelengths. There are regions of maximum wavelength discrimination in the middle of the visible spectrum but discrimination falls off rapidly at the spectral extremes.[45] Likewise, the ability to discriminate hue from white is wavelength dependent. Monochromatic colors from the ends of the visual spectrum are more easily discriminated from white because they are more saturated than colors in the middle of the spectrum.[46] The ability to discriminate nonspectral colors is also related to their chromaticities.[47]

Generally, color discrimination is best in the fovea and decreases toward the periphery. However, color discrimination for very small fields (20 min of arc or less) presented to the fovea is poor because there are very few short-wavelength S-cones in the center of the fovea. This effect is known as small-field tritanopia.[47]

The ability to discriminate between colors can be estimated in terms of distances in a uniform 3-D chromaticity space (see Chapter 4, Color). MacAdam[48] produced a series of ellipses around the chromaticity coordinates of a number of different colors (Figure 3-35). Each ellipse sets the boundary at which a given percentage of people are able to determine that two colors, one with chromaticity coordinates at the center of the ellipse and one with chromaticity coordinates on the ellipse, are just noticeably different. Full details are given in Reference 8.

MacAdam's ellipses were determined in conditions that offer the maximum sensitivity to color differences: side-by-side comparison, unlimited observation time, foveal viewing, and photopic operation of the visual system. Changing any of these factors and adding distracting or confusing stimuli can be expected to increase the difference in color needed to reach discrimination threshold. Of particular importance is the amount and spectral power distribution of the light reaching the retina.

The retinal illuminance is important because it determines the operating state of the visual system. If the retinal illuminance is in the scotopic range, no colors can be seen and no discrimination is possible. In the mesopic range, colors can be seen but the discrimination of colors is poor, particularly for low reflectance colors. The color discrimination threshold is reduced as the retinal illuminance increases. This process continues until a retinal illuminance of approximately 30 trolands is reached, after which there is little change in the ability to discriminate colors. The light spectrum is important because it changes the stimulus to the visual system.

SUPRATHRESHOLD VISUAL PERFORMANCE

Threshold visual performance deals with what can just be seen. Suprathreshold visual performance is concerned with tasks that are visible because their important aspects are well above threshold levels. This raises the question as to why lighting conditions make a difference to task performance once what has to be seen is visible. The answer is that although the stimuli are visible, lighting influences the speed and accuracy with which the visual information extracted from the stimuli can be processed. Like threshold visual performance, suprathreshold visual performance is governed by such parameters as retinal illuminance, task contrast, visual size, and the characteristics of the visual system. Retinal illuminance is largely determined by the luminance of the visual field that is viewed and hence by the illuminance on the surfaces that form that field.

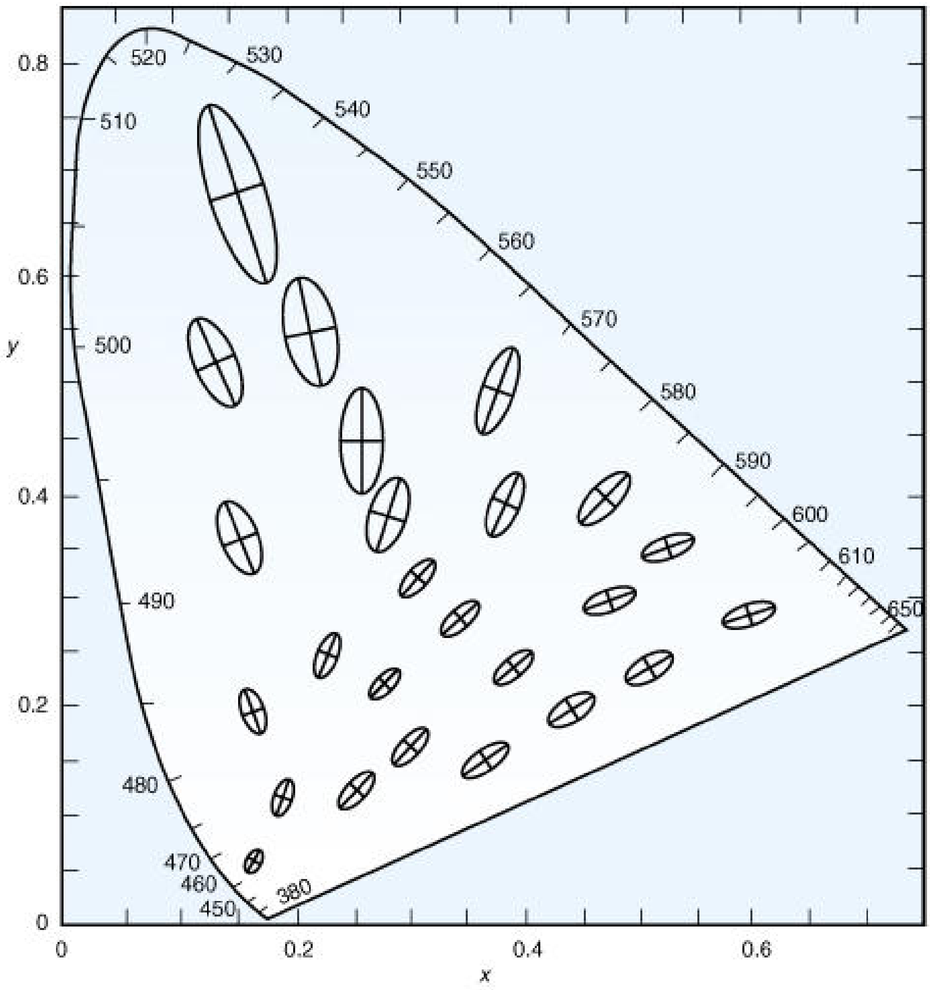


Figure 3-35. The 1931 CIE chromaticity diagram showing a selection of MacAdam ellipses, enlarged by a factor of ten. From G. Salvendy, *Handbook of human factors and ergonomics*, 2nd ed. Copyright © 1997. Reprinted by permission of John Wiley & Sons, Inc.

One approach to studying suprathreshold visual performance is to examine task performance for a variety of realistic tasks requiring vision. Several studies have been conducted mimicking realistic tasks to determine how illumination affects performance.[49-53] This approach allows the experimenter to assess performance for a specific task in suprathreshold conditions, but it is difficult to generalize the results with high precision to other, even superficially similar tasks because it is impossible to separate visual from nonvisual components of performance. An example of nonvisual components would be the time taken to turn the page in a proofreading task (see "Visual Performance, Task Performance, and Productivity" below for a discussion of task structure).

Another approach was developed by Blackwell based on his extensive psychophysical measurements of threshold contrast.[33,39,42] He developed several models for predicting suprathreshold performance from threshold performance.[54-56] These systems all used the same concept as the basis of prediction, namely a simple multiplier derived from the ratio of the actual contrast presented by a target to the threshold contrast at the same adaptation luminance. This multiplier is known as Visibility Level. Unfortunately for simplicity, it was later shown that it is not possible to predict suprathreshold performance accurately from threshold performance, because if the stimuli at threshold are different, the same Visibility Level produces different suprathreshold performances.[57] Further, the complexities introduced by nonvisual components and off-axis working were not fully appreciated. As a result, the number of factors that had to be introduced to make the predictions fit a set of experimental data increased dramatically as the number of data sets increased, eventually leading to a loss of credibility. As a result, attempts to use the systems have been few.

As early as 1935, Weston[58,59] recognized the importance of a systematic, direct study of suprathreshold performance utilizing variables that had been shown to be important to threshold vision, namely target size and target luminance contrast seen at different background luminances. The curves in Figure 3-36 demonstrate the effects of illuminance on detection of Landolt rings of different orientations and printed in different contrasts and sizes.[58-59] Performance was defined, in these studies, as an aggregate score based on speed and accuracy.

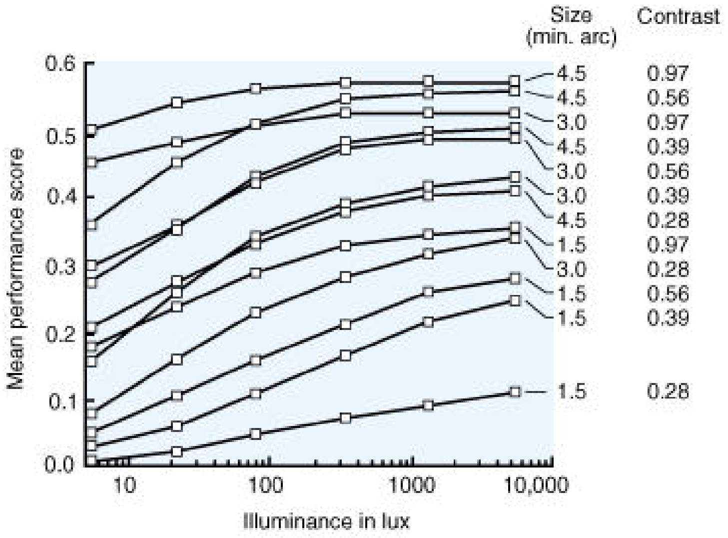


Figure 3-36. Mean performance scores for Weston's Landolt ring charts of different visual size and luminance contrast (see Equation 3-6), plotted against illuminance.

The performance score for each individual is given by the expression

$$\left[\left(\frac{\text{Total time taken}}{\text{Number of rings correctly cancelled}}\right) \times \left(\frac{\text{Total number of rings to be cancelled}}{\text{Number of rings correctly cancelled}}\right) - \text{manual time per ring}\right]^{-1}$$

An analysis of Weston's work[60] identified several design and analysis flaws, including a lack of documentation about specific visual characteristics and the use of a scoring system that failed to include correct rejections as part of the accuracy metric. Weston's performance data shown in Figure 3-36 can provide only general trends in suprathreshold response but, importantly, trends that cannot be gleaned from a knowledge of threshold vision.

In general, Weston showed that as background luminance increased, performance (measured in terms of speed and accuracy) increased rapidly at first but then less and less until a point was reached where very large changes in background luminance were required to make very small changes in performance. This trend of diminishing returns was more pronounced for high-contrast, large targets than for low-contrast, small targets. He also showed that performance for a small, low-contrast target could not be brought to the same level as a large, high-contrast target simply by increasing illuminance. Rather, changing the size and luminance contrast of the target often had a much larger effect on suprathreshold visual performance than increasing the illuminance over any practical range. Several studies of suprathreshold performance have extended Weston's approach.[50-53,61] All of these studies have produced results consistent with the general trends shown by Weston.

Models of On-Axis Visual Performance

Weston's results illustrate the general form of the relationship between the visual size, luminance contrast of the target, and the retinal illuminance. Other researchers have provided quantitative models using more precise techniques. The general trends of suprathreshold performance, shown by Weston, have not been contradicted by these models.

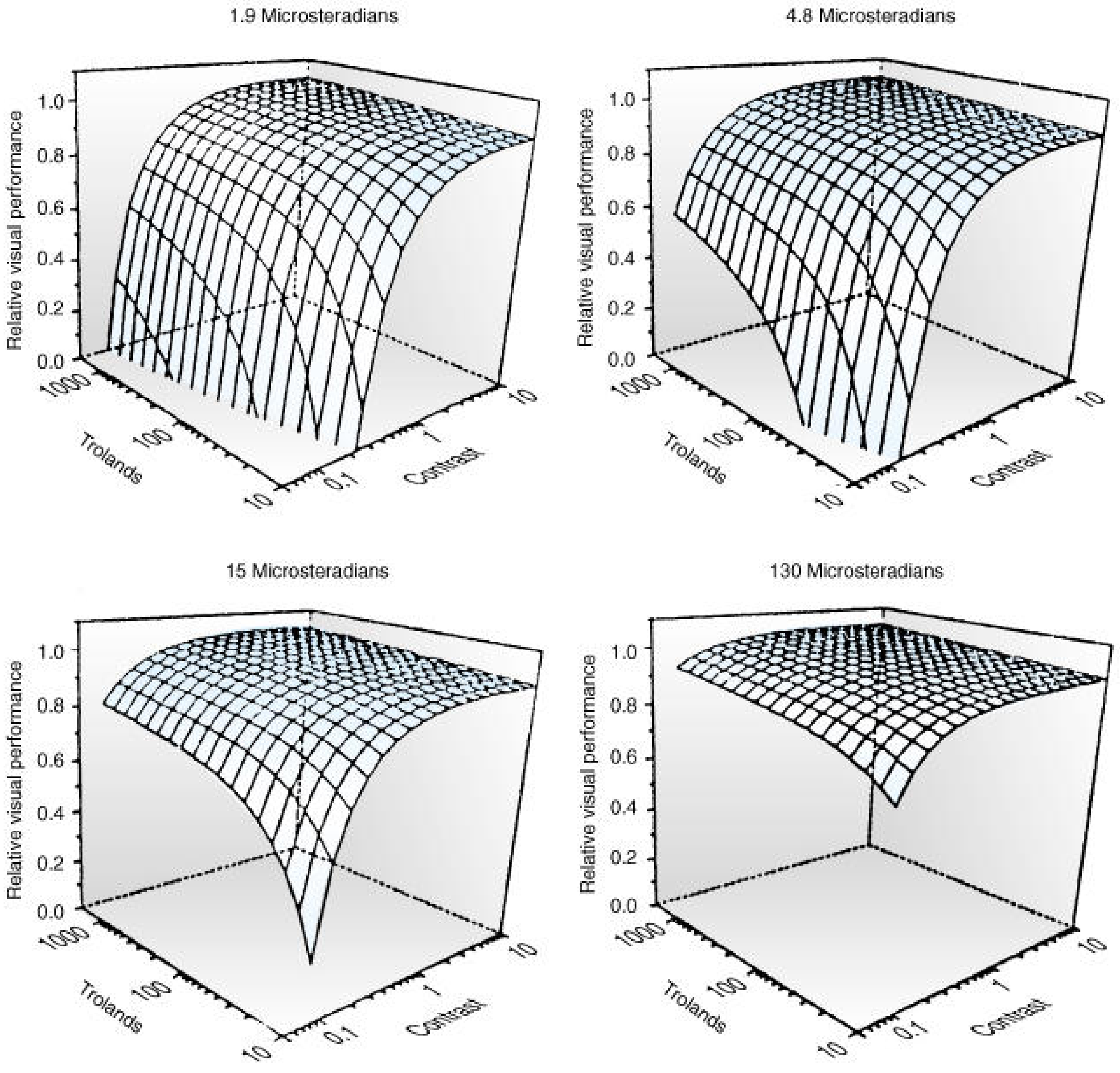


Figure 3-37. Relative visual performance (RVP) plotted as a function of task contrast (see Equation 3-7) and retinal illuminance (in trolands) for several different target sizes measured as solid angle (microsteradians).

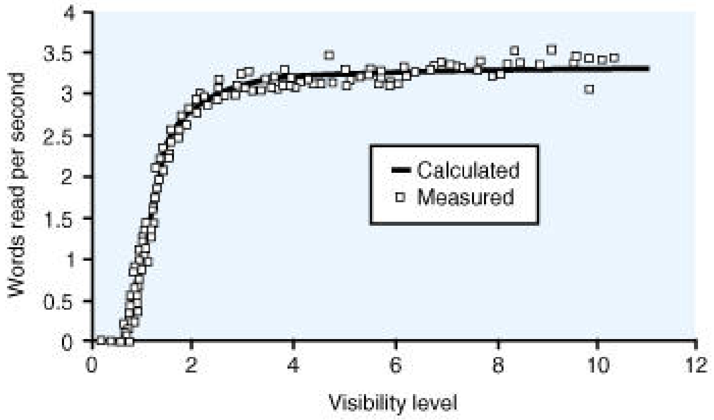


Figure 3-38. Reading speed in words/second plotted against visibility level (size).

The Relative Visual Performance (RVP) model of visual performance is a quantitative model based on an extensive dataset made up of the changes that occur in reaction time for the detection of visual stimuli seen by the fovea.[62-65] The conditions covered in the dataset represent a wide range of adaptation luminances, luminance contrasts, and visual sizes. By using simple reaction time as a measure, this model attempts to minimize the nonvisual components in the task. By basing the model on the difference in reaction time that occurs for different combinations of adaptation luminance, luminance contrast, and visual size, the effect of any remaining nonvisual components is further minimized. Therefore, the RVP model shows the effect of adaptation luminance, luminance contrast and visual size on suprathreshold visual performance undiluted by nonvisual components.

Figure 3-37 shows the form of the relative visual performance (RVP) model for four different visual size tasks, each surface being for a range of luminance contrasts and retinal illuminances. The overall shape of the relative visual performance surface has been described as a plateau and an escarpment.[63] In essence, it shows that the visual system is capable of a high level of visual performance over a wide range of visual sizes, luminance contrasts, and retinal illuminations (the plateau) but at some point either visual size, luminance contrast, or retinal illumination become insufficient and visual performance collapses rapidly (the escarpment) towards a threshold state.

The RVP model provides a quantitative means of predicting the effects of changing either task size, luminance contrast, or adaptation luminance for on-axis, suprathreshold visual performance. It is applicable to luminances in the photopic range but does not take into consideration the effect of reduced retinal image quality caused by limited accommodation, nor the effect of color differences between the target and the background. It can be only applied once a decision is made as to what constitutes the true critical size of the target. The RVP model has been validated in that it has been shown to predict the form of the change in performance produced by different lighting conditions, measured in three independent experiments, using different visual tasks.[60,66,67] It can be applied using input variables that can all be measured directly from the task.

The RVP model is based on reaction time data for detecting the presence of a square target. Such a target requires contrast discrimination but does not require resolution of detail. A task that does require resolution of detail is reading. Figure 3-38 shows task performance measured as reading speed plotted against the Visibility Level of the letters being read.[66] In this case, Visibility Level was defined as the ratio of the actual size to the threshold size of the letters of a given luminance contrast and at a set adaptation luminance. Figure 3-38 shows that reading speed changed little until the visibility level fell below a value of 3 but declined rapidly as the resolution threshold (VL = 1) was approached. Here too, there was a plateau and escarpment of task performance. For these reading speed data, a function based on Visibility Level was found to fit the data slightly better than the RVP model, most of the difference occurring for print sizes smaller than 6 point, where resolution might be expected to be important. Despite theoretical arguments,[68] in many ways the results of these studies of suprathreshold visual performance and task performance are more remarkable for their similarities than their differences. All show a plateau and escarpment form. This has important implications. The existence of a plateau of visual performance implies that for a wide range of visual conditions, visual performance changes little with changes in the lighting conditions. However, the RVP model does show that the plateau is not completely flat, there is a slight improvement in visual performance as adaptation luminance is increased, even when luminance contrast is high and visual size is large. What this means is that for many visual tasks, suprathreshold visual performance is insensitive to lighting conditions, but if it is required to maximize visual performance, increasing adaptation luminance can be effective.

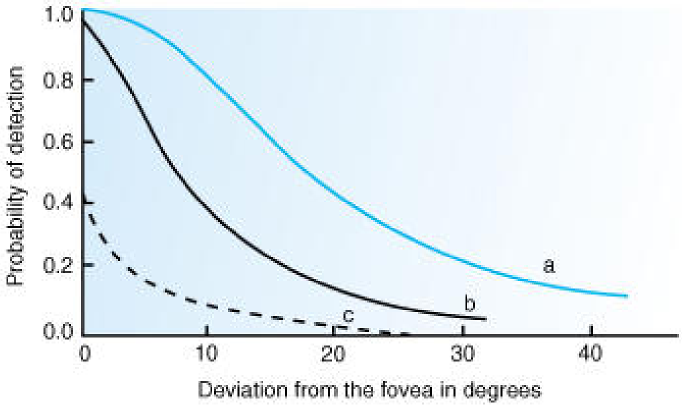


Figure 3-39. The probability of detection for targets of (a) contrast 0.058, size = 19 min. arc; (b) contrast = 0.08, size = 10 min. arc; (c) contrast = 0.044, size = 10 min. arc; within a single fixation pause, plotted against deviation from the visual axis. Each curve can be used to form a "visibility lobe" for each target by assuming symmetry about the visual axis.

It should also be noted that the RVP model is based on the luminance contrast presented to the observer, regardless of how that contrast is achieved. This means that both light polarization and distribution can affect visual performance for tasks that involve specularly reflecting materials, because both can change luminance contrast.[60,69] Light distribution can produce veiling reflections (see "Lighting Conditions That Can Cause Discomfort" below) that can make luminance contrast larger or smaller, depending on the specific arrangement of the materials. The change in luminance contrast can be large but it is difficult to control because it depends critically on the geometry between the source of luminance being reflected, the task, and the observer. A small change in position of any of these entities can markedly change the luminance contrast.[61] As for light polarization, in principle, polarized light is capable of eliminating specularly reflected light, but this too is very dependent on the geometry between the source of polarized light, the reflecting surface and the observer, as well as the magnitude and nature of the polarization.[69] A discussion on the physics of polarization is provided in Chapter 1, Light and Optics.

Visual Search

The RVP model discussed above is applicable to tasks that are imaged on the fovea. This is likely to be the situation when the observer knows where to look (e.g., reading). However, there is a class of tasks in which the object to be detected (i.e., target) can appear anywhere in the visual field (e.g., driving or industrial inspection). These tasks involve visual search. Visual search is typically undertaken through a series of eye fixations, the fixation pattern being guided either by expectations about where the target is most likely to appear or by what part of the visual scene is most important. Typically, the target is first detected in the periphery of the retina. Detection is followed by eye movements that bring the detected target onto the fovea, where it is identified. The speed with which a visual search task is completed depends on the size, luminance contrast, and color difference of the target; the presence of other targets in the search area; and the extent to which the target is different from the other targets. The simplest visual search task is one in which the target appears somewhere in an otherwise empty field, such as paint scratches on a car body. The most difficult visual search task is one in which the target is situated in a cluttered field, where the clutter is very similar to the target to be found, such as searching for a particular face in a crowd.

The speed of visual search is determined by both the task characteristics and the lighting conditions. The task characteristics that hasten visual search are those that make the target stand out from its background (i.e., make it visible) and make it different from surrounding clutter (i.e., make it conspicuous).

To make a target visible, its visual size and luminance contrast must be well above the threshold values. To make
a target conspicuous, it should differ from the surrounding clutter on as many perceptual dimensions as possible. Among such dimensions are size, shape, color, movement, and flicker.

The extent to which a lighting installation is effective in revealing a target can be estimated from the object's visibility lobe.[70] The visibility lobe is the distribution of the probability of detecting the object within one fixation pause (Figure 3-39). This probability is at maximum when the target is viewed with the fovea and decreases with increasing eccentricity from the fovea. The probability distribution is assumed to be radially symmetrical about the visual axis, resulting in circular contours of equal probability of detection within one fixation pause around the fixation point. Given that the interfixation distance is related to the visibility lobe and the search area is fixed, the time taken to find a target is inversely related to the size of the visibility lobe. For objects that appear on a uniform field, the visibility lobe is based on the detection of the object. For objects that appear among other similar objects, the visibility lobe is based on the discriminability of the object from the others surrounding it. Visual search is fastest for targets that have the largest visibility lobe.

Effect of Spectral Content on Suprathreshold Performance

The models of on-axis suprathreshold visual performance and visual search respectively discussed in "Models of On-Axis Visual Performance" and "Visual Search" ignore the possibility of the spectral content of the illuminant affecting the visual performance. This is reasonable given that previous research has shown little effect of spectral content on the performance of achromatic tasks.[71] However, there is little doubt that the spectral content of the illuminant can affect the performance of tasks requiring color discrimination, nor that spectral content is important for visual search where color is one of the dimensions on which the target differs from other objects around it.[72] In these situations, the spectral content of the illuminant changes the stimuli presented to the visual system. As a general rule, the higher the CIE General Color Rendering Index of the illuminant, the greater the color differences in the task and the easier it is to make the required discriminations.

While the spectral content of an illuminant might be expected to be important for any task where the spectral content changes an important aspect of the stimuli the task presents to the visual system, there is little evidence that it is important for all tasks. This has not stopped claims being made for what are called full-spectrum lamps. These lamps, which have no widely accepted definition, are typically fluorescent lamps with spectral emission in all parts of the visible spectrum and in the near UV, with a correlated color temperature of 5000 K or more and a CIE General Color Rendering Index of 90 or more. Claims have been made that the use of such lamps benefit task performance, human health, and happiness. These claims have little merit in most cases.[73]

However, in recent years a number of studies by Berman and his colleagues have shown that spectral content can influence performance for achromatic resolution tasks such as reading or rapidly identifying gaps in a Landolt C acuity target (Figure 3-40).[74-76] The proposed explanation of these findings rests on the role of pupil size. Specifically, pupil size in a large visual field is determined by the response of the rod photoreceptors, even in photopic conditions; the larger the response from the rods, the smaller the pupil area.[77] The response from the rod photoreceptors can be increased by increasing the amount of short wavelength energy received at the eye. A smaller pupil area has three effects on the retinal image: it reduces the retinal illumination, it increases the depth of field, and it reduces aberrations. The first of these effects, the reduction in retinal illuminance, can be expected to degrade visual performance. The other two, increasing the depth of field and reducing aberrations, can be expected to improve the quality of the retinal image and hence to improve visual performance. All these effects are small, and how they trade off will depend on the inherent quality of the individual's optical system. An individual who is perfectly refracted will gain little from increasing the depth of field, so this person might be expected to experience deterioration of visual performance under a light source that produces smaller pupil sizes. However, most people do not have perfect refraction. For these people, the evidence suggests that light sources that do promote smaller pupil sizes can increase visual performance where the task conditions place it close to threshold, e.g., low luminance contrast, limited exposure time, and when the surfaces being viewed reflect most of the incident short wavelength light. Figure 5-18 gives spectral reflectances of a number of common building surfaces.

Visual Performance, Task Performance, and Productivity

Although our understanding of the effects of lighting conditions on visual performance has grown in recent years, it is important to realize that there is an inherent limitation on the generalizability of this understanding to the performance of all visual tasks. Figure 3-41 shows a conceptual relationship between visual stimuli, visual performance, task performance, and productivity. The stimuli to the visual system are determined by the task characteristics and the way the task is lighted. These stimuli and the operating state of the visual system determine visual performance. Most visual tasks have three components: visual, cognitive, and motor. The visual component refers to the process of extracting information relevant to the performance of the task using the sense of sight. The cognitive component is the process by which these sensory stimuli are interpreted and the appropriate action determined. The motor component is the process by which the stimuli are manipulated to extract information and the consequential actions carried out. As an example, consider the task of rectifying a software bug using an instruction manual. The visual component is to see the marks on the page of the instruction manual. The cognitive task is understanding what it means. The motor component is striking the right keys on the keyboard. Every task is unique in its balance between visual, cognitive, and motor components and hence in the effect lighting conditions have on task performance. It is this uniqueness that makes it impossible to generalize from the effect of lighting on the performance of one task to the effect of lighting on the performance of another. The RVP model of visual performance for on-axis tasks and the visual search model discussed above can be used to quantify the effects of lighting conditions on visual performance, but there is no general model to translate those results to task performance. Unfortunately, task performance is what is needed in order to measure productivity and to establish cost-benefit ratios comparing the costs of providing a lighting installation with the resulting benefits in terms of better task performance. When reading the literature, it is important to note that measures of task performance are sometimes erroneously called measures of visual performance.

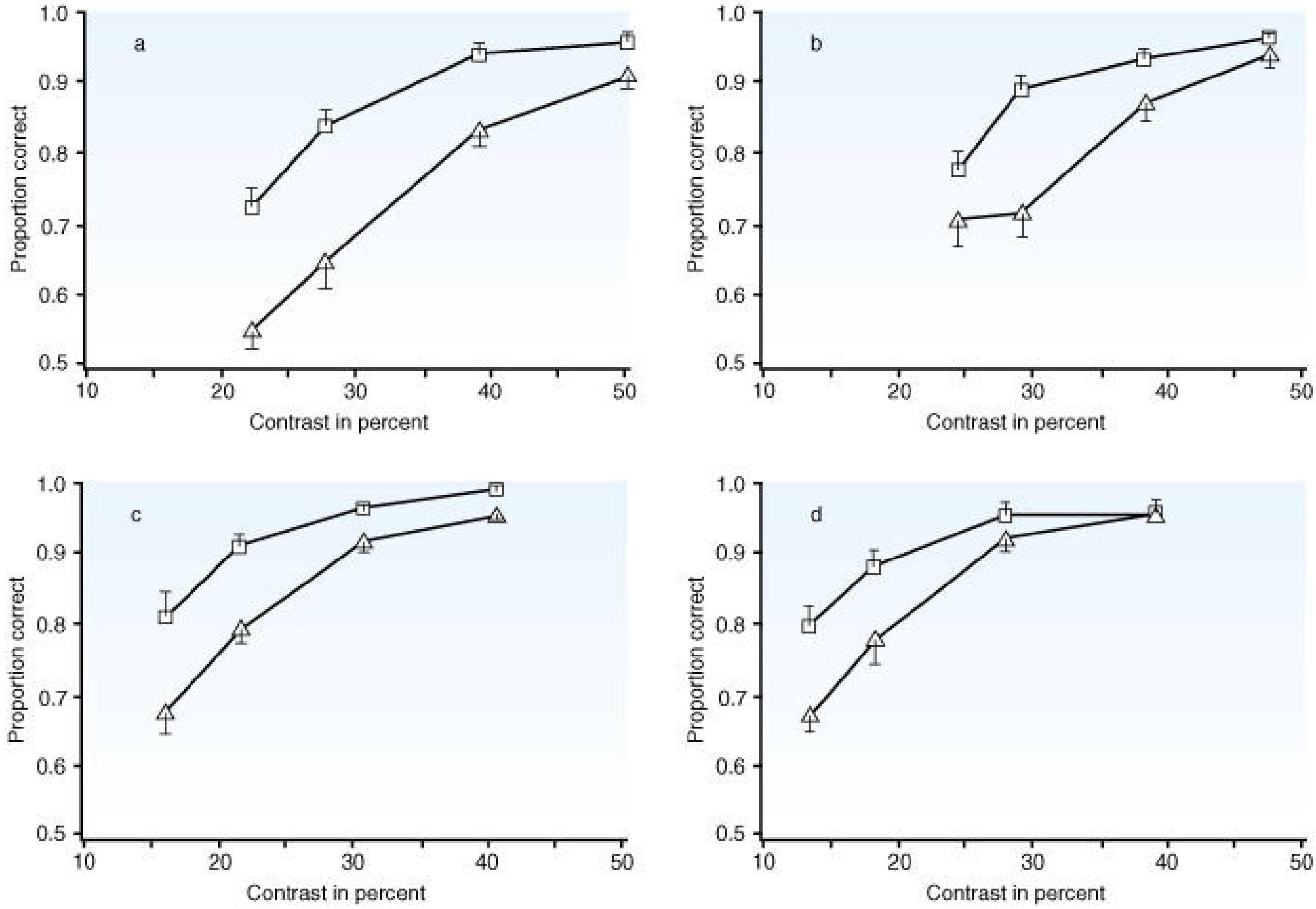


Figure 3-40. Means and associated standard errors of the proportion of Landolt ring orientations, presented for 200 ms on a spectrally neutral background, which were correctly identified; plotted against luminance contrast (see Equation 3-7), for four different target background luminances: (a) 11.9, (b) 27.7, (c) 47.0, (d) 73.4 cd/m^2. In all four diagrams, the upper curve is for a scotopically enriched illuminant (surround field scotopic luminance = 228 cd/m^2), and the lower

curve is for a scotopically deficient illuminant (surround field scotopic luminance = 13 cd/m^2). Both illuminants produce a surround field photopic luminance of 53 cd/m^2.

Improving Visual Performance

The main purpose of many lighting installations is to enable people to perform their work quickly, easily, comfortably, and safely. To achieve this aim, it is necessary to provide lighting that ensures people are operating on the plateau of visual performance and not on or close to the escarpment. Although the discussion above has been focused on lighting conditions, it is important to recognize that visual performance can be improved by changing the characteristics of the task as well as the lighting. The following list is divided into two parts: task changes and lighting changes. Not all the following suggestions apply in every situation, and not all are appropriate for every problem.

Changing the Task

- Increase the size of detail in the task, such as by magnification.
- Increase the luminance contrast of the detail in the task, for example, by adding toner to the printer.
- For off-axis tasks in a cluttered field, make the object to be detected clearly different from the surrounding objects on as many different dimensions as possible, such as by using size, contrast, color, and shape.
- Ensure the object presents a sharp image on the retina (for example, by going to an optometrist).

Changing the Lighting

- Increase the adaptation luminance, such as by increasing the illuminance.
- Where good color discrimination is needed, select a lamp with a high CRI (e.g., greater than 80).
- Design the lighting so that it is free from disability glare and veiling reflections, such as by eliminating any direct views of the light source and by using matte materials.

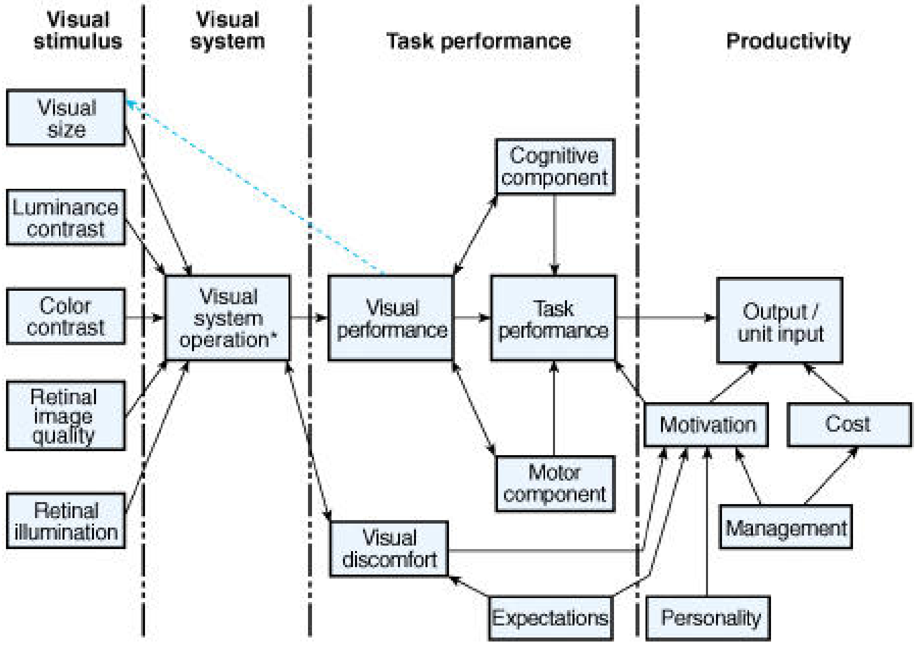


Figure 3-41. A conceptual diagram of the complex relationships between the stimuli to the visual system and their impact on visual performance, task performance, and productivity. The arrows indicate the direction of their effects. The dotted arrow between visual performance and visual size indicates that if visual performance is poor, a common response is to move closer to the stimulus to increase its visual size. From G. Salvendy, *Handbook of human factors and ergonomics*, 2nd ed. Copyright © 1997. Reprinted by permission of John Wiley & Sons, Inc.

VISUAL COMFORT

Lighting installations are rarely designed for visual performance alone. Visual comfort is almost always a consideration. The aspects of lighting that cause visual discomfort include those relevant to visual performance and extend beyond them.

Symptoms and Causes of Visual Discomfort

Visual discomfort can give rise to an extensive list of symptoms. Among the more common are red, sore, itchy, and watering eyes; headaches and migraine attacks; gastrointestinal problems; and aches and pains associated with poor posture. Visual discomfort is not the only possible source of these symptoms. All can have other causes. This vagueness makes it essential to consider other possible causes before ascribing an occurrence of any of these symptoms to the lighting conditions.

The visual system is designed to extract information from the visual environment. This is essentially a "signal-to-noise" problem with the signal being the information desired and the noise being all the other information in the visual environment. Features of the visual environment that reduce the signal-to-noise ratio, either by reducing the signal or increasing the noise, can cause visual discomfort. There are several different situations where signal-to-noise ratio problems can occur.

Any visual task that has characteristics that place it close to threshold has a low signal-to-noise ratio and hence has a high level of visual difficulty. One reaction to a high level of visual difficulty is to bring the task closer to increase its visual size. As the task is brought closer, the accommodation mechanism of the eye adjusts to keep the retinal image in focus, an adjustment that might make it operate close to its limits. This adjustment can lead directly to fatigue of the eye muscles, and indirectly to fatigue of other muscles caused by the observer adopting an unusual posture. Such muscle fatigue can produce symptoms of visual discomfort.

Even when it is not possible to move closer to the task, signals close to threshold can generate symptoms of visual discomfort. An example of this occurs when driving in fog or in a "whiteout" snowstorm. In both situations, the visual system is searching for information that is hidden but that may appear suddenly and require a rapid response. The stress while driving in these conditions is a common experience.

Symptoms of visual discomfort may also occur when there is a high visual noise level. Looking at a printed page that has large areas of high-contrast gratings has been associated with the occurrence of headaches, migraines, and reading difficulties.[78]

Symptoms of visual discomfort also occur when there are several disassociated strong signals in the visual field. The visual system has a large peripheral field that detects the presence of targets, which are then examined using the small, high-resolution fovea. For this system to work, objects in the peripheral field that are bright, moving, or flickering have to be easily detected. If, upon examination, these bright, moving, or flickering objects prove to be of little interest, they become sources of distraction because their attention gathering power is not diminished after one examination. Ignoring objects that attract attention is stressful and can lead to symptoms of visual discomfort.[79]

Another form of this source of visual discomfort occurs when there are two alternative views of the world. This can happen when a lighting installation is reflected from a computer monitor. The monitor presents both the generated image and a reflected image of the room.

Lighting Conditions That Can Cause Discomfort

There are many different aspects of lighting that can cause discomfort. Insufficient light for the easy performance of a task is an obvious problem that can be resolved by one of the approaches suggested in "Improving Visual Performance." Here, attention will be given to flicker, glare, shadows, and veiling reflections. It should be noted that the impact of these conditions on discomfort depends on the context. All can be used to positive effect in some contexts.

Flicker. A general lighting installation that produces visible flicker will be almost universally disliked, unless it is being used for entertainment. The magnitude of individual differences, and the fact that electrical signals associated with flicker can be detected in the retina even when there is no visible flicker,[44] imply that a clear safety margin is necessary if flicker is not to be perceived by anyone. The main variables that determine flicker perception are the frequency and percentage modulation of the oscillation in light output, the proportion of the visual field over which the flicker occurs, and the adaptation luminance. Temporal modulation transfer functions (see "Temporal Resolution" above) can be used to predict whether a given fluctuation of light output will be visible.

To eliminate the perception of flicker, it is necessary to increase the frequency of oscillation above the critical flicker frequency or to reduce the percentage modulation of the oscillation, the area of the visual field over which the oscillation occurs, or the adaptation luminance. The last two possibilities occur rarely with general lighting. A much more common approach is to use high-frequency control gear for discharge lamps and to mix the light from lamps powered from different phases of the electricity supply,[80] both of which increase the frequency and reduce the modulation of oscillation in light output. The use of high-frequency control gear has been associated with a reduction in the prevalence of headaches.[81]

Although flicker occurring over a large area of the visual field is almost always disturbing, flicker occurring over a very small part of the visual field is much less disturbing and is a very effective way to draw attention to a particular location. This technique is widely used with emergency vehicles.

Glare. Glare occurs in two ways. First, it is possible to have too much light. Too much light produces a simple photophobic response, in which the observer squints, blinks, or looks away. Too much light is common in full sunlight. The only solution to this problem is to reduce the retinal illuminance by obscuring a bright part of the visual field (e.g., by wearing a baseball cap) or by lowering the luminance of the whole visual field (e.g., by wearing sunglasses).

Second, glare occurs when the range of luminance in a visual environment is too large. Glare of this sort can have two effects: a reduction in visual performance until it is close to or on the escarpment of visual performance (see "Models of On-Axis Visual Performance"), and a feeling of discomfort. Glare that reduces visual performance is called disability glare and is due to light scattered in the eye, reducing the luminance contrast of the retinal image. The effect of scattered light on the luminance contrast of the target can be mimicked by adding a uniform "veil" of luminance to the target. The magnitude of disability glare can be estimated by calculating this equivalent veiling luminance.

Several investigators[82-85] have examined the role of glare-source luminance and angular separation from the primary object of regard as producers of disability glare; they have each derived slightly different functions, but a commonly used expression is

$$L_v = 9.2 \sum_{i=1}^{n} \frac{E_i}{\theta_i (\theta_i + 1.5)} \qquad (3\text{-}11)$$

where

L_v = equivalent veiling luminance in cd/m^2,
E_i = illuminance from the ith glare source at the eye in lux,
θ_i = angle between the target and the ith glare source in degrees.

The effect of disability glare on the luminance contrast of the perceived target can be determined by adding the equivalent veiling luminance to all elements in the formulas for luminance contrast (Eq. 3-6). For example, to include the effect of disability glare on the luminance contrast of print, the formula is

$$C = \frac{((L_t + L_v) - (L_b + L_v))}{(L_b + L_v)} = \frac{(L_t - L_b)}{(L_b + L_v)} \quad (3\text{-}12)$$

where

L_v = equivalent veiling luminance in cd/m^2,
L_t = target luminance in cd/m^2,
L_b = background luminance in cd/m^2.

Although disability glare is most commonly thought of as coming from discrete sources, such as oncoming automobile headlamps, every luminous point in space acts as a source of stray light for nearby points and reduces contrast, thereby making edges in the visual field less conspicuous. The illuminance at the eye term in Equation 3-11 integrates the scattering effects produced by stray light from all points.

Disability glare is rarely important in interior applications but is common on roads at night from oncoming headlights and during the day from the sun. Disability glare usually also causes discomfort, but it is possible to have disability glare without discomfort when the glare source is large. This can be seen by looking at a picture hung on a wall adjacent to a window. The picture will usually be much easier to see when the eyes are shielded from the window.

The other form of glare is called discomfort glare. Discomfort glare is a sensation of annoyance or pain caused by high luminances in the field of view. By definition, discomfort glare does not affect visual performance but does cause discomfort. While the cause of disability glare is well known (intraocular light scattering; see "Optical Components"), that of discomfort glare is not understood. Laboratory studies have related discomfort glare to pupillary and facial muscle activity,[86-88] but the validity of these mechanisms as causes of discomfort glare is not yet widely accepted.

Despite this lack of understanding, the desire for some method to determine if a lighting installation will produce discomfort glare has led to the development of a number of empirical prediction systems in different countries.[89] In North America, the empirical prediction system is called the Visual Comfort Probability (VCP) system. This system is based on assessments of discomfort glare for different sizes, luminances, and numbers of glare sources, their locations in the field of view, and the background luminance against which they are seen, for conditions likely to occur in interior lighting. The criterion used to measure the effect of these variables is the luminance just necessary to cause discomfort, a threshold criterion termed the borderline of comfort and discomfort (BCD).[90]

The visual comfort probability (VCP) system evaluates lighting systems in terms of the percentage of the observer population that will accept the lighting system and its environment as being comfortable, using the perception of glare due to direct light from luminaires to the observer as a criterion.

The following factors have been found to influence subjective judgments of discomfort glare:

- Room size and shape
- Room surface reflectances
- Illuminances
- Luminaire characteristics
- Number and location of luminaires
- Luminance of the entire field of view
- Observer location and line of sight
- Differences in individual glare sensitivity

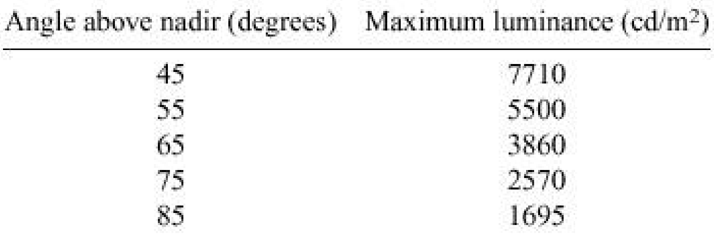
The VCP can be calculated for specific lighting systems and given observer lines of sight (see Chapter 9, Lighting Calculations). However, in order to systematize the calculations and to permit comparison of luminaires, standard conditions have been adopted.[91] These are:

- An initial illuminance of 1000 lx (100 fc)
- Room surfaces with 80% for the effective ceiling cavity reflectance, 50% for the wall reflectance, and 20% for the effective floor cavity reflectance
- Mounting heights above the floor of 2.6, 3, 4, and 4.9 m (8.5, 10, 13, and 16 ft)
- A range of room proportions to include square, long-narrow, and short-wide rooms
- A standard layout involving luminaires uniformly distributed throughout the space
- An observation point 1.2 m (4 ft) in front of the center of the rear wall and 1.2 m (4 ft) above the floor
- A horizontal line of sight looking directly forward
- A limit to the field of view corresponding to an angle of 53° above and directly forward from the observer

Luminaire manufacturers use the VCP formulas and the standard conditions to produce tabular estimates of the level of discomfort glare produced by a regular array of their luminaires for a range of standard interiors. These tables provide all the precision necessary for estimating the level of discomfort glare likely to occur in interiors.

By consensus, discomfort glare is not a problem in lighting installations if all three of the following conditions are satisfied:[91]

- The VCP is 70 or more.
- The ratio of the maximum luminance (luminance of the brightest 6.5 cm^2 [1 $in.^2$] area) to the average luminaire luminance does not exceed 5:1 at 45°, 55°, 65°, 75°, and 85° from nadir for crosswise and lengthwise viewing.
- Maximum luminances of the luminaire crosswise and lengthwise do not exceed the following values.



Angle above nadir (degrees)	Maximum luminance (cd/m^2)
45	7710
55	5500
65	3860
75	2570
85	1695

The principal research used to establish the VCP system involved luminances of magnitude comparable to those produced by fluorescent lamps.[90,92-98] Further, the most extensive field validation used lighting systems containing fluorescent luminaires. Although mathematically VCP can be applied to virtually any lamp and luminaire combination, extrapolation to lamps and luminaires with significantly different luminance patterns has not been validated. Therefore, the validity of applying VCP to clusters of small light sources, for example, is questionable.

The VCP system is based on empirical relations derived from a variety of experiments. It has been concluded that differences of 5 units or less are not significant. In other words, if two lighting systems do not differ in VCP rating by more than 5 units, there is no basis for judging that there is a difference in visual comfort between the two systems. Artifacts introduced by using different computational procedures for two lighting systems can further spread the VCP values for two systems that are not reliably different.[99]

An alternative, simplified method of providing an acceptable degree of comfort has been derived from the formulas for discomfort glare. This method is based on the premise that luminaire designers do not design different luminaires for rooms of different sizes but rather consider the probable range of room sizes and design for the "commonly found more difficult" potential glare situation (in rooms less than 6 m [20 ft] in length and width, the luminaires are largely out of the field of view). This simplified method is only applicable to flat-bottom luminaires.[100-102]

While the VCP system is used in North America, the rest of the world uses somewhat different discomfort glare prediction systems. Nearly all these systems are based on a formula that implies that discomfort glare increases as the luminance and solid angle of the glare source at the eye increase and decreases as the luminance of the background and the deviation of the glare source from the line of sight increases.[89] Comparative evaluations between the different discomfort glare prediction systems for a common range of installations have shown that their predictions are well correlated and that none is significantly more accurate than the others at predicting the sense of discomfort.[103] All give reasonable predictions for the average discomfort of a group of people but give only poor predictions of an individual's response.[104]

Given the impediment to trade represented by the different discomfort glare prediction systems in different countries and the apparent lack of difference between them regarding the accuracy of their predictions, the CIE produced a consensus system.[105] This system, called the Unified Glare Rating system, uses the formula:

$$\mathrm{UGR} = 8 \log_{10} \left(\frac{0.25\pi}{E_b} \right) \sum_{i=1}^{n} \frac{(L_i^2 \times \omega_i)}{p_i} \qquad (3\text{-}13)$$

where

UGR = Unified Glare Rating,
E_b = the illuminance (in lx) on the plane of the eye from the background (excluding the glare source),
L_i = the luminance (in cd/m^2) of the *i*th part of the glare source in the direction of the eye,
ω_i = the solid angle (in sr) of the *i*th part of the glare source,
p_i = the position index of the *i*th part of the glare source (consult Chapter 9, Lighting Calculations, for a procedure to calculate position index).

This formula results in UGR values ranging from 10 to 30. Different lighting applications can be given a criterion value; for example office lighting is given a limiting value of 20. The relationship (Figure 3-42) between this discomfort glare scale and the more familiar VCP values has been calculated as VCP values of 50%, 60%, 70%, 80%, and 90% correspond to UGR values of 24.0, 21.6, 19.0, 16.0, and 11.6, respectively.[106] The accuracy with which the UGR system can predict the level of discomfort produced by a glare source for a group of people has been experimentally tested in the laboratory and in the field and has been found to be high.[107]

Shadows. Shadows occur when light from a particular direction is intercepted by an opaque object. Large objects reduce the illuminance over a large area. This is typically the problem in industrial lighting where large pieces of machinery cast shadows in adjacent areas. The effect of these shadows can be overcome either by increasing the proportion of interreflected light by using high-reflectance surfaces or by providing local lighting in the shadowed area. If the object is small and close to the area of interest, the shadow can be cast over a meaningful area, which in turn can cause perceptual confusion, particularly if the shadow moves. An example of this is the shadow of a hand cast on a blueprint. This problem can be reduced by increasing the interreflected light in the space or by providing local lighting that can be adjusted in position.

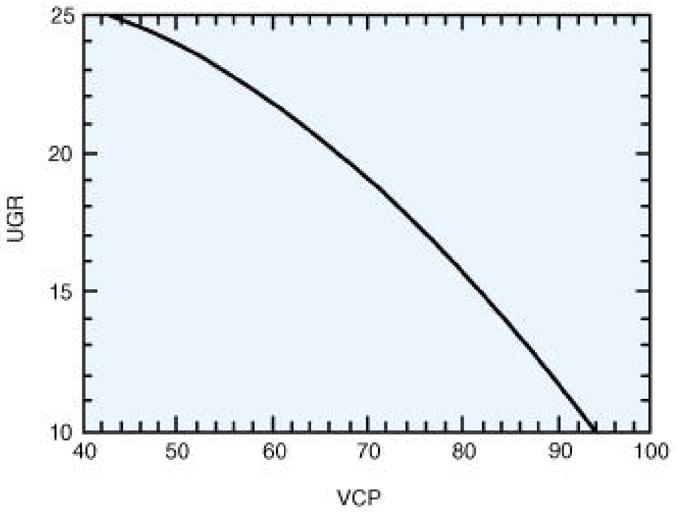


Figure 3-42. The relationship between VCP and the UGR discomfort glare scale.

Although shadows can cause visual discomfort, it should be noted that in the form of shading, they are a valuable element in revealing the form of three-dimensional objects. Techniques of display lighting are based around the idea of creating highlights and shadows to change the perceived form of the object being displayed.

The number and nature of shadows produced by lighting installations depend on the size and number of light sources and the extent to which light is interreflected. The strongest shadows are produced from a single point source in a black room. Weak shadows are produced when the light sources are large in area and the degree of interreflection is high.

Veiling Reflections. Veiling reflections are luminous reflections from specular or semi-matte surfaces that physically change the contrast of the visual task and therefore change the stimulus presented to the visual system. Veiling reflections and disability glare are similar in that both change the luminance contrast of the retinal image but differ in that veiling reflections change the luminance contrast of the task while disability glare changes the luminance contrast of the retinal image.

The two factors that determine the nature and magnitude of veiling reflections are the specularity of the material being viewed and the geometry between the observer, the target, and any sources of high luminance. If the object is a perfect diffuse reflector (i.e., a lambertian reflector), no veiling reflections can occur. If it has a specular reflection component, veiling reflections can occur. The positions where veiling reflections occur are those where the incident ray corresponding to the reflected ray that reaches the observer's eye from the target comes from a source of high luminance. This means that the strength and magnitude of such reflections can vary dramatically within a single lighting installation.[108]

Veiling reflections can cause visual discomfort because they can reduce the luminance contrast and hence the difficulty of the task. In some cases, luminance contrast can increase as veiling reflections increase. One such case is when a combination of specular and diffuse reflecting materials are used for the target and background. Then, a high enough luminance can cause the polarity of luminance contrast to reverse.

The effect of veiling reflections on contrast may be quantified by adding the luminance of the veiling reflection to the appropriate components in one of the luminance contrast formulas (Equations 3-6, 3-7, 3-8). What the appropriate components are depends on the reflection properties of the material being viewed. For glossy ink writing on matte paper, the luminance of the veiling reflections should only be added to the luminance of the ink. For a glossy magazine page or a VDT screen, where there is a specularly reflecting transparent coating over the whole surface, veiling reflections occur over the whole surface. In this case the luminance of the veiling reflections should be added to all terms in the luminance contrast formula.

The reflections that occur on materials that have a uniform specularly reflecting surface, such as a VDT screen, can do more than just modify the luminance contrast. Wherever there is an extended specular reflecting surface, a reflected image of the scene is formed by the surface. This image represents an alternative view of the world to that shown by the printed page or the VDT display. This perceptual conflict can cause discomfort (see "Symptoms and Causes of Visual Discomfort" above). Further, the reflected image is at a different focal distance than the surface, so fluctuations in accommodation and vergence eye movements occur as attention is switched from one image to the other, which may cause fatigue and discomfort to the worker during prolonged viewing. It is therefore quite important to limit the magnitude of veiling reflections in offices (see Chapter 11, Office Lighting).

Like shadows, veiling reflections can also be used positively, but in these cases they are called highlights. Physically, veiling reflections and highlights are the same thing. Display lighting of specularly reflecting objects is all about producing highlights to reveal the specular nature of the surface.

The extent to which changes in luminance contrast changes visual performance can be estimated using one of the models of visual performance discussed earlier but the extent to which it causes discomfort is different. Whereas veiling reflections affect visual performance when the luminance contrast without veiling reflections is low, it has been shown that about a 20% reduction in luminance contrast is the limit of what is acceptable, regardless of the luminance contrast without veiling reflections (Figure 3-43).[109]

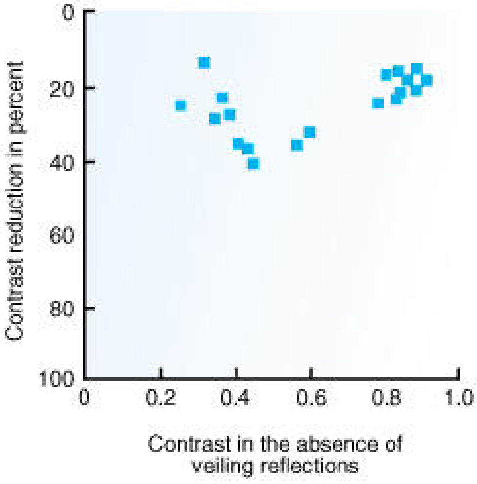


Figure 3-43. The luminance contrast reduction considered acceptable by 90% of observers plotted against the luminance contrast (see Equation 3-6) of the materials when no veiling reflections occurred.

Comfort, Performance, and Expectations

While lighting conditions that compromise visual performance are almost always considered uncomfortable, lighting conditions that allow a high level of visual performance can also be considered uncomfortable. Figure 3-50 below shows the mean detection speed for finding one number from many laid out at random on a table, and the percentage of people considering the lighting "good." As might be expected, increasing the illuminance on the table increases mean detection speed and the percentage considering the lighting "good." However, as the illuminance exceeds 2000 lx (200 fc), the percentage considering the lighting "good" declines even though the mean detection speed continues to increase. Assuming that lower values of "good" means more discomfort, this result indicates both that if you wish to achieve a satisfactory lighting installation it is necessary to provide lighting that allows easy visual performance and avoids discomfort, and that visual discomfort is more sensitive to lighting conditions than visual performance.

There is another aspect of visual comfort that distinguishes it from visual performance. Visual performance is determined solely by the capabilities of the visual system. Visual comfort is linked to people's expectations. Any lighting installation that does not meet expectations may be considered uncomfortable even though visual performance is adequate; and expectations can change over time. Figure 3-41 also suggests another potential impact of visual comfort. Lighting conditions that are considered uncomfortable may influence task performance by changing motivation even when they have no effect on the stimuli presented to the visual system and hence on visual performance.

Approaches to Improving Visual Comfort

In order to ensure visual comfort it is necessary to ensure that the lighting allows a good level of visual performance and does not cause distraction. This can be done by the following:

- Identify the visual tasks to be performed and then determine the characteristics of the lighting needed to allow a high level of visual performance of the tasks, for example, by using the RVP model.
- Eliminate flicker from the lighting by using high-frequency control gear for discharge lamps. If this is not possible, reduce the percentage modulation of the perceived flicker by mixing light from sources operating on different phases of the electricity supply.
- Reduce disability glare by selection, placement, and aiming of luminaires to reduce the luminance of the luminaires close to the common lines of sight.
- Reduce discomfort glare by selection and layout of luminaires. Use VCP or UGR to estimate the magnitude of discomfort glare. Using high-reflectance surfaces in the space will help reduce discomfort glare by increasing the background luminance against which the luminaires are seen.
- Consider the density and extent of any shadows that are likely to occur. If shadows are undesirable and large-area shadows are likely to occur, use high-reflectance surfaces in the space to increase the amount of interreflected light and use more lower-wattage lamps to supply the desired illuminance. If shadows cannot be avoided because of the extent of obstruction in the space, provide supplementary task lighting in the shadowed areas. If dense, small-area shadows occur in the immediate work area, use adjustable task lighting to moderate their impact.
- Reduce veiling reflections by reducing the specular reflectance of the surface being viewed, or by changing the geometry between the viewer, the surface being viewed, and the observer, or by increasing the amount of interreflected light in the space.
- If the reflections are occurring on a self-luminous surface, such as a VDT screen, use dark letters on a bright background. This will reduce the impact of any veiling reflections seen on the screen.[110,111]

PERCEPTION OF LIGHTING

The perception of the visual world is not solely determined by the physical stimuli presented to the visual system as the retinal image. The existence of a large number of visual illusions is sufficient to demonstrate this. Rather, the stimuli to the visual system provide information which the visual system interprets on the basis of past experience and coincident information. Figure 3-44 shows a surface with dents and dings in it. However, if this page is inverted the dents become dings and vice versa, because it is unconsciously assumed that the light which is casting the shadows always comes from above.

When considering how we perceive the world, the overwhelming impression is one of stability in the face of continuous variation. As the eyes move in the head and the head itself moves about, the retinal images of objects move across the retina and change their shape and size according to the laws of physical optics. Further, throughout the day, the spectral emission and distribution of daylight changes as the sun moves across the sky and the meteorological conditions vary. Despite these variations in the retinal image, our perception of reality changes very little. This invariance of perception is called perceptual constancy. The advantage in being able to recognize a tiger as a tiger over a wide range of lighting conditions is obvious.

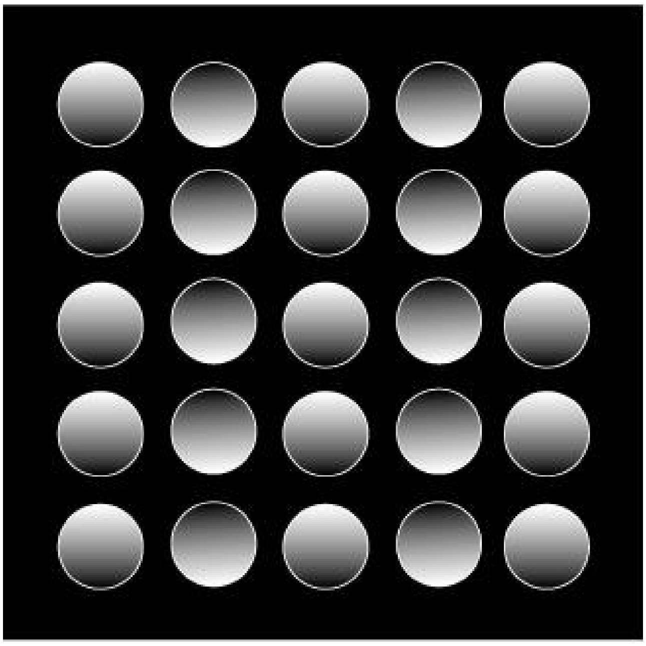


Figure 3-44. The effect of light on the perception of depth. This surface has both dents (a bulge into the page) and dings (a bulge out of the page). Turning the page upside down makes dents appear as dings and vice-versa because, perceptually, we have learned that the lighting comes from above. Used, by permission, from R. Sekuler and R. Blake, *Perception.* © 1994. McGraw-Hill.

The Perceptual Constancies

There are four fundamental attributes of an object that are constant over a wide range of lighting conditions. They are:

1. Lightness. Lightness is the perceptual attribute related to the physical quantity of reflectance. In most lighting situations, it is possible to distinguish between the illuminance on a surface and its reflectance, that is, to perceive the difference between a low-reflectance surface receiving a high illuminance and a high-reflectance surface receiving a low illuminance, even when both surfaces have the same luminance. It is this ability to perceptually separate the luminance of the retinal image into its components of illuminance and reflectance that ensures that a piece of coal placed near a window is always seen as black while a piece of paper far from the window is always seen as white, even when the luminance of the coal is higher than the luminance of the paper.

2. Color. Physically, the stimulus a surface presents to the visual system depends on the spectral content of the light illuminating the surface and the spectral reflectance of the surface. However, quite large changes in the spectral content of the illuminant can be made without causing any changes in perceived color. This is evident from the ease with which two similar colors can be discriminated when seen side by side and from the difficulty in discrimination when they are seen successively. See Chapter 4, Color, for additional discussion of color constancies.

3. Size. As an object gets farther away, the size of its retinal image gets smaller but the object itself is not seen as getting smaller. This is because, by using clues such as texture and masking, it is usually possible to estimate the distance and then to compensate unconsciously for the increase in distance. Figure 3-45 shows an illustration of a room, called the Ames room after the inventor, where the cues to distance have been deliberately designed to be misleading when viewed from a specific position. The distortion in perceived size of the people standing in the two corners of the room is startling even after seeing the illusion many times.

4. Shape. As an object changes its orientation in space, its retinal image changes. Nonetheless, in most lighting conditions it is possible to distinguish the orientation in space so a circular plate will always look circular even when its tilted image is elliptical.

These constancies represent the application of everyday experience and the integration of all the information about the lighting available in the whole retinal image to the interpretation of a part of the retinal image that bears several alternative interpretations. Given this process it should not be too surprising that the constancies can be broken by restricting the information available coincident with the object being viewed. For example, viewing a surface through an aperture that limits the view to a limited part of the surface will often eliminate lightness constancy. Likewise, eliminating cues to distance will destroy size constancy; changing cues to the plane in which an object is lying will reduce shape constancy and eliminating information on the spectral content of the illuminant will reduce color constancy. In general, constancy is likely to break down whenever there is insufficient or misleading information available from the surrounding parts of the visual field. The conditions recommended for maintaining the constancies are:[112]

- Adequate light
- No disability glare
- Good color renderinged
- High chroma colors, particularly on dimly lighted surfaces
- A variety of surface colors, including some small white surfaces
- No large glossy areas
- Materials with characteristic colors and textures
- Obvious but not necessarily visible sources of light

Lighting conditions used in display lighting usually set out to break the constancies, particularly lightness constancy.[112,113]

Even when the lighting conditions are such as to support perceptual constancy, lightness and color constancy will break down if large changes in illuminance or spectral content occur. Figure 3-46 shows the apparent Munsell values of spectrally neutral surfaces, plotted against the illuminance on the surfaces. Figure 3-46 shows that as the illuminance is decreased, the apparent Munsell values (i.e., the lightnesses) are reduced for all the Munsell samples, until at very low illuminance all the Munsell values are in the range of gray to black. It should also be pointed out that this gradual breakdown in lightness constancy requires very large changes in illuminance relative to those that typically occur in interior lighting.

Modes of Appearance

While lighting has an important role in preserving or eliminating constancy, it also has a role in determining the perceived visual attributes of objects. It has been argued that objects can have five different attributes--brightness, lightness, hue, saturation, transparency, and glossiness--depending on their nature and the way they are lighted.[114] These attributes are defined as follows:

1. Brightness. An attribute based on the extent to which an object is judged to be emitting more or less light.

2. Lightness. An attribute based on the extent to which an object is judged to be reflecting or transmitting a greater or lesser fraction of the incident light.

3. Hue. An attribute based on the classification of a color as reddish, yellowish, greenish, bluish, or their intermediaries, or as having no color.

4. Saturation. An attribute based on the extent to which a color is different from a color of the same brightness or lightness.

5. Transparency. An attribute based on the extent to which colors are seen behind or within an

object.

6. Glossiness. An attribute based on the extent to which a surface is different from a matte surface with the same lightness, hue, saturation, and transparency.

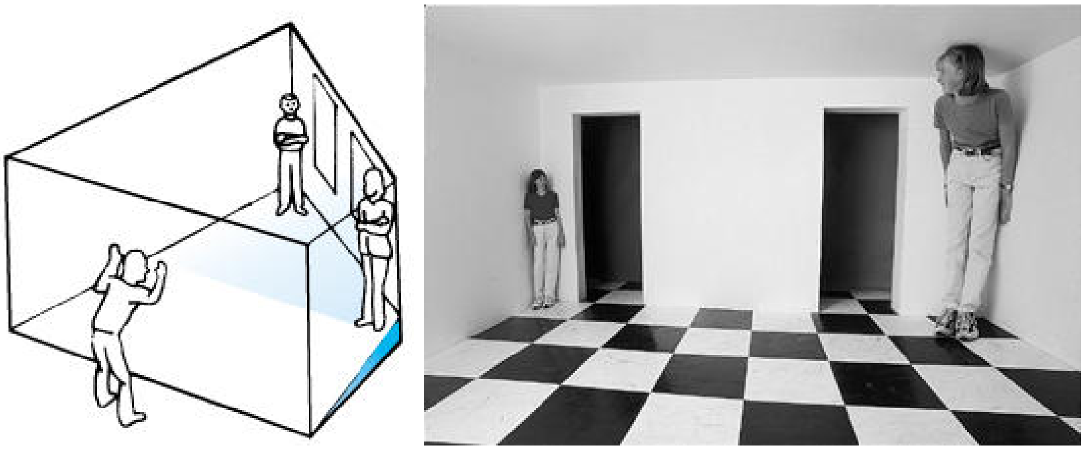


Figure 3-45. The Ames room: a demonstration that providing false cues to distance will break size constancy.

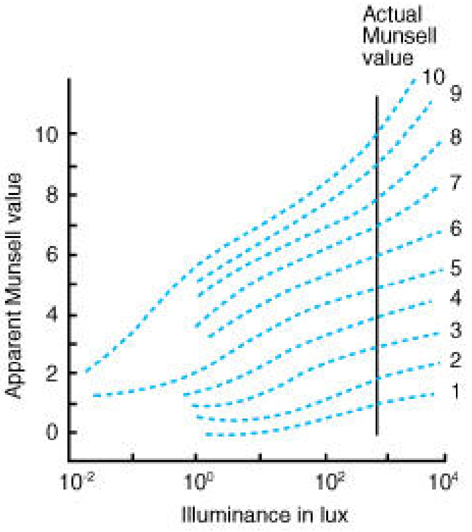


Figure 3-46. Apparent Munsell values at different illuminances for surfaces seen against a background of reflectance = 0.2. The vertical line at an illuminance of 786 lx indicates the reference condition. At this illuminance the apparent Munsell values of the surfaces have been normalized to their actual Munsell values.

Not all these attributes occur in every situation. Rather, different combinations of attributes occur in different modes of appearance. The four modes of appearance are:

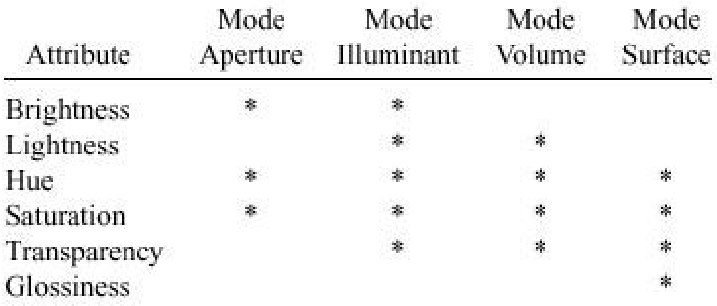
1. Aperture mode. This occurs when an object or surface has no definite location in space, as occurs when a surface is viewed through an opening.

2. Illuminant mode. This occurs when an object or surface is seen to be emitting light.

3. Object mode, volume. This occurs when a three-dimensional object has a definite location in space with defined boundaries.

4. Object mode, surface. This occurs when a two-dimensional surface has a definite location in space with defined boundaries.

The following table shows which of the attributes are associated with each mode of appearance.



Attribute	Mode Aperture	Mode Illuminant	Mode Volume	Mode Surface
Brightness	*	*		
Lightness		*	*	
Hue	*	*	*	*
Saturation	*	*	*	*
Transparency		*	*	*
Glossiness				*

Of particular interest to the perception of lighting is the shift between the attributes of brightness and lightness in different modes of appearance. An object that appears in the self-luminous mode, such as a VDT screen or a lamp, is perceived to have a brightness but not a lightness. In this mode of appearance, the concept of reflectance is meaningless. However, an object that appears in the volume mode, such as a VDT screen or a lamp that is turned off, does not have an attribute of brightness but does have a lightness in that its reflectance can be estimated.

A similar transformation occurs between the volume or surface modes of appearance and the aperture mode. Even reflective objects, when seen in the aperture mode, are perceived as having a brightness but not a lightness. When seen in the object mode they have a lightness and not a brightness. This is important because lighting can be used to change the mode of appearance. For example, a hung painting has a lightness attribute when lighted so that both it and the wall appear in the surface mode. However, if the painting is illuminated solely with a carefully aimed framing spot so that the edge of the beam coincides with the edges of the painting, the painting is seen in the aperture mode and takes on a self-luminous quality with a brightness attribute. Adjusting the modes of appearance is an important technique in display lighting, both indoors and outdoors.

Brightness Perception

For objects in the illuminant or aperture modes, the perception of brightness is a function of luminance. Specifically, brightness is related to luminance by a power law[115] of the form:

$$B = a \times L^{0.33} \qquad (3\text{-}14)$$

where

B = brightness,
a = constant,
L = luminance in cd/m^2.

Despite the logical inconsistency of describing a perception of brightness to an object in the surface mode, studies of the perception of brightness of surfaces in an interior have been made.[116] The room contained both self-luminous objects, which appeared in the illuminant mode, and reflecting surfaces, which appeared in the surface mode. The luminance range in the interior was two log units. These studies have shown that the perceived brightness of any single surface increases with luminance according to a power law with an exponent of 0.35, but that the brightness of a number of surfaces seen simultaneously follows a power law with an exponent of approximately 0.6. These relationships can be used to estimate the relative brightness of surfaces in an interior by assuming that the brightest surface in the room has a brightness given by:

$$B_{max} = L_{max}^{0.35} \qquad (3\text{-}15)$$

Then, other surfaces will have a brightness given by:

$$B = a \times L^{0.6}\text{, where } a = \frac{B_{max}}{L_{max}^{0.6}} \qquad (3\text{-}16)$$

This simple system underestimates the brightness of highly saturated colored surfaces and overestimates the brightness of translucent surfaces. These relationships are given for guidance only. The data from which these relationships were derived represented just over half the data collected. The data from other subjects were eliminated to reduce the "noise" in the data, "noise" that may reflect the lack of meaning some people find in attempting to describe the brightness of an object in the surface mode.

Holistic Perceptions

The above discussion of perceptual constancy and modes of appearance is concerned mainly with the perception of individual objects in an interior. This section is concerned with the factors that determine the perception of the whole interior.

Lighting Cues. An experiment designed to address the holistic perception of a space was carried out in a small office lit in eighteen different ways.[117] The illuminance on the desk was always 500 lx, but the distribution of light in the rest of the room varied widely. A panel of people was asked to evaluate the room lighted by each lighting installation using an extensive questionnaire. Using factor analysis, three independent factors were identified in the responses: the first was simply whether people liked the installation; the second was the brightness, in the sense of the amount of light in the office; the third was interest. Figure 3-47 shows the positions of the eighteen installations (a) on a map formed by the brightness and interest dimensions. The contours on the map show the relative preference for the different parts of the map. Clearly, for this work space people preferred lighting that was both bright and interesting. Regular arrays of luminaires can produce brightness but are rarely interesting. Irregular arrangements of lighting equipment can be interesting but may not produce enough brightness. Designing lighting to be bright and interesting would seem to be a good approach to designing lighting for work spaces.

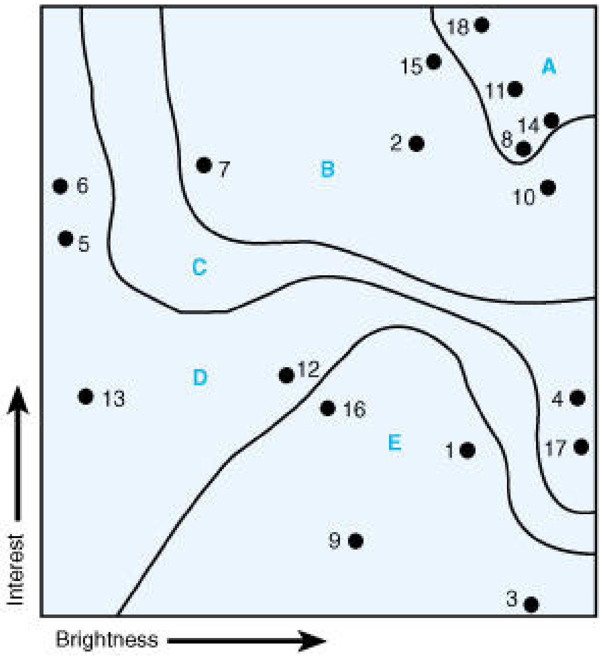
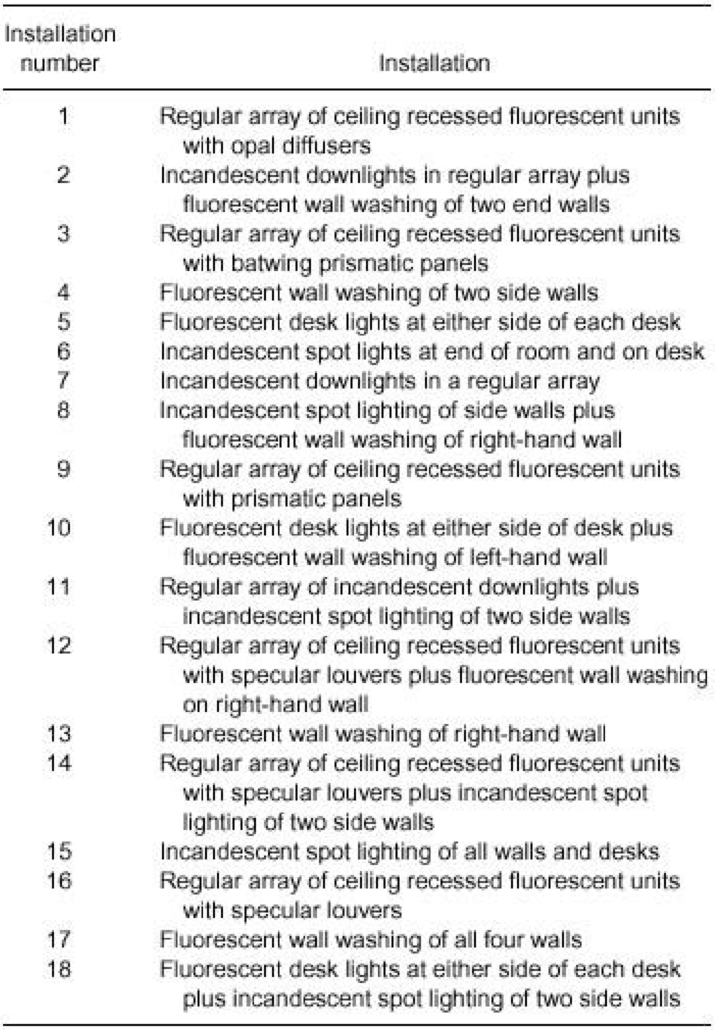


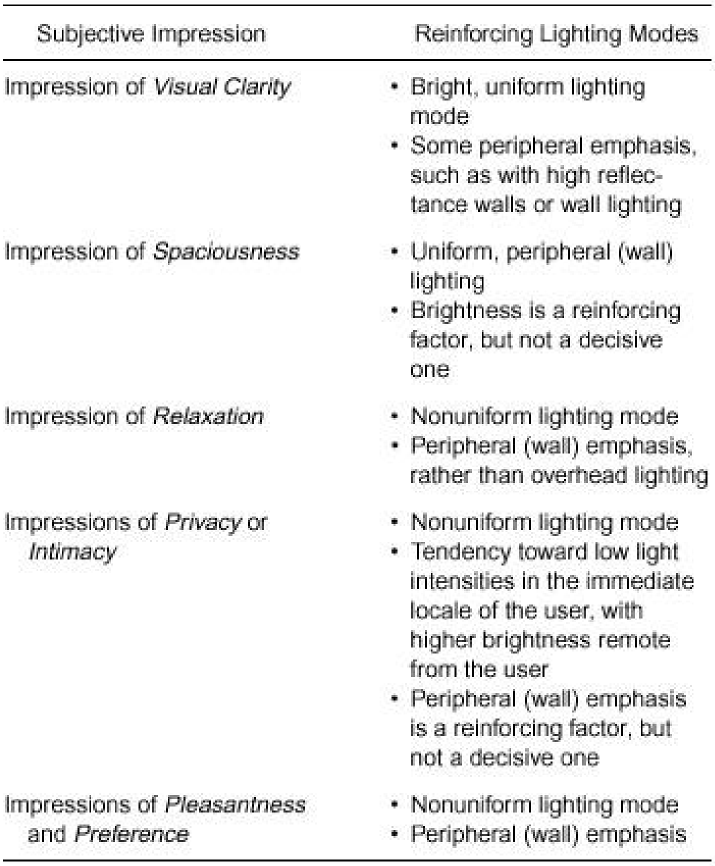
Figure 3-47a. A map showing the location of the listed office lighting installations on the two

dimensions, interest and brightness, identified by factor analysis. Superimposed on this map are isopreference contours based on preference ratings of the same installations. These contours define areas of equal preference from area A (most preferred) to area E (least preferred).



Installation number	Installation
1	Regular array of ceiling recessed fluorescent units with opal diffusers
2	Incandescent downlights in regular array plus fluorescent wall washing of two end walls
3	Regular array of ceiling recessed fluorescent units with batwing prismatic panels
4	Fluorescent wall washing of two side walls
5	Fluorescent desk lights at either side of each desk
6	Incandescent spot lights at end of room and on desk
7	Incandescent downlights in a regular array
8	Incandescent spot lighting of side walls plus fluorescent wall washing of right-hand wall
9	Regular array of ceiling recessed fluorescent units with prismatic panels
10	Fluorescent desk lights at either side of desk plus fluorescent wall washing of left-hand wall
11	Regular array of incandescent downlights plus incandescent spot lighting of two side walls
12	Regular array of ceiling recessed fluorescent units with specular louvers plus fluorescent wall washing on right-hand wall
13	Fluorescent wall washing of right-hand wall
14	Regular array of ceiling recessed fluorescent units with specular louvers plus incandescent spot lighting of two side walls
15	Incandescent spot lighting of all walls and desks
16	Regular array of ceiling recessed fluorescent units with specular louvers
17	Fluorescent wall washing of all four walls
18	Fluorescent desk lights at either side of each desk plus incandescent spot lighting of two side walls

Figure 3-47b. Installations Used by Hawkes *et al.*



Subjective Impression	Reinforcing Lighting Modes
Impression of *Visual Clarity*	• Bright, uniform lighting mode • Some peripheral emphasis, such as with high reflectance walls or wall lighting
Impression of *Spaciousness*	• Uniform, peripheral (wall) lighting • Brightness is a reinforcing factor, but not a decisive one
Impression of *Relaxation*	• Nonuniform lighting mode • Peripheral (wall) emphasis, rather than overhead lighting
Impressions of *Privacy* or *Intimacy*	• Nonuniform lighting mode • Tendency toward low light intensities in the immediate locale of the user, with higher brightness remote from the user • Peripheral (wall) emphasis is a reinforcing factor, but not a decisive one
Impressions of *Pleasantness* and *Preference*	• Nonuniform lighting mode • Peripheral (wall) emphasis

Figure 3-48. A Summary of Lighting Cues to Produce Specific Impressions

Behind this approach lies the belief that the experience of room lighting is, in part, an experience of interpreting complex light patterns. This implies that different patterns of light can be treated as cues to the "meaning" of the space, which in turn carries information about its likely suitability for its function. The most comprehensive data on how perceptions of space can be altered by changing the amount and distribution of light come from the work of Flynn and his colleagues.[118,119] Following an extensive series of experiments, Flynn and his colleagues identified a series of lighting cues that could be used to reinforce specific perceptions. Figure 3-48 sets out these cues. Some designers have found this listing to be useful in their work. Various aspects of the methodology used in some of these studies have been criticized,[120,121] so the guidelines given in Figure 3-48 should be treated as indicative rather than definitive. Nonetheless, there is sufficient evidence to suggest that the underlying concept--that different amounts and distributions of light can change the perception of a space--is correct.

Gloom. An alternative methodology has been used to explore the perception of gloom in obviously functional spaces.[122,123] Gloom is likely to be perceived when any of the following conditions are provided:

- Low surround luminances, irrespective of task illuminance
- Conditions in which fine detail in the periphery are obscured
- High task illuminances with low luminances on the peripheral surfaces
- Adaptation luminances in the mesopic region.

Room Brightness. Given that the surfaces in a conventionally lighted room appear in the object mode, it seems likely that when one talks about the brightness of a room the amount of light in the room is being evaluated. The most obvious lighting variable determining the perception of room brightness is the illuminance on the working plane.[118,119] However, there is evidence that maximum luminance, light distribution, and light spectrum also influence the perception of room brightness to a significant extent. Studies have shown that the presence of a sparkling luminous element increases the perceived brightness of the room by approximately 20%.[124,125] As for light distribution, a study of room brightness for a uniformly and a nonuniformly illuminated room, using a psychophysical technique, showed that the latter required about 5 to 10% less illuminance on the working plane to match the uniformly lit room for equal room brightness.[126] Finally, the effect of light spectrum on perceived room brightness has been studied for many years under the title of visual clarity. Several studies have shown that light spectra that give surface colors greater saturation require about 10 to 30% lower working plane illuminances for the rooms to be seen as equally bright.[127-129] Why this should occur is unknown, but it has been suggested that it has to do with the scotopic content of the spectrum.[130] The brightness perception appears to be related to the function of rods, even at photopic light levels.

These results are consistent with the other holistic studies in that there are several different ways to achieve the same perception. Further, the perception is influenced by the lighting of the whole space, not just the task area. It is important to note that these holistic studies have all taken place in functional interiors. It is at least possible that the holistic perception generated by the same lighting conditions varies with context. For example, lighting conditions that generate a perception of gloom in an office might generate a perception of privacy in a restaurant.

Guidelines for Acceptable Lighting

There have been a number of studies that have examined the acceptability of specific aspects of lighting, usually in a specific context. This section considers what is known about the preference for three lighting variables, all of which are under the control of the lighting designer.

Illuminance. The acceptability of different illuminances in offices and other working areas has been examined to try to determine the effect of illuminance on observer preference.[131] Figure 3-49 shows the percentage of observers considering the lighting of a room with systematically varied room surface luminances up to 150 cd/m^2 to be too dark, good, or too bright. Independent of the wall and ceiling luminances, the maximum proportion of "good" appraisals occurred when the luminance of the working plane was 130 cd/m^2.

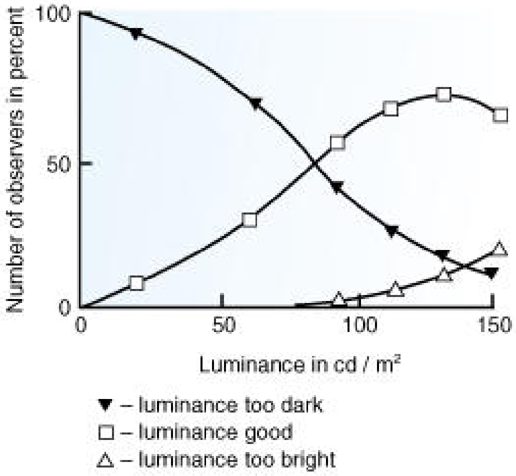


Figure 3-49. The percentages of observers rating the luminance of their desks as too dark, good, or too bright.

These findings were verified and extended over a wider range of illuminance.[132-134] In one experiment,[132] the task of searching a random array of numbers for a particular number was carried out under illuminances ranging from 50 to 10,000 lx, and with varying contrast (black numbers on white and gray paper). Each subject gave an opinion of the lighting, indicating whether it was "too dark," "good," or "too bright." Judgments of optimum illuminance increased with age and with decreasing task contrast. Most subjects preferred 1000 lx when searching the higher-contrast number lists, but preferred 1800 lx when searching the lower-contrast materials. On average, for both contrast levels, the younger subjects (less than 50 years of age) indicated that 2000 lx was preferable, while the older subjects required 5000 lx to achieve comparable satisfaction. At the highest illuminances (5000 to 10,000 lx), rated acceptability decreased even though performance of the task continued to increase (Figure 3-50).

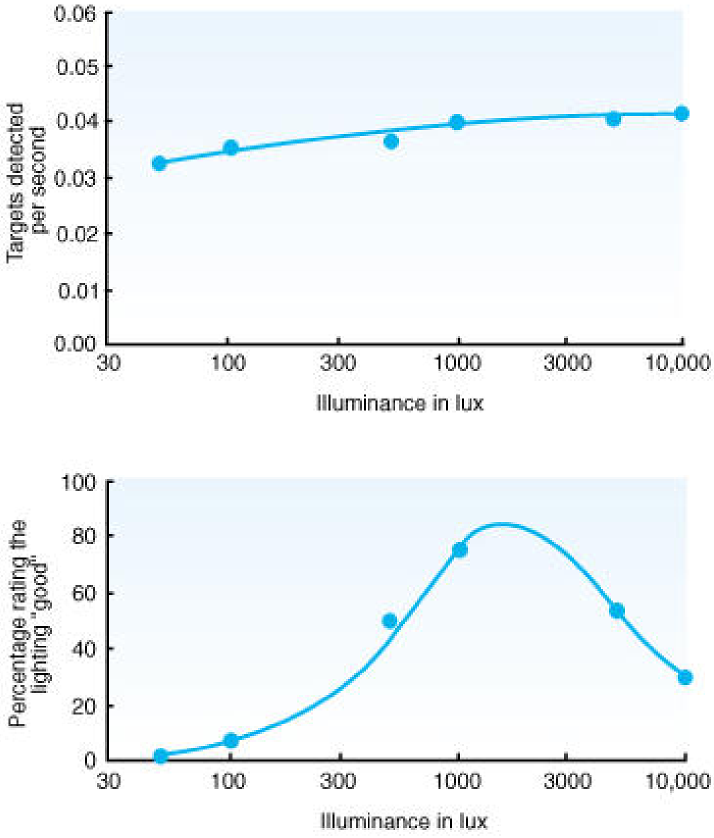
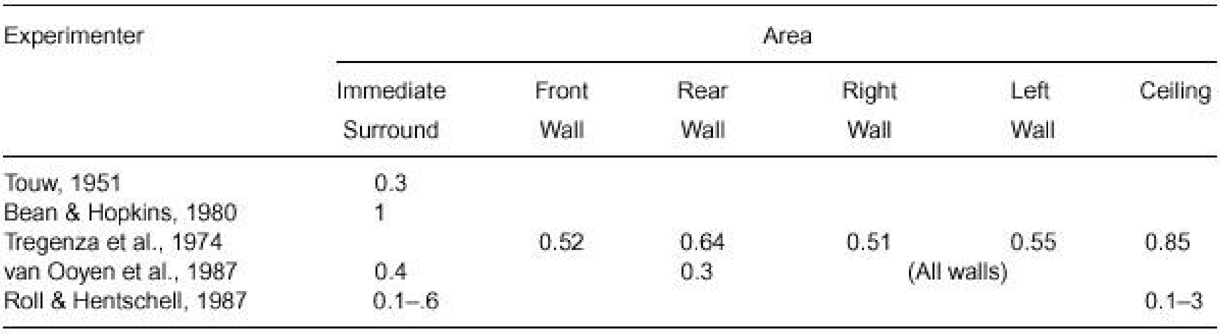


Figure 3-50. (a) Mean detection speeds for locating a specified number from among others at different illuminances; (b) the percentage who considered the lighting "good," at each illuminance

Experimenter	Preferred Average Light Level at Working Plane	
	Illuminance (lux)	Luminance (cd/m²)
Balder, 1957		130
Bodmann, 1962–67	700–3000	90–380
Saunders, 1969	800–1000	
Bean & Hopkins, 1980	> 200	
Nemecek & Grandjean, 1973	400–850	

Figure 3-51. Preferred Illuminances in Offices



Experimenter	Area					
	Immediate Surround	Front Wall	Rear Wall	Right Wall	Left Wall	Ceiling
Touw, 1951	0.3					
Bean & Hopkins, 1980	1					
Tregenza et al., 1974		0.52	0.64	0.51	0.55	0.85
van Ooyen et al., 1987	0.4		0.3	(All walls)		
Roll & Hentschell, 1987	0.1–.6					0.1–3

Note: All entries are relative to the task background luminances.

Figure 3-52. Preferred Luminance Ratios of Room Surfaces

This general trend of increased preference for higher illuminances for more visually difficult tasks, followed by a decrease in satisfaction at even higher illuminances, has been replicated by subsequent investigators using a variety of tasks and subjective scaling techniques in offices.[71,135-138] Ranges of preferred illuminances identified in these studies are presented in Figure 3-51.[131-133,137-139] An inspection of Figure 3-51 suggests that the illuminance ranges are wide and that there is no sharp preference for a specific illuminance. This is to be expected from the plateau of visual performance discussed in "Models of On-Axis Visual Performance." Of course, the illuminance ranges do reflect the effect of different tasks and the wide range of individual differences present in any subjective judgment of lighting. These individual differences are the most likely reason why the percentage of people considering the lighting good in Figure 3-49 does not exceed approximately 70%.

Spatial Distribution. Reports that changing the spatial distribution of light affects vision have been known since the mid-nineteenth century.[41] The effects of different spatial distributions of light on visual performance and preference have been studied extensively. Many studies have focused on performance.[41,140-149] In general, the more uniform the light distribution in the visual field and the larger the area of the visual field it covers, the better one sees the visual task.

The spatial distribution of illuminance across the working area is also important. Studies of acceptable illuminance uniformity across an office desk have shown that acceptability starts to decline as the minimum-to-maximum illuminance ratio over the working area falls below approximately 0.7.[138,149] It should be noted that this nonuniformity consisted of a steady change in illuminance across the desk such as would be produced by large spacings in a regular array of luminaires. If the variation in illuminance had involved a sharp edge, such as would be produced by the shadow of a shelf, acceptability would start to decline at a higher minimum-to-maximum illuminance ratio.

Another aspect of localized illuminance distributions is the preferred ratio of task to desktop luminances under different levels of ambient illuminance. Subjects were asked to sit at each of six desks (different unspecified reflectance of each desk top) under four illuminances (50, 100, 500, 1000 lx) and copy figures from one white sheet of paper onto another.[150] They were then asked to indicate at which desk they preferred to perform this task under the different illuminances. As the illuminance increased, the subjects preferred lower-reflectance desk tops. For higher illuminances (500 lx) the preferred ratio between the paper and the desk was 3:1, whereas for lower illuminances 2:1 was preferred.

Subsequent investigators broadened the scope of this work, examining the effects on preferences of varying the luminances of surfaces other than the immediate surround, such as walls and ceilings. Figure 3-52 summarizes the results of these studies.[139,150-153] Inspection of Figure 3-52 suggests that although some consensus on preferred ratios of task to immediate surround luminances can be identified, less agreement exists about preferences for luminances of more remote surfaces. Obviously, more systematic research is required before a complete specification of preferred luminance ratios throughout the visual environment can be identified.

As a guide for design purposes, luminance ratio limits have been recommended for various applications, such as offices, educational facilities, institutions, industrial areas, and residences (see the application chapters). For additional guidance, recommended limits on reflectances (both upper and lower) of large surfaces are given for the same applications. The use of these reflectance limits, along with a selection of appropriate colors, should help to control luminances and keep within the ratio limits without creating a bland and uninteresting environment.

Color of Illumination. The color of illumination can be described by two independent properties: chromaticity, or correlated color temperature (CCT), and color rendering. There is often confusion between chromaticity and color rendering. In simple terms, chromaticity refers to the color appearance of a light source, "warm" for low CCT values and "cool" for high CCT values. Color rendering refers to the ability of a light source, with its particular CCT, to render the colors of objects the same as a reference light source of the same CCT. This aspect is typically measured in terms of the CIE General Color Rendering Index. For more information see Chapter 4, Color.

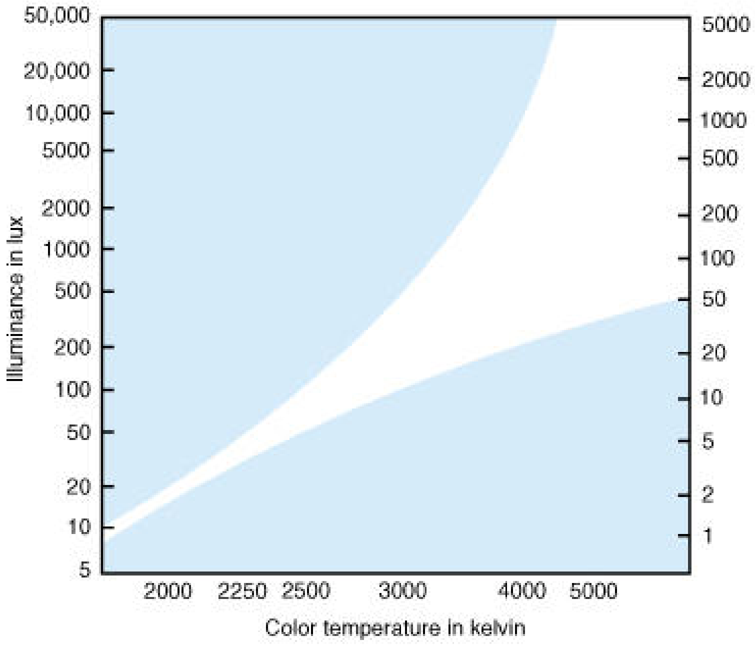


Figure 3-53. The Kruithof effect: The white area defines the preferred combinations of the color temperature of a light source and the illuminance. Color temperature/illuminance combinations in the lower shaded area are claimed to produce cold, drab environments, while those in the upper shaded area are believed to produce overly colorful and unnatural environments.

Experiments examining the psychological effects of varying CCT and illuminance have suggested that using lamps with high CCT values at low illuminances will make a space appear cold and dim. Conversely, using lamps with low CCT values at high illuminances will make a space appear artificial and overly colorful. Figure 3-53 illustrates this so-called Kruithof effect.[154] Although these findings have been broadly replicated,[155] other investigators have failed to find a similar tradeoff of CCT and illuminance.[156,157] Rather they found that when people spent sufficient time in the room for color adaptation to occur, the perceptions of rooms lighted with lamps of different color temperature was dominated by illuminance. This implies that where color adaptation occurs with no opportunity to compare lamps with different CCTs the CCT of the light source is relatively unimportant to perception. Where comparisons can be made or color adaptation does not occur, CCT is more likely to be important. At the very least this confusion means that the widespread belief about the tradeoff of CCT and illuminance should be treated with some skepticism.

LIGHTING AND BEHAVIOR

Lighting has been shown to have an effect on overt behavior. Specifically, lighting can be used to cue orientation and circulation in humans and increases alertness and activation. However, these findings should be interpreted with caution for at least two reasons. First, the range of illuminances studied has been small. In many experiments the effects of only two or three levels have been studied. More important, the effects of illuminance have been shown to interact with other independent variables.[158,159] Simple models are often insufficient for describing relationships among different environmental variables; effects may be facilitated or inhibited depending on the presence of other moderating factors.[160] Hence, further studies using a wider range of lighting conditions and additional independent variables are required before firm conclusions about the effects of illuminance on orientation, wayfinding, activation, and attention can be drawn.

Light clearly affects spatial orientation and wayfinding. For example, when navigating around a barrier, people tend to follow the direction of higher illuminance.[161] These results support the notion that the distribution of light might be used to direct circulation, and as an aid to wayfinding.

Similar findings have been reported in another context. An investigation of the effects of spatial distribution of light on seat choice and orientation in a cafeteria showed that people selected seats facing bright areas. When the lighting was changed to highlight a different surface, patterns of seat selection and orientation changed to face the new bright area.[118] The effects of wall lighting on desk selection have also been observed. Subjects entered a room and sat at one of three desks to complete a series of questionnaires. Desks were located next to the door, in the middle of the room, and at the far side of the room opposite the door. When the wall opposite the door was illuminated, most subjects crossed the room and sat at the desk located next to that wall. When that wall was not illuminated, most subjects sat at the desk located next to the door.[162]

These studies can be interpreted as examining the use of light as a means of directing attention. A more direct study of this possibility involved supplementary classroom lighting in a primary school.[163] Lists of words used in spelling tests were displayed at the front of classrooms. Supplementary lighting was used to highlight the word lists in one condition of the experiment but not in the control condition. Significantly more inattentive behaviors were coded in the control condition than when the word lists were highlighted.

Lighting can also affect activities not directly related to vision. A significant reduction in sound level in a school hallway was found when the illuminance was low.[164] Other researchers extended these findings by examining possible interactions between illuminances and other variables in their effects on human performance. An interaction was found between light and sound levels in their effects on the performance of a reaction time task. The presence of a white-noise sound increased reaction times under higher illuminances and had no effect in the dark.[165] More generally, when working at night, exposure to bright light has been shown to increase core body temperature and brain activity in ways usually associated with increased alertness[166] and to change performance on complex cognitive tasks.[167] Whether similar alerting effects of light exposure occur during daytime remains to be determined.

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Color

Architects, engineers, interior and industrial designers, colorists and color stylists, and lighting designers all need to understand color. This chapter has been prepared to increase mutual understanding among those responsible for creating the environment and making it visible and visually functional.

Electromagnetic radiant energy provides a physical stimulus that enters the eye and causes the sensation of color (see Chapter 3, Vision and Perception). The spectral characteristics of the stimulus are integrated by the visual system and cannot be differentiated without the use of an instrument. Because the color and the color rendering properties of light sources are increasingly important in the design of an illuminated environment, lighting designers need a good working knowledge of the vocabulary and practices of modern color science.

The aesthetic use of color to produce pleasing interiors requires coordination between the interior designer and the person designing the lighting. Each needs to know how to use color to help provide the desired brightness levels and distributions. Today's lighting designer is faced not only with a choice of color in light sources but also with wide variations in color rendering properties of light sources that can be identical in color.[1]

To provide lighting designers with a basis for their studies in color, the IESNA committees have developed several reports[2-5] that provide useful background material for this chapter. In addition, the chapter concludes with examples of several fields of special applications. Other chapters contain brief discussions of color, with specialized applications. Information on colorimetry of light sources is not contained in this chapter, but is found in *IES LM-16-1984*.[2]

Color is a fundamental parameter of vision and perception. Discussions related to color threshold discrimination, color vision abnormalities, visual processing channels, and perceptions of lighting are provided in Chapter 3, Vision and Perception.

BASIC CONCEPTS OF COLOR

Color Terms

In the Glossary, color terms are defined carefully to provide a way of distinguishing between several commonly confused meanings of the word "color." Whether one makes strict use of the definitions or not, an understanding of the purpose and need for the differentiations that are made is basic to an understanding of the subject. For additional information on color, see Plates 1, 2, and 3 at the end of this chapter.

The perceived color, the color perceived as belonging to an object or light source, is something perceived instantaneously. It is so common an experience that many people find it hard to understand why color is not simple to explain in a few easy lessons. But a color perception results from the complex interaction of many factors including the characteristics of the object or light source, the light incident on an object, the surround, the viewing direction, observer characteristics, and the observer's adaptation. Characteristics of object, light, surround, and observer can vary both spectrally and directionally, each in a different manner. The observer might vary in regard to time of seeing, what was seen last, or how attention was focused in relation to the time of seeing. Unless the circumstances of a former situation with which the layperson, interior designer, or lighting designer might be familiar are similar enough in all important respects, a new situation cannot be responded to by reference to past experience alone. Laypersons can cope with a new situation by making certain assumptions or by limiting themselves to the use of conditions with which they are familiar. But lighting designers cannot do this if they are to deal with all types of architectural situations, with all types of light sources, and with requirements that will fit new or specialized situations.

Color (sometimes called psychophysical color) is defined as the characteristic of light by which an observer can distinguish between patches of light of the same size, shape, and structure. It reduces itself to a basic description of light in terms of amounts of radiant power at the different wavelengths of the visually effective spectrum, which for most practical purposes is considered to extend from 380 to 780 nm. (To identify colors due in part to fluorescent dyes activated by energy in the ultraviolet [UV] region, it is necessary in specifying the spectral distribution of a light source to extend the wavelength range beyond that which is visually effective, down to 300 nm in the UV region, particularly for sources that are intended to reproduce daylight.) Identical colors are produced not only by identical spectral power distributions (SPDs) but also by many different SPDs. Such different SPDs are called metamers.

The color of an object, or object color, is defined as the color of light reflected or transmitted by an object when it is illuminated by a standard light source. For this purpose, a Commission Internationale de l'Éclairage (CIE) standard observer, using standardized conditions of observation, must be assumed.

The word "color" often is used to cover all three meanings discussed above. When the assumed standard conditions are satisfied, then there is little need for distinguishing between the perceived color, the psychophysical color, and the object color. However, if designers are to handle new problems in color, including new light sources that can vary widely in spectral distributions, they must know the differences between the meanings of color and keep these distinctions in mind even when using the one term to cover all three.

The term "color temperature" is widely used--and often misused--in illumination work. It relates to the color of a completely radiating (blackbody) source at a particular temperature and of light sources that color-match such a body. The color temperature of a light source is the absolute temperature of a blackbody radiator having a color equal to that of the light source. Its correlated color temperature is the absolute temperature of a blackbody whose color most nearly resembles that of the light source.

Abnormal Color Vision

Approximately 8% of males and 0.4% of females have color vision that differs from that of the majority of the population. These people are usually called "color blind," although very few (less than 0.01% of the total population) can see no color at all.[6] Most color-blind people can distinguish yellows from blues but confuse reds and greens. Their data should be excluded from any color measurements or color evaluation procedures that are to be used for application to the general population. See Chapter 3, Vision and Perception, and Figure 3-21 for additional discussion and data on abnormal color vision.

Color Rendering

Color rendering is a general expression for the effect of a light source on the color appearance of objects in conscious or subconscious comparison with their color appearance under another (reference) light source. Methods of measuring and specifying color rendering properties of light sources depend on the color appearance of objects under a reference, or standard, light source compared with the appearance of the same objects under the test source.

The color rendering properties of a light source cannot be assessed by visual inspection of the source or by a knowledge of its color.[7] For this purpose, full knowledge of its SPD is required. Viewed in succession under lamps that look quite alike but are different in spectral distribution, objects might look entirely different in color. An extreme case is a pair of color-matched low-pressure sodium and yellow fluorescent lamps. Most objects, which in daylight might look red, yellow, green, blue, or purple, will appear quite different under these two lamps. Under the sodium lamp objects will lose their daylight appearance, appearing more or less as one hue, from light to very dark (near-black). Under the yellow fluorescent lamp, more hues can be recognized, but the color of objects will still differ considerably from their daylight color.

Basis for Measurements

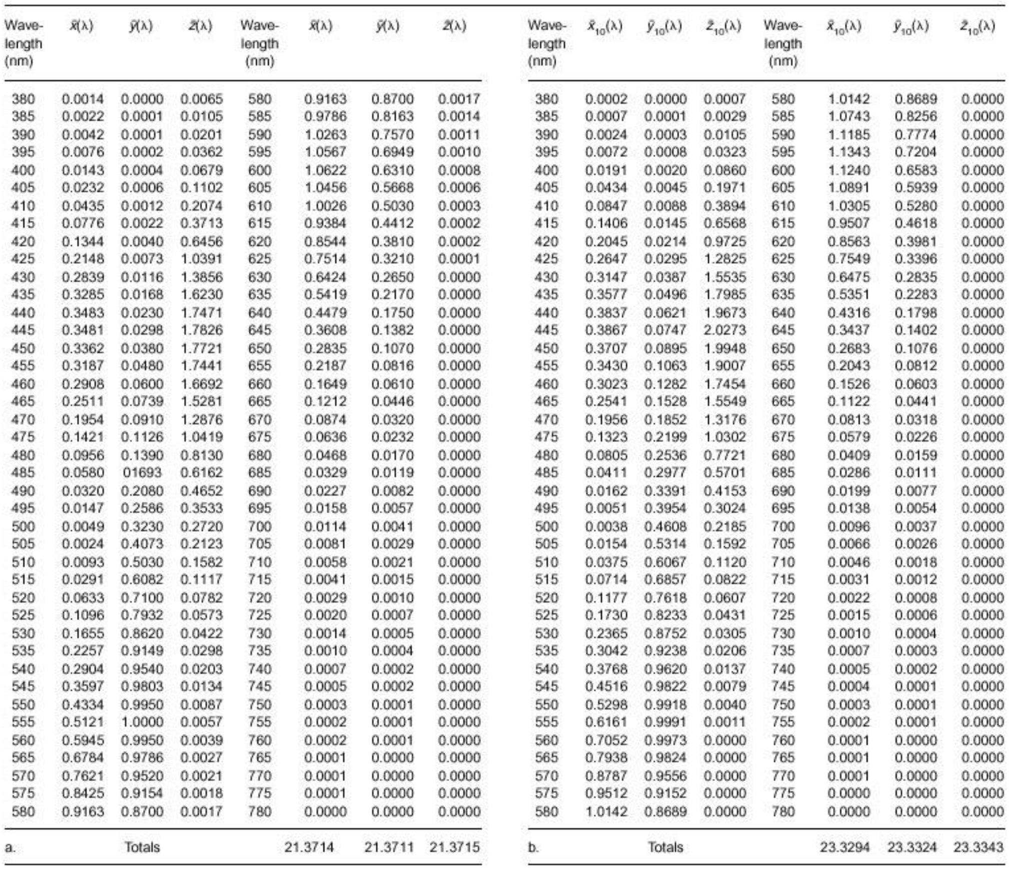
Because color is the characteristic by which a human observer distinguishes patches of light, and light is visually evaluated radiant energy, color can be computed by combining physical measurements of radiant power, wavelength by wavelength, with data on how an observer matches colors. The color matching characteristics of the internationally adopted CIE standard observers, defined by the tristimulus values of an equal-power spectrum, are provided in Figures 4-1 and 4-2. These are the color matching functions. With data for a standard observer and the spectroradiometric measurement of a light source, the chromaticity of that light source can be calculated. Thus spectroradiometry becomes a tool for color measurement. Measurements of radiant power are physical, while evaluation of radiant power by a human observer, based solely on perception, is psychological. Visual evaluations, quantified through measurements made for standardized conditions of test, provide psychophysical methods of measurement.

Visual evaluation of the appearance of objects and light sources can be in terms derived wholly from one's perceptions. One convenient and useful set of terms describing these perceptions for light sources is hue, brightness, and saturation.[8] Hue is the attribute according to which an area appears to be similar to one, or to proportions of two, of the perceived colors red, yellow, green, and blue. Brightness is the attribute according to which an area appears to be emitting more or less light. Saturation is the attribute by which an area appears to exhibit more or less chromatic color (that is, departure from gray), judged in proportion to its brightness.

Many widely used psychophysical methods for describing and specifying color show poor correlation with perceptual factors, and often these are converted to more meaningful visual terms, usually to a more uniform color spacing, of which the Munsell system[9] and the CIE 1976 Uniform Color Spaces[10,11] are prime examples.

CIE Method of Color Specification

Basic CIE Method.[10] This is a method originally recommended in 1931 by the CIE to define all metameric pairs by giving the amounts *X*, *Y*, *Z* of three imaginary primary colors required by a standard observer to match the color being specified. These amounts can be calculated as a summation of the spectral compositions of the radiant power of the source or the illuminated color specimen, times the spectral tristimulus values for an equal-power source (Figure 4-1). For example,



Wavelength (nm)	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$	Wavelength (nm)	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$
380	0.0014	0.0000	0.0065	580	0.9163	0.8700	0.0017
385	0.0022	0.0001	0.0105	585	0.9786	0.8163	0.0014
390	0.0042	0.0001	0.0201	590	1.0263	0.7570	0.0011
395	0.0076	0.0002	0.0362	595	1.0567	0.6949	0.0010
400	0.0143	0.0004	0.0679	600	1.0622	0.6310	0.0008
405	0.0232	0.0006	0.1102	605	1.0456	0.5668	0.0006
410	0.0435	0.0012	0.2074	610	1.0026	0.5030	0.0003
415	0.0776	0.0022	0.3713	615	0.9384	0.4412	0.0002
420	0.1344	0.0040	0.6456	620	0.8544	0.3810	0.0002
425	0.2148	0.0073	1.0391	625	0.7514	0.3210	0.0001
430	0.2839	0.0116	1.3856	630	0.6424	0.2650	0.0000
435	0.3285	0.0168	1.6230	635	0.5419	0.2170	0.0000
440	0.3483	0.0230	1.7471	640	0.4479	0.1750	0.0000
445	0.3481	0.0298	1.7826	645	0.3608	0.1382	0.0000
450	0.3362	0.0380	1.7721	650	0.2835	0.1070	0.0000
455	0.3187	0.0480	1.7441	655	0.2187	0.0816	0.0000
460	0.2908	0.0600	1.6692	660	0.1649	0.0610	0.0000
465	0.2511	0.0739	1.5281	665	0.1212	0.0446	0.0000
470	0.1954	0.0910	1.2876	670	0.0874	0.0320	0.0000
475	0.1421	0.1126	1.0419	675	0.0636	0.0232	0.0000
480	0.0956	0.1390	0.8130	680	0.0468	0.0170	0.0000
485	0.0580	01693	0.6162	685	0.0329	0.0119	0.0000
490	0.0320	0.2080	0.4652	690	0.0227	0.0082	0.0000
495	0.0147	0.2586	0.3533	695	0.0158	0.0057	0.0000
500	0.0049	0.3230	0.2720	700	0.0114	0.0041	0.0000
505	0.0024	0.4073	0.2123	705	0.0081	0.0029	0.0000
510	0.0093	0.5030	0.1582	710	0.0058	0.0021	0.0000
515	0.0291	0.6082	0.1117	715	0.0041	0.0015	0.0000
520	0.0633	0.7100	0.0782	720	0.0029	0.0010	0.0000
525	0.1096	0.7932	0.0573	725	0.0020	0.0007	0.0000
530	0.1655	0.8620	0.0422	730	0.0014	0.0005	0.0000
535	0.2257	0.9149	0.0298	735	0.0010	0.0004	0.0000
540	0.2904	0.9540	0.0203	740	0.0007	0.0002	0.0000
545	0.3597	0.9803	0.0134	745	0.0005	0.0002	0.0000
550	0.4334	0.9950	0.0087	750	0.0003	0.0001	0.0000
555	0.5121	1.0000	0.0057	755	0.0002	0.0001	0.0000
560	0.5945	0.9950	0.0039	760	0.0002	0.0001	0.0000
565	0.6784	0.9786	0.0027	765	0.0001	0.0000	0.0000
570	0.7621	0.9520	0.0021	770	0.0001	0.0000	0.0000
575	0.8425	0.9154	0.0018	775	0.0001	0.0000	0.0000
580	0.9163	0.8700	0.0017	780	0.0000	0.0000	0.0000
a.	Totals				21.3714	21.3711	21.3715

Wavelength (nm)	$\bar{x}_{10}(\lambda)$	$\bar{y}_{10}(\lambda)$	$\bar{z}_{10}(\lambda)$	Wavelength (nm)	$\bar{x}_{10}(\lambda)$	$\bar{y}_{10}(\lambda)$	$\bar{z}_{10}(\lambda)$
380	0.0002	0.0000	0.0007	580	1.0142	0.8689	0.0000
385	0.0007	0.0001	0.0029	585	1.0743	0.8256	0.0000
390	0.0024	0.0003	0.0105	590	1.1185	0.7774	0.0000
395	0.0072	0.0008	0.0323	595	1.1343	0.7204	0.0000
400	0.0191	0.0020	0.0860	600	1.1240	0.6583	0.0000
405	0.0434	0.0045	0.1971	605	1.0891	0.5939	0.0000
410	0.0847	0.0088	0.3894	610	1.0305	0.5280	0.0000
415	0.1406	0.0145	0.6568	615	0.9507	0.4618	0.0000
420	0.2045	0.0214	0.9725	620	0.8563	0.3981	0.0000
425	0.2647	0.0295	1.2825	625	0.7549	0.3396	0.0000
430	0.3147	0.0387	1.5535	630	0.6475	0.2835	0.0000
435	0.3577	0.0496	1.7985	635	0.5351	0.2283	0.0000
440	0.3837	0.0621	1.9673	640	0.4316	0.1798	0.0000
445	0.3867	0.0747	2.0273	645	0.3437	0.1402	0.0000
450	0.3707	0.0895	1.9948	650	0.2683	0.1076	0.0000
455	0.3430	0.1063	1.9007	655	0.2043	0.0812	0.0000
460	0.3023	0.1282	1.7454	660	0.1526	0.0603	0.0000
465	0.2541	0.1528	1.5549	665	0.1122	0.0441	0.0000
470	0.1956	0.1852	1.3176	670	0.0813	0.0318	0.0000
475	0.1323	0.2199	1.0302	675	0.0579	0.0226	0.0000
480	0.0805	0.2536	0.7721	680	0.0409	0.0159	0.0000
485	0.0411	0.2977	0.5701	685	0.0286	0.0111	0.0000
490	0.0162	0.3391	0.4153	690	0.0199	0.0077	0.0000
495	0.0051	0.3954	0.3024	695	0.0138	0.0054	0.0000
500	0.0038	0.4608	0.2185	700	0.0096	0.0037	0.0000
505	0.0154	0.5314	0.1592	705	0.0066	0.0026	0.0000
510	0.0375	0.6067	0.1120	710	0.0046	0.0018	0.0000
515	0.0714	0.6857	0.0822	715	0.0031	0.0012	0.0000
520	0.1177	0.7618	0.0607	720	0.0022	0.0008	0.0000
525	0.1730	0.8233	0.0431	725	0.0015	0.0006	0.0000
530	0.2365	0.8752	0.0305	730	0.0010	0.0004	0.0000
535	0.3042	0.9238	0.0206	735	0.0007	0.0003	0.0000
540	0.3768	0.9620	0.0137	740	0.0005	0.0002	0.0000
545	0.4516	0.9822	0.0079	745	0.0004	0.0001	0.0000
550	0.5298	0.9918	0.0040	750	0.0003	0.0001	0.0000
555	0.6161	0.9991	0.0011	755	0.0002	0.0001	0.0000
560	0.7052	0.9973	0.0000	760	0.0001	0.0000	0.0000
565	0.7938	0.9824	0.0000	765	0.0001	0.0000	0.0000
570	0.8787	0.9556	0.0000	770	0.0001	0.0000	0.0000
575	0.9512	0.9152	0.0000	775	0.0000	0.0000	0.0000
580	1.0142	0.8689	0.0000	780	0.0000	0.0000	0.0000
b.	Totals				23.3294	23.3324	23.3343

Figure 4-1. Color Matching Functions. (a) CIE 1931 Standard Observer (2°); (b) CIE 1964 Standard Observer (10°)

$$X = k \sum_{\lambda = 380\ \mathrm{nm}}^{780\ \mathrm{nm}} S(\lambda)\, \rho(\lambda)\, \bar{x}(\lambda)\, \Delta\lambda \qquad \text{(4-1a)}$$

where

$S(\lambda)$ = spectral irradiance distribution of the source (Figure 4-3)
$\rho(\lambda)$ = spectral reflectance of the specimen,
k = a normalizing factor

$\bar{x}(\lambda)$ = spectral tristimulus value from Figure 4-1

with similar expressions for Y and Z, wherein $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ respectively are substituted for $\bar{x}(\lambda)$.

The normalizing factor k can be assigned any arbitrary value provided it is kept constant throughout any particular application. Where only the relative values of X, Y, and Z are required, the value of k is usually chosen so that Y has the value 100.0. In the special case where the absolute values of $S(\lambda)\,\Delta\lambda$ are given (for example, in watts), it is convenient to take $k = K_m = 683$ lm/W, whereby the value of Y gives the equivalent luminous quantity in lumens. Here, the accepted symbol for $S(\lambda)$ is $\Phi_{e,\lambda}$ (see Glossary under luminous flux).

For colors of reflecting objects, the reflectance factor, $R(\lambda)$, must be introduced, so that

$$X = k \sum_{\lambda = 380\text{ nm}}^{780\text{ nm}} S(\lambda)\,R(\lambda)\,\bar{x}(\lambda)\,\Delta\lambda \qquad (4\text{-}1b)$$

In this case, the normalizing factor k is usually given the value

$$k = \frac{100}{\Sigma\, S(\lambda)\,\bar{y}(\lambda)\,\Delta\lambda} \qquad (4\text{-}2)$$

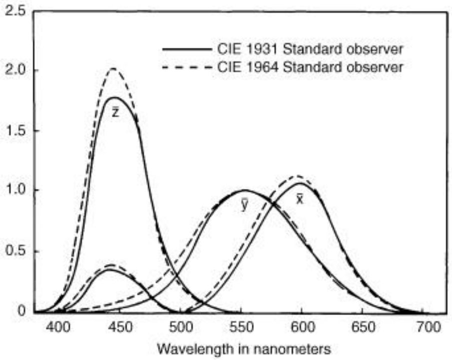


Figure 4-2. Graph of CIE 1931 and 1964 color-matching functions. (y-axis represents the tristimulus values.)

With this normalization, the value of Y is the luminous reflectance factor expressed in percent.

Use of the reflectance factor, $R(\lambda)$, is appropriate for calculating tristimulus values that relate to the appearance of objects. For such other applications as calculations of light flux in a space, the reflectance, $\rho(\lambda)$, might be more appropriate. (For transmitting objects, the transmittance or transmittance factor must be used in place of the reflectance or reflectance factor.) Precise definitions of $R(\lambda)$ and $\rho(\lambda)$ are given in the Glossary under "reflectance of a surface or medium" and "reflectance factor." The essential difference between the two quantities is that the reflectance factor is directional and is measured relative to a perfect diffuser. Consequently it might be greater than 1 in certain directions as long as this is compensated by values less than 1 in other directions.

The CIE has recommended two sets of standard color matching functions. The first is known as the CIE 1931 Standard Observer (Figure 4-1a) and is intended for use when the angular subtense of the field of view is between 1 and 4°. The second is the CIE 1964 Standard Observer (Figure 4-1b), intended for use with angular subtenses greater than 4°.

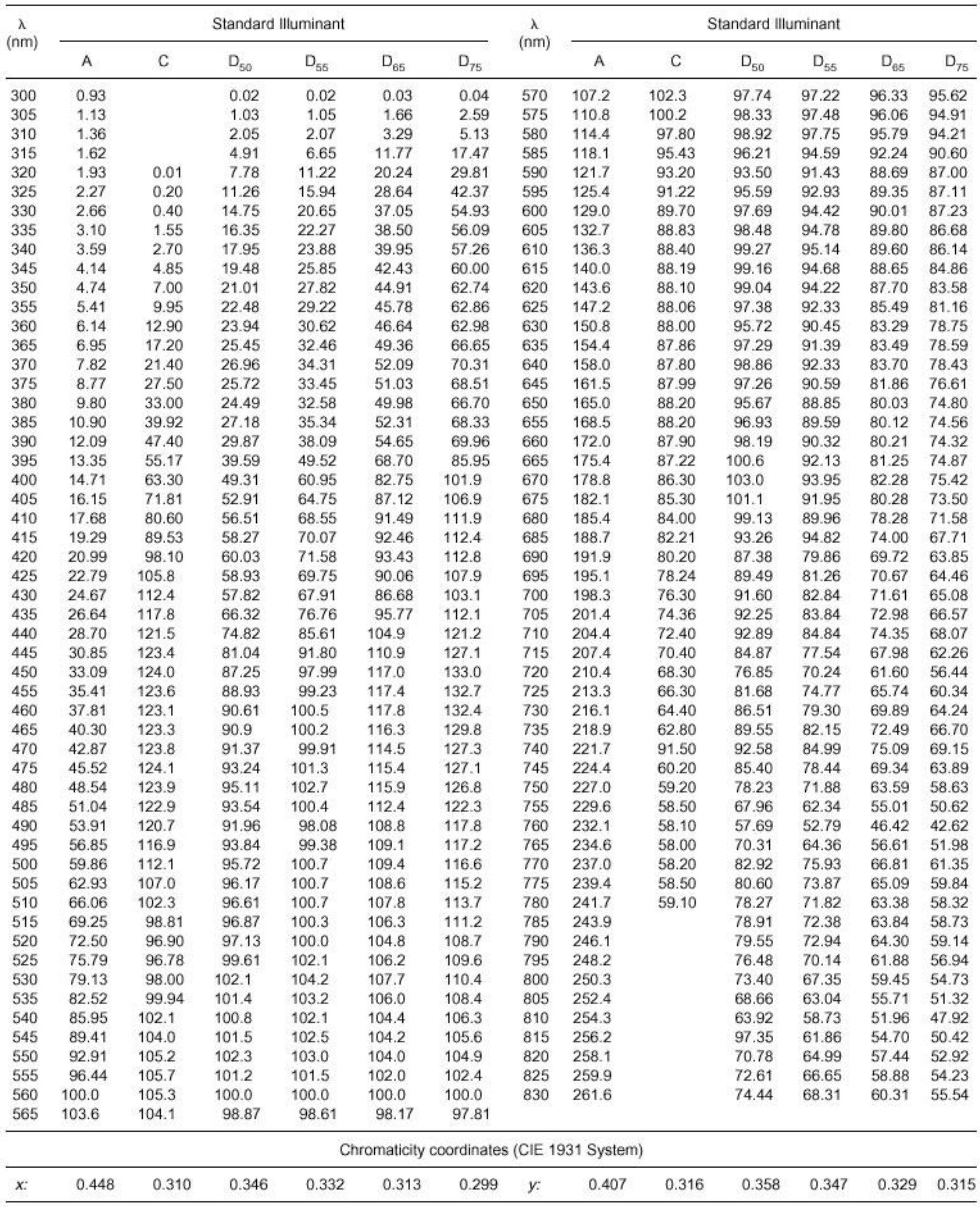
The CIE has also recommended several standard illuminants (spectral power distributions) for use in computing object colors. The most commonly used are listed in Figure 4-3. They include Standard Illuminant A (representing a blackbody radiator at a color temperature of 2856 K; see also Figure 2-5), Standard Illuminant C (based on a laboratory simulation of average daylight), and Standard Illuminant D_{65} (a more modern and preferred representation of a phase of daylight at a correlated color temperature of approximately 6500 K). In addition, the CIE recommends a calculation method for standard illuminants representing phases of daylight at any correlated color temperature between 4000 and 25,000 K. In its recommendation, the CIE distinguishes between illuminants and sources. The term "source" refers to a physical emitter of light, such as a lamp or the sun and sky. The term "illuminant" refers to a specific SPD.

The most accurate calculation method recommended by the CIE is summation at 1-nm intervals from 360 to 830 nm. However, the color matching functions have relatively small values at the ends of the spectrum, and furthermore, many sources and objects have fairly smooth spectral distributions so that summation from 380 to 780 nm at 5-nm intervals will suffice for many practical purposes, allowing the use of simpler instrumentation and computation. If data are available only for a restricted wavelength range (for example, 400 to 700 nm) or for a wider wavelength interval (for example, 10 or 20 nm), the appropriate values can be selected from Figures 4-1 and 4-3. An accurate method for dealing with incomplete data is to use special tables given in ASTM Standard Method E 308, *Computing Colors of Objects by Using the CIE System*.[12] An important practical consideration for such sources as discharge lamps, which do not have smooth SPDs, is that the measurement bandwidth should be a multiple of the wavelength interval.

The fractions $X/(X + Y + Z)$, $Y/(X + Y + Z)$, and $Z/(X + Y + Z)$ are known as the chromaticity coordinates, x, y, z, respectively. Note that $x + y + z = 1$, and specification of any two fixes the third. By convention, chromaticity usually is stated in terms of x and y and plotted in a rectangular coordinate system as shown in Figure 4-4. In this chromaticity diagram, the points representing light of single wavelengths plot along a horseshoe-shaped curve called the spectrum locus. The line joining the extremities of the spectrum locus is known as the purple boundary and is the locus of the most saturated purples obtainable.

A sample calculation for determining the CIE coordinates is shown in Figure 4-5 for a deep-red surface when illuminated by CIE illuminant D_{65}. In Figure 4-5, column I is a listing of wavelengths in 5-nm steps, column II is a tabulation of spectral reflectance values for the deep-red surface at each wavelength in column I, and column III lists the CIE tristimulus computational data for CIE illuminant D_{65}. By multiplying the row entry in column II by the corresponding one in column III and summing the products given in column IV, the values of X, Y, and Z are determined. Then by using the three fractions above, the chromaticity coordinates are determined. The percentage luminous reflectance is determined by multiplying the Y value by the normalizing factor $k = 100/\Sigma S(\lambda)\bar{y}(\lambda)\Delta\lambda = 0.0095$

A final recommendation of the CIE concerns geometrical arrangements for measuring colors of reflecting objects. Four alternative conditions for illuminating/viewing a test sample are specified: (1) 45°/normal, (2) normal/45°, (3) diffuse/normal, and (4) normal/diffuse (diffuse illuminating or viewing is usually achieved by placing a sample in an integrating sphere). Consult Wyszecki and Stiles's *Color Science*[13] for an extended discussion of the calculation and application of CIE data, including extensive tables of quantitative data and methods of colorimetry.



λ (nm)	Standard Illuminant						λ (nm)	Standard Illuminant					
	A	C	D_{50}	D_{55}	D_{65}	D_{75}		A	C	D_{50}	D_{55}	D_{65}	D_{75}
300	0.93		0.02	0.02	0.03	0.04	570	107.2	102.3	97.74	97.22	96.33	95.62
305	1.13		1.03	1.05	1.66	2.59	575	110.8	100.2	98.33	97.48	96.06	94.91
310	1.36		2.05	2.07	3.29	5.13	580	114.4	97.80	98.92	97.75	95.79	94.21
315	1.62		4.91	6.65	11.77	17.47	585	118.1	95.43	96.21	94.59	92.24	90.60
320	1.93	0.01	7.78	11.22	20.24	29.81	590	121.7	93.20	93.50	91.43	88.69	87.00
325	2.27	0.20	11.26	15.94	28.64	42.37	595	125.4	91.22	95.59	92.93	89.35	87.11
330	2.66	0.40	14.75	20.65	37.05	54.93	600	129.0	89.70	97.69	94.42	90.01	87.23
335	3.10	1.55	16.35	22.27	38.50	56.09	605	132.7	88.83	98.48	94.78	89.80	86.68
340	3.59	2.70	17.95	23.88	39.95	57.26	610	136.3	88.40	99.27	95.14	89.60	86.14
345	4.14	4.85	19.48	25.85	42.43	60.00	615	140.0	88.19	99.16	94.68	88.65	84.86
350	4.74	7.00	21.01	27.82	44.91	62.74	620	143.6	88.10	99.04	94.22	87.70	83.58
355	5.41	9.95	22.48	29.22	45.78	62.86	625	147.2	88.06	97.38	92.33	85.49	81.16
360	6.14	12.90	23.94	30.62	46.64	62.98	630	150.8	88.00	95.72	90.45	83.29	78.75
365	6.95	17.20	25.45	32.46	49.36	66.65	635	154.4	87.86	97.29	91.39	83.49	78.59
370	7.82	21.40	26.96	34.31	52.09	70.31	640	158.0	87.80	98.86	92.33	83.70	78.43
375	8.77	27.50	25.72	33.45	51.03	68.51	645	161.5	87.99	97.26	90.59	81.86	76.61
380	9.80	33.00	24.49	32.58	49.98	66.70	650	165.0	88.20	95.67	88.85	80.03	74.80
385	10.90	39.92	27.18	35.34	52.31	68.33	655	168.5	88.20	96.93	89.59	80.12	74.56
390	12.09	47.40	29.87	38.09	54.65	69.96	660	172.0	87.90	98.19	90.32	80.21	74.32
395	13.35	55.17	39.59	49.52	68.70	85.95	665	175.4	87.22	100.6	92.13	81.25	74.87
400	14.71	63.30	49.31	60.95	82.75	101.9	670	178.8	86.30	103.0	93.95	82.28	75.42
405	16.15	71.81	52.91	64.75	87.12	106.9	675	182.1	85.30	101.1	91.95	80.28	73.50
410	17.68	80.60	56.51	68.55	91.49	111.9	680	185.4	84.00	99.13	89.96	78.28	71.58
415	19.29	89.53	58.27	70.07	92.46	112.4	685	188.7	82.21	93.26	94.82	74.00	67.71
420	20.99	98.10	60.03	71.58	93.43	112.8	690	191.9	80.20	87.38	79.86	69.72	63.85
425	22.79	105.8	58.93	69.75	90.06	107.9	695	195.1	78.24	89.49	81.26	70.67	64.46
430	24.67	112.4	57.82	67.91	86.68	103.1	700	198.3	76.30	91.60	82.84	71.61	65.08
435	26.64	117.8	66.32	76.76	95.77	112.1	705	201.4	74.36	92.25	83.84	72.98	66.57
440	28.70	121.5	74.82	85.61	104.9	121.2	710	204.4	72.40	92.89	84.84	74.35	68.07
445	30.85	123.4	81.04	91.80	110.9	127.1	715	207.4	70.40	84.87	77.54	67.98	62.26
450	33.09	124.0	87.25	97.99	117.0	133.0	720	210.4	68.30	76.85	70.24	61.60	56.44
455	35.41	123.6	88.93	99.23	117.4	132.7	725	213.3	66.30	81.68	74.77	65.74	60.34
460	37.81	123.1	90.61	100.5	117.8	132.4	730	216.1	64.40	86.51	79.30	69.89	64.24
465	40.30	123.3	90.9	100.2	116.3	129.8	735	218.9	62.80	89.55	82.15	72.49	66.70
470	42.87	123.8	91.37	99.91	114.5	127.3	740	221.7	91.50	92.58	84.99	75.09	69.15
475	45.52	124.1	93.24	101.3	115.4	127.1	745	224.4	60.20	85.40	78.44	69.34	63.89
480	48.54	123.9	95.11	102.7	115.9	126.8	750	227.0	59.20	78.23	71.88	63.59	58.63
485	51.04	122.9	93.54	100.4	112.4	122.3	755	229.6	58.50	67.96	62.34	55.01	50.62
490	53.91	120.7	91.96	98.08	108.8	117.8	760	232.1	58.10	57.69	52.79	46.42	42.62
495	56.85	116.9	93.84	99.38	109.1	117.2	765	234.6	58.00	70.31	64.36	56.61	51.98
500	59.86	112.1	95.72	100.7	109.4	116.6	770	237.0	58.20	82.92	75.93	66.81	61.35
505	62.93	107.0	96.17	100.7	108.6	115.2	775	239.4	58.50	80.60	73.87	65.09	59.84
510	66.06	102.3	96.61	100.7	107.8	113.7	780	241.7	59.10	78.27	71.82	63.38	58.32
515	69.25	98.81	96.87	100.3	106.3	111.2	785	243.9		78.91	72.38	63.84	58.73
520	72.50	96.90	97.13	100.0	104.8	108.7	790	246.1		79.55	72.94	64.30	59.14
525	75.79	96.78	99.61	102.1	106.2	109.6	795	248.2		76.48	70.14	61.88	56.94
530	79.13	98.00	102.1	104.2	107.7	110.4	800	250.3		73.40	67.35	59.45	54.73
535	82.52	99.94	101.4	103.2	106.0	108.4	805	252.4		68.66	63.04	55.71	51.32
540	85.95	102.1	100.8	102.1	104.4	106.3	810	254.3		63.92	58.73	51.96	47.92
545	89.41	104.0	101.5	102.5	104.2	105.6	815	256.2		97.35	61.86	54.70	50.42
550	92.91	105.2	102.3	103.0	104.0	104.9	820	258.1		70.78	64.99	57.44	52.92
555	96.44	105.7	101.2	101.5	102.0	102.4	825	259.9		72.61	66.65	58.88	54.23
560	100.0	105.3	100.0	100.0	100.0	100.0	830	261.6		74.44	68.31	60.31	55.54
565	103.6	104.1	98.87	98.61	98.17	97.81							
Chromaticity coordinates (CIE 1931 System)													
x:	0.448	0.310	0.346	0.332	0.313	0.299	*y:*	0.407	0.316	0.358	0.347	0.329	0.315

Figure 4-3. Spectral Power Distributions of CIE Standard Illuminants

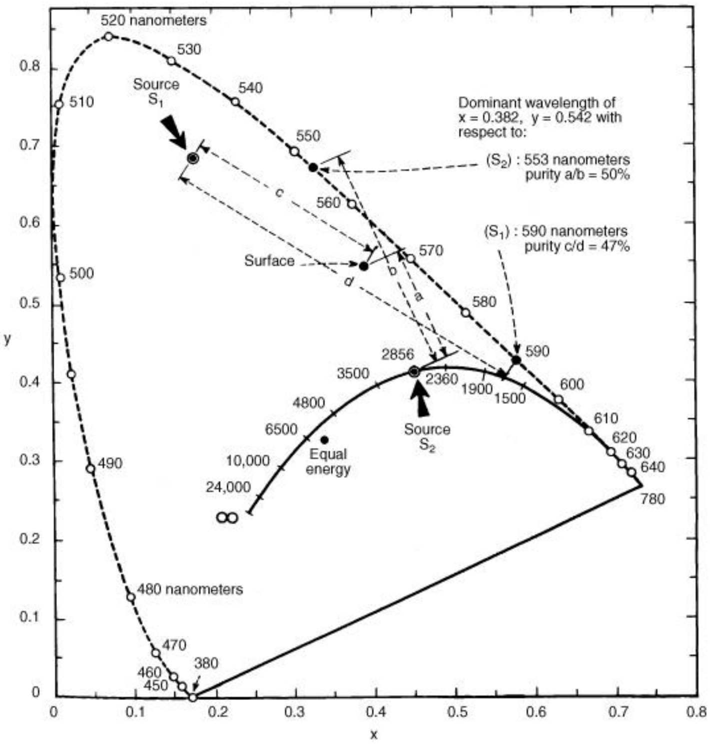


Figure 4-4. The 1931 CIE chromaticity diagram showing method of obtaining dominant wavelength and purity for different samples under different light sources.

Dominant Wavelength and Excitation Purity. Dominant wavelength and excitation purity are quantities more suggestive of the color appearance of objects than a CIE *x*, *y* specification and can be determined on an *x*, *y* diagram in relation to the spectrum locus and an assumed achromatic point (for object colors this is usually the point for the light source) (Figure 4-4). The dominant wavelength of all colors whose *x*, *y* coordinates fall on a straight line connecting the achromatic point with a point on the spectrum locus is the wavelength indicated at the intersection of that line with the spectrum locus. For some colors, the straight line from the achromatic point through the test chromaticity will strike the purple boundary rather than the spectrum locus. For these colors the line must be extended backwards from the achromatic point. The point where the extended line strikes the spectrum locus determines the complementary wavelength of such a color. The excitation purity is defined as the distance from the achromatic point to (*x*, *y*) divided by the total distance in the same direction from the achromatic point to the spectrum locus or the purple boundary.

I Wavelength λ (nm)	II Reflectance $\rho(\lambda)$	III CIE Data for Illuminant D_{65}			IV (II × III)		
		$\bar{x}(\lambda)S(\lambda)$	$\bar{y}(\lambda)S(\lambda)$	$\bar{z}(\lambda)S(\lambda)$	$\rho(\lambda)\bar{x}(\lambda)S(\lambda)$	$\rho(\lambda)\bar{y}(\lambda)S(\lambda)$	$\rho(\lambda)\bar{z}(\lambda)S(\lambda)$
380	0.051	0.06	0.00	0.29	0.00	0.00	0.01
385	0.051	0.10	0.00	0.49	0.01	0.00	0.03
390	0.051	0.21	0.01	0.97	0.01	0.00	0.05
395	0.051	0.46	0.01	2.19	0.02	0.00	0.11
400	0.051	1.06	0.03	5.05	0.05	0.00	0.26
405	0.051	1.81	0.05	8.58	0.09	0.00	0.44
410	0.051	3.52	0.10	16.77	0.18	0.00	0.86
415	0.051	6.40	0.18	30.59	0.33	0.01	1.56
420	0.050	11.28	0.33	54.15	0.56	0.02	2.71
425	0.050	17.89	0.59	86.14	0.89	0.03	4.32
430	0.050	23.56	0.92	114.76	1.18	0.05	5.74
435	0.050	30.80	1.51	151.78	1.54	0.08	7.59
440	0.050	36.30	2.28	181.45	1.81	0.11	9.07
445	0.049	38.75	3.15	197.52	1.90	0.15	9.68
450	0.047	39.68	4.24	207.79	1.86	0.20	9.77
455	0.046	37.91	5.38	206.76	1.74	0.25	9.46
460	0.045	35.02	6.77	198.95	1.58	0.30	8.95
465	0.045	30.30	8.25	182.02	1.36	0.37	8.19
470	0.044	23.75	10.02	153.77	1.05	0.44	6.77
475	0.044	17.57	12.45	125.79	0.77	0.55	5.53
480	0.043	12.09	15.47	99.30	0.52	0.67	4.27
485	0.042	7.26	18.28	73.28	0.30	0.77	3.08
490	0.041	3.96	21.70	53.53	0.16	0.89	2.19
495	0.041	1.91	27.00	40.68	0.08	1.11	1.67
500	0.041	0.69	33.74	31.29	0.03	1.38	1.28
505	0.041	0.24	42.27	24.26	0.01	1.73	0.99
510	0.041	0.75	52.06	18.17	0.03	2.13	0.75
515	0.041	2.55	62.39	12.76	0.10	2.56	0.52
520	0.041	5.80	72.39	8.79	0.24	2.97	0.36
525	0.041	10.57	82.64	6.46	0.43	3.39	0.26
530	0.041	16.57	91.48	4.84	0.68	3.75	0.20
535	0.041	22.63	96.02	3.40	0.93	3.94	0.14
540	0.041	28.93	98.90	2.30	1.19	4.05	0.09
545	0.042	36.01	101.73	1.52	1.51	4.27	0.06
550	0.042	43.53	103.30	0.99	1.83	4.34	0.04
555	0.043	50.60	101.99	0.64	2.18	4.39	0.03
560	0.043	57.78	99.69	0.42	2.48	4.29	0.02
565	0.046	64.95	96.47	0.29	2.99	4.44	0.01
570	0.050	71.82	92.30	0.21	3.59	4.61	0.01
575	0.062	79.42	88.71	0.18	4.92	5.50	0.01
580	0.075	86.43	84.27	0.16	6.48	6.32	0.01
585	0.110	89.22	76.34	0.13	9.81	8.40	0.01
590	0.145	90.29	68.22	0.10	13.09	9.89	0.01
595	0.218	94.04	63.21	0.09	20.50	13.78	0.02
600	0.290	95.67	57.95	0.08	27.75	16.81	0.02
605	0.378	94.38	52.05	0.06	35.67	19.68	0.02
610	0.465	90.77	46.20	0.03	42.21	21.48	0.02
615	0.520	84.47	40.19	0.02	43.92	20.90	0.01
620	0.575	76.56	34.47	0.02	44.02	19.82	0.01
625	0.599	86.08	28.45	0.01	39.58	17.04	0.01
630	0.623	55.29	22.96	0.00	34.44	14.30	0.00
635	0.636	46.87	18.87	0.00	29.81	12.00	0.00
640	0.648	39.02	15.31	0.00	25.29	9.92	0.00
645	0.658	30.90	11.88	0.00	20.27	7.79	0.00
650	0.667	23.85	9.02	0.00	15.91	6.02	0.00
655	0.675	18.49	6.91	0.00	12.48	4.67	0.00
660	0.683	14.02	5.20	0.00	9.58	3.55	0.00
665	0.691	10.49	3.86	0.00	7.25	2.67	0.00
670	0.699	7.68	2.81	0.00	5.37	1.97	0.00

Figure 4-5. *Continued*

I Wavelength λ (nm)	II Reflectance $\rho(\lambda)$	III CIE Data for Illuminant D_{65}			IV (II × III)		
		$\bar{x}(\lambda)S(\lambda)$	$\bar{y}(\lambda)S(\lambda)$	$\bar{z}(\lambda)S(\lambda)$	$\rho(\lambda)\bar{x}(\lambda)S(\lambda)$	$\rho(\lambda)\bar{y}(\lambda)S(\lambda)$	$\rho(\lambda)\bar{z}(\lambda)S(\lambda)$
675	0.706	5.43	1.98	0.00	3.84	1.40	0.00
680	0.713	3.90	1.42	0.00	2.78	1.01	0.00
685	0.719	2.62	0.95	0.00	1.88	0.68	0.00
690	0.725	1.70	0.62	0.00	1.24	0.45	0.00
695	0.732	1.20	0.43	0.00	0.88	0.32	0.00
700	0.739	0.87	0.31	0.00	0.64	0.23	0.00
705	0.744	0.63	0.23	0.00	0.47	0.17	0.00
710	0.749	0.46	0.17	0.00	0.35	0.12	0.00
715	0.756	0.30	0.11	0.00	0.23	0.08	0.00
720	0.762	0.19	0.07	0.00	0.15	0.05	0.00
725	0.768	0.14	0.05	0.00	0.11	0.04	0.00
730	0.775	0.11	0.04	0.00	0.08	0.03	0.00
735	0.780	0.08	0.03	0.00	0.06	0.02	0.00
740	0.785	0.06	0.02	0.00	0.04	0.02	0.00
745	0.788	0.04	0.01	0.00	0.03	0.01	0.00
750	0.791	0.02	0.01	0.00	0.02	0.01	0.00
755	0.793	0.01	0.00	0.00	0.01	0.00	0.00
760	0.795	0.01	0.00	0.00	0.01	0.00	0.00
765	0.796	0.01	0.00	0.00	0.01	0.00	0.00
770	0.797	0.01	0.00	0.00	0.00	0.00	0.00
775	0.798	0.00	0.00	0.00	0.00	0.00	0.00
780	0.798	0.00	0.00	0.00	0.00	0.00	0.00
Sums		2006.81	2109.47	2309.09	X = 497.42	Y = 285.41	Z = 107.25

x = 0.559, y = 0.321, z = 0.120   Luminous reflectance = 13.5%

Figure 4-5. Determination of CIE Chromaticity Coordinates from the Spectrophotometric Curve for a Surface Illuminated by Standard Illuminant D_{65}

An *x*, *y* specification of any object color relates it only to the light source for which the object color is calculated. Consequently, the dominant wavelength and excitation purity of any object depend on the spectral composition of its illumination.

CIE Uniform Color Spaces. Distances in the CIE *x*, *y* diagram or *X*, *Y*, *Z* space do not correlate well with the perceived magnitudes of color differences. This gives rise to the shapes and different sizes of MacAdam ellipses (Figure 3-35) which set the bounds for threshold discrimination between two colors; one at the center of the ellipse and the other anywhere on the edge of the ellipse. In a uniform color space, the ellipses would appear as circles of equal radii. Various transformations have been suggested that provide more uniform spacing.

In 1960, the CIE provisionally recommended that whenever a diagram is desired to yield chromaticity spacing more uniform than the CIE *x*, *y* diagram, a uniform chromaticity-scale diagram (CIE 1960 UCS Diagram) based on that described in 1937 by MacAdam[14] be used. The ordinate and abscissa of this *u*, *v* diagram are defined as

$$u = \frac{4X}{X + 15Y + 3Z} = \frac{4x}{-2x + 12y + 3} \qquad (4\text{-}3a)$$

$$v = \frac{6Y}{X + 15Y + 3Z} = \frac{6y}{-2x + 12y + 3} \qquad (4\text{–}3b)$$

In 1976, after additional investigation, the CIE modified its 1960 UCS Diagram as follows:

$$u' = u \qquad (4\text{-}4a)$$

$$v' = 1.5\,v \qquad (4\text{-}4b)$$

Figure 4-6 illustrates the CIE 1976 UCS Diagram.

To convert the CIE 1960 UCS Diagram to a three-dimensional system that is useful in studying color differences, the CIE, in 1964, added a recommendation developed for the purpose by Wyszecki[15] that converts *Y* to a lightness index, *W**, by the relationship

$$W^* = 25\,Y^{1/3} - 17 \qquad (1 \le Y \le 100) \qquad (4\text{-}5)$$

and converts the chromaticity coordinates *u*, *v* to chromaticness indices *U*, *V* by the relationships

$$U^* = 13W^*(u - u_n) \qquad (4\text{-}6)$$

$$V^* = 13W^*(v - v_n) \qquad (4\text{-}7)$$

The lightness index *W** approximates the Munsell value function in the range of *Y* from 1 to 100%. The chromaticity coordinates u_n, v_n refer to the nominally achromatic (neutral) color (usually that of the source) placed at the origin of the *U**, *V** system.

In 1976, the CIE[10,11] recommended two new uniform color spaces, known as CIELUV and CIELAB. Although these give a more uniform representation of color differences and therefore supersede the *U**, *V**, *W** space for most purposes, the earlier system is still used for the calculation of CIE color rendering indices. Two spaces were recommended, rather than one, because experimental evidence was insufficient to select a single space that would be satisfactory for most industrial applications.

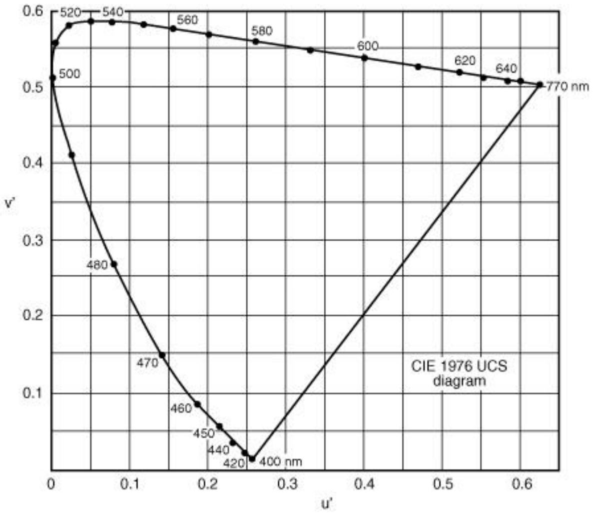


Figure 4-6. The CIE 1976 UCS diagram.

The three coordinates of CIELUV are *L**, *u**, and *v**, defined by

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16 \qquad \text{for } \frac{Y}{Y_n} > 0.008856 \qquad (4\text{-}8)$$

$$L^* = 903.29\,\frac{Y}{Y_n} \qquad \text{for } \frac{Y}{Y_n} \leq 0.008856 \qquad (4\text{-}9)$$

$$u^* = 13L^*(u' - u'_n) \qquad (4\text{-}10)$$

$$v^* = 13L^*(v' - v'_n) \qquad (4\text{-}11)$$

where

$u' = 4X/(X + 15Y + 3Z)$,
$v' = 9Y/(X + 15Y + 3Z)$,

u'_n, v'_n, Y_n = values of u', v', and Y for the nominally achromatic color (usually that of the source with $Y_n = 100$).

The major change from the U^*, V^*, W^* system is that $v' = 1.5v$. The quality L^* is a minor modification of W^*; u' is the same as u.

The three coordinates of CIELAB are L^*, a^*, and b^*, defined by

$$L^* = 116f(Y/Y_n) - 16 \qquad (4\text{-}12)$$

$$a^* = 500[f(X/X_n) - f(Y/Y_n)] \qquad (4\text{-}13)$$

$$b^* = 200[f(Y/Y_n) - f(Z/Z_n)] \qquad (4\text{-}14)$$

where

$$f(q) = \begin{cases} q^{1/3} & \text{for } q > 0.008856 \\ 7.787q + \dfrac{4}{29} & \text{for } q \leq 0.008856 \end{cases}$$

(with $q = X/X_n$, Y/Y_n, or Z/Z_n). Here X_n, Y_n, and Z_n are the values of X, Y, and Z for the nominally achromatic color (usually that of the source with $Y_n = 100$). The lightness index L^* is the same for both CIELUV and CIELAB.

Loci of constant Munsell hue and chroma for value 5/ (see discussion of Munsell Color System below) are plotted in u^*, v^* and a^*, b^* diagrams[16] in Figure 4-7. The Munsell Color System is often used to test if the color space associated with a color-difference formula provides uniform spacing. If either diagram provided uniform spacing of the Munsell system, these loci would be straight, equally spaced radial lines and concentric, equally spaced circles. While neither diagram is perfect in this respect, Robertson noted that the Munsell data represent color differences much larger than threshold and are not necessarily suitable for comparing color-difference formulas that are intended to quantify near-threshold differences. He concluded that insufficient data are available to determine which of the color difference formulas is best.[11]

These two uniform color spaces each have associated with them a color-difference formula by which a measure of the total difference between two object colors can be calculated. In the CIELUV system, the color difference is measured by

$$\Delta E^*_{uv} = [(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2]^{1/2} \qquad (4\text{-}15)$$

In the CIELAB system it is measured by

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \qquad (4\text{-}16)$$

These two formulas are useful for setting color tolerances in industrial situations. They are recommended by the CIE to unify practice, which in the past has involved the use of 10 or 20 different color-difference formulas.

Correlates of the subjective attributes lightness, perceived chroma, and hue can be derived from either CIELUV or CIELAB as follows:

$$\text{CIE 1976 lightness} = L^* \qquad (4\text{-}17a)$$

$$\text{CIE 1976 } u,v \text{ chroma} = C^*_{uv} = (u^{*2} + v^{*2})^{1/2} \qquad (4\text{-}17b)$$

or

$$\text{CIE 1976 } a,b \text{ chroma} = C^*_{ab} = (a^{*2} + b^{*2})^{1/2} \qquad (4\text{-}17c)$$

and

$$\text{CIE 1976 } u,v \text{ hue angle} = h_{uv} = \arctan\left(\frac{v^*}{u^*}\right) \qquad (4\text{-}17d)$$

or

$$\text{CIE 1976 } a,b \text{ hue angle} = h_{ab} = \arctan\left(\frac{b^*}{a^*}\right) \qquad (4\text{-}17e)$$

Although these quantities are approximate correlates of the respective subjective attributes, the actual perceived color depends significantly on the viewing conditions, for example, the nature of the surround. The exact degree of agreement of these measures with the corresponding subjective attributes, even for standard daylight viewing conditions, has not been determined. In commercial situations involving small color differences, tolerances often are set differently for L^*, C^*, and h because the acceptability can be different for the three components.

The geometrical relationships among CIELAB coordinates are illustrated in Figure 4-8. The relationships in CIELUV (Figure 4-9) are similar.

The 1976 CIELAB-CIELUV recommendation has been much more successful than the 1964 (U^*, V^*, W^*) convention. Both formulas are in widespread use, the choice between them being based mainly on practical considerations other than uniformity of spacing. In industries concerned with such self-luminous colors as television screens and video displays, both CIELUV (Figure 4-8) and CIELAB (Figure 4-9) have been used. The same has been true of industries concerned with object colors. Indeed, some formulas (e.g., the CMC formula[17,18] developed since 1976) continue to use CIELAB as a base and add extra complexity to improve the fit to visual acceptability data.

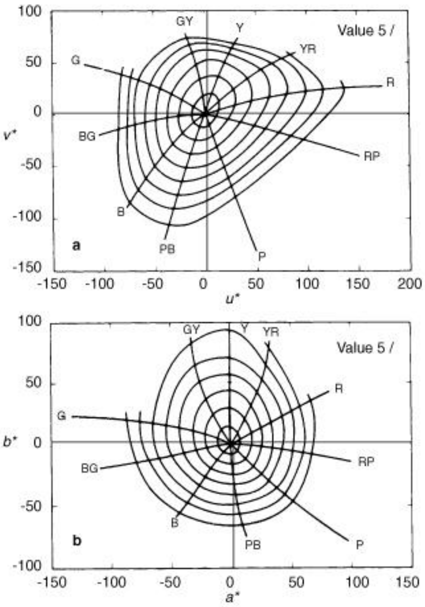


Figure 4-7. Loci of constant Munsell hue and chroma plotted in the CIE 1976 u^*v^* diagram (a), and the CIE 1976 a^*b^* diagram (b).

Other Systems of Color Specification

Munsell System. This is a system of specifying color on scales of hue, value, and chroma. The hue scale consists of 100 steps in a circle containing five principal and five intermediate hues. The value scale contains ten steps from black to white, 0 to 10. The chroma scale can contain 20 or more steps from neutral gray to highly saturated. Each of the three scales is intended to represent equal visual intervals for a normal observer fully adapted to daylight viewing conditions (CIE source C) with gray to white surroundings. Under these conditions the Munsell hue, value, and chroma of a color correlate closely with the hue, lightness, and perceived chroma of color perception; under other conditions the correlation is lost. It is only for daylight conditions that Munsell samples are expected to appear equally spaced. When problems of color adaptation are fully solved, it might be possible to calculate the change in appearance and spacing that takes place when samples are viewed under a light source of different SPD.

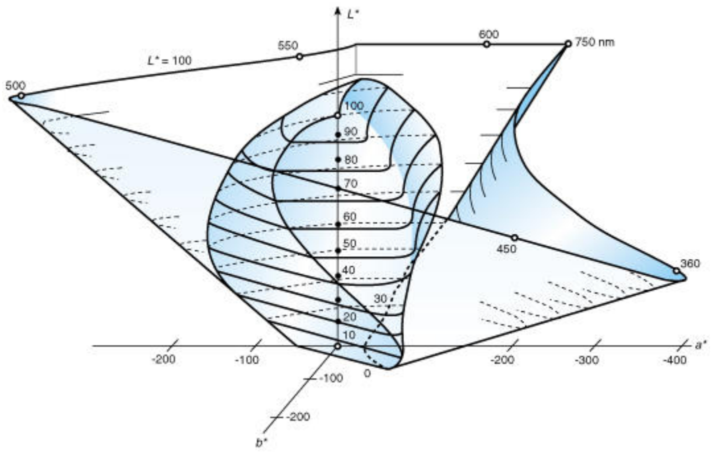


Figure 4-8. Sketch of CIE 1976 ($L^*a^*b^*$) color space with outer boundary generated by optimal color stimuli with respect to CIE standard illuminant D_{65} and the CIE 1964 supplementary standard observer. The colors of all object-color stimuli fall within this boundary. This is also the gamut within which the CIE 1976 color-difference formula $\Delta E(L^*a^*b^*)$ is intended to be valid. Note that the spectrum locus of the monochromatic stimuli is generally well outside the boundary of object-color stimuli. From G. Wyszecki and W. Stiles, *Color science*. Copyright © 1982. Reprinted by permission of John Wiley & Sons, Inc.

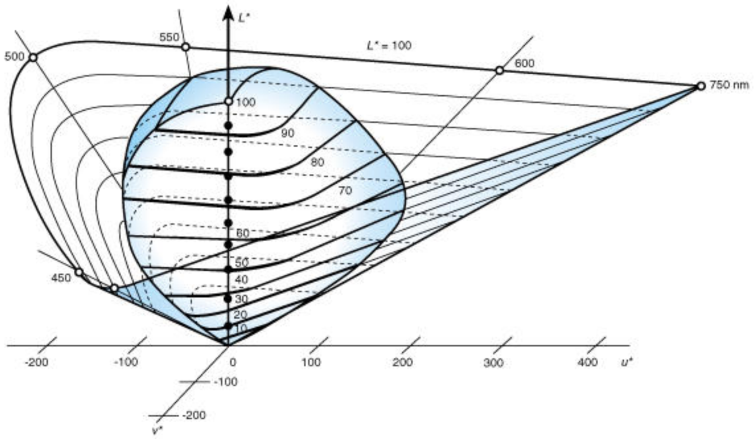


Figure 4-9. Sketch of CIE 1976 ($L^*u^*v^*$) color space with outer boundary generated by optimal color stimuli with respect to CIE standard illuminant D_{65} and the CIE 1964 supplementary standard observer. The colors of all object-color stimuli fall within this boundary. This is also the gamut within which the CIE 1976 color-difference formula $\Delta E(L^*u^*v^*)$ is intended to be valid. Note that the spectrum locus of monochromatic stimuli is generally well outside the boundary of object-color stimuli. From G. Wyszecki and W. Stiles, *Color science*. Copyright © 1982. Reprinted by permission of John Wiley & Sons, Inc.

Munsell notation is useful whether or not reference is made to Munsell samples. It has the form [hue] [value]/[chroma], for example, 5R 4/10. This is read "5 red, 4 over 10" or "5 red, 4 slash 10." Colors of zero chroma, which are known as neutral colors, are written N1/, N2/, etc., as shown in Figure 4-10. One widely used approximation of equivalence between hue, value, and chroma units is 1 value step = 2 chroma steps = 3 hue steps (when the hue is at chroma 5).

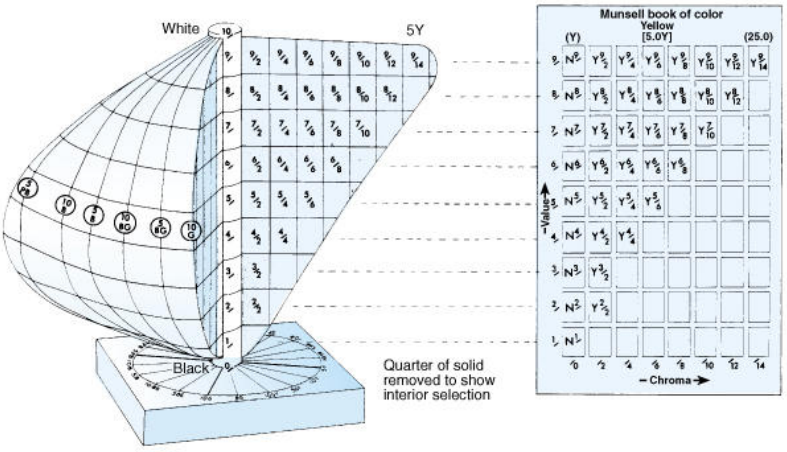
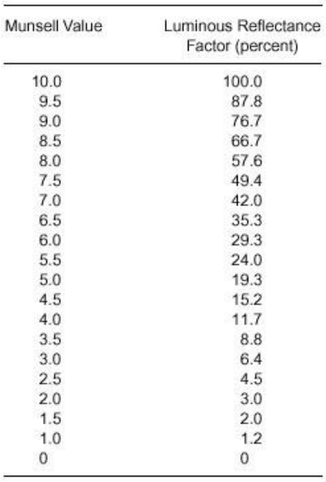


Figure 4-10. Cut-away view of the Munsell color solid showing notation scales of hue, value, and chroma (for example, 5Y 5/4), and the relation of constant hue charts to the three-dimensional representation.

The Munsell scales are exemplified by a collection of color chips forming an atlas of charts that show linear series for which two of the three variables are constant (Figure 4-10). For use as standards or in technical color control, collections of carefully standardized color chips in matte or glossy surface can be obtained from Munsell Color Company, c/o Macbeth, P.O. Box 230, Newburgh, NY 12550, in several different forms. Since 1943 the smoothed renotation for the system, recommended by the Optical Society of America's Colorimetry Committee, has been recognized as the primary standard for these papers.

Instructions for obtaining Munsell values by calculation, or by conversion through CIE are contained in several publications.[6,9,19] The relationship between Munsell value and CIE luminous reflectance factor is summarized in Figure 4-11.



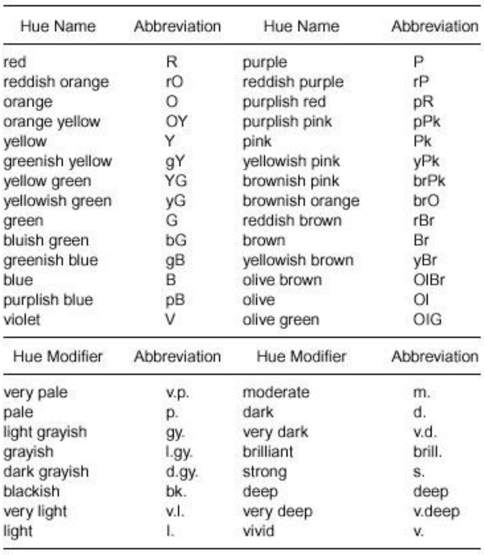
Munsell Value	Luminous Reflectance Factor (percent)
10.0	100.0
9.5	87.8
9.0	76.7
8.5	66.7
8.0	57.6
7.5	49.4
7.0	42.0
6.5	35.3
6.0	29.3
5.5	24.0
5.0	19.3
4.5	15.2
4.0	11.7
3.5	8.8
3.0	6.4
2.5	4.5
2.0	3.0
1.5	2.0
1.0	1.2
0	0

Figure 4-11. Relationship between Munsell Value and Luminous Reflectance Factor

ISCC-NBS Method of Designating Colors. The Inter-Society Color Council-National Bureau of Standards method of designating colors appeared in its original form in 1939 as NBS Research Paper RP 1239. The second edition appeared in book form in 1955 as NBS Circular 553, usually called the *Color Names Dictionary* (CND). The first Supplement to the CND, called the *Centroid Color Charts* (1965),[20] provides useful low-cost color charts that illustrate, with 1-in.^{2} samples, the centroid color for as many (251) of the 267 color names in the system as could be matched at that time. Each of the names defines a block in color space. This method is distinguished from all others in that the boundaries of each name are given, rather than points. These boundaries are defined in Munsell notation. A method for pinpointing colors is not provided, but the system does give an understandable color description. When close distinctions must be made between samples that might bear the same ISCC-NBS designation, such specifications as CIE or Munsell should be used.

The method is simple in principle: terms "light," "medium," and "dark" designate decreasing degrees of lightness, and the adverb "very" extends the scale to "very light" and "very dark"; adjectives "grayish," "moderate," "strong," and "vivid" designate increasing degrees of saturation. These and a series of hue names, used in both noun and adjective forms, are combined to form names for describing color in terms of its three perceptual attributes: hue, lightness, and perceived chroma. A few adjectives are added to cover combinations of lightness and perceived chroma: "brilliant" for light and strong, "pale" for light and grayish, and "deep" for dark and strong. The hue names and modifiers are listed in Figure 4-12.

The second supplement to the CND, entitled *The Universal Color Language* (UCL), was published also in 1965.[21] The UCL serves as the means of updating the CND. It brings together all the well-known color-order systems and methods of designating colors and interrelates them in six correlated levels of fineness of color designation, each higher level indicating a finer division of the color solid. It follows closely and extends the original requirements of the ISCC-NBS method of designating colors in the CND. The CND and the UCL have been published together as NBS Special Publication SP 440, with the UCL illustrated in color.[22]



Hue Name	Abbreviation	Hue Name	Abbreviation
red	R	purple	P
reddish orange	rO	reddish purple	rP
orange	O	purplish red	pR
orange yellow	OY	purplish pink	pPk
yellow	Y	pink	Pk
greenish yellow	gY	yellowish pink	yPk
yellow green	YG	brownish pink	brPk
yellowish green	yG	brownish orange	brO
green	G	reddish brown	rBr
bluish green	bG	brown	Br
greenish blue	gB	yellowish brown	yBr
blue	B	olive brown	OlBr
purplish blue	pB	olive	Ol
violet	V	olive green	OlG
Hue Modifier	**Abbreviation**	**Hue Modifier**	**Abbreviation**
very pale	v.p.	moderate	m.
pale	p.	dark	d.
light grayish	gy.	very dark	v.d.
grayish	l.gy.	brilliant	brill.
dark grayish	d.gy.	strong	s.
blackish	bk.	deep	deep
very light	v.l.	very deep	v.deep
light	l.	vivid	v.

Figure 4-12. ISCC-NBS Standard Hue Names and Modifiers

OSA UCS System. The Optical Society of America (OSA) has produced a set of 558 color chips to illustrate uniform visual spacing on a regular rhombohedral lattice.[23] Each chip is intended to be equally different from its 12 nearest neighbors in the lattice. Because of the noneuclidean nature of color space, perfectly uniform spacing is impossible to achieve in a three-dimensional lattice. Thus, the OSA Committee on Uniform Color Scales was forced to make some compromises in specifying the colors. These compromises are not evident on casual study, although they can be seen in more careful analyses. The set is sold by the Optical Society of America, 2010 Massachusetts Avenue NW, Washington, DC 20036, and has generated much interest, especially among artists, designers, and color scientists.

Natural Color System (NCS). The NCS[24] is based on a principle entirely different from that of the Munsell or the OSA system. The principle is that of resemblances to six elementary perceived colors: red, yellow, blue, green, black, and white. Of these, the four chromatic colors are those in which no trace of the others can be seen. In a geometric representation, they are placed 90° apart on a hue circle. Black and white are perceived colors that contain no trace of each other or of any of the four chromatic colors. They are placed at the apexes of two opposite cones with their bases on the hue circle. Any color resembles at most two of the chromatic elementary colors plus black and white. It is claimed that the degree of resemblance can be estimated to within approximately 5%, even by naive observers.

DIN System. The DIN color system[25] is the official German standard. It is organized in terms of hue (*Färbton*), saturation (*Sattigung*), and darkness (*Dunkelstufe*). The system is defined in terms of CIE chromaticity and luminance factors with certain compromises made to keep the relationships as simple as possible. It attempts to show uniform steps of color difference and uses CIE colorimetry extensively for interpolation and extrapolation.

Correlation Among Methods. Frequently it is desirable to convert from one system of specification to another, or to convert or identify the color of samples on a chart or color card to terms of another. If the coordinates or samples of one system are given in CIE or Munsell terms, they can be converted or compared to any other system for which a similar conversion is available. Color charts of the German standard 6164 DIN system are provided with both CIE and Munsell equivalents. The Japanese standard system of color specification, JIS Z 8721-1958, is in terms of hue, value, and chroma of the Munsell renotation system, according to the CIE x, y coordinates recommended by the Optical Society of America's 1943 subcommittee report.[9] The name blocks of the ISCC-NBS method are in terms of the Munsell renotation system with samples measured in CIE terms. Having a common conversion language helps promote international cooperation and understanding of the subject. Complete sets of CIE-Munsell conversion charts are contained in ASTM Test Method D1535.[19] Many of the available conversions are referenced in a 1957 paper by Nickerson.[26] For more detailed descriptions of color systems or conversions, consult *Color in Business, Science and Industry*.[6] For a useful survey of color order systems, consult Reference 27.

Color Temperature

Blackbody characteristics at different temperatures are defined by Planck's radiation law (see Chapter 1, Light and Optics). The perceived colors of blackbody radiators at different temperatures depend on the state of adaptation of the observer. Plate 4 gives an approximate illustration of the perceived colors at various color temperatures for various states of adaptation; it shows that, as the temperature rises, the color changes from red to orange to yellow to white to blue.

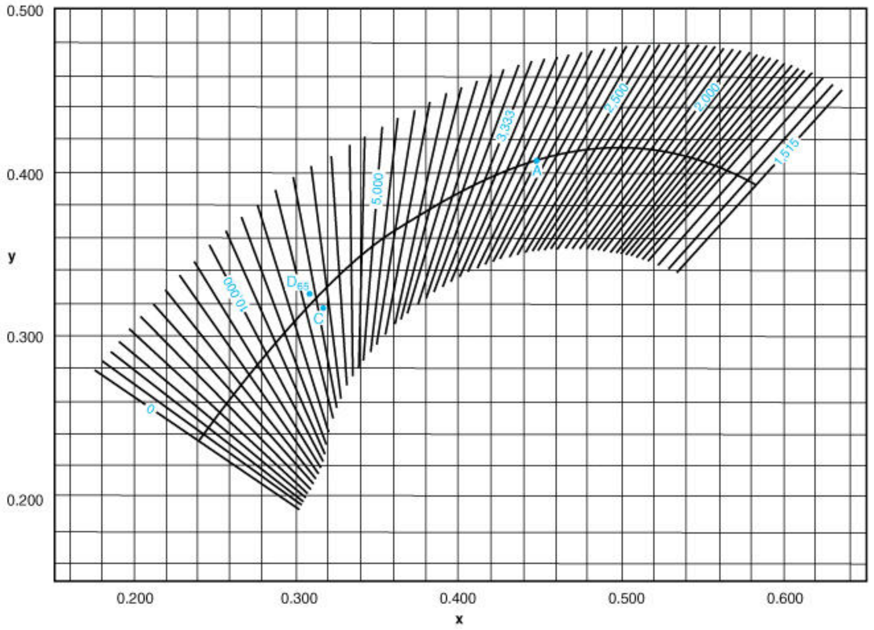


Figure 4-13. CIE 1931 (x, y) chromaticity diagram showing lines of constant correlated color temperature, in kelvin, together with three standard illuminants: A, C, and D_{65}).

The locus of blackbody chromaticities on the x, y diagram is known as the planckian locus. Any chromaticity represented by a point on this locus can be specified by color temperature. Strictly speaking, color temperature should not be used to specify a chromaticity that does not lie on the planckian locus. However, what is called the *correlated* color temperature (the temperature of the blackbody whose chromaticity most resembles that of the light source) is sometimes of interest. The correlated color temperature can be determined from diagrams[28] similar to the one shown in Figure 4-13, either by graphical interpolation or by a computer program.[29] It should be noted that the concept becomes less meaningful as the distance from the planckian locus increases.

Equal color differences on the planckian locus are more nearly expressed by equal steps of reciprocal color temperature than by equal steps of color temperature itself. The usual unit is the reciprocal megakelvin (MK^{-1}), so that the reciprocal color temperature is 10^6 divided by the color temperature in kelvin (K). The term "mired" (pronounced mi' red), an abbreviation for "micro-reciprocal-degree," was formerly used for the unit. A difference of 1 reciprocal megakelvin indicates approximately the same color difference anywhere on the color temperature scale above 1800 K; yet it corresponds to a temperature difference that varies from approximately 4 K at 2000 K to 100 K at 10,000 K.

Color temperature is a specification of chromaticity only. It does not represent the SPD of a light source. Chromaticities of many "daylight" lamps plot very close to the planckian locus, and their colors can be specified in terms of correlated color temperature. However, this specification gives no information about SPD, which can, and often does, depart widely from that of daylight. In particular, the addition of light from two sources each having blackbody distribution but different color temperatures does not produce a blackbody mixture. Figure 4-14 shows spectral curves for planckian distributions for different color temperatures. Distributions based on daylight[30] are also available for several correlated color temperatures (see Figure 8-1 in Chapter 8, Daylighting). Most tungsten filament lamps approach the relative SPD of a blackbody quite closely. The color temperature of such lamps varies with the current passing through them. By varying the voltage across such a lamp, a series of color temperatures can be obtained covering a wide range up to approximately 3600 K.

Color Constancy and Adaptation[4,31,32]

A nonluminous colored object contributes to observed color by modifying the SPD of the light radiated to the eye. The color of the light reflected or transmitted by the object when it is illuminated by a standard light source is known as the object color and can be calculated by assuming certain conventions (as in the CIE system). The color seen when the object is viewed normally in daylight is a perceptual phenomenon referred to as the perceived color of the object. While there are exceptions, the perceived colors of objects, when illuminated by various sources, do not change as much as might be expected from the calculated difference in chromaticities. This phenomenon is known as color constancy. Objects whose perceived colors change greatly when there is a wide change in illumination, as for example from daylight to incandescent filament light, are said to have unstable colors. It is important to remember that whereas the perceived color of an object might not change much with a change of light source color, the object color (as specified for example by CIE chromaticity coordinates) will change. For example, a piece of white paper will appear white under both incandescent light and daylight, but the object color will be quite different in the two cases because the paper, being spectrally neutral, will have almost the same chromaticity as the source in each case.

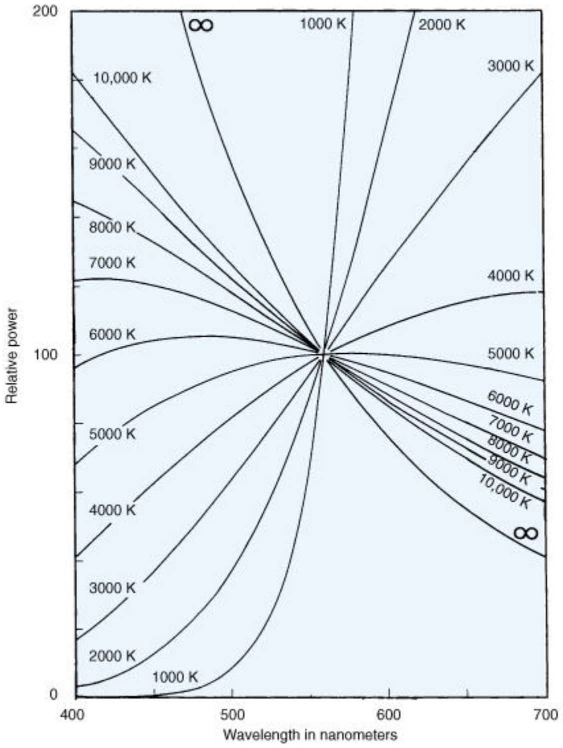


Figure 4-14. Family of planckian distribution curves.

The impression that the perceived colors of most objects do not change greatly with the SPD of the light source is due primarily to a low degree of spectral selectivity in daylight and incandescent sources. Color constancy is affected by such factors as awareness of the illuminant, persistence of memory of colors, consistency of attitude toward the object, and adaptation of the visual mechanism. Adaptation is, in effect, a rebalancing of the color response of the visual system as the spectral composition of the visual scene changes. Thus, adaptation tends to counteract the shift in chromaticity of the source and thereby preserves the appearance of object colors. However, there are cases where even slight residual shifts can be noticeable, annoying, or even intolerable. Such cases might be encountered with foodstuffs, with displayed merchandise, or in the grading of various commercial products.

The facts of color constancy and adaptation are not yet known well enough to make possible the computation of color rendering properties of a lamp with sufficient accuracy except when the reference or standard lamp is required to have the same correlated color temperature as the test lamp. When it becomes possible to compute the effects of constancy and adaptation so that the results agree with the subjective experience, then it will be possible to calculate the color rendering properties of a lamp irrespective of its SPD. In the meantime, as will be seen later, the CIE color rendering index does make an allowance for chromatic adaptation, even though the allowance is not perfectly accurate. See the section "Perceptual Constancies" in Chapter 3, "Vision and Perception," for details on other types of perceptual constancy.

Color Appearance Models

The CIE has worked for many years to develop a mathematical model for color appearance, especially for comparisons between different media such as CRT displays and color printers. Several models have been proposed, including one by Hunt[33] and another by Nayatani et al.[34] In 1997, the CIE recommended a model called CIECAM97[35] which includes features from many of the common models.

Color Contrast

Color contrast is sometimes used colloquially to describe the property by which two adjacent fields of equal luminance but different chromaticity can be distinguished from one another. It should be noted that color contrast is not a quantifiable parameter as is luminance contrast (Equations 3-6 to 3-8). The color separation between two fields is more correctly specified in terms of the CIELUV (Equation 4-15) or CIELAB (Equation 4-16) color difference formulas.

Color appearance is affected markedly by the color of adjacent areas, particularly if one surrounds the other. For example, a color patch appears brighter (less gray) if it is surrounded by a large dark area. It appears dimmer (more gray) if it is surrounded by a similar light area. Juxtaposed areas also induce shifts in hue and saturation in one another. Hues shift in opposite directions in color space, tending to induce complementary hues. Similarly, saturation interacts, magnifying saturation differences in juxtaposed palates of color. In general, there tends to be a simultaneous and complex shift in all three attributes when colors are placed side by side.

Metameric and Conditional Color Matches

If two lights are visually indistinguishable because they have the same spectral compositions, they are said to form a spectral match. However, two lights can be visually indistinguishable in spite of having quite different SPD. Such a color match is said to be metameric, and the lights to be metameres. In the CIE system, the computed match is identified by application of color matching functions, which show that the tristimulus values for one light are identical to those for the other. If the lights are viewed by an observer characterized by different color matching functions, they might no longer match. All metameric matches are therefore conditional matches. The metameric character of a match sometimes will be revealed by looking at a spectrally selective object and noting that the object is of different color when illuminated by the two lights. This is illustrated in Figure 4-15.

Objects with identical spectral reflectance distributions (see samples A and B in Figure 4-16) are said to produce an unconditional match. They match to everyone, no matter what source illuminates it. If, however, the color-matched reflected light comes from identically illuminated objects that have different spectral reflectances (see samples E and F in Figure 4-16), the match is metameric. Substitution of another light source, or another observer, might upset the match; thus objects that can produce a metameric match, though identically illuminated, can be said to produce a match that is both observer conditional and source conditional. Such a match is illustrated in Plate 5.

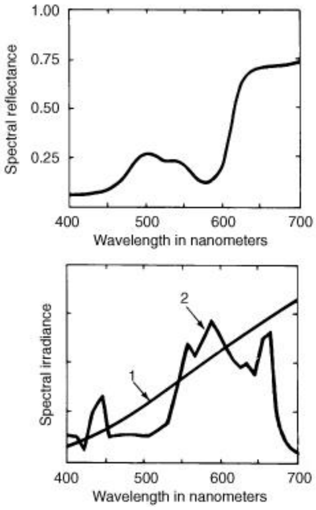


Figure 4-15. Illustration of effect of metamerism of light sources. The two light sources, 1 and 2 in the bottom figure, have different spectral power distributions but are, themselves, metamers when illuminating a spectrally flat object. An object, such as the one whose spectral reflectance curve is shown in the top figure, may have different color appearances when illuminated by each of the two sources.

Sometimes it has been argued wrongly that, because the presence of metamerism always corresponds to a conditional match, a metameric match is the same as a conditional match. Not all conditional matches, however, are metameric. Figure 4-16 shows the reflectance curves of two samples, C and D, that have different colors if the light source contains a significant amount of radiant power between 380 and 480 nm, but produce a match if the power of the source is confined to wavelengths greater than 500 nm. Samples C and D thus form a source-conditional match; no metamerism is involved because there is no source for which the SPD reflected from C and D have the same color but are spectrally different.

There is a necessary though not sufficient condition that must be satisfied by the spectral reflectances of objects that, identically illuminated, can produce metameric reflected lights. First, the two reflectance curves must be different in some part of the visible spectrum, or else the reflected lights will be a spectral rather than a metameric match. Second, to be a color match the two objects must reflect equal amounts of the incident light, and this means that the curves must cross at least once within the visible spectrum. Third, the two objects must not differ in the yellow-blue sense (if the curves cross at only one wavelength within the visible spectrum, a yellow-blue difference is implied; therefore, the curves must cross at least at two wavelengths). Finally, the two objects must not differ in the purple-green sense (if the curves cross at only two wavelengths, a purple-green difference is implied). Therefore, the reflectance curves of objects capable of producing a metameric match for some combination of trichromatic observer and source must cross at least three wavelengths in the visible spectrum. Samples E and F in Figure 4-16 have this property and thus for some source-observer combination might produce a metameric pair of reflected lights, that is, they might match. For a discussion of the exact conditions under which a certain number of intersections is required, see Stiles and Wyszecki.[36]

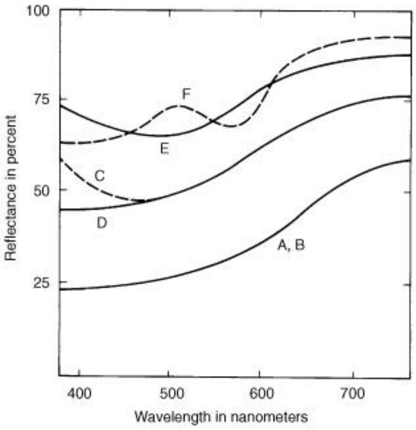


Figure 4-16. Color matches. A and B are nonmetameric matches and will match for any observer under any light source. C and D will match for any observer under a source with no power at wavelengths less than 500 nm, but will not match for some observers under a source that does have some power in the wavelength region from 380 to 480 nm. C and D produce a source-conditional match, but they do not form a metameric pair, any more than A and B do, because the matching beams do not have different spectral compositions. E and F may form a metameric pair for some source-observer combinations.

USE OF COLOR

Reflectance

Every object reflects some fraction of the light incident upon it. The larger the fraction reflected, the "lighter" is the color of the object and the higher is the assigned Munsell value. In the Munsell color solid of Figure 4-10, the lightness dimension is in the vertical direction, along the scale of Munsell value, and ranges from black at the bottom to perfectly reflecting at the top. In the two-dimensional CIE chromaticity diagram of Figure 4-4 are plotted the two CIE coordinates that are related to Munsell perceived hue and to Munsell perceived chroma or saturation, constituting a horizontal plane in the color solid of Figure 4-10.

Figure 4-17 shows how the lightness dimension relates to the chromaticity diagram. In the CIE system, the *Y* tristimulus value of the light reflected from an object represents the luminous reflectance factor expressed as the percentage of the light that would be reflected by a perfectly reflecting diffuser. Computation of the percentage luminous reflectance is demonstrated in Figure 4-5, and its relation to Munsell value is shown in Figure 4-11.

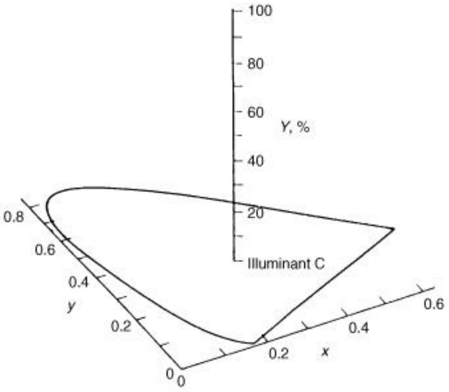


Figure 4-17. The chromaticity diagram can be extended by adding a third axis for luminance factor. Lighter colors then appear directly above the points representing their chromaticity at a height representing their lightness.

The luminous reflectance scale is not visually uniform between 0 and 100%, black and white. An object that reflects 50% does not look halfway between black and white, but looks much nearer to white. On the other hand, the purpose of the Munsell value scale is to illustrate equal visual steps for a given set of standard conditions. In Figure 4-11 (a condensed table), reflectance and Munsell value units are related. Thus, under daylight conditions, and for a light gray surround, a Munsell value of 5 should look approximately halfway in lightness between the black and white endpoints of the scale. Yet the luminance factor of a value-5 sample is only approximately 20%. A color with Munsell value 7 is called a light color, yet it reflects less than half (only 42%) of the light it receives. This is an important point for lighting designers to consider, for unless all the colors in the color scheme of a room layout are very light, well over 50% of the light is absorbed. If value-5 colors are used, as much as 80% of the incident light might be absorbed. With practice in the use of a Munsell value scale, particularly the special set of Munsell scales developed for lighting and interior designers, one can learn to estimate Munsell values rather accurately and convert them to luminous reflectance by means of Figure 4-11. Value-reflectance conversion tables for every Munsell value in steps of 0.1 are available in several publications[6,9,19] or can be calculated as follows:[6]

for $Y > 0.9$

$$V = UY^{W} \tag{4-18a}$$

for $Y \geq 0.9$

$$\begin{aligned} V = AY^{1/3} - B - \frac{C}{(DY - E)^2 + F} \\ + \frac{G}{Y^H} + J\sin(KY^{1/3} + 1) \\ + \frac{M}{Y}\sin[N(Y - 2)] \\ - \frac{P}{QY}\sin[S(Y - T)] \end{aligned} \tag{4-18b}$$

where

$A = 2.49268$
$B = 1.5614$
$C = 0.985$
$D = 0.1073$
$E = 3.084$
$F = 7.54$
$G = 0.0133$
$H = 2.3$
$J = 0.0084$
$K = 4.1$
$M = 0.0221$
$N = 0.39$
$P = 0.0037$
$Q = 0.44$
$S = 1.28$
$T = 0.53$
$U = 0.87445$
$W = 0.9967$
V = Munsell value,
Y = luminous reflectance relative to a perfect diffuser (in %).

where

V = Munsell value,
Y = luminous reflectance relative to a perfect diffuser (in %).

Multiply Y by 1.0257 to convert it to the formerly used scale on which smoked magnesium oxide had the value of 100.

The luminous reflectance of spectrally nonselective white, gray, and black objects remains constant for all light sources, but the luminous reflectances of colored objects will differ in accordance with the SPD of the light source. For example, with illumination from incandescent sources, which have relatively high radiant power in the middle- and long-wavelength portions of the visible spectrum and low power at the short-wavelength end, yellow objects appear lighter and blue objects darker than they do under daylight illumination; under blue sky the reverse will be true. On many sets of Munsell scales for judging reflectance, reflectances of each sample are given for three light sources: CIE A at 2856 K, CIE D_{65} at 6500 K, and cool white fluorescent at 4300 K.

Light walls and ceilings, whether neutral or chromatic, are much more efficient than dark walls in distributing light uniformly. Step-by-step changes studied by Brainerd and Massey in 1942[37] have been reported in terms of illuminance and coefficients of utilization and are shown in Figure 4-18. Mathematical analyses by Moon[38] on the effect of wall colors on illuminance and luminance ratios in cubical rooms show that an increase of wall reflectance by a factor of 9 can result in an increase in illuminance by a factor of approximately 3. Moon[38] has also published much information concerning spectral and colorimetric characteristics of materials used in room interiors.

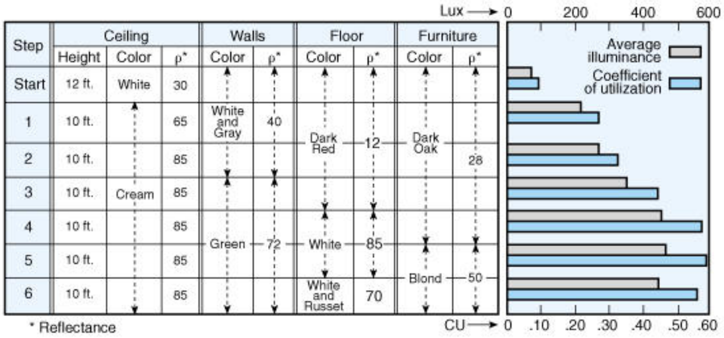


Figure 4-18. Variation of illuminance and utilization coefficient with color scheme. The luminaire used for these results had a general diffuse distribution.

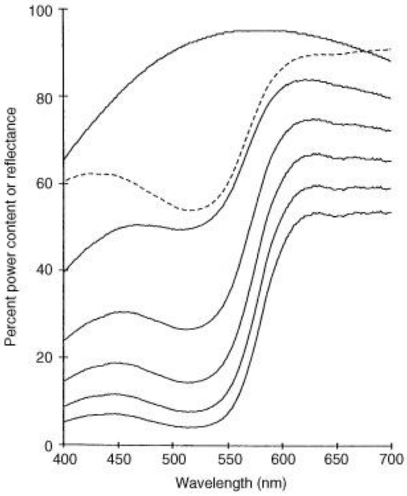


Figure 4-19. Graph showing how the spectral power distribution of sunlight when interreflected on a surface (spectral reflectance shown by the dashed line) changes with successive reflections in distribution and overall intensity. The top curve is the original source and the bottom the light after five reflections.

When neutral and chromatic surfaces of equal reflectance are uniformly and directly illuminated, they will have equal luminances. But by interreflections in a room, the light reaching a working surface will have undergone several reflections from ceiling and walls, and the perceived colors of ceiling and walls, as well the light reaching the working surface, will have become more saturated. Figure 4-19 shows the measured spectral reflectance (dashed curve) of a pale pink surface. The SPD of incoming sunlight is represented by the topmost solid curve. The lower curves are the result, respectively, of one to five reflections from the pale pink surface. The remaining light deepens in color progressively. Figure 4-20 lists for the six SPDs the computed chromaticity, remaining power content, remaining lumen content, and perceived color of the light. It is clear that multiple reflections are costly in lumen content of the illumination and can cause unpleasant intensification of its color.

Number of Reflections	Computed Chromaticity		Remaining Radiant Flux (%)	Remaining Luminous Flux (%)	Perceived Color
	x	y			
0	0.345	0.352	100	100	white
1	0.386	0.350	71	69	pinkish white
2	0.428	0.350	54	50	orange-pink
3	0.469	0.350	42	37	deep orange pink
4	0.507	0.350	34	28	deep orange pink
5	0.540	0.350	28	22	reddish-orange

Figure 4-20. Characteristics of Illumination as It Enters a Space and After Successive Reflections

Spencer and Sanborn,[39] O'Brien,[40] and Jones and Jones[41] have published basic studies in this field. Spencer and Sanborn have analytically found the color shift due to interreflection in an infinite room and in a finite rectangular room, and O'Brien has developed and used computer methods and results to provide charts and tables to aid designers in making detailed predictions of illuminance and luminance distributions in rooms, a prerequisite for solving the problem for color interreflections. In France, Barthès has published experimental measurements for a model room.[42] In Japan, Krossawa[43] has computed data on a closed surface painted with a uniform color and derived a general empirical formula for the color shift due to interreflections for different colors. Yamanaka and Nayatani[44] have compared results for computed and actual rooms, and consider the agreements to be quite satisfactory under the model conditions. Gradually the data based on such studies will reach a form in which the practicing designer can use them. Meanwhile designers should understand the general principles so that color change by room interreflections can be taken into consideration in planning a lighting layout.

Color Schemes: Choosing Suitable Colors

No set of simple rules can allow for tastes of different people, or for different conditions and changing fashions. However, the following suggestions provide a place to start:

1. Ceilings are assumed to be white, or slightly tinted. (Note: Some hospital ceilings can be treated as a fifth wall for the supine patient.)

2. Walls, floors, and other structural elements, which will be changed infrequently, must be considered first in the color scheme.

3. Smaller areas (e.g., machinery or furniture) need only blend or contrast with walls and floors.

4. Color schemes, represented by material, surfacing, or paint (coating) samples, should be assembled and evaluated under lighting conditions closely duplicating those under which the scheme will be used. This will help avoid the problem of significant color shifts and of failures in metameric matches.

5. Because major surfaces can contribute considerably to the distribution of light by reflection and interreflection, the luminous reflectance (Munsell value) should be high where high task luminances are important.

6. The prime purpose of the color scheme needs consideration. Visibility can be most important in a schoolroom, dignity in a church, a sense of well being in a factory, an atmosphere of excitement in a circus, and quiet in an office.

7. Limitations can exist for redecoration schemes that must be built around existing colors of carpeting or other flooring, draperies, or furniture.

The 1962 report of the Color Committee[3] has three useful color charts. The first provides scales of hue, value, and chroma to help in understanding color terminology used in interior design. The second provides a series of 66 color chips arranged to show strong versus weak chromas and warm versus cool colors, with reflectances and Munsell notation for each sample, for colors used for interior surfaces. The third shows a 10-sample hue circle of typical wall colors at 60% reflectance, and three sample color scheme selections.

To assist the designer, the following narrative describes current thinking on color schemes. Only limited research data support these conclusions, however. Color schemes usually are variations of basic plans classified as monochromatic (single-hued), complementary, adjacent or analogous, split complementary, or triads. The dominant character usually is determined by the largest area, and in three-hued schemes this usually is the least saturated. A large pattern, strong in value contrast, makes a room seem smaller; a small pattern, in gentle contrast and high reflectance, can make it seem larger. The absence of pattern can provide the illusion of maximum space. The effects of strong contrasts of color or pattern are similar to each other, that is, they both are stimulating, make people restless, and make time seem longer. They are effective for corridors, places of entertainment, entrance halls, public washrooms, quick lunch counters, and other locations where it is desired that people spend a short time; but they are undesirable in hospitals, for example. Gentle contrast is restful and makes time seem shorter. The play of molded form and texture can add interest; contrasts of natural wood, brick, stone, and woven materials add interest to smooth painted walls.

Although personal tastes in color vary with climate, nationality, age, gender, and personality, there is almost universal agreement to call yellows, yellow-reds, reds, and red-purples warm colors, and to call greens, blue-greens, blues, and purple-blues cool colors. All grays approach neutral.

The apparent size and position of objects are affected by color. High-chroma, warm colors usually are the most advancing, and cool colors the most receding. Lowering the chroma reduces the effect on apparent position. Light colors make objects appear larger; dark colors make objects appear smaller.

Selection Guide

By considering such factors as warmth, spaciousness, and excitement level, it is possible to determine a suitable dominant color and degree of contrast. These considerations can be dealt with in four steps[3] to help decide on values, hues, chromas, and contrasts in the Munsell system.

Step 1: Value determination. This step helps decide the value, that is, how light or dark a color scheme should be. If a high level is necessary, colors with a high reflectance should be used. Dark colors tend to reduce luminance and contrast and produce luminance ratios that are unsatisfactory for efficient seeing. For areas in which illuminances of 750 lx (75 fc) or higher are recommended, the dominant values should be kept high, with reflectances of 40 to 60% or higher where the task is critical. Where lower illuminances are recommended, around 300 lx (30 fc), lower values can be introduced, at reflectances of 35 to 60%. For still lower levels, the dominant values can be even lower, with reflectances for large areas down to 15 to 35%. Where the best feasible visibility at low illuminances must be the goal, as for example in a parking garage, light colored (high-value) walls and ceilings are recommended.

Step 2: Hue determination. Use warm, exciting, advancing colors where rooms have northern exposure, cool temperatures, and low noise element; where the room is too large and has smooth textures; where there is light physical exertion, time exposure is short, and a stimulating atmosphere is required; and where lamps are cool fluorescent. Use cool, restful, receding colors for rooms with southern exposure, warm temperatures and high noise element; for small rooms with rough texture; where physical exertion is heavy, time exposure is long, and a restful atmosphere is desired; and where lamps are incandescent or warm fluorescent.

Step 3: Chroma determination. Strong chromas are used primarily for advertising, display, accents, and food merchandising; achromatic colors are primarily used for fashion areas, general interiors, and other merchandising. Use strong chromas if the time of occupant exposure is short, the general level of responsibility is low, a lively atmosphere is desired, the noise level is low, and a sense of taste or smell is unimportant. Use gray, low-chroma colors if the time exposure is long, the level of responsibility is high, an atmosphere of dignity is desired, the noise level is high, or a sense of taste or smell is important.

Step 4: Contrast determination. Contrast is obtained by using light with dark, hues that are complementary, and low with high chromas. Little or no contrast should be used if the time of occupant exposure is long, the room size is small, a dignified atmosphere is required, or the wall surfaces are textured. Strong contrast should be used if the time of occupant exposure is short, the room size is large, a lively or exciting atmosphere is desired, or the wall surfaces are flat.

These recommendations represent a consensus from working knowledge of designers and architects, based on field experience. Inasmuch as results from scientific investigations do not contradict them, they remain generally accepted. The designer must realize that in some cases a new or different approach can overrule common practice for a number of reasons.

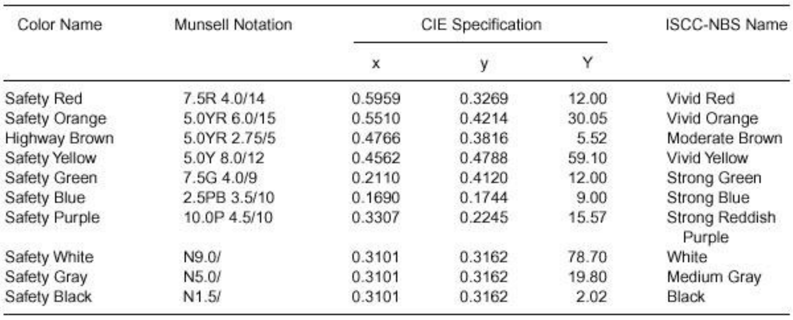
Color Preference

Research by Helson[45-48] and others[49,50] have added to our understanding of color preference in lighting. In his reports, Helson states the pleasantness of object colors depends on the interaction of the light source with the background color and with the hue, lightness, and saturation of the object color. The best background colors for enhancing the pleasantness of object colors were found to have either very high Munsell values (8/ or 9/) or very low values (2/ or 1/), and, with only one exception, very low or zero chroma. The background color was found to be more important than the SPD of the light source. Neutrals rank high as background colors, but very low for object colors. High chromas are preferred over low for object colors.

The chief single factor responsible for pleasant color harmonies was found to be lightness contrast between object and background colors. The greater the lightness contrast, the greater are the chances of pleasant color combinations; this can be because lightness contrast is also most important for pattern vision. The influences of hue and saturation difference cannot be stated simply. A certain amount of variety, change, differentiation, or contrast is pleasant; sameness, monotony, and repetition tend to be unpleasant. Configurations of colors should contain some variations in hue, lightness, and saturation, and over a period of time different configurations of colors should be employed to prevent satiation by overly familiar patterns of stimulation. Color preferences can differ due to such factors as function, size, configuration, climate, and sociocultural background.

Safety Colors

Safety colors are used to indicate the presence of a hazard or safety facility such as an explosive hazard or a first aid station. These are carefully developed colors that are specified in American National Standard Z535.1-1998.[51] The background around these safety colors should be kept as free of competing colors as possible, and the number of other colors in the area should be kept to a minimum. These colors should be illuminated by a light source to levels that both will permit positive identification of the color and the hazard or situation that it identifies and will not distort it and thereby obscure the message it conveys.



Color Name	Munsell Notation	CIE Specification			ISCC-NBS Name
		x	y	Y	
Safety Red	7.5R 4.0/14	0.5959	0.3269	12.00	Vivid Red
Safety Orange	5.0YR 6.0/15	0.5510	0.4214	30.05	Vivid Orange
Highway Brown	5.0YR 2.75/5	0.4766	0.3816	5.52	Moderate Brown
Safety Yellow	5.0Y 8.0/12	0.4562	0.4788	59.10	Vivid Yellow
Safety Green	7.5G 4.0/9	0.2110	0.4120	12.00	Strong Green
Safety Blue	2.5PB 3.5/10	0.1690	0.1744	9.00	Strong Blue
Safety Purple	10.0P 4.5/10	0.3307	0.2245	15.57	Strong Reddish Purple
Safety White	N9.0/	0.3101	0.3162	78.70	White
Safety Gray	N5.0/	0.3101	0.3162	19.80	Medium Gray
Safety Black	N1.5/	0.3101	0.3162	2.02	Black

Figure 4-21. Specification of ANSI Safety Colors Viewed Under CIE Standard Illuminant C

The specification of these colors is given in Figure 4-21. Designers must be aware that these color specifications are based on illuminant C. The colors will be recognizable under daylight and conventional incandescent and fluorescent light sources, which have a broad spectrum. High-intensity discharge light sources render some colors differently than the sources mentioned above. They can cause some confusion, especially at illuminances of 5 lx (0.5 fc) and lower, which are not uncommon in industrial spaces. Possible solutions are given in References 52 and 53. Color tolerance charts showing the safety colors and their tolerance limits are available from Hale Color Consultants.

Chromaticity and Illuminance

The chromaticity of the light source should be matched to the illuminances.[54] From experience it has been found that at low illuminances a "warm light" (less than 3300 K) is usually preferred, but the color temperature of the light source should increase as the illuminance increases.[54] Recent data, however, both support and contradict this assertion, so these statements cannot be taken as conclusive.

COLOR RENDERING

As previously discussed, lamps cannot be assessed for color rendering properties by visual inspection of the lamps themselves. To provide a color rendering index (CRI), it is necessary to have accurate and precise spectroradiometric measurements of light sources (see Chapter 2, Measurement of Light and other Radiant Energy). It is also necessary to understand the mechanisms of color vision, particularly chromatic adaptation. Knowledge in this area is still incomplete. However, in most cases it is possible to provide a useful answer. The recommendations below are based on the following assumptions.

The color shift that occurs when an object is observed under different light sources can be classified in three ways: as a colorimetric shift, an adaptive shift, or a resultant color shift in which the first two are combined. To understand the subject it is extremely important that the three concepts be understood:

1. Colorimetric shift is the difference between the color (luminance and chromaticity) of an object illuminated by a nonstandard source and the color of the same object illuminated by the standard source, usually measured on a scale appropriate for assessing color differences.

2. Adaptive color shift is the difference in the perceived color of an object caused solely by chromatic adaptation.

3. Resultant color shift is the difference between the perceived color of an object illuminated by a nonstandard source and that of the same object illuminated by the standard source for specified viewing conditions. The conditions usually are that the observer shall have normal color vision and be adapted to the environment illuminated by each source in turn. The color shift is the resultant of the colorimetric and adaptive color shifts.

The colorimetric shift can be determined using standard CIE conventions, but determination of the adaptive shift requires some assumptions about the effects of chromatic adaptation.

CIE Test-Color Method

The CIE recommends a test-color method for measuring and specifying the color rendering properties of light sources.[1] It rates lamps in terms of a color rendering index (CRI) that represents the degree of resultant color shift of a test object under a test lamp in comparison with its color under a standard lamp of the same correlated color temperature. The indices are based on a general comparison of the lengths of chromaticity-difference vectors in the 1964 uniform color space. The rating consists of a general index, R_a, which is the mean of the special indices, R_i, for a set of eight test-color samples that have been found adequate to cover the hue circuit (Plate 6). This can be supplemented by special indices based on such special test samples as CIE colors 9 to 14. Unless otherwise specified, the reference light source for sources with a correlated color temperature below 5000 K is a planckian radiator of the same correlated color temperature (Figure 4-14). For 5000 K and above, the reference source is one of a series of spectral energy distributions of daylight based on reconstituted daylight data[30] developed from daylight measurements made in Enfield, England; Rochester, N.Y.; and Ottawa, Canada. Tables of colorimetric data are included in the CIE recommendations for planckian radiators up to 5000 K, and on these reconstituted daylight curves from 5000 K to infinity, for eight general and six special test-color samples.

The current version of the CIE method is basically the same as an earlier version but with a better correction for the adaptive color shift. A paper by Nickerson and Jerome[55] on the earlier version provides a working text and formulas, discusses the meaning of the index, and shows applications to a number of lamps. A 1962 IES report[4] discusses in more detail the problems involved in the more-than-ten-year study of the subject. It indicates some of the problems, particularly those of chromatic adaptation, that remain to be solved before an all-purpose, completely satisfactory method can be established for rating a lamp, regardless of its color, against a single standard (probably daylight). Because of these problems, the index is not an absolute figure. For example, a 6500-K daylight lamp and a 3000-K warm white lamp having equal values on the general color rendering index will differ from their respective reference illuminants, the CIE phase of daylight D_{65} and the 3000-K planckian radiator by approximately the same amount. These reference illuminants differ from one another in their color rendering, and so will the two lamps tested, even though they have the same general color rendering index.[1] Figure 4-22 shows the basis for the CIE index where the test and reference lamp have the same chromaticity.

CIE ratings are in terms of a single index, R_a, but to provide more information on the color rendering properties of a lamp, it is recommended that this be accompanied by a listing of the eight special index values on which the rating is based. Since the eight test samples cover the hue circuit, this makes it possible to obtain a record of the relative colorimetric shift in the different hues under the test lamp. Plotting the chromaticity difference vectors provides even more information, for this indicates the direction as well as the degree of colorimetric shift that is involved.

If two lamps differ in R_i by approximately 5 units, the colors of test sample *i* rendered by the two lamps will be just perceptibly different under the best conditions, provided that the directions of the color shifts are nearly the same. No such simple rule can be given for R_a. It is obtained as the mean of eight R_i values, and even when two lamps have exactly the same R_a, differences of approximately 5 units or more in one or more of the R_i values can still be possible, so that their color rendering properties will be different for the object colors in question. Where the R_a values are close to 100, the R_i values are unlikely to show variations large enough to result in noticeable color differences. But as the value of R_a decreases from 100, the corresponding special indices R_i show increasing spread. Ratings are illustrated in Figure 4-23 for a number of typical lamps. The best color rendering lamps not only have a high index but also have the least variation in special indices for the different hues that are used as test samples. The closer one comes to a perfect color matching lamp, the tighter must be these tolerances.

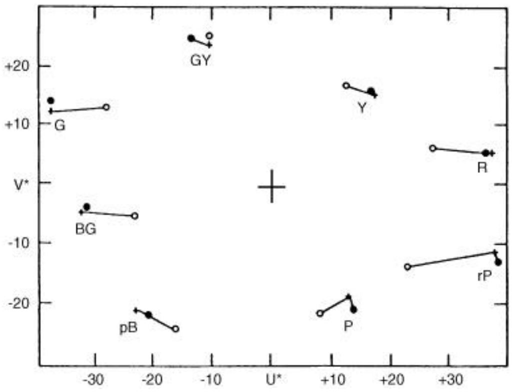


Figure 4-22. Graphic basis for color rendering index.

It makes sense to compare color rendering indices only of lamps with chromaticities close to each other. The standard illuminants A and D_{65} both have CRIs of 100 yet render colors quite differently. Likewise, commercial daylight and warm white lamps will render colors differently even if their CRI values match.

The CIE Technical Committee TC 1-33 might change its recommendations for computing CRI in the future. The present method is based on the CIE 1964 uniform color space, which is now obsolete. In any case, it will eventually be more appropriate to change the basis of color rendering to a color appearance model.

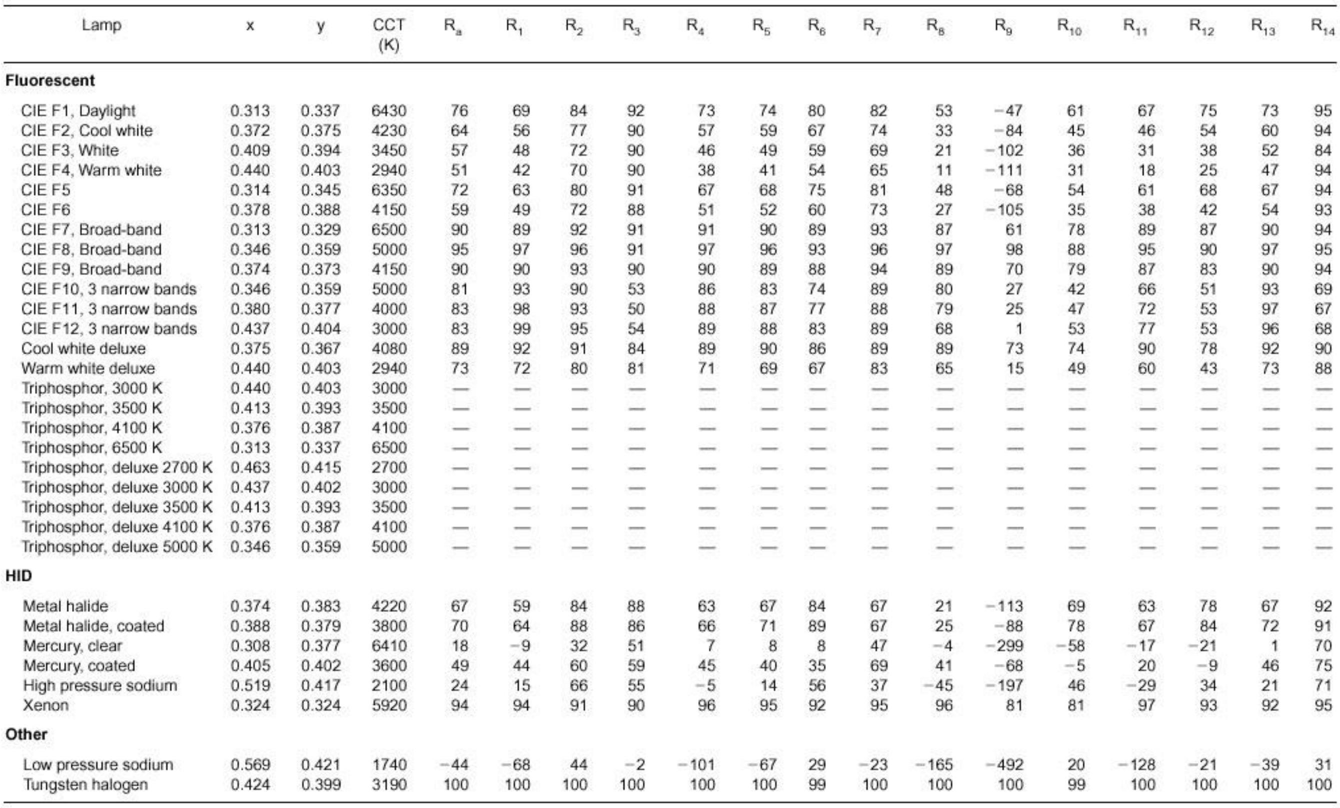
Visual Clarity

The concept of "visual clarity" has been used in several studies[56,57] to indicate a preferred appearance of scenes containing colored objects when illuminated by certain sources. "Visual clarity" seems to be a combination of various factors including perceived color and contrast, color rendering, color discrimination, color preference, and border sharpness, but it is not as yet a well-understood notion.

LIGHT SOURCES FOR COLOR APPRAISAL, COLOR MATCHING, AND COLOR REPRODUCTION

General Principles

General lighting can be unsatisfactory for the precise appraisal of the colors of objects, including matching and reproducing colors. Such tasks are necessary in industries that make and market pigments and dyes, and in arts and industries involving color production (e.g., painting, textile dyeing, photography, and color printing). These tasks are also necessary in commercial evaluation of such naturally colored objects as fibers, foods, minerals, and gemstones. Although color processes often are controlled by means of instrumentation, the ultimate approval of colored products is based on visual judgment, generally the comparison of the product with a colored standard. The grade of a natural material can be based on a visual judgment of the correspondence of its colors to a series of standards.



Lamp	x	y	CCT (K)	R_a	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}	R_{13}	R_{14}
Fluorescent																		
CIE F1, Daylight	0.313	0.337	6430	76	69	84	92	73	74	80	82	53	−47	61	67	75	73	95
CIE F2, Cool white	0.372	0.375	4230	64	56	77	90	57	59	67	74	33	−84	45	46	54	60	94
CIE F3, White	0.409	0.394	3450	57	48	72	90	46	49	59	69	21	−102	36	31	38	52	84
CIE F4, Warm white	0.440	0.403	2940	51	42	70	90	38	41	54	65	11	−111	31	18	25	47	94
CIE F5	0.314	0.345	6350	72	63	80	91	67	68	75	81	48	−68	54	61	68	67	94
CIE F6	0.378	0.388	4150	59	49	72	88	51	52	60	73	27	−105	35	38	42	54	93
CIE F7, Broad-band	0.313	0.329	6500	90	89	92	91	91	90	89	93	87	61	78	89	87	90	94
CIE F8, Broad-band	0.346	0.359	5000	95	97	96	91	97	96	93	96	97	98	88	95	90	97	95
CIE F9, Broad-band	0.374	0.373	4150	90	90	93	90	90	89	88	94	89	70	79	87	83	90	94
CIE F10, 3 narrow bands	0.346	0.359	5000	81	93	90	53	86	83	74	89	80	27	42	66	51	93	69
CIE F11, 3 narrow bands	0.380	0.377	4000	83	98	93	50	88	87	77	88	79	25	47	72	53	97	67
CIE F12, 3 narrow bands	0.437	0.404	3000	83	99	95	54	89	88	83	89	68	1	53	77	53	96	68
Cool white deluxe	0.375	0.367	4080	89	92	91	84	89	90	86	89	89	73	74	90	78	92	90
Warm white deluxe	0.440	0.403	2940	73	72	80	81	71	69	67	83	65	15	49	60	43	73	88
Triphosphor, 3000 K	0.440	0.403	3000	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Triphosphor, 3500 K	0.413	0.393	3500	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Triphosphor, 4100 K	0.376	0.387	4100	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Triphosphor, 6500 K	0.313	0.337	6500	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Triphosphor, deluxe 2700 K	0.463	0.415	2700	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Triphosphor, deluxe 3000 K	0.437	0.402	3000	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Triphosphor, deluxe 3500 K	0.413	0.393	3500	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Triphosphor, deluxe 4100 K	0.376	0.387	4100	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Triphosphor, deluxe 5000 K	0.346	0.359	5000	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
HID																		
Metal halide	0.374	0.383	4220	67	59	84	88	63	67	84	67	21	−113	69	63	78	67	92
Metal halide, coated	0.388	0.379	3800	70	64	88	86	66	71	89	67	25	−88	78	67	84	72	91
Mercury, clear	0.308	0.377	6410	18	−9	32	51	7	8	8	47	−4	−299	−58	−17	−21	1	70
Mercury, coated	0.405	0.402	3600	49	44	60	59	45	40	35	69	41	−68	−5	20	−9	46	75
High pressure sodium	0.519	0.417	2100	24	15	66	55	−5	14	56	37	−45	−197	46	−29	34	21	71
Xenon	0.324	0.324	5920	94	94	91	90	96	95	92	95	96	81	81	97	93	92	95
Other																		
Low pressure sodium	0.569	0.421	1740	−44	−68	44	−2	−101	−67	29	−23	−165	−492	20	−128	−21	−39	31
Tungsten halogen	0.424	0.399	3190	100	100	100	100	100	100	99	100	100	100	99	100	100	100	100

Figure 4-23. Color and Color Rendering Characteristics of Common Light Sources

Since two objects might match under one kind of illumination but not match under another, the kind of illumination used for inspection is crucial. The specification of the illuminant must be expressed in any written or oral contract or other commitment involving color production. Very often the intention is to have the product match the standard satisfactorily under any kind of illumination likely to be encountered. This requires that the product be compared with the standard under several kinds of illumination, typically two phases of daylight of widely different correlated color temperature, as well as fluorescent and incandescent light. Natural daylight is highly variable, not available at night, and not easily available in interior spaces, so a source of electric light that simulates daylight is usually used.

Clearly, lighting for these purposes must meet specifications far more stringent than those that are applied to general interior and exterior lighting, and these specifications have been agreed to by national and international standardizing bodies. Fortunately for the practicing illuminating engineer, the specifications are easily met because viewing booths that exclude extraneous light and provide several kinds of illumination meeting these standards are commercially available and are customarily used in these applications.

Light used for these purposes must have a specified SPD. Because of the widespread natural occurrence and deliberate use of fluorescence, the ultraviolet spectrum must be specified as well as the visible spectrum. Other, less restrictive means of specifying light are not satisfactory. A given correlated color temperature permits an infinite variety of chromaticities and a given chromaticity permits an infinite variety of spectra. The spectral quality of light sources that simulate standard daylight for judging colors is assessed by a method adopted by the CIE.[58] The basic premise of this method is that the best of several available sources is the one that causes the least average color difference for specified pairs of hypothetical colored surfaces that match metamerically in daylight.

In some cases, especially in the grading of natural materials, the color difference between grades can be accentuated and made more readily apparent by a well-chosen light source. For example, if materials yellow with age, yellowness can be regarded as undesirable. Slight differences in yellowness can be more readily perceived with a light source that appears white but is rich in the short-wavelength end of the spectrum.

Illuminance affects color judgment and must be specified. Dark colors require more illuminance than light colors.

Some materials, notably wood and textiles as well as metallic and pearlescent paints, might match under certain angular conditions of illumination and viewing, but not under others. For this reason, the geometry of illumination and viewing must be specified. In most specifications, opaque surfaces are illuminated at 45° to their normal and viewed on the normal, or the reverse of this arrangement.

The background or surround color influences color judgments, so it must be specified. Small color differences are best perceived if the surround is of a color between the two colors being compared. This ideal is usually approximated by the use of a neutral (black, gray or white) surround of approximately the same lightness as the specimens. A neutral surround does not influence the appearance of hue.

When glossy specimens are viewed at 45° to their normal, something on the opposite side of the normal can be seen reflected in the surfaces. That specularly reflected light is added to the diffusely reflected light, interfering with color judgment. It is standard practice to minimize this effect by placing black velvet on the opposite side.

Color differences usually are controlled through the use of a set of seven colors that constitutes a color tolerance standard. The set utilizes an ideal color, the lightest and darkest acceptable colors of the same hue and chroma, the two extremes of acceptable hue variation with the same lightness and chroma, and the weak and strong (chroma) limits with the same lightness and hue. The colors are arranged on a card with slots permitting the direct comparison of the underlying surface with each of the standard colors.

Standard Viewing Conditions

The grading of raw cotton, on the basis of its color, is a visual task of great commercial importance. Studies in the U.S. Department of Agriculture, reported as early as 1939, provided the basis for specifying 600 to 800 lx (60 to 80 fc) and a SPD closely simulating daylight, with a correlated color temperature of 7500

K, for this task. To minimize glare, the geometric relationship of the luminaires to the work surface is also specified.[59]

Recommendations for viewing textiles have been made by the American Association of Textile Chemists and Colorists, and for judging diamonds by the Gemological Institute of America. The results of experiments coordinated by a committee of the Inter-Society Color Council indicated that textile color matchers prefer a range of correlated color temperatures that depends on the illuminance, as shown in Figure 4-24.[60]

Conditions for comparison of opaque specimens, in general, have been standardized by the American Society for Testing and Materials (ASTM).[61] Several different SPD are specified, so proposed color matches can be examined under various lights to test for or optimize metamerism. In addition to daylight, a light simulating sunlight, a typical tungsten source, and cool white fluorescent lamps are specified. For materials of medium lightness, an illuminance of 1000 to 1250 lx (100 to 125 fc) is recommended for critical evaluation, and 750 to 1750 lx (75 to 175 fc) for general evaluation. For very light materials, 500 lx (50 fc) is adequate, and for very dark materials, the illuminance can be increased to as much as 2000 lx (200 fc).

Specifications for viewing conditions in photography and graphic arts have been standardized by the American National Standards Institute (ANSI). Efforts in improving these specifications are ongoing.[62] In these applications, it is standard practice to use illumination simulating a phase of daylight having a correlated color temperature of 5000 K. Large transparencies are viewed against a luminous surface of standard luminance and spectral distribution, and small transparencies are viewed by means of a standardized projection system. Both methods permit direct comparison of transparencies and opaque prints.

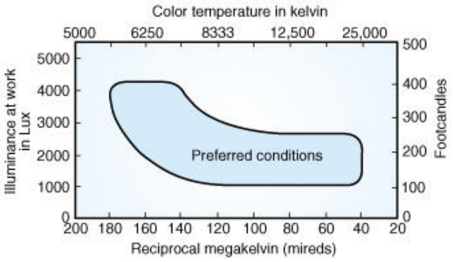


Figure 4-24. Tests conducted under the direction of the Inter-Society Color Council show the characteristics of preferred daylight illumination conditions for color matching, grading, and classing.

In the United States, standards other than those for photography and color printing specify a phase of daylight having a correlated color temperature of 7500 K, typical of light from a slightly overcast north sky (south sky in the southern hemisphere). Most of the rest of the world follows a recommendation of the CIE to use 6500 K, which corresponds to average daylight. Viewing booths of both kinds are commercially available.

Color in Imaging Technology

Color photography is based on the same general principle as color vision: the eye employs three kinds of cones, and color film has three photosensitive layers, each maximally sensitive to a different part of the visible spectrum. Films designed for making transparencies are different from those designed for making opaque prints, but the same three-layer principle is used. The spectral sensitivities of the three film layers differ considerably from those of the human visual system, and the dye images are at best metameric matches to the objects photographed. Objects that match when viewed directly might not match in the photograph, and objects that do not match when viewed directly might match in the photograph. Color films are designed to give satisfactory color rendition when the subject is illuminated with a specific kind of source. Flash lamps, for example, are designed to simulate daylight. ANSI and the International Organization for Standardization (ISO) have adopted standards specifying light sources for testing films, the color contribution of camera lenses, and methods for testing flash equipment, as well as conditions for viewing prints and transparencies.[63-67]

Television images are mediated through the spectral sensitivities of the camera, the electronic processing of the image, and the three color phosphors on the face of the display tube. The problems associated with color reproduction in photography are also experienced in television, with the added burden of a far greater variety in the characteristics of the final display medium. The quality of the color reproduction depends, of course, on the spectral quality of the illumination of the scene to be televised, as well as the characteristics of the equipment.

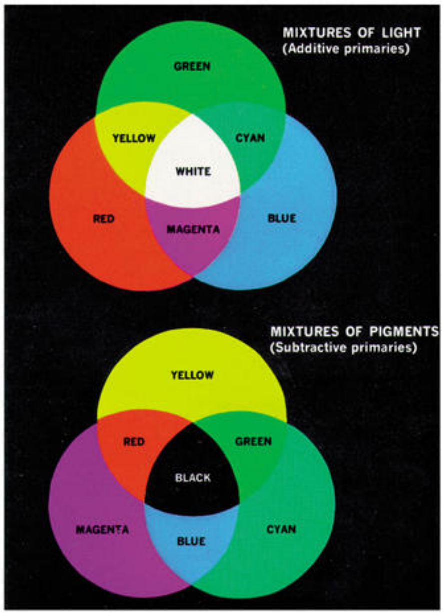
In color printing, various kinds of plates are used to apply colored inks to paper. The inks are usually yellow, magenta, cyan, and black. The plates are made by photoengraving or by electronic scanners. Like color photography, color printing also can suffer from discrepancies in color appearance with the actual objects.

The color rendition of color reproduction processes can be evaluated by the use of a commercially available colored test chart designed for this purpose.[68] The chart is photographed, viewed by television equipment, or printed, and the resulting image is compared with the original chart or a second chart of the same kind, under standardized viewing conditions. The comparison can be made quantitative by performing color difference measurements. These charts also can be used to make simple direct visual appraisals of the color rendering of light sources.

The CIE recognizes that lighting is critical for the appearance of colors displayed by CRTs and printers. The CIE has established a new division (Division 8 Image Technology) to address these important issues.

Plate 1

Primary and secondary colors of light and pigment

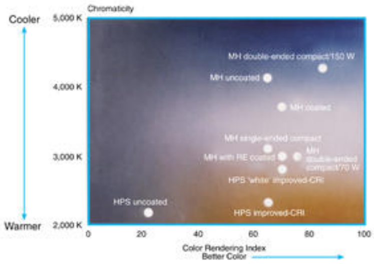


The primary colors of light (red, green, and blue) can be added to produce the secondary colors of light— magenta (red plus blue), cyan (green plus blue), and yellow (red plus green). Thus, the colors of light are called "additives." A secondary color of light mixed in the right proportions with its opposite primary will produce white light. For example, a mixture of yellow and blue light will result in white light. Thus, yellow and blue are complementary colors of light, as are cyan and red, and magenta and green. Color television reception is an example of the "additive" nature of light colors.

In pigments or colorants, however, a primary color is defined as one that subtracts or absorbs a primary color of light and reflects or transmits the other two. So the primary colors in pigments (sometimes called subtractive primaries) are magenta, cyan, and yellow— the secondary colors of light.

This subtractive nature of pigments is easily demonstrated by placing magenta, cyan, and yellow pigment filters over a source of white light (see adjacent illustration). Each of the pigment filters absorbs or subtracts one of the primary colors from the light. Where two filters overlap, one of the primaries of light is transmitted. For example, yellow filter absorbs blue (transmitting red and green) and the magenta filter absorbs green (transmitting red and blue). Together, the filters transmit only red, having, in effect, subtracted the other two primary colors from the white light. Where the three pigment filters are superimposed at the center, all light is absorbed. Complementary pigment colors are the same as those in light—yellow and blue, cyan and red, magenta and green.

Plate 2



The chart above shows both dimensions of light source color–chromaticity and color rendering–for several types of HID light sources. Designers often chose a chromaticity first to match the "atmosphere" appropriate for the application. Then a light source is selected with the highest color rendering and best performance and physical characteristics to meet the requirements of the installation.

Plate 3

ADDITIVE SPATIAL FUSION. The green dot pattern in the shape of the United States will merge into a solid gray when viewed from a distance. At that distance, the eye can no longer distinguish individual colors (yellow and green) and the phenomenon produced is "gray." This same phenomenon is used in all lithographic printing in this book.

CHAMELEON EFFECT. Colors of medium value and chroma will appear to change in the direction of lighter, brighter colors – or darker, duller colors surrounding it. The blue bars in this illustration are all printed with exactly the same color of ink – but they appear lighter next to yellow, and darker next to black.

DAY-NIGHT VISION. Under good lighting conditions the red flower will appear brighter than the blue. If viewed for five to ten minutes in very dim light, the red flower will almost disappear while the blue flower will stand out as light gray. Look one or two inches to the side of the blue flower to see it more clearly since the rods (used for scotopic or night vision) in the eye are most numerous in the retina just outside the foveal pit.

COMPLEMENTARY AFTERIMAGE. To see red and white fireworks in a blue-violet sky, stare for 30 seconds at the black dot just below center – then look at the black dot in the white space. Prolonged concentration on any colors will reduce eye sensitivity to them, and the reverse, or complementary colors, remaining unaffected, will dominate the afterimage for a brief period until balance is restored.

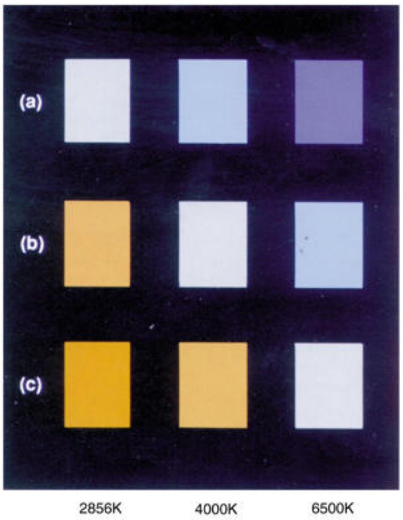


Plate 4. Illustration of appearance of sources of different color temperatures after different chromatic adaptations. (a) After adaptation to 2856 K; (b) after adaptation to 4000 K; (c) after adaptation to 6500 K. Colors shown are only approximate representations.

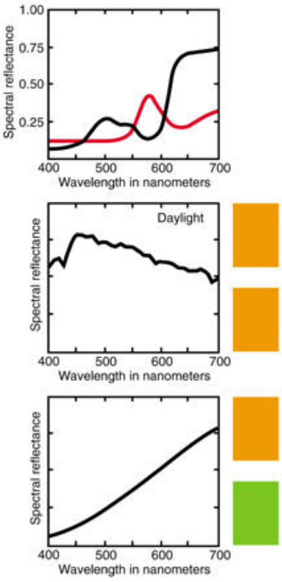


Plate 5. Illustration of metamerism of reflecting objects. The objects whose spectral reflectance curves are shown here have the same color when illuminated by daylight but are quite different in color when illuminated by an incandescent source. The actual colors shown are for illustration purposes only and are not accurate representations of the color appearance.

Test color no.	Munsell notation	CIE specification			ISCC-NBS name
		x	*y*	*y*	
1	7.5 R 6/4	0.375	0.331	29.9	Light grayish red
2	5 Y 6/4	0.385	0.395	28.9	Dark grayish yellow
3	5 GY 6/8	0.373	0.464	30.4	Strong yellow green
4	2.5 G 6/6	0.287	0.400	29.2	Moderate yellowish green
5	10 BG 6/4	0.258	0.306	30.7	Light bluish green
6	5 PB 6/8	0.241	0.243	29.7	Light blue
7	2.5 P 6/8	0.284	0.241	29.5	Light violet
8	10 P 6/8	0.325	0.262	31.5	Light reddish purple
9	4.5 R 4/13	0.567	0.306	11.4	Strong red
10	5 Y 8/10	0.438	0.462	59.1	Strong yellow
11	4.5 G 5/8	0.254	0.410	20.0	Strong green
12	3 PB 3/11	0.155	0.150	6.4	Strong blue
13	5 YR 8.4	0.372	0.352	57.3	Light yellowish pink (Caucasian complexion)
14	5 GY 4/4	0.353	0.432	11.7	Moderate olive green (leaf green)

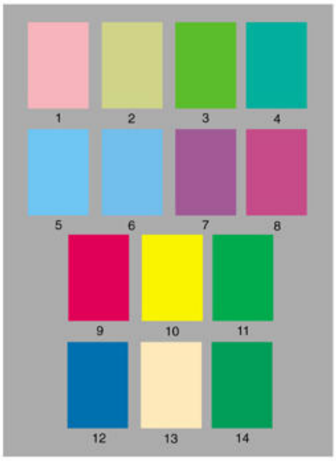


Plate 6. Specifications of test colors used in calculating the CIE color rendering index (calculated for CIE standard illuminant C). The definitive specifications are in terms of spectral radiance factor. The colors shown are approximations and should not be used in place of the actual samples.

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5

Nonvisual Effects of Optical Radiation

Humans, animals, and plants have complex physiological responses to the daily and seasonal variations in solar radiation under which they evolved. The spectral power distribution of solar radiation is shown in Figure 5-1.

The study of the interaction of biological systems with nonionizing radiant energy in the ultraviolet (UV), visible, and infrared (IR) portions of the electromagnetic spectrum is known as photobiology. Photobiological responses result from chemical and physical changes induced by the quantal absorption of radiation by specific molecules in the living organism. The absorbed radiation produces excited electronic states in these molecules, which can lead to photochemical reactions of biological consequence. The distinguishing feature of photochemical reactions is that the activation energy is provided by the quantum absorption of nonionizing photons, which cause reactions to occur at low (physiological) temperatures.

The human visual system is discussed in Chapter 3, Vision and Perception. Extravisual photobiological effects occurring in humans, animals, microorganisms, and plants, as well as nonbiological effects on matter, are covered in this chapter. The term "optical radiation" refers to the wavelength of the radiant energy described in this chapter (between 100 nm and 1 mm), primarily consisting of UV, visible, and IR radiation.

EFFECTS ON HUMANS AND ANIMALS (PHOTOBIOLOGY)

The effects of solar radiation on humans and animals include such wide-ranging phenomena as damage to ocular tissues, skin effects, tumor formation, and the synchronization of biological rhythms. A variety of diseases have been treated with visible or UV energy, alone or in combination with sensitizing drugs. Since the beginning of recorded history, psoralen, a UV-activated drug, combined with exposure to solar UV radiation, has been the therapy for vitiligo, a skin condition marked by an absence of normal pigment. By the turn of the century, lupus vulgaris, a condition where skin nodules are present, was shown to be cured with UV either from sunlight or from carbon arcs. Psoriasis, a skin condition where lesions are covered with scales, is now being alleviated with the same therapy that has been applied to vitiligo, using electric light sources of more constant UV output than from the sun. Visible radiation, particularly the short wavelengths (400 to 500 nm), is used in the phototherapy of jaundiced infants. Photodynamic therapy (PDT) is a rapidly developing field for the treatment of such disorders as cancers involving rapid cell division. A photoactive dye is absorbed by dividing cells. When the dye is photoactivated in the presence of oxygen, free radicals develop that critically damage the reproducing cells. Other extravisual effects of light include the regulation of biological rhythm and neuroendocrine responses.

Effects on the Eye[1-38]

For the purposes of this discussion, the optical radiation spectrum is divided into three components: UV, 100 to 380 nm; visible and near-IR, 380 to 1400 nm; and IR, 1400 nm to 1 mm. Figure 5-2 summarizes in abbreviated form the overall effects of radiation as a function of wavelength and indicates that UV bands, in particular, induce such adverse effects as actinic erythema (reddening of the skin), photokeratitis (an inflammation of the cornea, also commonly known as "flash blindness" or "welder's burn"), and photosensitized skin damage, as well as some beneficial effects, as in phototherapy. Three elements are involved in optical radiation damage to various components of the eye: the accessibility of a given wavelength to the tissue in question, the absorbance of that wavelength, and the ability of the tissue to deal with the insult that the absorption of energy represents.

UV Radiation Effects. The UV region of the electromagnetic spectrum is subdivided by the Commission International de l'Éclairage (CIE) into near (UV-A, 315 to 400 nm), middle (UV-B, 280 to 315 nm) and far (UV-C, 100 to 280 nm) UV bands. Figure 5-3 shows that for wavelengths less than 320 nm, nearly all of the radiation is absorbed by the cornea. Between 320 and 400 nm, much of the UV radiation is absorbed by the lens; the proportion is dependent on age (Figure 5-4). The optical media of the human eye, until early adulthood, transmit a small percentage of UV radiation to the retina, resulting in a theoretical visual response for wavelengths as short as 300 nm.

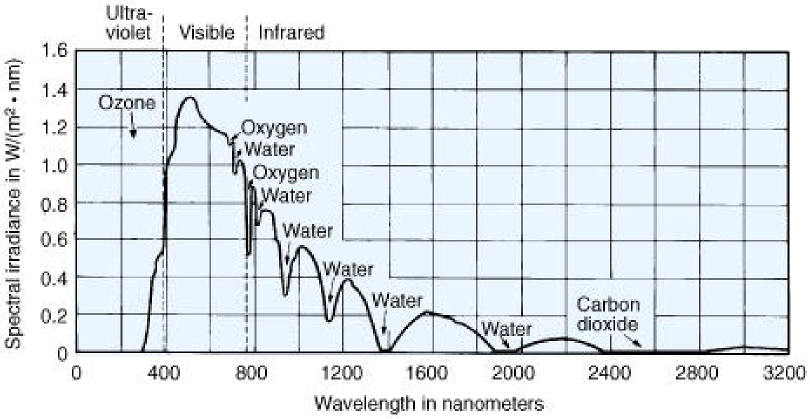


Figure 5-1a. Spectral power distribution of solar radiation at sea level, showing the ozone, oxygen, water, and carbon dioxide absorption bands.

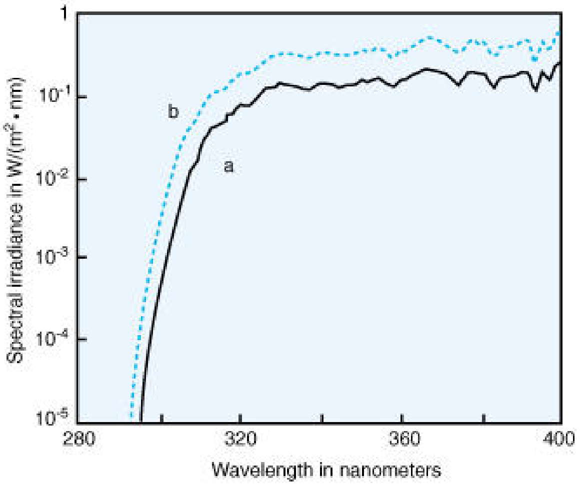
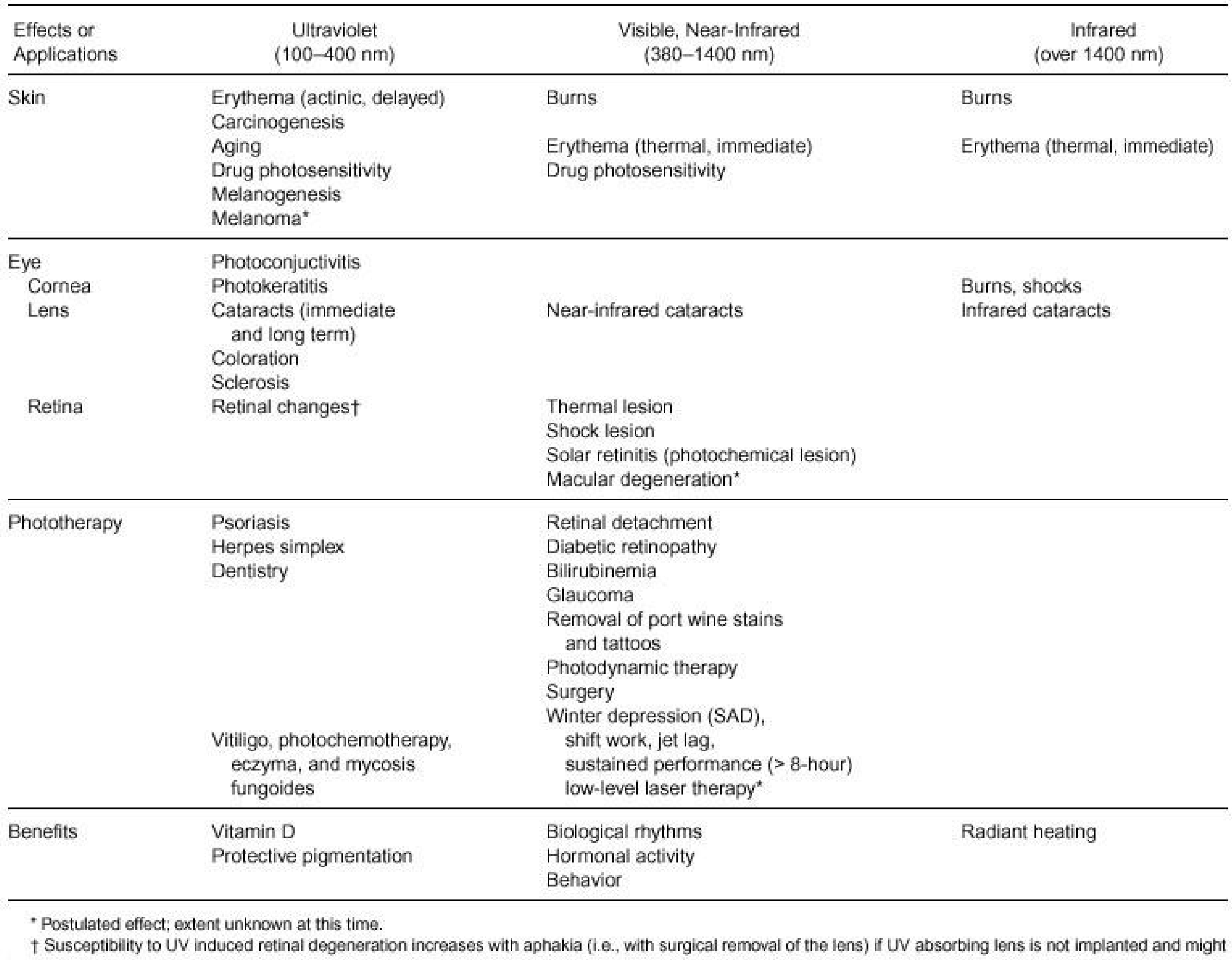


Figure 5-1b. Global irradiance, solar noon at Durham, UK (55° N) : (a) 2 October 1986 (uniform light cloud); (b) 1 July 1986 (clear sky).

Photokeratitis is a painful but not necessarily serious inflammation of the epithelial (outermost) layer of the cornea. The period of latency between exposure and the onset of symptoms varies from 2 to 8 hours, depending on the amount of radiation received. For moderate exposures, the effects are more frightening than serious. The symptoms include inflammation of the conjunctiva accompanied by a reddening of the surrounding skin and eyelids. There is a sensation of sand in the eyes, tearing, sensitivity to light, and twitching of the eyelids. Recovery is rapid and usually complete within 48 hours except for severe cases. The action spectrum, similar to that for skin erythema, peaks at 270 to 280 nm (with recent research suggesting that it is closer to 270 nm) (Figure 5-5).

Lenticular effects from UV radiation recently have been undergoing extensive investigation. The lens shows a number of changes with aging, including a yellowing coloration, an increasing proportion of insoluble proteins, sclerosis with loss of accommodation, and cataract. There is a growing body of evidence, mostly epidemiological, to implicate UV radiation in these changes. For example, cataract extractions are significantly more frequent in India than in western Europe. Part of the difference may be due to diet and genetic factors, but most authorities believe that exposure to sunlight plays an important role. While many of the early epidemiological studies of cataract have been inconclusive, more recent attempts have shown statistical significance in the relationship between cortical lens opacities and lifelong UV-B exposure in persons living and working in high levels of solar energy.[35] Suggestions have been made that UV-A also may have a role in cataract formation. There are arguments[21] that UV exposure might not be a significant causal factor for cataracts. Until these issues are resolved, the conservative approach is to minimize unnecessary UV exposure of the eyes.

Retinal effects of UV radiation are difficult to categorize because they depend on the individual filtering capabilities of the preretinal ocular media. In adults, the crystalline lens, which typically absorbs wavelengths below about 400 nm, effectively shields the retina from UV radiation. Studies have shown, however, that a small percentage of UV radiation can reach the retina in human adults up to 30 years of age. Removal of the lens in cataract surgery renders the retina more susceptible to damage from wavelengths down to 300 nm. If a UV-blocking intraocular lens (IOL) is surgically implanted, however, then the UV absorption is restored. UV shielding is also available for rigid gas-permeable (RGP) and hydrogel varieties of contact lenses. Data on UV radiation from some common sources can be found in the "Museum" section of Chapter 14, Lighting for Public Places and Institutions.



Effects or Applications	Ultraviolet (100–400 nm)	Visible, Near-Infrared (380–1400 nm)	Infrared (over 1400 nm)
Skin	Erythema (actinic, delayed)	Burns	Burns
	Carcinogenesis		
	Aging	Erythema (thermal, immediate)	Erythema (thermal, immediate)
	Drug photosensitivity	Drug photosensitivity	
	Melanogenesis		
	Melanoma*		
Eye	Photoconjuctivitis		
Cornea	Photokeratitis		Burns, shocks
Lens	Cataracts (immediate and long term)	Near-infrared cataracts	Infrared cataracts
	Coloration		
	Sclerosis		
Retina	Retinal changes†	Thermal lesion	
		Shock lesion	
		Solar retinitis (photochemical lesion)	
		Macular degeneration*	
Phototherapy	Psoriasis	Retinal detachment	
	Herpes simplex	Diabetic retinopathy	
	Dentistry	Bilirubinemia	
		Glaucoma	
		Removal of port wine stains and tattoos	
		Photodynamic therapy	
		Surgery	
	Vitiligo, photochemotherapy, eczyma, and mycosis fungoides	Winter depression (SAD), shift work, jet lag, sustained performance (> 8-hour) low-level laser therapy*	
Benefits	Vitamin D	Biological rhythms	Radiant heating
	Protective pigmentation	Hormonal activity	
		Behavior	

* Postulated effect; extent unknown at this time.

† Susceptibility to UV induced retinal degeneration increases with aphakia (i.e., with surgical removal of the lens) if UV absorbing lens is not implanted and might

Figure 5-2. Physiological Effects or Applications of Ultraviolet, Visible and Near-Infrared, and Infrared Radiation

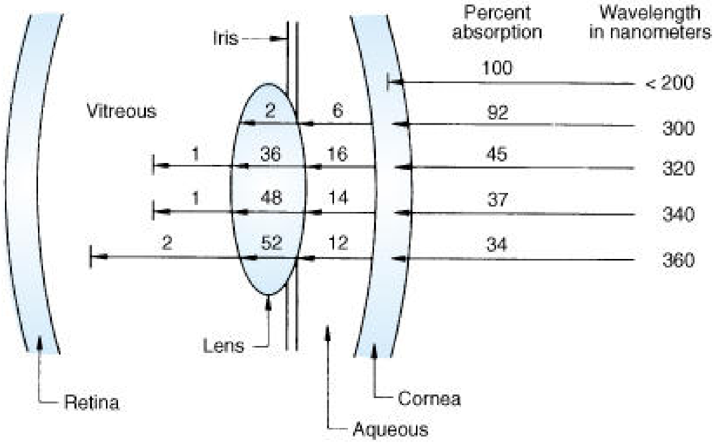


Figure 5-3. Percentage of energy on the surface of the cornea absorbed by various layers in the normal adult eye.

Visible and Near-IR Effects. The IR region of the electromagnetic spectrum has been divided into three subregions: IR-A (near-IR, 780 to 1400 nm), IR-B (middle-IR, 1400 to 3000 nm), and IR-C (far-IR, 3000 nm to 1 mm) bands. Visible radiation occupies the wavelength region bounded by UV and IR, falling between approximately 400 and 780 nm.

While the sun radiates at all wavelengths across the electromagnetic spectrum, only UV, IR, and visible radiation reach the earth's surface. Retinal injury resulting in a loss of vision (scotoma) following observation of the sun has been described throughout history. The incidence of chorioretinal injuries from fabricated light sources is extremely small and is no doubt far less than the incidence of eclipse blindness. Until recently, chorioretinal burns resulting from industrial operations were rare occurrences. Indeed, this is still largely true, since the normal aversion to high-brightness light sources (the blink reflex and movement of the eyes away from the source) provides adequate protection unless the exposure is hazardous within the duration of the blink reflex. The recent revolution in optical technology, however, forged principally by the invention of the laser, has meant a great increase in the use of high-intensity, high-radiance sources. Many such sources have output parameters significantly different from those encountered in the past and may present serious chorioretinal burn hazards. In addition to lasers, one may encounter the following sources of continuous optical radiation in industry: compact arc lamps (as in solar simulators), tungsten-halogen lamps, gas and vapor discharge tubes, electric welding units, and sources of pulsed optical radiation, such as flash lamps and exploding wires. The intensities of these sources may be of concern if adequate protective measures are not taken. Extreme IR irradiances have been linked to corneal, lenticular, and retinal damage; although the ocular structures can adequately dissipate the heat from low-power diffuse IR exposures, the same amount of energy delivered in pulses to very small areas of tissue can cause damage. Coherent light generated by yttrium aluminum garnet (YAG) and argon lasers can penetrate to intraocular structures. Light from krypton, HeNe, and ruby lasers can reach the retina. Such sources have been used therapeutically in retinal photocoagulation procedures.

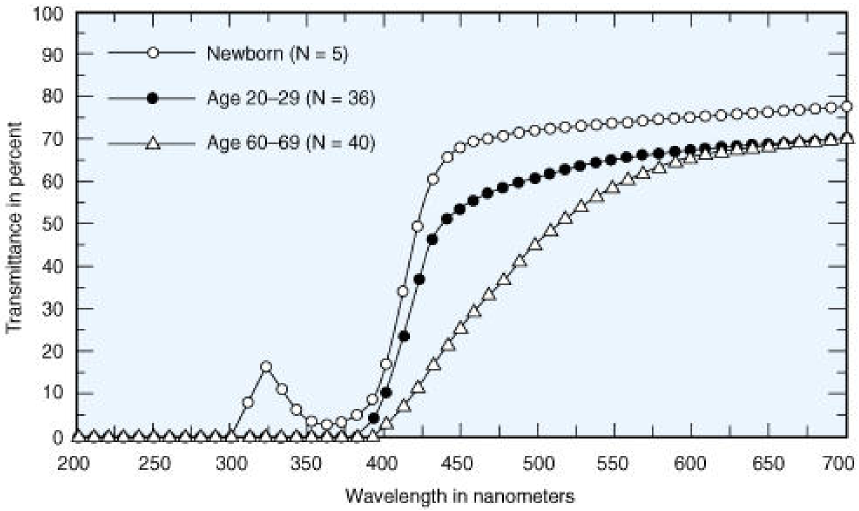


Figure 5-4. Human lens average transmittance.

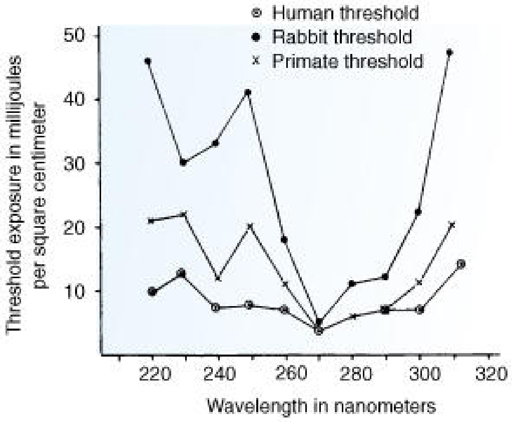


Figure 5-5. Comparison of the radiant exposure thresholds for injuring the cornea of the human, the primate and the rabbit. The data were established by exposing 238 rabbit eyes, 83 primate eyes, and 39 human eyes to ultraviolet radiation.

To place chorioretinal injury data in perspective, Figure 5-6 shows the retinal irradiance for many light sources. It is reemphasized that several orders of magnitude in radiance or luminance exist between sources that cause chorioretinal burns and those levels to which individuals are continuously exposed. The retinal irradiances shown are only approximate and assume minimal pupil sizes and some squinting for the very high luminance sources (except the xenon searchlight, for which a 7-mm-diameter pupil was assumed so as to apply to nighttime illumination).

Light entering the cornea passes through the anterior chamber (which contains the aqueous humor), the lens, and the vitreous humor and impinges upon the retina (Figure 3-1 in Chapter 3, Vision and Perception). Examination of Figure 3-6 shows that between 400 and 1400 nm the retina is vulnerable to radiation effects. Between these wavelengths the retina is by far the most sensitive tissue of the body.

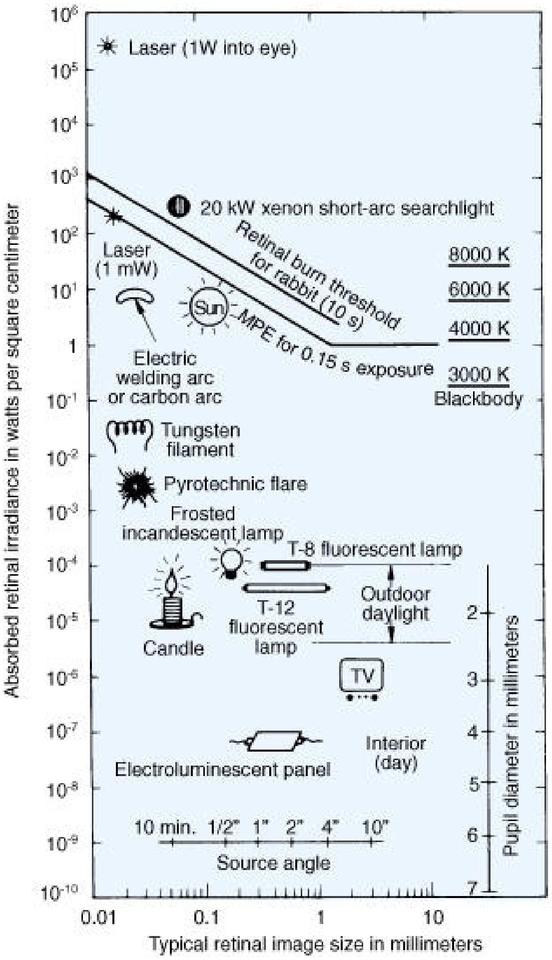


Figure 5-6. The eye is exposed to light sources having radiances varying from about 10^4 to 10^6 W/(cm^{-2} · sr) or less. The resulting retinal irradiances vary from about 200 down to 10^{-7} W/cm^{-2} and even lower; retinal irradiances are shown for typical image sizes for several sources. A minimal pupil size was assumed for intense sources, except for the searchlight. The retinal burn threshold for a 10-s exposure of the rabbit retina is shown as the upper solid line. The maximum permissible exposure (MPE) applied by the U.S. Army Environmental Hygiene Agency in evaluating momentary viewing of continuous-wave light sources is shown as the lower solid line. Approximate pupil sizes are shown at the lower left, based upon exposure of most of the retina to light of the given irradiance.

In the retina, light passes through multiple layers of neural cells before encountering the photoreceptor cells (the rods and cones). Photoreceptors are neural transducers, converting absorbed photons of light into electrical impulses sent to the brain via the optic tract. Just behind the rods and cones is a single layer of heavily pigmented cells (the pigment epithelium), which absorbs a large portion of the light passing through the neural retina. The pigment epithelium acts like a dark curtain to absorb and prevent backscatter from those photons that are not absorbed in the outer segments of the rods and cones. The neural retina itself is almost transparent to light. The pigment epithelium is approximately 10 µm thick, while the choroid, a layer of blood vessels behind it, ranges in thickness from 100 to 200 µm. Most of the light that reaches the retina is converted to heat by the pigment epithelium and the choroid. Sufficiently large quantities of light can generate sufficient heat to damage the retina.

Research in recent decades has demonstrated that for radiant energy between 400 and 1400 nm, there are at least three different mechanisms leading to retinal damage. These are:

1. Thermal damage from pulse durations extending from microseconds to seconds. Except for minor variations in transmittance through the ocular media and variations of absorbance in the pigmented epithelium and choroid, thermal damage is not wavelength dependent.

2. Photochemical damage from exposure to short wavelengths in the visible spectrum for time durations and power densities on the retina that preclude thermal effects. Photochemical damage is wavelength dependent.

3. Mechanical (shock-wave) damage from picosecond and nanosecond pulses of mode-locked or Q-switched lasers.

In terms of exposure time and wavelength there is no abrupt transition from one type of damage to the other. For example, a YAG laser emitting a pulse train of Q-switched pulses (several ns in duration) at 1064 nm can produce a combination of shock-wave and thermal damage depending on the pulse width and the time interval between pulses, whereas an acoustically modulated pulse train from an argon ion laser emitting 10-µs pulses of 488-nm radiation might produce a combination of thermal and photochemical damage.

A number of researchers have shown that long-term exposure to light can cause retinal damage in some animals. For example, when rats and mice are subjected to cool white fluorescent lighting for extended periods of time (weeks to months), they become blind. Histological examination reveals that the photoreceptors in the retinae of these animals have degenerated. Although rodent retinal photoreceptors can be damaged with long exposures to relatively low levels of white light,[37,38] such damage in primates has been demonstrated only with the eyes dilated and at a continuous exposure of 10,800 lux for 12 hours. Exposure of the undilated monkey eye at that illuminance for 12 hours per day for 4 weeks did not produce photoreceptor damage.[34]

The role of light in the incidence of retinopathy of prematurity (ROP) in low-birthweight infants has been explored by several researchers,[9,14,16] because these infants often are exposed to high levels of ambient or phototherapy light. One potential mechanism involves the ability of light of sufficient intensity to catalyze oxygen-producing chemical reactions at the retina.[30,32] Elevated oxygen levels had been implicated as a risk factor for ROP in the 1950s.[2] High intensities of light also increase the rate of blood flow in the ophthalmic artery,[3] which also might elevate oxygen concentrations at the retina. A relationship between light and ROP remains to be demonstrated. Several studies failed to find a link between the two.[1,29]

Far-IR Effects. Very little IR radiation of wavelengths longer than 1400 nm reaches the retina (see Chapter 3, Vision and Perception), but such radiation can produce ocular effects leading to corneal and lenticular damage. Cataracts from exposure to IR radiation have been reported in the literature for a long time, but there are few and no recent data to substantiate the clinical observations. It was previously thought that long-term exposure to IR radiation produces an elevated temperature in the lens which, over a period of years, leads to denaturation of the lens proteins with consequent opacification. It is now believed that IR radiation is absorbed by the pigmented iris and converted to heat that is conducted to the lens, rather than by direct absorption of radiation in the lens. IR cataractogenesis has been reported to occur among glassblowers, steel puddlers, and others who undergo long-term occupational exposure to IR radiation. Present industrial safety practices have virtually eliminated this effect.

Photosensitization. Retinal and other ocular effects also can be increased or decreased in severity by the presence of endogenously or exogenously supplied photoactive compounds. Psoralens, hematoporphyrin derivatives, and other phototherapeutic agents can enhance the damaging effects of various wavelengths on the eye and other tissues. In contrast, vitamin E can act as a quencher of excited-state and related species and has been hypothesized to increase the threshold for light-induced damage. Many new pharmaceutical agents contain conjugated bond and ring structures that also can increase the potential for phototoxic effects.

Effects of UV Radiation on the Skin[39-56]

There are at least two known benefits of UV radiation exposure on skin: the production of vitamin D from precursor chemicals, which are formed in the skin (see below), and the induction of protective pigmentation. Known harmful effects include sunburn, skin cancer, and morphologic alterations (wrinkling, irregularity, altered pigmentation, thinning and thickening of skin), which appear as premature aging. Delayed tanning and increased thickening of skin is a protective response initiated by UV radiation. The function of immediate tanning is uncertain.

Optical Properties of the Skin. The reflectance of skin for wavelengths shorter than 320 nm is low, regardless of skin color; however, from 320 to 750 nm the reflectance is dependent on skin pigmentation. The transmission of UV radiation through the skin depends on wavelength, skin color (melanin content), and skin thickness. In general, transmission increases with increasing wavelength from 280 to 1200 nm. Typically, for those of European descent, the transmittance through the top layer of skin (stratum corneum) is 35% at 300 nm and 60% at 400 nm. In persons of African descent, the transmittance of the stratum corneum is about 20% at 300 nm and 40% at 400 nm. Transmission decreases with increasing melanin content of the skin and with increasing skin thickness (Figures 5-7 and 5-8).

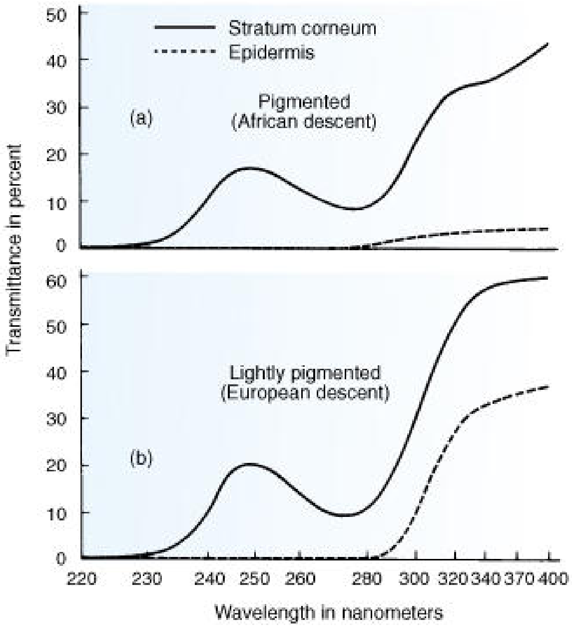


Figure 5-7. Spectral transmission of two individuals, one with heavily pigmented skin and one with lightly pigmented skin. The dashed lines indicate the spectral transmission through the entire epidermis; the solid lines are for the top layer of the epidermis, the stratum corneum, alone.

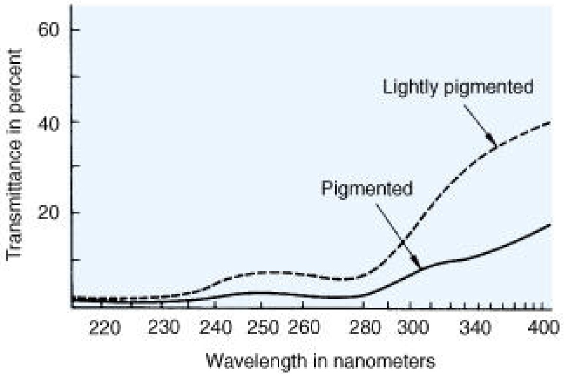


Figure 5-8. Spectral transmission through the epidermis of equal thickness (12 μm). The dashed line is for one person with lightly pigmented skin; the solid line is for one person with heavily pigmented skin.

While skin color is the genetically determined result of a number of factors, the primary factor is melanin. Melanin protects against UV damage by reducing transmission through absorption and scattering. Its quantity, granule size, and distribution all affect skin color. The immediate tanning that occurs with exposure to UV-A radiation and extending into the visible region is the darkening of existing melanin. Delayed tanning results from UV stimulation of the melanin-producing cells (the melanocytes) to produce additional melanin. Pigmentation from this process begins immediately at the subcellular level. Fading requires months, as melanin is lost during the normal shedding process.

Erythema. The delayed reddening (actinic erythema) of the skin caused by exposure to UV radiation is a widely observed phenomenon. The spectral efficiency of this process (Figure 5-9a and b), particularly for sunlight radiation between 290 and 320 nm, has been well studied. The reported erythema action spectrum for wavelengths shorter than 290 nm varies considerably among observers because of differences in the degree of erythema taken as the endpoint criterion and differences in the time of observation after irradiation. In the past, no single erythemal action spectrum had been universally adopted. One based on the work of Coblentz[42] has been used frequently, but subsequent studies have shown significant differences. In 1987, a reference erythemal spectrum was proposed by the CIE (Figure 5-9a and b),[43] and it should supplant the various functions used in the past. Erythema is a component of skin inflammation and results from increased blood volume in superficial cutaneous vessels. Affected skin can therefore be warm and tender.

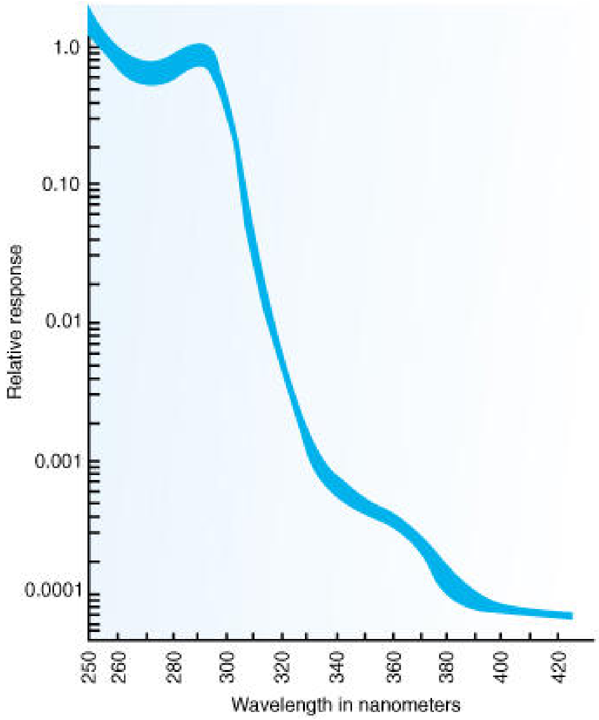


Figure 5-9a. Erythema action spectrum for human skin. Note logarithmic vertical axis.

Relative Erythemal Effectiveness EE(λ)

Wavelength (nm)	EE(λ)
250–298	1.0
300	0.65
310	7.4E-2
320	8.6E-3
330	1.4E-3
340	9.7E-4
350	6.8E-4
360	4.8E-4
370	3.4E-4
380	2.4E-4
390	1.7E-4
400	1.2E-4

$EE(\lambda) = 1.0$ $(250 \le \lambda \le 298 \text{ nm})$
$EE(\lambda) = \exp[0.094\,(298 - \lambda)]$ $(298 \le \lambda \le 328 \text{ nm})$
$EE(\lambda) = \exp[0.015\,(139 - \lambda)]$ $(328 < \lambda \le 400 \text{ nm})$
$\exp(x) = 10^x$

Figure 5-9b. Values Used to Approximate

Approximately 25 mJ/cm^2 of energy at the most effective wavelength (297 nm) causes a barely perceptible reddening in fair-skinned caucasions.[44] This amount of effective energy can be experienced during a 12-min exposure under overhead sun in the tropics where the stratospheric ozone layer is thinner. When the sun is 20° from its zenith and the ozone layer thickness is greater, an exposure of 20 min is typically required for the same degree of reddening.

Exposure to UV radiation (particularly at high irradiance levels) can cause immediate erythema. Fading can occur a few minutes after irradiation ceases, and can reappear after 1 to 3 hours. The greater the dose, the faster the reappearance, and the longer the persistence of erythema.

If the erythema is severe, skin peeling (desquamation) can begin approximately 10 days after exposure. This rapid sloughing off of the top skin layer results from the increased proliferation of skin cells during recovery after UV damage. Desquamation carries away some of the melanin granules stimulated by the UV radiation.

Photoprotection, in its common usage, refers to the protection against the detrimental effects of optical radiation afforded by sunscreens topically applied to the skin. These sunscreens reduce the effect of UV exposure primarily by absorption, but also by reflection in some cases. Some sunscreens are effective and relatively resistant to being washed away by sweating or swimming. Paraaminobenzoic acid (PABA) in an alcohol base has proven quite effective in preventing sunburn. Other materials in use include benzophenones, cinnamates, and salicylates.

Effects of Dermal Radiation on the Immune System. Photoimmunology is the study of nonionizing radiation, predominantly in the UV portion of the spectrum, on the immune system. The photoimmunologic effects of UV radiation are selective: only a few immune responses are affected. The alterations studied in greatest detail are the induction of susceptibility to UV-induced neoplasia and systemic and local suppression of contact hypersensitivity. Most observations have been made in experimental animal systems, although some photoimmunologic effects have been observed in humans.

UV radiation can affect immunity systematically. For example, exposure of the skin to UV at one place on the body can reduce the sensitivity to UV at unexposed sites. This probably occurs through the release of mediators from the skin at the exposure site, which in turn results in the formation of antigen-specific T suppressor lymphocytes (white blood cells); such cells have been found in the spleens of animals.

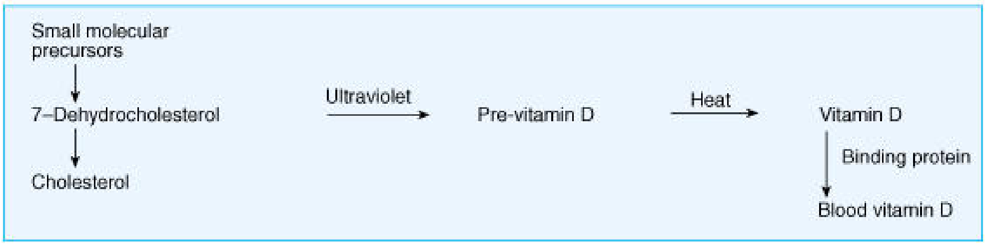


Figure 5-10. Steps in the photoproduction of vitamin D in the skin.

Skin Cancer. The three varieties of skin cancer are basal cell, squamous cell, and malignant melanoma. The frequency of occurrence is in the order stated, basal cell cancer being the most common. The prevalence of basal cell carcinoma varies inversely with latitude. The prevalence of both basal and squamous cell cancer correlates positively with solar UV exposure, but there is some evidence that UV exposure after age 10 might not contribute to basal cell cancer. Basal and squamous cell cancers often are cured if treated promptly. Melanomas are considerably rarer, have a poorer cure rate, and show a poorer correlation with UV exposure.

Whether commonly used electric light sources provide enough UV radiation to increase carcinogenic risk is not certain. The unfiltered, quartz-bulb halogen lamps can emit enough UV radiation to induce actinic erythema in people who work under them for extended periods at high illuminances. Quartz halogen luminaires commonly include glass filters to reduce UV emissions. The Commission Internationale de l'Éclairage (CIE) concludes that there is insufficient evidence to support the hypothesis that common fluorescent lamps can cause malignent melanoma.[53]

Effects of Light on Vitamin D and Calcium Metabolism[57-61]

UV radiation plays an important role in the production of vitamin D in the skin (Figure 5-10). This vitamin is essential for normal intestinal absorption of calcium and phosphorus from the diet and for the normal mineralization of bone. Vitamin D deficiency causes a deficiency of calcium and phosphorus in the bones (such that they bend, fracture, or become painful) and causes such bone-softening diseases as rickets in children and osteomalacia in adults. Vitamin D poisoning, on the other hand, leads to excessive absorption of calcium and phosphorus from the diet and consequently a toxic effect on the skeleton. There is also a resultant increase in the blood calcium concentration and a precipitation of calcium phosphate deposits in vital organs, causing permanent damage or even death. Vitamin D poisoning also causes increased excretion of calcium in the urine, which can produce kidney stones or bladder stones. Mild cases of vitamin D poisoning lead only to increased urinary calcium excretion.

Studies in animals and humans clearly show that UV-B radiation is effective in producing vitamin D in the skin. The action spectrum for this effect has been determined directly in human skin, with a peak of effectiveness near 297 nm. Melanin content in the skin, sunscreen use, and aging decrease the capacity of the skin to produce vitamin D. Furthermore, such environmental factors as changes in latitude, season, and time of day also greatly influence the cutaneous production of vitamin D. Increased exposure to sunlight results in an increased production of vitamin D, which can be detected in the blood. Most of the vitamin D requirement (upwards of 90%) for children and adults comes from casual exposure to sunlight. Elderly or infirm persons who consequently might not be exposed to normal environmental levels of UV radiation depend on dietary sources and supplements for their vitamin D requirement.

Light Versus Diet as Sources of Vitamin D.

Natural foods contain little vitamin D, with the exception of certain fatty fish and fish liver oils. To reduce the dependence on environmental radiation, dairy products, cereals, and certain other foods sometimes are fortified with vitamin D. In some areas, the fortification of dairy products is accomplished with a form of vitamin D (D_2) that is biologically similar to but chemically distinct from the vitamin D (D_3) produced in the skin.

Fortification has virtually eliminated childhood vitamin D deficiency in areas where it was formerly a common and serious public health problem, such as countries in high latitudes. Since many adults do not eat vitamin-D-fortified foods, they remain relatively dependent on cutaneous synthesis to meet their requirements for vitamin D. The current recommended dietary allowance for vitamin D in adults in the United States is 10 μg/day, or 400 international units. Excessive exposure to sunlight does not cause vitamin D intoxication; however, excessive vitamin D intake can occur, although this usually requires ingestion of over 1000 μg (40,000 international units) of vitamin D daily for some time.

Biological Rhythms[6,8,62-99]

Cyclic changes in biological parameters have been observed across species throughout the plant and animal kingdoms. These rhythmic alterations are loosely termed biological rhythms. Biological rhythms manifest themselves at both the macroscopic (multicellular) and microscopic (unicellular and subcellular) levels. Each rhythm has a characteristic amplitude, or magnitude of periodic change, and a characteristic period or frequency of oscillation.

The timing of all biological rhythms involves the coordination, or entrainment, of external time cues (called exogenous zeitgebers) with an internal, or endogenous, pacemaker. External cues are for the most part derived from one or more of four geophysical cycles occurring in the natural environment: the tidal cycle, day-night cycle, lunar cycle, and seasonal cycle. Each natural cycle causes the synchronization of a particular rhythm (called a circarhythm). For example, circadian rhythms (entrained to the day-night cycle) are manifest in almost every plant (the raising and lowering of plant leaves throughout the day) and animal (the sleep-wake cycle). Seasonal rhythms, or circannual rhythms, are also widely manifest, as in plant seed germination and the seasonal breeding of many mammalian species. In addition to circarhythms, many cyclic patterns have been observed that cannot be directly linked to an external environmental synchronization. These rhythms tend to be shorter than one day (ultradian) as in the 90-min sleep cycle, or longer than one day (infradian), as in the female estrous or menstrual rhythm. In short, the timing of all biological rhythms, irrespective of period length, is dependent on both exogenous and endogenous entrainment cues.

Circadian Rhythms.

Rhythms that occur on an approximate 24-h schedule are termed circadian rhythms. Circadian rhythms are of particular interest because they characterize the pattern of variation observed in the majority of human physiologic rhythms, including body temperature, sleep pattern, hormone secretion, and blood pressure. Environmental light is the primary stimulus that mediates entrainment in the mammalian circadian system. Some evidence suggests that behavioral cues (social interaction) and artificial cues (alarm clocks) can also serve as entraining factors in humans.

Evidence for an internal timing mechanism (or biological clock) can be produced by placing an organism under constant conditions (constant light or darkness), thereby denying it access to exogenous time cues. Organisms placed under such conditions continue to manifest circadian rhythms, but at a period characteristic of their own internal clocks. Such rhythms, which vary in period among species, are said to be free-running. In mammals, for example, nocturnal (night-active) species tend to have faster internal clocks with periods less than 24 h, whereas diurnal (day-active) species tend to have slower clocks with periods greater than 24 h. The average human free-running period is longer than 24 h.

Retinal and Ocular Physiology.

In the mammalian circadian system, photic information is processed by the retina and relayed to the hypothalamus of the brain via a neural pathway called the retinohypothalamic tract (RHT). The retinal photoreceptors and photopigments employed in the visual system are discussed in Chapter 3, Vision and Perception. It remains to be determined which photoreceptors and photopigments are responsible for signal transduction in the circadian system. In examining studies from many laboratories, some data have indicated that the peak sensitivity of the circadian and neuroendocrine system is near 500 nm. This supports the hypothesis that rhodopsin or a rhodopsin-based molecule is the primary receptor for circadian and neuroendocrine regulation. Other data, however, have suggested that other photopigments might be involved in these regulatory effects. In rodents, for example, short wavelengths of sufficient intensity in the UV region of the spectrum as well as long wavelengths in the visible region are capable of suppressing melatonin (a hormone secreted by the pineal gland that follows a circadian pattern), entraining circadian rhythms, and influencing reproductive responses. Further studies are required to identify conclusively which specific photoreceptors and photopigments are involved in regulating the circadian and neuroendocrine systems among different animals. Ongoing studies are exploring the role of ocular elements for processing photic stimuli involved in circadian regulation. Specifically, the elements for stimulus processing of the circadian system include gaze behavior relative to the light source, the spectral characteristics of the light source, and the transmission of light through the pupil and ocular media. The ability of the circadian system to integrate photic stimuli spatially and temporally also is under study.

In mammals, most investigators have operated from the assumption that retinal photoreceptive physiology in the eye, as opposed to a photoreception in the skin or some other part of the body, is responsible for circadian and neuroendocrine regulation. Indeed, there are experimental data supporting this assumption in mammals.[64,78,99] However, an intriguing theory proposed that bloodborne elements circulating through the eye might be responsible for transducing photic stimuli for circadian and neuroendocrine regulation.[90] In one study, a single 3-hr bright light pulse of 13,000 lx delivered to the back of the knees of healthy humans systematically reset circadian body temperature and melatonin rhythms.[71] In contrast, a similar bright light exposure failed to elicit acute melatonin supression in healthy humans.[82] Further work is needed to determine whether or not the eyes are exclusive sites for circadian photoreception in humans.

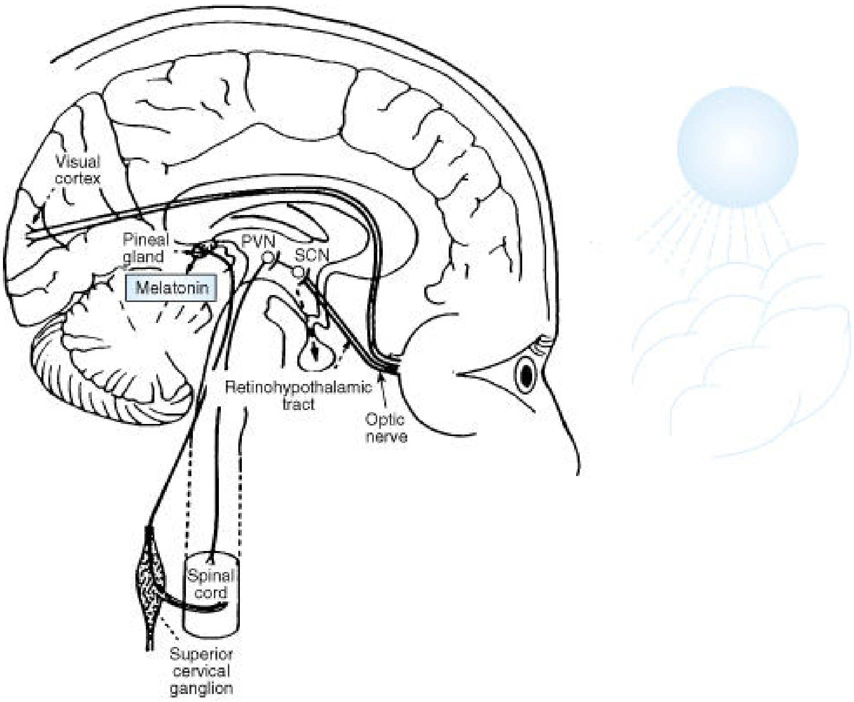


Figure 5-11. Simplified illustration of pathway from the retina to the suprachiasmatic nucleus (SCN) or the hypothalamic "clock" and its long multisynaptic projection to the pineal gland by way of the paraventricular nucleus (PVN) in the hypothalamus. Note this pathway is anatomically separate from the pathway to the visual cortex, which serves the sensory capacity of vision.

Neural Pathway. After retinal detection of photic information, the RHT projects directly to a bilateral structure known as the suprachiasmatic nucleus (SCN), which is believed to be the principal circadian pacemaker in mammals. Ablation of the SCN in rats and hamsters causes arrhythmia (loss of circadian rhythmicity). Neural projections from the SCN travel to many diverse control centers in the nervous system, including other areas of the hypothalamus as well as the thalamus, midbrain, brain stem, and spinal cord. One nerve pathway that carries nonvisual photic information extends from the SCN to the pineal gland (located in the brain itself) via a multisynaptic pathway, with connections being made sequentially in the paraventricular hypothalamus, the upper thoracic intermediolateral cell column, and the superior cervical ganglion (Figure 5-11). Cycles of light and darkness relayed by the retina entrain SCN neural activity, which in turn entrains the rhythmic production and secretion of melatonin from the pineal gland. In all vertebrate species studied to date, including humans, high levels of melatonin are secreted during the night and low levels are secreted during the day.

In addition to entraining melatonin secretion from the pineal gland, light can have an acute suppressive effect on melatonin. Specifically, exposure of the eyes to light during the night can cause a rapid decrease in the high nocturnal synthesis and secretion of melatonin. Numerous studies have examined how the photic parameters of light intensity, wavelength, exposure duration, and timing interact with melatonin regulation.

Human Biological Rhythms and the Circadian System. There are a myriad of measurable human physiological quantities that vary cyclically on a 24-h schedule.,[8,63-65,73,78,80,83,84,86,87,97,98] The core body temperature reaches its peak during midday, dropping approximately 1°C to a nadir during sleep. Concentrations of various hormones (for example, melatonin) change regularly with the time of day. Other measurable quantities, including blood pressure, hand grip strength, alertness, cognitive performance, and visual sensitivity, also show circadian rhythmicity.

The effects of drugs on the body vary with a circadian rhythmicity as well. Chronopharmacology examines rhythmic sensitivity to drugs. Certain drugs and dosages may elicit a response at one time of day but prove ineffective after another administration that same day. Sophisticated drug prescription and administration considers the circadian variation in drug response sensitivity.

Desynchronization of Rhythms. The various circadian rhythms detailed above are all synchronized by the internal clock, which is in turn entrained to the external 24-h daily schedule. Sleep deprivation, placement in constant conditions, and exposure to light during the night hours can cause a loss of entrainment to the environment. Thus, the internal clock can become phase shifted, or out of synchrony, with the external world. This desynchronization often contributes to feelings of discomfort, as commonly manifested in the jet lag syndrome. Symptoms of jet lag can include a disturbance in sleep and wakefulness, digestive difficulties, physical fatigue, menstrual irregularity, confusion and irritability, and reduced cognitive performance.

Certain occupational requirements often involve mandatory phase shifting of the internal clock. Perhaps the most common of these is shift work. By the broadest definition, shift workers are persons who do not work a standard daytime schedule. Instead, they work nights, evenings, rotating shifts, split shifts, or extended shifts. In a report from the U.S. Congress,[97] it was estimated that one out of five full-time workers in the United States is a shift worker. In agreement with many investigators, that report indicated that the two most common and destructive problems associated with shift work are a reduced quality of sleep following night work and a reduced capacity to maintain alertness while at work. These side-effects translate into increased accidents, decreased production, and performance deficits among those who are working at night.

Furthermore, evidence indicates that shift workers have increased health problems, including a higher risk of cardiovascular disease, gastrointestinal distress, and cognitive and emotional problems. They also are likely to experience one or more of the symptoms attributed above to jet lag. In both conditions, chronic desynchronization of internal biological rhythms is thought to be a cause of such symptoms.

Additional research is underway to study whether a link exists between lighting in the shift work environment,[70] and melatonin deficiency or irregularity with respect to a risk of breast cancer. In addition to the currently understood effects of light on melatonin concentrations, the "melatonin hypothesis"[95] suggests a link between melatonin disruption and the incidence of breast cancer. This is presently a controversial area of study and others have advanced the theory that there is no health risk associated with light, magnetic fields, melatonin, and breast cancer.

Researchers believe that poor chronobiological adjustment to a permanent or rotating schedule causes some of these ailments. Not all of them, however, are solely due to a maladapted biological clock. In addition to a desynchronized circadian system, shift workers generally tend to be chronically sleep-deprived and experience domestic stresses that are more or less independent of circadian adaptation.

On the frontiers of shift-work research, some investigators are attempting to develop strategies of light stimulation in an effort to improve circadian entrainment and to enhance performance and alertness in night workers. This new form of light therapy is discussed below.

Phototherapy[8,86,97,100-179]

Phototherapy, or the use of light as the primary or supplementary source of treatment for a disorder, is an established and burgeoning field. Light has been used therapeutically in a wide variety of applications, including dermatology, photochemistry, psychiatry, and oncology. Some forms of treatment, such as photochemotherapy, are established and have been practiced for decades, while others, such as low-level laser therapy, remain experimental.

Retinal Photocoagulation. A therapeutic effect of both incoherent and coherent (laser) radiation in the 400- to 1400-nm wavelength bands involves photocoagulation techniques used to repair retinal detachment. The original coagulation process, involving the welding of the detached retina to the sclera, was accomplished with incoherent white light from a xenon lamp coagulator. The lamp has been superseded in most ophthalmological clinics by ruby, argon, and diode laser coagulators. Today, the photocoagulation technique in ophthalmology has been applied to the treatment of diabetic retinopathy, age-related maculopathy, and many other pathologies involving the eye.

Phototherapy of Neonatal Hyperbilirubinemia.[100-106] Hyperbilirubinemia in neonates is more commonly known as jaundice of the newborn. It is estimated that 60% of all infants born in the United States develop jaundice during the first week of life and that about 7 to 10% of neonates have hyperbilirubinemia of sufficient severity to require medical attention.

Jaundice is the symptom and not the disease. It results from the accumulation of a yellow pigment, bilirubin, as a result of the infant's inability to rid itself of bilirubin as rapidly as it is produced. Bilirubin is chemically a tetrapyrrole and is derived principally from the degradation of hemoglobin. At normal concentrations, bilirubin is transported in the blood by binding to albumin. When the bound bilirubin reaches the liver, it is conjugated from a lipophilic to a hydrophilic substance that can be excreted in the urine. Infants with hyperbilirubinemia lack the ability to bind and excrete bilirubin in the normal manner.

In neonates, increased amounts of unconjugated bilirubin circulate in the blood. This is a result of normal red corpuscle degradation coupled with the functional immaturity of the neonatal liver. Peak levels of bilirubin between 5 and 13 mg/dL typically occur in healthy full-term neonates between the second and fifth day of life. By the seventh day of life, they typically decrease to normal adult levels. In the case of premature infants, bilirubin levels build up more slowly to reach peak levels betwen 10 and 15 mg/dL, and then slowly decline to adult levels over a period of up to four weeks.

As the plasma concentration of bilirubin increases, there is a danger of exceeding the body's albumin-binding capacity, allowing free bilirubin to circulate. If unconjugated bilirubin reaches high levels (10 to 15 mg/dL) in a newborn, the pigment can penetrate the blood-brain barrier and accumulate in the brain, thus producing bilirubin encephalopathy and irreversible damage from toxic injury to brain cells, a condition known as kernicterus. Kernicterus often leads to the development of neurological injuries, including learning impairment, cerebral palsy, deafness, and in extreme cases death. After detection of hyperbilirubinemia, the condition can be monitored by measurement of the blood plasma bilirubin level. Phototherapy[102-106] can be used to prevent the dangerous rise in plasma bilirubin.

Typically, phototherapy is administered with one of three types of systems: a conventional or overhead system of fluorescent lamps, an overhead tungsten-halogen spotlight, or a relatively newer fiberoptic pad. The light sources may be filtered to maximize radiation in the short visible wavelength region and to minimize unnecessary UV and IR radiation.

Overhead systems may be portable or incorporated into incubators, radiant warmers, or bassinets. They typically are mounted 25 to 50 cm from the infant, depending on the intensity required. Because of the blue appearance of the illumination from these systems, changes in infant skin color can be difficult to detect. Blue illumination also may contribute to irritation or nausea in some caregivers. For these reasons, the American Academy of Pediatrics (AAP) recommends a mixture of blue and white lamps in overhead phototherapy systems.

During phototherapy, the infants are naked except for eye patches or goggles that protect the eyes from injury. In practice, such patches can be difficult to work with; they can slip off the eyes of particularly active infants and can interfere with circadian rhythms and parent-infant contact.

Fiberoptic phototherapy pads developed in the late 1980s obviate some of the problems associated with overhead systems. The light from a tungsten-halogen lamp is delivered via fiberoptic cables to the pad, where they emit the light through the sides and ends of the fibers. Some pads can be wrapped around infants. If properly secured and covered, eye patches need not be used with phototherapy pads.

The AAP suggests a minimum average spectral irradiance of 4 mW/cm^2/nm in the range between 425 and 475 nm for photochemical reduction of bilirubin. Most medical textbooks recommend average treatment levels between 6 and 12 mW/cm^2/nm. When bilirubin levels are dangerously high, many physicians use even higher irradiances, accomplished by moving sources closer to the infants in overhead systems, multiple overhead systems, or a combination of overhead and fiberoptic pad systems. Brief exposure to sunlight also can provide sufficient irradiance for phototherapy in full-term infants, provided that precautions are taken to avoid injury to the eyes and skin.

The AAP recommends that phototherapy for full-term infants with nonpathological hyperbilirubinemia (no hemolysis) not begin until bilirubin levels reach concentrations of 15 to 20 mg/dL. If levels reach 20 to 25 mg/dL, exchange transfusions might be required, depending on the age of the infant and the judgment of the clinician. Phototherapy typically lasts for three days with preterm infants and for one to two days for full-term infants. Sometimes, phototherapy is performed in the home. The effect of phototherapy on plasma-free bilirubin concentration is shown in Figure 5-12.

In contrast to exchange transfusion, phototherapy is noninvasive and poses less risk to the infant. Nevertheless, several side-effects have been observed (Figure 5-13). Phototherapy should be carried out only under the supervision of a suitably trained clinician.

Phototherapy of Skin Disease.[107-109] UV radiation is used for the treatment of various skin diseases such as psoriasis and eczema. The most effective wavelengths appear to be in the UV-B portion of the spectrum. Patients are usually given a small, whole-body exposure to a suberythemogenic or minimally erythemogenic dose of radiation three to five times a week. Usually twenty to forty such treatments are required to clear the skin. Maintenance treatments are then necessary at weekly intervals to control the condition until remission occurs. Various sources of radiation have been used, but at this time fluorescent and metal halide lamps are preferred. Adverse effects from this treatment are uncommon except for the short-term problem of erythema. Photoaging of the skin and presumably skin cancer are potential long-term problems, although the degree of risk of the latter effect has not been evaluated fully.

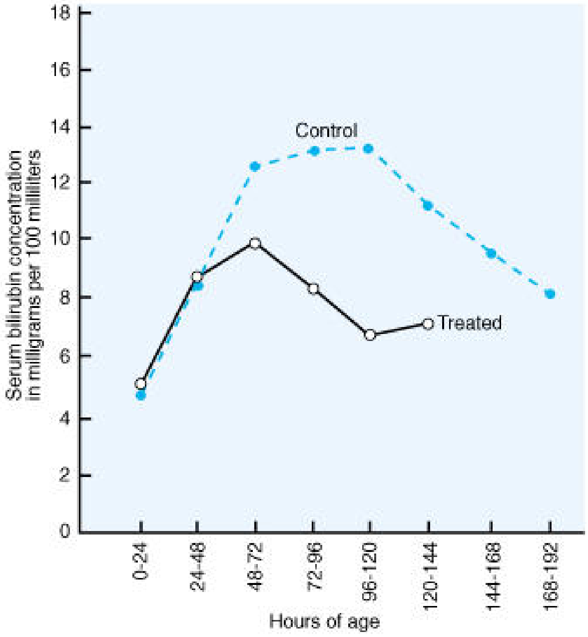


Figure 5-12. The effect of phototherapy of neonatal hyperbilirubinemia upon the mean serum bilirubin concentrations of 32 infants compared with that of 33 hyperbilirubinemic infants who received no treatment.

Determined *in vitro*
1. Albumin denaturation
2. Diminished riboflavin levels
3. G-6-PD activity loss
4. Glutathione reductase activity loss
5. Mutagenesis in cell cultures

Determined *in vivo* (animals)
1. Retinal damage
2. Increased liver glycogen in rats
3. Retarded gonadal growth (not function) in rats

Determined *in vivo* (human infants)
1. Excess body heat from thermal output of lamps
2. Temporary growth retardation
3. Increased insensible water loss
4. Transient hemolysis (uncommon)
5. Loose, discolored stools
6. Transient skin rash
7. Reduction of whole blood riboflavine
8. Alteration of tryptophan—kynurenine metabolism
9. Alteration of biologic rhythms
10. Physical hazards from inappropriate phototherapy—unit construction
11. Increase in gut transit time
12. Increase in respiration
13. Increase in peripheral blood flow
14. Decrease in circulating platelets

Figure 5-13. Side Effects of Phototherapy

Photochemotherapy of Skin Disorders.[117-122] Photochemotherapy is defined as the combination of nonionizing electromagnetic radiation and a drug to bring about a beneficial effect. Usually, in the doses used, neither the drug alone nor the radiation alone has any significant biologic activity; it is only the combination of drug and radiation that is therapeutic. PUVA (psoralen and UV-A) is a term used to describe oral administration of psoralen and subsequent exposure to UV-A. PUVA has proven to be effective in treating psoriasis, vitiligo, certain forms of severe eczema, a malignant disorder called mycosis fungoides, and a growing list of other skin disorders.

Psoralens are naturally occurring tricyclic, furocoumarin-like chemicals, some of which can be photoactivated by UV-A. In living cell systems, absorption of energy from photons within the 320- to 400-nm waveband (with a broad peak at 340 to 360 nm) results in thymine-psoralen photoproducts and the transient inhibition of DNA synthesis. When certain psoralens are delivered to the skin either by direct application or by oral route, subsequent exposure to UV-A can result in redness and tanning, which are delayed in onset, occurring hours to days after exposure.

The redness, or skin inflammation, from PUVA can be severe and is the limiting factor during treatment. The occurrence and degree of redness, however, is predictable and related to the doses of both the drug and UV-A irradiance. The redness that results from PUVA differs from sunburn in its time course. PUVA redness can be absent or just beginning at 12 to 24 h after UV exposure (when sunburn redness is normally at its peak) and peaks at 48 to 72 h or later. Because skin diseases can be treated at PUVA dose exposures that are less than those causing severe redness, careful dosimetry permits safe PUVA treatments. The pigmentation that results from PUVA appears histologically and morphologically similar to true melanogenesis (delayed tanning). Pigmentation reaches a maximum at approximately 5 to 10 days after PUVA exposure and lasts weeks to months.

Psoriasis is a genetically determined hyperproliferative epidermal disorder. Until its cause or basic mediators are known, the most effective therapeutic agents must be those that have cytotoxic effects. Many such agents are effective but have potential cytotoxic effects on other than cutaneous organ systems. Since PUVA effects require UV-A, which penetrates into the skin but does not reach internal organs, PUVA offers the potential for combining the ease of systemic administration with the relative safety of limiting the biologic effects to the irradiated skin.

Repeated PUVA exposures cause the disappearance of lesions of psoriasis in most patients. Ten to thirty treatments, given twice weekly, are usually adequate to achieve clearing. Weekly maintenance treatments keep most psoriatics free of symptoms. Psoriasis sometimes recurs weeks to months after PUVA therapy ceases. These patients respond to repeated PUVA therapy. The scalp, body folds, and other areas not exposed to UV-A do not respond to the therapy.

During therapy, patients are typically exposed to UV-A 2 hours after ingestion of 0.6 mg/kg body weight of 8-methoxypsoralen. The initial UV-A exposure (1.0 to 5.0 J/cm^2) depends on the degree of melanization and on the sunburn history. The exposure must be increased as tanning occurs, because the pigmented skin diminishes UV-A penetration to the deeper levels of skin. Ideal radiation sources are those that have high radiant output of UV-A, the capability to irradiate the entire body surface, little UV-B and IR output, and uniform irradiance at all sites within the radiation chamber. Safety devices and reliable methods of measuring and delivering exact exposures are essential.

The sun can be used as a PUVA radiation source but carries the disadvantage of unpredictable and varying UV irradiance and spectral distribution at the earth's surface. In tanned or pigmented patients, long exposure times can be required. For example, the exposure duration for both front and back of the body can be two to three times that needed for a single total-body treatment in a photochemotherapy system. Some patients, however, are willing to tolerate the heat and boredom of sun exposure in order to have the advantage of home treatment. Intense sun, clear skies, metering devices, careful instruction, and intelligent, cooperative, and motivated patients are required to make sun PUVA therapy a reasonable alternative to hospital or office treatment.

Exposure to high irradiances of UV-A for prolonged periods of time can cause cataract and skin cancer in laboratory animals. These effects are enhanced by psoralens. The exposures used in these studies are much greater than therapeutic exposures. Observations in animal systems indicate that the extent of skin cancer induction varies with dose and route of psoralen administration and UV exposure. Both basal cell and squamous cell carcinomas have been observed in patients treated with PUVA. The incidence of these tumors is highest in patients with a prior history of exposure to ionizing radiation or a previous cutaneous carcinoma. These findings suggest that the potential risk of PUVA-related cutaneous carcinogenesis should be carefully weighed against the potential benefit of this therapy. Special care must be taken in treating patients with prior histories of cutaneous carcinoma or exposure to ionizing radiation.

Experimental animal studies indicate that 8-methoxypsoralen also sensitizes the cornea and lens of certain species to UV-A exposure. It is not yet known how this sensitization relates to the use of psoralens in photochemotherapy of humans. Although humans have used 8-methoxypsoralen therapeutically for decades, no cataracts attributable to PUVA have been reported. It seems wise, however, to limit the use of psoralen photochemotherapy to those with significant skin disease and to use adequate UV-A eye protection during the course of therapy. After ingesting psoralens, patients should protect their eyes for at least the remainder of that day.

Physicians must be aware of these theoretical concerns and must carefully observe patients for signs of accelerated actinic damage. Glasses that are opaque to UV-A decrease total UV-A exposure to the lens and should be worn on treatment days.

Photochemotherapy of Tumors.[123-127] The photochemotherapy of tumors (also known as photodynamic therapy) employs visible radiation of a particular wavelength band as a catalyst in a photodegradation reaction. The products of this reaction are cytotoxic and effectively destroy tumor cells. The chemical hematoporphyrin derivative (HpD), when introduced into the blood, locates and binds to tumor cells. Exposure of the tumor to radiation at 630 nm causes the production of singlet oxygen from its previously bound triplet state in HpD. Singlet oxygen is highly cytotoxic and consequently causes tumor cell degradation.

Filtered xenon and tungsten lamps can be used to treat cutaneous lesions. A pumped dye argon laser radiating at 630 nm, connected to an optical delivery system such as fiber optics, can be used with an endoscope or similar device to reach internal cavities. Photodynamic therapy has achieved partial or complete response in 85% of patients with lung, esophageal, bladder, ocular, head and neck, neurological, and gynecological tumors. Despite this success, treatment generally has been limited to cutaneous and subcutaneous tumors (including breast cancers, melanomas and basal cell carcinomas). The photoreactivity of HpD also can be employed in tumor localization and detection, as radiation of 400 nm causes HpD to fluoresce. HpD is not toxic in the absence of light; however, as the substance is retained in the skin, it can cause photosensitivity that may persist for 3 to 4 weeks after infusion.

Light Therapy for Seasonal Affective Disorder (SAD).[99,128-147] During the past decade, the specific condition of fall and winter depression, or seasonal affective disorder (SAD), has been formally described in the scientific literature and included in the latest edition of the American Psychiatric Association's diagnostic manual, DSM-IV-R. Independent studies in the United States and Europe suggest that winter depression is a widespread syndrome. A study of the frequency of SAD manifestation on the east coast of the United States estimated that SAD occurs in less than 2% of the population in Florida, but in New Hampshire nearly 10% of the population show symptoms during fall and winter. From this study, it has been projected that as many as 10 million Americans have SAD and possibly an additional 25 million are susceptibility to a milder, subclinical form of SAD.

People affected with this malady experience a dramatic decrease in their physical energy and stamina during the fall and winter months. As days become shorter, persons with SAD often find it increasingly difficult to meet the routine demands at work and at home. In addition to this general decrease in energy, SAD sufferers experience emotional depression, feelings of hopelessness, and despair. Other symptoms of winter depression or SAD can include increased sleepiness and need for sleep, increased appetite (particularly for sweets and other carbohydrates), and a general desire to withdraw from society. Fortunately, daily light therapy has been found to effectively reduce symptoms in many patients.

There are now numerous clinics across North America that offer light therapy for people who are afflicted with winter depression. Specific treatment protocols vary somewhat among clinics. In the earlier days of light treatment for SAD, a patient often was instructed to sit a specific distance from a light panel that provided an illuminance of 2500 lx to the face. The patient was told not to gaze steadily at the bright light, but rather to glance directly at the unit for a few seconds each minute over a two-hour period. During the therapy period, a patient read, watched television, worked at a computer or did other hand work. Response to this therapy often was noted after two to seven days of light treatment. Benefits continued as long as the treatment was repeated regularly throughout the months that the individual experienced winter depression.

Considerable research has been directed at determining the optimum illuminance, exposure, and time of day for the light treatment of winter depression. Most studies using light boxes or work stations indicate that illuminances from 2500 to 10,000 lx produce strong therapeutic results in treating SAD. In determining the best dosage of light, the intensity and exposure duration must be considered together. To date, no genuine dose-response functions have been established for light therapy, but exposure durations ranging from 30 min to 6 h in single or split sessions have been tested. The strongest therapeutic responses have been documented with a 2500-lx exposure over 2 to 4 h and with a 10,000-lx exposure over 30 min. Considerable data suggest that morning light treatment is superior, but not all investigators agree on this point.

Current evidence supports the hypothesis that light therapy works by way of an ocular pathway as opposed to a dermal or transdermal mechanism. Several studies have investigated the action spectrum for SAD light therapy. Ultimately, a thoroughly defined action spectrum can both guide the development of light treatment devices and yield important information about the photosensory mechanism responsible for the beneficial effects of light therapy. Currently, it is premature to predict which photopigments or photoreceptors mediate the antidepressant effects of light.

A practical issue debated among researchers concerns the role of UV in light therapy. Most of the early studies on SAD therapy used fluorescent lamps that emitted white light containing a small portion of UV-A energy. Those early findings erroneously led to the suggestion that UV-A is necessary for successful therapy. The current literature, however, clearly shows that SAD symptoms can be reduced by lamps that emit little or no UV. Hence, UV radiation does not appear to be necessary for eliciting positive therapeutic results.

Most of the clinical trials treating winter depression have employed white light emitted by commercially available lamps. The white light used for treating SAD can be provided by a range of lamp types, including incandescent and cool white fluorescent. There is an assortment of light devices specifically designed for the treatment of SAD. Light therapy instruments come in a variety of shapes and configurations, including workstations, head-mounted light visors, and automatic dawn simulators. These devices are configured to shorten therapeutic time, increase patient mobility or permit therapy during the sleep period. Light visors appear to therapeutically benefit SAD patients with substantially lower energy requirements than those emitted by light boxes and work stations. Because dose-response comparisons have not been performed among different lamp types and light devices, it is not possible to distinguish which, if any, type of light is superior for treating depression.

Light Therapy for Jet Lag, Shift Work, and Sustained Performance.[97,128-160] As scientists have explored the physiology of the human biological clock under normal conditions, they have also examined how that clock functions or dysfunctions under more unusual situations. Jet lag is a condition that results from rapidly moving across time zones. Although the human biological clock adjusts within three to seven days after such an event, during the adjustment period many people experience uncomfortable symptoms, which may include sleep and wake disruptions, gastric distress, irritability, depression, and confusion. Such symptoms can pose serious problems for the business traveler and can diminish the enjoyment of a vacation for the leisure traveler. Some studies have tested the use of light exposure to prevent or ameliorate jet lag symptoms. Investigators are optimistic that light can be a useful tool for the immediate resetting of the traveler's biological clock and can help overcome some of the problems associated with jet travel. It is generally agreed that there currently are insufficient data for a set prescription on how to best use light for this malady.[97,159]

Shift work poses a problem analogous to that found in jet lag. Instead of rapidly flying to distant places, shiftworkers may just as suddenly change the time period that they are awake or asleep. These individuals are awake and working during the night and attempting to sleep during the daylight hours. Although some individuals prefer night work over day work and are well adapted to shift schedules, shift work often is associated with decreased production, performance deficits, and increased health complaints. Some investigators have tested strategies of light stimulation to enhance performance and alertness in night workers. Studying simulated shift work over a 2- to 5-day period, different groups of investigators have shown that night workers had better circadian adaptation and improved alertness and cognitive performance when they worked under bright light (1,000 to 12,000 lx) than under dim light (100 to 150 lx). Other studies on simulated shift work have shown that exposure to bright white fluorescent light at specific times can improve sleep quality, enhance performance, and speed the adjustment of the circadian system.

The U.S. military currently has a triservice research program aimed at finding ways of enhancing physical and mental performance in personnel who are on continuous duty for prolonged periods of time. A major focus of this program has been to study pharmacological agents that can help sustain alertness without degrading performance. Sustained performance studies have shown that workers exposed to bright light (3000 or 5000 lx) exhibited significantly improved behavioral and cognitive performance on selected tasks compared to their own performance on a separate occasion under 100 lx. In addition to these behavioral effects, there were significant differences in the body temperatures and plasma melatonin levels associated with light stimuli. In these acute studies, it is not clear how light influences performance. There is, nevertheless, a consensus among scientists that it is still premature to formulate a prescription on how to best use light for both short-term and long-term work applications.[97,159]

Potential Placebo Responses in Light Therapy, Mood, and Performance Effects.[161,162] In considering the newer uses of light for therapeutically reducing the symptoms of winter depression, jet lag, and shift work, it is important to examine whether the observed effects are due to specific light therapy or to a nonspecific or placebo response. When using light experimentally on humans, either for therapeutic purposes or for work or travel applications, investigators are confronted with a dilemma. Simply put, when volunteers can readily see that a manipulation of light is part of an experiment, there is a distinct possibility of finding a placebo reaction to the light treatments.

In the medical literature it has been well documented that patients with a wide range of disorders--depression, schizophrenia, and anxiety as well as cancer, diabetes, and ulcers--can respond to placebo treatments. Hence it is likely that SAD patients, world travelers, and shift workers show some level of placebo response to light therapy. The degree to which the patients' response to light therapy is due to a nonspecific placebo response or to a genuine clinical response remains an open question.

Low-Level Laser Therapy.[163,164] Although not yet approved for routine medical use in the United States, low-level lasers at 633, 830, and 904 nm are used widely throughout the world in sports medicine clinics and by veterinarians to accelerate wound healing, treat sprains, and control certain types of pain. Unfortunately, low-level lasers also are used to treat other conditions for which there is little hard evidence of benefit. The scientific community should encourage this fledgling field to establish proper controls and to learn more photobiology in order to establish unequivocally which clinical conditions are improved by this type of therapy and which are not. Attempts have been made to explain the photobiological basis of how visible and IR radiation can produce similar clinical and cellular responses.

Photorefractive Keratectomy. A surgical technique known as photorefractive keratectomy (PRK), using lasers to sculpt the cornea of the eye, thus altering its refractive power, has been developed and tested in Europe and the United States. It has been used to correct refractive errors such as myopia and astigmatism. The use and acceptance of this technique appears to be increasing; however, clinical trials to assess long-term effects are currently underway.[165]

Lighting Safety Criteria.[166-175] Human exposure limits for nonionizing optical radiation are consensus values. The Threshold Limit Values (TLVs) of the American Conference of Governmental Industrial Hygienists (ACGIH)[171] normally are used in the United States and are widely accepted internationally. These TLVs are reviewed and updated annually to represent the best current scientific consensus for exposure safety. It is explicitly stated that these TLVs "represent conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse health effects." Because they are presented as specific values, concern might arise if an exposure exceeds one of these values. The ACGIH explicitly addresses this concern by stating that the TLVs are guidelines, not specific breakpoints between safe and dangerous exposures.

The TLVs are the basis of the ANSI/IESNA RP-27.1-96 recommended practice.[173] This document covers optical radiation of lamps and lamp systems between 200 nm and 3000 nm except for lasers and light-emitting diodes used in optical fiber communications. It expands upon and details methods for applying TLV criteria, which can be described as follows:

1. UV actinic effects of photokeratitis and photoconjunctivitis of the eye, and erythema (sunburn) of the skin. A spectral weighting function from 200 to 400 nm is used to collectively represent the potential hazard of radiation with respect to these effects.[171]

2. UV cataractogenesis. Until the possibility of an increased risk of cataracts owing to long-term exposure is resolved, ocular exposure to radiation between 320 and 400 nm should be limited as a precaution.

3. Retinal photochemical injury ("blue-light" hazard). The retinal image of a source with high levels of energy primarily between 400 and 500 nm can produce photochemical injury of the retina. Radiation between 400 and 700 nm is spectrally weighted by a function to establish the potential for injury.

4. Retinal thermal energy. Viewing a high-radiance source can elevate retinal temperature. The radiant power between 400 and 1400 nm is spectrally weighted by a function related to ocular transmittance and retinal absorbance. Because retinal heat transfer depends on the image area, this criterion includes the angular size and shape of the source. This type of injury is dominant over retinal photochemical injury for exposures less than 10 s.

5. IR cataractogenesis. Chronic exposure to high levels of irradiance between 770 and 3000 nm can increase the risk of certain types of cataracts.[168]

6. Skin thermal injury. Cellular injury occurs if skin temperature reaches approximately 45°C. Because this temperature is associated with intolerable pain, injurious exposure tends to be self-limited by discomfort for extended exposure times, and this criterion is applied only to short duration exposure to radiation between 400 and 3000 nm.

These criteria are applied to specific exposure situations. Another recommended practice[174] extends these criteria to develop risk group classification for lamps. Lamps are divided into four groups each associated with a degree of potential hazard. The absolute degree of risk or safety cannot be determined for most lamps independent of their specific use in an application. The four risk groups and the philosophical basis for each of them are as follows:

1. Exempt group: The lamp does not pose any photobiological hazard within the limits specified in ANSI/IESNA RP-27.3.[174]

2. Risk group 1 (low risk): The lamp does not pose any photobiological hazard due to normal behavioral limitations on exposure.

3. Risk group 2 (moderate risk): The lamp does not pose any photobiological hazard due to the aversion response to very bright sources or due to thermal discomfort.

4. Risk group 3 (high risk): The lamp may pose a photobiological hazard even for momentary or brief exposures.

ANSI/IESNA RP-27.3[174] defines exposure conditions (including time and distance) based on the philosophy of the risk groups. Using the characteristics of a lamp, the resulting exposures are evaluated in accordance with the criteria of ANSI/IESNA RP-27.1[173] to determine the risk group classification for the lamp. The system places a lamp in a single risk group based on the likelihood and seriousness of the potential risk. Specific lamp labeling and informational requirements are specified for each risk group.

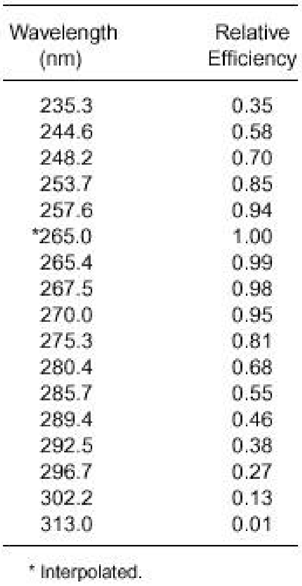
Owing to concern about eye safety and products that incorporate laser-type emitting devices, including certain light-emitting diodes (LEDs, see Chapter 6, Light Sources), the International Electrotechnical Commission (IEC) and

European Committee for Electrotechnical Standardization (CENELEC) have developed standards to minimize risks of eye injury from use of products containing LEDs. These standards include maximum permissible exposure (MPE) levels and required testing methods for products using LEDs, as well as eye safety labeling recommendations based on the amount and type of emission produced by these products, just as with other light sources.[168]

EFFECTS ON MICROORGANISMS

Germicidal (Bactericidal) UV Radiation[176-191]

Electromagnetic radiation in the wavelength range between 180 and 700 nm is capable of killing many species of bacteria, molds, yeasts, and viruses. The germicidal effectiveness of the different wavelength regions can vary by several orders of magnitude, but wavelengths shorter than 300 nm are generally the most effective for bactericidal purposes.



Wavelength (nm)	Relative Efficiency
235.3	0.35
244.6	0.58
248.2	0.70
253.7	0.85
257.6	0.94
*265.0	1.00
265.4	0.99
267.5	0.98
270.0	0.95
275.3	0.81
280.4	0.68
285.7	0.55
289.4	0.46
292.5	0.38
296.7	0.27
302.2	0.13
313.0	0.01

* Interpolated.

Figure 5-14. Tentative Germicidal (Bactericidal) Efficiency of Ultraviolet Radiation at Mercury Emission Lines

The bacterium most widely used for the study of bactericidal effects is *Escherichia coli*. Studies have shown the most effective wavelength range to be between 220 and 300 nm, corresponding to the peak of photic absorption by bacterial deoxyribonucleic acid (DNA). The absorption of the UV radiation by the DNA molecule produces mutations or cell death. The relative effectiveness of different wavelengths of radiation in killing a common strain of *E. coli* is shown in Figure 5-14.

Germicidal (Bactericidal) Lamps. The most practical method of generating germicidal radiation is by passage of an electric discharge through low-pressure mercury vapor enclosed in a special glass tube that transmits shortwave UV radiation. Approximately 95% of the energy from such a device is radiated at 253.7 nm, which is very close to the wavelength corresponding to the greatest lethal effectiveness. These lamps come in various sizes and shapes including linear and compact sources.

Hot-cathode germicidal lamps are similar in physical dimensions and electrical characteristics to the standard preheat 8-, 15-, and 30-W fluorescent lamps. While both types of lamps operate on the same auxiliaries, germicidal lamps contain no phosphor and the envelope is made of a UV- transmitting glass. Quartz envelopes are used for some germicidal lamps. Slimline germicidal lamps are instant-start lamps capable of operating at several current densities within their design range, 120 to 420 mA, depending on the ballast with which they are used. Cold-cathode germicidal lamps are instant-start lamps with a cylindrical cathode. They are made in many sizes and operate from a transformer.

The life of the hot-cathode and slimline germicidal lamps is governed by the electrode life and frequency of starts. (Their effective life is sometimes limited by the transmission of the bulb, particularly when operated at low temperatures.) The electrodes of cold-cathode lamps are not affected by the number of starts, and their useful life is determined entirely by the transmission of the bulb. All types of germicidal lamps experience a decrement in UV emission as the total hours of operation increase. Lamps should be checked periodically for UV output to ensure that their germicidal effectiveness is maintained.

The majority of germicidal lamps operate most efficiently in still air at room temperature. For lamp efficiency measurements, UV output is standardized at an ambient temperature of 25°C. Temperatures either higher or lower than this value decrease the output of the lamp.

Slimline germicidal lamps operated at currents ranging from 300 to 420 mA and certain preheat germicidal lamps operated at 600 mA are designed exceptions to this general rule. At these high current loadings, the lamp temperature is above the normal value for optimum operation; therefore, cooling of the bulb does not have the same adverse effect as with other lamps. These lamps are well suited for use in air conditioning ducts.

In addition to emissions at 253.7 nm, some germicidal lamps generate a controlled amount of 184.9-nm radiation, which produces ozone (Figure 5-15). Since ozone is highly toxic, its environmental concentrations have been limited by an Occupational Safety and Health Administration (OSHA) regulatory mandate to 0.1 parts per million (ppm), or 0.2 mg/m^3. Care should be taken when choosing germicidal lamps to meet the requirements of these regulations.

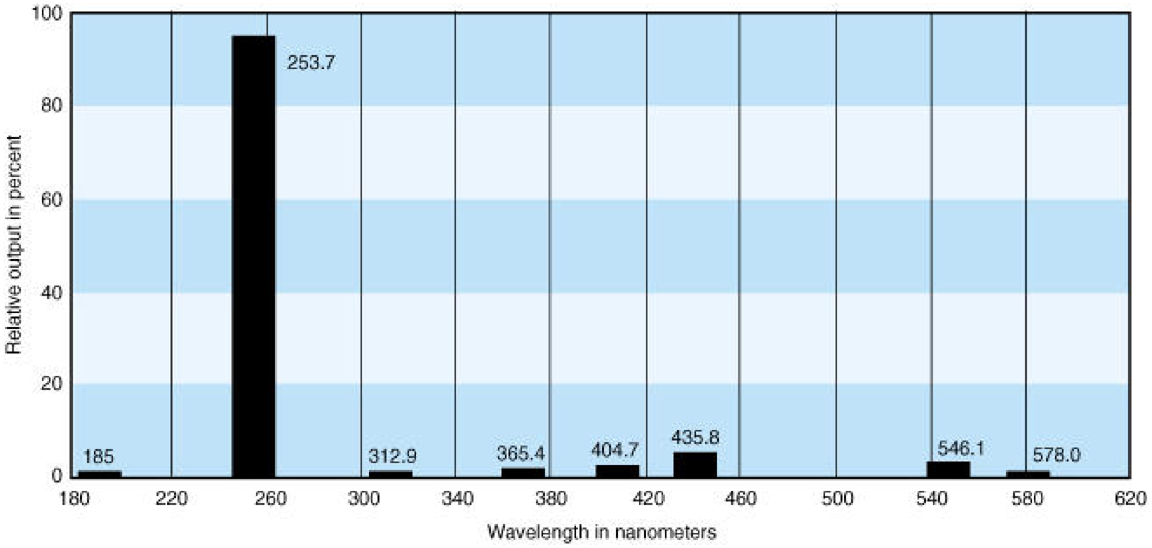


Figure 5-15. Relative spectral distribution of energy emitted by ozone-producing germicidal lamps.

Photoreactivation. It has been observed that the survival of UV-irradiated bacteria could be greatly enhanced if the cells were subsequently exposed to an intense source of blue light. Researchers have demonstrated the existence of a photoreactivating enzyme and established its basic properties in repair of damaged DNA. The enzyme combines in the dark with cyclobutyl pyrimidine dimers in UV-irradiated DNA to form an enzyme-substrate complex. When the complex is activated by the absorption of energy between 320 and 410 nm, the cyclobutyl pyrimidine dimers are converted to monomeric pyrimidines and the enzyme is released.

Under certain experimental conditions, as much as 80% of the lethal damage induced in bacteria by low-energy UV radiation at 253.7 nm can be photoreactivated, thus indicating the importance of cyclobutyl pyrimidine dimers as lethal lesions. Photoreactivating enzymes have been found in a wide range of species, from the simplest living cells to the skin and white blood cells of humans.

Germicidal Effectiveness. The effectiveness of germicidal radiation is dependent on many parameters, including the specific susceptibility of the organism, the wavelength of radiation emitted, the radiant flux, and the time of exposure. Figure 5-16 lists the exposure intensity (J/m^2) of the 253.7-nm UV radiation necessary for the inhibition of colony formation (a 90% reduction in population) in a wide variety of microorganisms.

Organism		Exposure (joules per square meter)
Bacillus anthracis		45.2
S. enteritidis		40.0
B. megatherium sp. (veg.)		37.5
B. megatherium sp. (spores)		27.3
B. paratyphosus		32.0
B. subtilis		71.0
B. subtilis spores		120.0
Corynebacterium diphtheriae		33.7
Dysentery bacilli		22.0
Eberthella typhosa		21.4
Escherichia coli		30.0
Micrococcus candidus		60.5
Micrococcus sphaeroides		100.0
Neisseria catarrhalis		44.0
Phytomonas tumefaciens		44.0
Proteus vulgaris		26.4
Pseudomonas aeruginosa		55.0
Pseudomonas fluorescens		35.0
S. typhimurium		80.0
Sarcina lutea		197.0
Seratia marcescens		24.2
Shigella paradysenteriae		16.3
Spirillum rubrum		44.0
Staphylococcus albus		18.4
Staphylococcus aureus		26.0
Streptococcus hemolyticus		21.6
Streptococcus lactis		61.5
Streptococcus viridans		20.0
Yeast		
Saccharomyces ellipsoideus		60.0
Saccharomyces sp.		80.0
Saccharomyces cerevisiae		60.0
Brewer's yeast		33.0
Baker's yeast		39.0
Common yeast cake		60.0
Mold Spores	Color	
Penicillium roqueforti	Green	130.0
Penicillium expansum	Olive	130.0
Penicillium digitatum	Olive	440.0
Aspergillus glaucus	Bluish green	440.0
Aspergillus flavus	Yellowish green	600.0
Aspergillus niger	Black	1320.0
Rhizopus nigricans	Black	1110.0
Mucor racemosus A	White gray	170.0
Mucor racemosus B	White gray	170.0
Oospora lactis	White	50.0

Figure 5-16. Incident Radiation at 253.7 nm Necessary to Inhibit Colony Formation in 90% of the Organisms

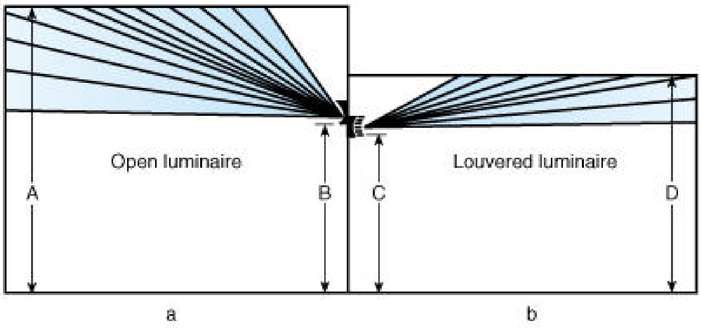
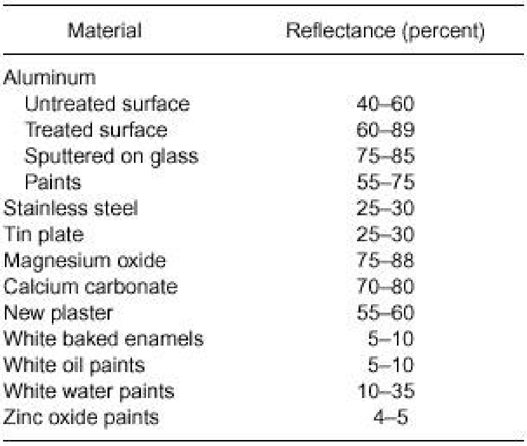


Figure 5-17. Germicidal lamps for air disinfection in occupied rooms: (a) open unit used in rooms over 2.7 m (9 ft) in height; (b) louvered unit used where ceilings are lower than 2.7 m (9 ft). Dimensions: *A*, 3.7 m (12 ft);

B, 2.1 m (7 ft); *C*, 2 m (6.5 ft); *D*, 2.7 m (9 ft).

Germicidal effectiveness is proportional to the product of intensity and time (from 1 µs to several h). A nonlinear relationship exists between UV exposure and germicidal efficacy. For example, if a certain UV exposure kills 90% of a bacterial population, doubling the exposure time or intensity can kill only 90% of the residual 10%, for an overall germicidal efficacy of 99%. Likewise, a 50% decrease in intensity or exposure time decreases germicidal efficacy only from 99% to 90%. Humidity can reduce the effectiveness of germicidal UV radiation.



Material	Reflectance (percent)
Aluminum	
Untreated surface	40–60
Treated surface	60–89
Sputtered on glass	75–85
Paints	55–75
Stainless steel	25–30
Tin plate	25–30
Magnesium oxide	75–88
Calcium carbonate	70–80
New plaster	55–60
White baked enamels	5–10
White oil paints	5–10
White water paints	10–35
Zinc oxide paints	4–5

Figure 5-18. Reflectance of Various Materials for Energy of Wavelengths in the Region of 253.7 nm

Precautions. Exposure to germicidal UV radiation can produce eye injury and skin erythema and has produced skin cancer in laboratory animals. The ACGIH limit for exposure of the unprotected skin or eyes to radiation at 253.7 nm is 6 mJ/cm^2 within an 8-h period. For example, this conservative limitation would be 0.2 µW/cm^2 for an 8-h continuous exposure, 0.4 µW/cm^2 for a 4-h continuous exposure, and 10 µW/cm^2 for a 10-min continuous exposure. The maximum exposure time is only 1 min for 100 µW/cm^2. Some common G30T8 unshielded germicidal lamps can deliver this irradiance from 0.75 m.

Based on the potential for producing threshold keratitis, the National Institute of Occupational Safety and Health (NIOSH) has proposed that half of the intensity-time relationship established by ACGIH above be used as a safe industrial exposure for the eye. Eye protection is essential for all who are exposed to the direct or reflected radiation from lamps emitting UV radiation, especially those germicidal lamps emitting UV-C radiation. Ordinary window or plate glass or goggles that shield the eyes from wavelengths shorter than 340 nm are usually sufficient protection. However, if the radiation is intense or is viewed for some time, special goggles should be used. Failure to wear proper eye protection can result in temporary but painful inflammations of the conjunctiva, cornea, and iris; photophobia; blepharospasm; and ciliary neuralgia. Skin protection, achieved by wearing clothing and gloves that are opaque to germicidal radiation, is advised if the UV radiant intensity is high or if the exposure duration is long. Accidental overexposure can be avoided by education of maintenance workers. Warning signs in appropriate languages should be posted.

Applications

Air Disinfection in Rooms. With the resurgance of multiple-drug-resistant forms of airborne disease (e.g., *Mycobacterium tuberculosis*), new attention is being given to using UV air-mixing systems to prevent transmission. These systems can provide cost-effective controls in strategically placed areas and possibly in the whole building.

In occupied rooms, irradiation by an open-luminaire germicidal lamp should be confined to the area above the heads of occupants as shown in Figure 5-17. The ceiling of the room to be disinfected should be higher than 2.9 m (9.5 ft), and occupants should not remain in the room for more than 8 h. If either of the above conditions does not meet the requirements of the workspace, louvered equipment should be used to avoid localized high concentrations of flux that may be reflected onto room occupants. Louvered luminaires using compact sources and electronic ballasts can provide energy efficient wall-, corner-, and pendant-mounted upper-room options. Some of these luminaires meet OSHA and NIOSH limits for rooms with 2.9 m ceilings for surface-mounted units and pendant units at a height of at least 3 m. An average irradiation of 20 to 25 µW/cm^2 is effective for slow circulation of upper air and maintains freedom from respiratory disease organisms comparable to outdoor air.

Upper-air disinfection, as practiced in such areas as hospitals, schools, clinics, jails, shelters, transportation systems, and offices, can be effective in providing relatively bacteria-free air at the breathing level of room occupants. Personnel movement, body heat, and winter heating methods create convection currents through a room sufficient to mix upper and lower room air. All surfaces irradiated by UV germicidal radiation (including ceilings and upper walls) should have a UV reflectance below 5% (characteristic of most oil and some waterbase paints) (Figures 5-18 and 5-19). "White coat" plaster or gypsum-product surfaced wallboard and acoustical tile can have higher germicidal reflectances and should always be painted with a less reflective substance. Unpainted white plaster walls and ceilings can limit safe exposure to only 2 to 3 h even with louvered luminaires. These precautions are especially important in hospital infant wards because children can be more sensitive to UV radiation than adults.

In operating rooms where prolonged surgery is performed, UV sources are mounted above doorways to disinfect air entering through the doorways. Face and skin protection are required for anyone passing through these doorways.

Air Duct Installations. It is possible to provide a sufficiently high level of UV radiation to kill 90 to 99% of most bacteria within very short exposure times at usual duct air velocities. Duct installations are especially valuable where central air heating and ventilating systems recirculate air through all of the otherwise isolated areas of a building. Slimline germicidal lamps, especially designed for cool, high-velocity ducts, commonly are installed inside access doors in the sides of ducts, either along or across the duct axis. Where possible, the best placement for lamps is across the duct to secure longer travel of the energy before absorption by the duct walls and to promote turbulence to offset the variation in UV radiation levels throughout the duct. Lamps should be cleaned periodically because dust buildup lowers UV emission.

Sanitization Techniques. Three general methods of germicidal lamp placement can be employed to establish a sanitary environment: upper-air irradiation, barrier-type irradiation, and direct irradiation. As previously outlined, upper-air irradiation maintains purified air at the normal breathing level of room occupants. It also permits safe continuous occupancy. Barrier irradiation techniques employ a narrow beam of UV directed across an opening, effectively preventing live organisms from passing from one space to another. Direct irradiation exposes whole surfaces to germicidal radiation. The most effective and efficient form of sanitization, direct irradiation, is hazardous to room occupants. In such conditions, proper eye and skin protection must be worn while germicidal lamps are operated. Alternatively, direct irradiation can be used when the room is unoccupied; provisions to prevent entry during irradiation are therefore unnecessary.

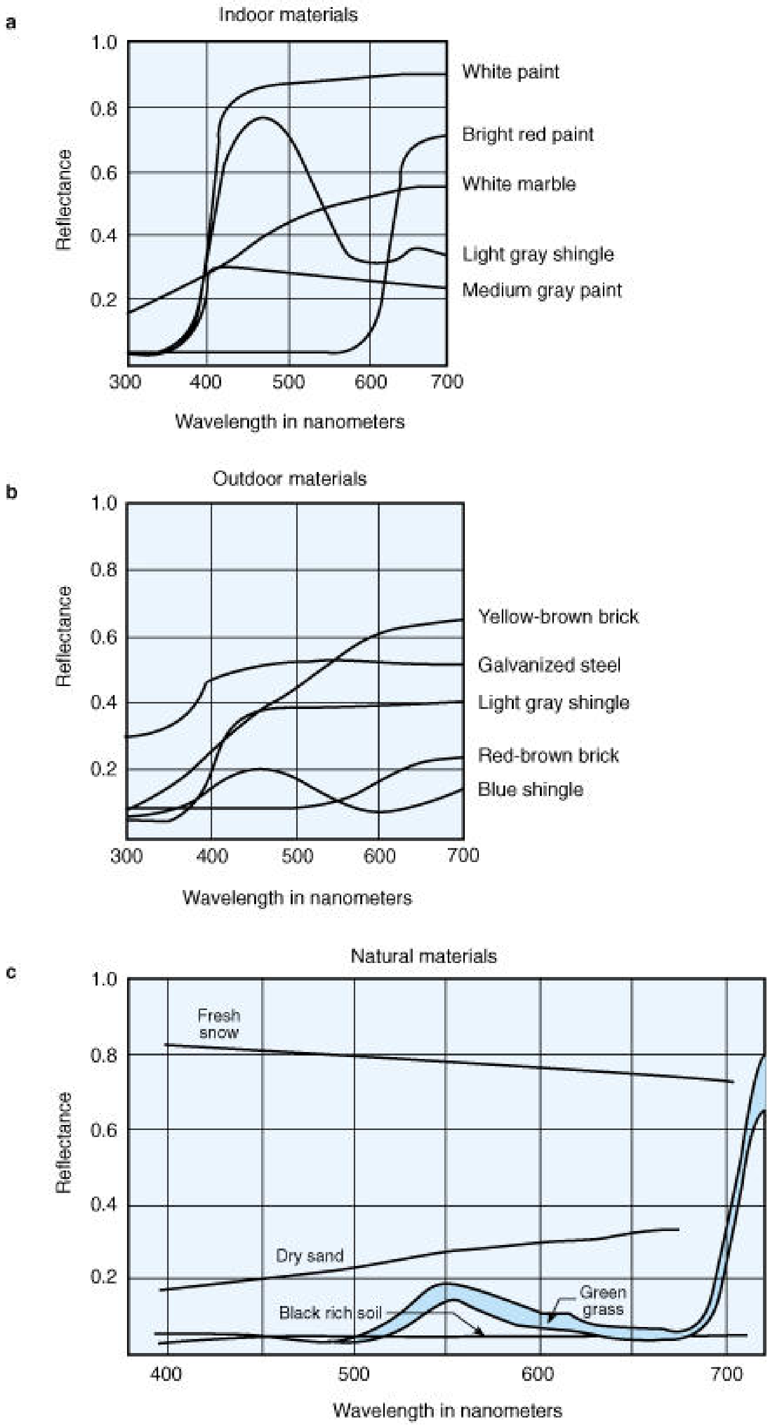


Figure 5-19. The spectral reflectance of (a) indoor, (b) outdoor, and (c) natural materials.

Liquid Disinfection. UV disinfection of water is used when it is essential to eliminate residual substances or taste. UV radiation is absorbed by natural chemical contaminants in water (e.g., iron-based and organic compounds) and by the DNA of water-dwelling organisms. Hence, disinfection of water often involves exposure times and intensities 40 to 50 times greater than those used in air sanitation. Such exposures are secured by slow gravity flow of water through shallow tanks under many lamps, or by immersing lamps enclosed in quartz tubes directly into the water.

Liquids of high absorbance (e.g., fruit juices, milk, blood, serums, and vaccines) are disinfected with various film spreaders. These range from high-speed centrifugal devices and surface-adhering rotating cylinders to gravity-flow-down screens and inclined planes. Such devices spread a film of liquid to approximately the thickness of its molecular size.

Disinfection of Granular Material. The surfaces of granular materials (e.g., sugar) are disinfected on traveling belts of vibrating conveyors designed to agitate the material during travel under banks of closely spaced germicidal lamps. In the case of sugar, thermoduric bacteria survive the vacuum evaporator temperatures of a sugar-syrup concentration and, forced out of the sugar crystals during lattice formation, remain in the final film of dilute syrup left on the crystal surface. Ordinarily harmless, these bacteria can cause serious spoilage in canned foods and beverages.

Product Protection and Sanitation. Product protection and sanitation are achieved by both air disinfection and surface irradiation (as with granular material). In this field, however, the usefulness of germicidal UV radiation generally is limited to the prevention of contamination during processing rather than the disinfection of product. For example, where sufficient irradiation to kill mold spores might be impractical, the vegetative growth of mold can be prevented by continuous irradiation at levels lethal to ordinary bacteria. Germicidal lamps installed in concentrating reflectors are used to disinfect air that might contaminate a product during processing and packaging, as in the travel of bottles from washing to filling to capping. Lamps serve to replace or supplement heat in processes where sterilization by heat might be destructive. Intensive irradiation of container surfaces can also supplement or replace washing between uses. UV sanitization techniques are used in bakeries, breweries, and packaging plants for liquid sugar, syrup, fruit juices, and beverages.

EFFECTS ON INSECTS

Insect Responses[192-199]

The increasing popularity of outdoor living, drive-in businesses, and outdoor recreational establishments is accompanied by intensified insect problems caused particularly by nocturnal insects attracted to light. Similar problems are encountered at lighted farmsteads, animal pens, feedlots, processing plants, and industries operating at night in lighted facilities. Many of these problems can be prevented or greatly reduced if the responses of the insect pests are considered when designing and planning these facilities.

The insect nuisance problems associated with lighting have four distinct but related aspects: the existing insect population in the surrounding vicinity, the attractiveness to insects of the activity carried on in the lighted area, the attractiveness of the lighting system used, and the suitability of the area for sustaining insect life. The circumstances of each situation are different, and usually little can be done about the insect population in the vicinity.

A knowledge of the insects in relation to their normal habitats and of the activities to be carried on in the desired insect-free areas usually helps to anticipate problems. Preventive action can be based on the known behavioral patterns of the expected insects. Insects likely to cause problems can be broadly categorized as follows:

Insects Not Attracted by Light. Insects not necessarily attracted to light are indigenous to enclosures and buildings, and most live continuously within the area. Included are cockroaches, ants, and flour beetles.

Diurnal Insects. These insects normally live outside the area and are active during the day. They are attracted to the area for food, shelter, or breeding sites. Examples are houseflies, pomance or fruit flies, and honey bees.

Nocturnal Insects. This group usually feeds and lives beyond the area and is attracted by electromagnetic radiation. These insects are the true problem associated with lighting systems. Most nocturnal insects, including moths, leafhoppers, mayflies, caddisflies, and various beetles, midges, and mosquitoes, are capable of flight and are active primarily at night. Phototaxis is the term applied to the movement of insects toward electromagnetic radiation. Insects that are attracted to a radiation source are said to be photopositive or to exhibit positive phototaxis. The spectral region most attractive to a wide range of insect species, especially nocturnal species, is in the UV-A range. Other species are known to respond to energy in the visible and IR regions as well. Research and experience have shown that insect problems can be greatly reduced with properly designed lighting systems and with proper management of the area.

Lighting System Attraction

One means of reducing the insect nuisance is to select light sources having low insect attractiveness. In practice, this involves sources with high energy at long wavelengths (yellow or red) and low energy in the UV and short visible wavelengths (blue). High-pressure sodium lamps have approximately one-third as much associated insect nuisance as a comparable-wattage mercury lamp system. Incandescent and warm fluorescent lamps designed to minimize short visible wavelength and UV radiation are available.

If insect-attractive lamps must be used, they can be shielded so that all their radiant output is confined to the area to be illuminated. If lamps must remain visible from the outside, consideration should be given to the use of refractors, filters, and shields made of glass or plastic material to filter out the UV radiation. If lamps emitting short-wavelength (blue) light and near-UV energy are used for lighting, they should not be directly visible at distances beyond a few meters from the illuminated area.

Exposed lamps, including incandescent, should not be located directly over entrances because insects are attracted to these bright sources and gain access to the interior when a door is opened. Any type of lamp used to light an entrance or work area should be located a short distance away, with the light directed toward the area to be illuminated. If a lamp must be placed near the entrance, it should be shielded so that its radiant output is directed downward and confined to the immediate area. Since insects are also attracted to reflected radiant energy, care should be taken to avoid using a surface or a paint with a high reflectance for short visible wavelength or UV radiation.

Decoy Lamps and Insect Traps

In addition to careful lamp selection and shielding designs, the number of night-flying insects within an area also can be reduced by placing attracting "black light" fluorescent or mercury decoy lamps at 30- to 60-m distances around the perimeter of the area to intercept those insects trying to enter.

Insect traps commonly contain black light lamps to attract photopositive insects as a means of killing or trapping them. One of the common killing mechanisms is an electric grid that electrocutes the insects attracted to the black light. Various designs are available for commercial, industrial, and residential use. The placement and number of traps should vary with the individual situation and the species of insects involved. Specialists in this field usually are required to determine the best placement of traps for solving specific insect problems. If grid traps are used, they should not be placed so that electrocuted insects fall or are blown into working and food processing areas. System designs and installations should be in compliance with the National Electrical Code or the Canadian Electrical Code.[199]

In agriculture, various insect traps have been used for survey purposes to detect insects in a crop area, to predict the need for pesticide application, and to evaluate effects of insecticide measures. Survey traps used over large areas can be used to determine migration of insects and to predict potential infestation. The trap designs usually include a black light or other fluorescent lamp and a means of trapping insects. Designs are altered for specific insect species.

Studies with black light insect traps in large tobacco- or tomato-growing areas of over 300 km^2 (10 mi^2) have shown that one or more traps per square kilometer reduce tobacco and tomato hornworm populations. Indications are that insect traps are best used in conjunction with insecticides. The use of such traps would generally reduce the number of insecticide applications in a growing season.

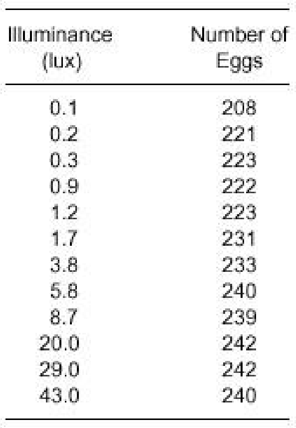
EFFECTS ON POULTRY[200]

Egg Production

Light affects egg production of laying chickens by causing the release of LH and FSH hormones from the anterior pituitary gland. These hormones increase the growth of ova in the ovary. A minimum daylength of 11 to 12 h is required for the effect to take place. Optimal daylength is 14 h, and there are indications that daylengths in excess of 17 h can decrease egg production. The most effective wavelengths are 664 to 740 nm, the region of peak spectral response of the chicken's visual system. The hormone secretions are governed only by light received by the eye and not by other areas of the body. A minimum illuminance of 10 lx at bird level is generally recommended for egg production. Additional illuminance gives no additional benefit (Figure 5-20a) and can decrease productivity by increasing such behaviors as hyperactivity, pecking, and cannibalism. This concern applies equally to the production of meat chickens.

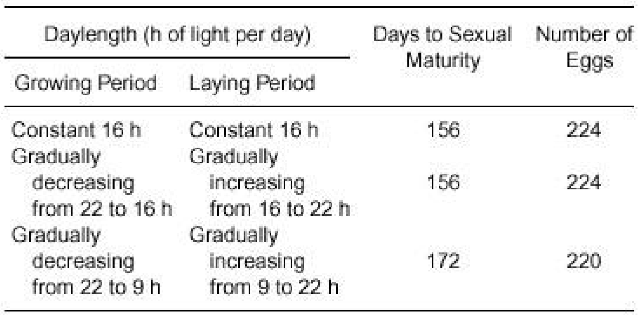
Chick Growth and Development

Light also affects the development of growing chickens (Figure 5-20b). As with the productivity of layers, daylength is the governing factor rather than illuminance, provided a threshold of approximately 10 lx is maintained. When daylength is reduced below 11 to 12 h during the growing period, time to sexual maturity is delayed by up to 3 weeks. The size of eggs during the first production period is increased without significantly affecting the total number of eggs produced. This increases profit because larger eggs are usually in greater demand. Consequently, daylight is typically excluded from commercial laying houses and illumination programs are controlled strictly. See Chapter 27, Lighting Controls.



Illuminance (lux)	Number of Eggs
0.1	208
0.2	221
0.3	223
0.9	222
1.2	223
1.7	231
3.8	233
5.8	240
8.7	239
20.0	242
29.0	242
43.0	240

Figure 5-20a. The Effect of Illuminance on Total Egg Production During the First 45 Weeks of Lay



Daylength (h of light per day)		Days to Sexual Maturity	Number of Eggs
Growing Period	Laying Period		
Constant 16 h	Constant 16 h	156	224
Gradually decreasing from 22 to 16 h	Gradually increasing from 16 to 22 h	156	224
Gradually decreasing from 22 to 9 h	Gradually increasing from 9 to 22 h	172	220

Figure 5-20b. The Effect of Light Treatment Upon Sexual Maturity and Number of Eggs Produced During the First 47 Weeks of Lay

Embryonic Growth

Photoacceleration is a poorly understood but effective technique for improving embryonic growth. It involves placing the large end of the egg as close as possible to a white light source without overheating. The effects are summarized as follows:

- Reduced embryonic mortality due to accelerated growth during the critical first hours of development
- Earlier hatching, by 20 to 48 h
- Increased weight at hatching, by up to 15%
- Increased weight thereafter, by up to 100 g
- Earlier sexual maturity

The process requires continual exposure during the first 18 days.

EFFECTS ON PLANTS[201-224]

Because plants and humans share the same terrestrial environment, daylight has been important to the evolution of their respective spectral sensitivities. Most of the energy incident on earth from the sun is in the visible portion of the electromagnetic spectrum (Figure 5-1). However, plants and the human visual system have evolved very different spectral sensitivities. Strictly speaking, the term "light" is reserved for humans as visually effective radiant energy. Nevertheless, "light" also is used loosely to describe all radiant energy within the visible portion of the electromagnetic spectrum; for the purposes of discussion in this section, the term "light" is used in this latter sense.

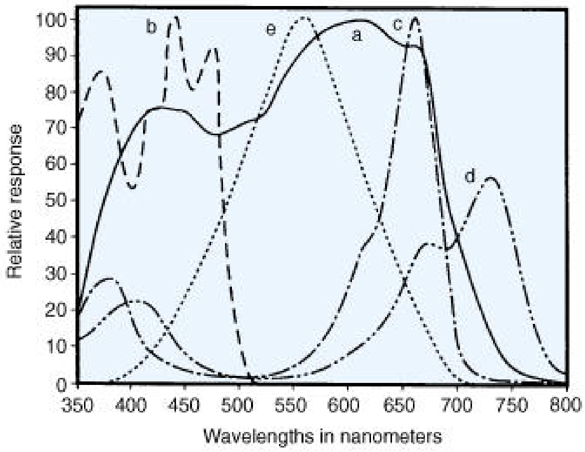


Figure 5-21. Relative quantum yield for photosynthesis (a), the action spectra for the short-wavelength-absorbing photoreceptor (b), the phytochrome in its long-wavelength-induced form (c), and the infrared-induced form (d) compared to human photopic vision (e).

Plant Responses

Photosynthesis. Plants respond to light in many ways (Figure 5-21). Light provides the energy necessary for the conversion of carbon dioxide and water by chlorophyll-containing plants into carbohydrates in the process known as photosynthesis. These carbohydrates are essential foods and are the substrate for proteins, fats, and vitamins required for the survival of all other living organisms. Oxygen, formed as a by-product, is the major source of atmospheric oxygen. Most fossil fuel resources are derived from photosynthetic processes of a past geological period.

Light is also essential for the formation of such important plant pigments as chlorophyll, carotenoids, xanthophylls, anthocyanins, and phytochrome. Light is effective in the opening of stomates, the setting of internal biological clocks, and the modification of such factors as plant size and shape; leaf size, movement, shape, and color; internodal length; flower production, size and shape; petal movement; and fruit yield, size, shape, and color.

Respiration. The reverse of photosynthesis is respiration, whereby the carbohydrates formed in photosynthesis are oxidized to carbon dioxide, water, and energy. Respiration requires neither light nor chlorophyll, but it does require food, enzymes, and oxygen. Respiration is continuous, whereas photosynthesis occurs only in light.

At moderate to high irradiance, photosynthesis in plants exceeds respiration, so the net effect is the production of oxygen from leaves. If irradiance decreases to the point where the carbohydrate produced is equal to that used in respiration, the apparent photosynthetic rate is zero and there is no diffusion of gas from the leaf pores (stomata). This phenomenon is called the compensation point. Plants lighted at the compensation point cannot survive long, because stored carbohydrate is used during the dark period. When the carbohydrate reserves are depleted, the plant dies. This is an important fact in the maintenance of plants in interior environments.

Many plant species under high light levels experience an increase in respiration. This phenomenon, called photorespiration, results in a decrease in the apparent photosynthetic rate.

Other Photoresponses. Photomorphogenesis is light-controlled enlargement, development, and differentiation of a plant due to responses initiated by the short-wavelength-absorbing photoreceptor and by phytochrome. The spectral responses of the major photoreceptors are shown in comparison with that of human vision (Figure 5-21). The short-wavelength-absorbing photoreceptor appears to be a flavin but may differ among species of plants. Phytochrome is a blue-green biliprotein; it has a chromophore that absorbs radiant energy and undergoes excitation, which is used to change its molecular structure. The photomorphogenic responses include flowering, seed germination, stem elongation, and anthocyanin pigment formation.

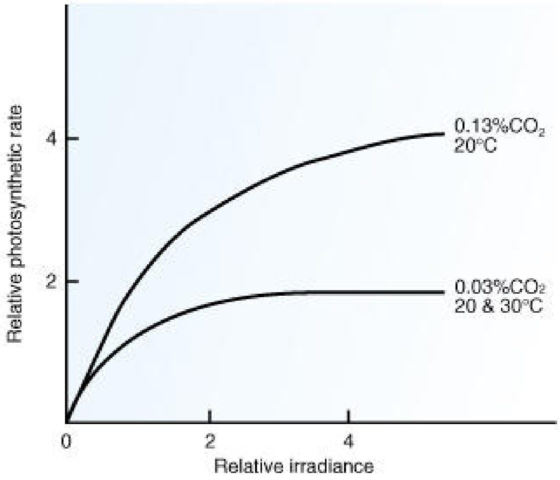


Figure 5-22. Relative photosynthetic rate in relation to irradiance and carbon dioxide concentration.

Light-induced movements of plants are phototropism, photonasty, and phototaxis. Phototropism is the bending of an organ toward or away from the direction of the source of light and is controlled by a photoreceptor that is responsive to short-wavelength radiation. Photonasty is the movement of plant organs, such as the closing of flowers at night and opening during the day, due to changes in irradiance. Phototaxis is the movement of the whole organism in response to light and is restricted to sex cells of aquatic plants and unicellular aquatic plants.

Limiting Factors for Growth

In addition to light, which provides the energy for plants, other requirements must be available in optimum amounts for rapid photosynthesis and growth. These requirements are water, nutrients (inorganic salts), suitable temperature, and carbon dioxide. Lack of any one of these places the plant in stress and limits or halts growth. The relationship between carbon dioxide and irradiance is shown in Figure 5-22, where it can be seen that the photosynthetic rate is accelerated by an increase in irradiance or in the carbon dioxide level. These principles are important in the application of light to accelerate plant growth.

PLANT LIGHTING

Plant lighting is the application of light sources for the control of growth, flowering, or maintenance of plants.

Light Sources

Electric lamps that emit sufficient energy between 300 and 800 nm are effective in photosynthesis and other photoresponses of plants. Experimental work in plant science uses many types of light sources, including incandescent, fluorescent, xenon, low- and high-pressure sodium, and metal halide lamps. Various combinations of lamp types are sometimes used, the most common combinations being incandescent and fluorescent. Other combinations include high-pressure sodium plus metal halide and metal halide plus incandescent. See Figure 5-23.

Generally, the most efficacious lamps for plant growth provide the greatest portion of their energy between 580 and 700 nm. Of the various fluorescent lamps, common rare-earth lamps appear to be efficient in the synthesis of dry matter in plants. Incandescent lamps, which emit a greater proportion of long-wavelength radiation, are widely used in the control of flowering horticultural crops.

Special fluorescent lamps, termed "plant growth lamps," have been developed with phosphors providing emissions that match the absorption maxima of chlorophyll (Figure 5-24). These lamps have found some use in residential lighting for the growth and color enhancement of house plants requiring low energy levels, especially African violets and gloxinias. They are more expensive and have not been found to be superior to common rare-earth fluorescent lamps for photosynthesis. They are therefore not in general use.

Figure 5-23. This modern greenhouse in a college science building has high pressure sodium lighting in addition to large expanses of glazing that allow for plant growth with daylight.

Radiant-Energy Measurement

As previously noted, plants respond to radiant energy quite differently than the human eye (Figure 5-21). Therefore, it is not accurate to measure plant irradiance in terms of illuminance. This is especially important when comparing the effects on plants of lamps with different spectral power distributions.

Photosynthesis is a photochemical conversion in which each molecule is activated by the absorption of one photon in the primary photochemical process. Consequently, photosynthesis correlates better with the number of photons than with energy. McCree[209] established that photon (quantum) flux between 400 and 700 nm is a good measure of photosynthesis. Photosynthetically Active Radiation (PAR) is defined in terms of the number of moles of photons between 400 and 700 nm. One mole of photons is approximately 6×10^{23} photons (Avogadro's number). The Photosynthetic Photon Flux Density (PPFD), or the photon irradiance, is expressed in mol/s/m^2. Quantum meters with a bandpass from 400 to 700 nm can be used to measure PPFD. For a specific spectral power distribution, PPFD can be related to irradiance or illuminance. For most light sources, the conversion from illuminance to PPFD is in the range between 0.01 to 0.02 $\mu\text{mol/s/m}^2$ per lx.

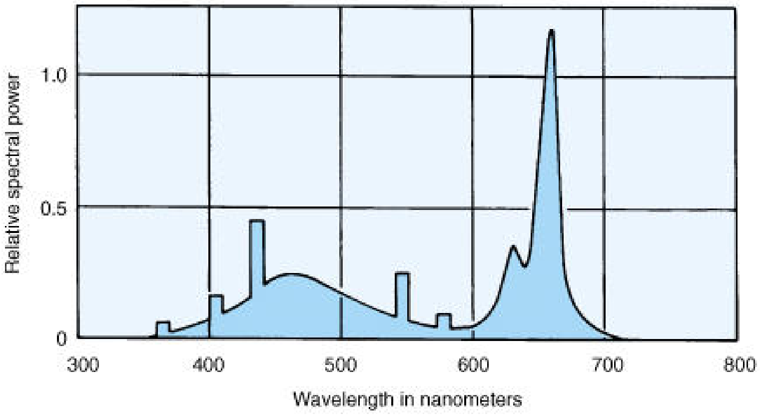


Figure 5-24. Fluorescent lamps for plant growth have been designed with emission spectra that closely match the absorption spectra of chlorophyll (a in Figure 5-21).

PLANT APPLICATIONS

In plant science there are two main uses for lighting: photosynthesis and photoperiodism. In lighting for photosynthesis, light is applied to plants to sustain, partly or wholly, the photosynthetic processes necessary for desired growth. In lighting for photoperiodism, light is applied to plants to sustain, partly or wholly, the photoperiod necessary to produce a desired flowering response. For many plants, the quantity of light required for photosynthesis can be from 10 to more than 100 times greater than that required for photoperiodism.

Photosynthetic Lighting in Greenhouses

Photosynthetic lighting is used in the greenhouse during periods of diminished sunlight in winter months for the growth of out-of-season crops (Figure 5-25). This supplementary lighting can be much less intense than full sunlight, depending on the requirements of the particular plant species.

The different applications of lighting for photosynthesis are lighting in the greenhouse before sunrise or after sunset to extend the light period; lighting in the greenhouse on dark, overcast days for the whole light period; and lighting in the middle of the dark period.

Figure 5-25. Commercial lettuce production under a 400-W metal halide lighting canopy. This greenhouse is 100% artificially lighted. This method of plant growth is highly effective in cold climates where days are short. This particular grower is in Newfoundland.

Figure 5-26. Growth chamber for lettuce seedlings that employs water-jacketed high pressure sodium lamps as the sole light source. The first 11 days of lettuce production take place in this germination area. Seedlings develop best under constant lighting conditions. Light intensity is maintained at 50 μmol/s/m^2 of PAR during the plants' first 24 hr in the growth chamber. For the remaining 10 days, the light intensity is maintained at 250 μmol/s/m^2. The photoperiod (or day length) is 24 hr. Seedlings also require closely controlled specific temperature, relative humidity, carbon dioxide, and irrigation.

Photosynthetic Lighting in Growth Rooms

Photosynthetic lighting in these areas includes lighting provided totally by lamps within commercial growth facilities or research chambers. It also includes lighting for plants used for aesthetic purposes in any interior space, including commercial and residential gardening.

Considerable attention has been given to the development of commercial production of salad crops, particularly lettuce, in growth rooms to compete with conventional crop production. Such production of crops is called controlled environment agriculture. Hydroponic (soilless) culture of plants is used in these ventures.

Plant growth rooms and chambers are now used extensively for research in agricultural experimental stations, educational institutions, and industrial research laboratories for the growth of plants under controlled environmental conditions (Figure 5-26 to 5-28). The environmental conditions that are controlled and monitored include light quantity and duration, temperature, humidity, and carbon dioxide. A research facility that consists of several plant growth chambers (controlled environment rooms) is called a phytotron or, when combined with rooms for animals, a biotron.

The maximum radiant flux that fluorescent systems can produce in conventional applications is 400 μmol/s/m^2. To obtain this radiant flux, 1500-mA, 2.4-m (8-ft) T-12 fluorescent lamps can be closely spaced and mounted under a white perforated ceiling through which lamp heat is exhausted. Spaced at uniform intervals between the fluorescent lamps are 60- or 100-W incandescent lamps, which provide the long-wavelength and near-IR component desired for some plants.

For photon levels of 1000 μmol/s/m^2 or higher, high-intensity discharge (HID) or xenon lamps must be used. Most growth rooms have been fitted with HID lamps because the cost is less and the lamps have much longer lives. Rooms are fitted either with metal halide lamps alone or with a combination of metal halide and high-pressure sodium lamps. The former scheme ensures a more uniform spectral distribution in the room but has lower photosynthetically active radiation, and metal halide lamps degrade faster over time than do high-pressure sodium lamps. Both of these HID lamps, as well as xenon lamps, produce more radiant heat than photosynthetically active radiation (PAR), and serious leaf and soil heating problems result at high photon levels unless special precautions are taken to absorb the radiant heat before it reaches the plants.

For closer control, some growth chamber walls are made either of glossy-white, thermally fabricated material, which absorbs lamp heat, or of specular material that reflects more light to the plants. Uniformly spaced groups of lamps are separately circuited to provide several steps of photon levels while maintaining uniform light distribution. To compensate for lumen depreciation, the system should be designed to produce initially higher photon levels than the maximum level. Photosensors can be used to regulate levels as lamps age (see Chapter 27, Lighting Controls). Quantum meters are used to check levels periodically. Most growth chamber fluorescent or HID lighting systems are operated with ballasts located outside the growing area. This arrangement reduces cooling requirements.

In many commercial greenhouses, electric HID lighting is used to supplement daylight and extend growing periods (Figure 5-29).

Photoperiodic Lighting

In the United States and Canada the greatest use of lighting in plant reproduction is that of photoperiodism to control the out-of-season flowering of certain species of plants that require specific ratios of light to dark periods for flowering. Plants are classified as to the relative length of light period to dark period needed to set flower buds and to bloom. This knowledge is used to bring plants into bloom when there is a particular market need or advantage. In Florida and California the flowering of plants grown for the commercial market is controlled by this type of lighting in the field.

During winter months it is essential to extend the day length to promote the flowering of long-day (short-night) plants and to inhibit the flowering of short-day (long-night) plants. It is also essential that the grower be able to shorten the day length to promote the flowering of short-day plants and to inhibit the flowering of long-day plants. During summer months, the grower must apply an opaque cloth or plastic covering over the plants for part of the day to simulate a short day. It is essential that the material used be opaque and that the plants be exposed to no light during this time, because very low levels are effective in this response. The use of lighting and opaque covering permits the growth and flowering of both long-day and short-day plants the year round. Long-day responses for both short-day and long-day plants usually are obtained by irradiating plants 4 to 8 h before sunrise or after sunset or by the more effective 2- to 5-h light period in the middle of the dark period (called a night break).

Figure 5-27. After the lettuce plants have germinated, they are brought to the pond area of the greenhouse where they are given constant light (through conventional 600-W high pressure sodium lamps), irrigation, and nutrients, until they reach full size at approximately 21 days. For the production of 1000 heads of lettuce per day, a 660 m^2 (6342 ft^2) growing area is required. This greenhouse serves as a "controlled environment agriculture" demonstration site for hydroponic leaf lettuce. Research methods employed here will be applied to commercial greenhouses.

Figure 5-28. The Biomass Production Chamber at Kennedy Space Center, where they are developing systems to raise food in the space colonies of the future. The lighting is high pressure sodium at a very high intensity. The plants in this picture are potatoes.

Figure 5-29. Commercial cucumber production in a northern climate using 1000-W high pressure sodium lamps to supplement daylight. Approximately 1MW of electricity was used per acre.

Commercially, the most important group of photoperiodic plants are short-day plants: chrysanthemums and poinsettias. Such plants remain vegetative with a continuous light period greater than 12 h or with a night break. When flowering is desired, the photoperiod is shortened to approximately 10 h and the night break is discontinued. By providing such long-day plants as China aster and Shasta daisy with a continuous 16- to 18-h day as well as supplementary light, they can be brought into flower, whereas continuous short days inhibit flowering.

Incandescent and fluorescent lamps are used for photoperiodic lighting. Clear incandescent lamps in industrial reflector luminaires or reflector incandescent lamps are commonly used in the field or in the greenhouse. Some HID and incandescent lamps can produce greater internodal elongation in some plants, and this might be undesirable.

Home and Hobby Applications

With available lighting equipment for indoor plant culture, flowering and foliage plants can be taken off the window sill to a place in the room where they can be grown and displayed to best advantage. Some luminaires are equipped with trays to hold moisture to raise the humidity around the plants and with timers to turn lights on and off automatically.

Figure 5-30. Both amateur and professional growers have found value in basement gardens. They allow the amateur to increase the size of the hobby and enable the professional grower to use unproductive space for rooting of cuttings and growth of seedlings.

Some amateurs have set up basement gardens of varying sizes in which plants are grown from seed, cuttings, and bulbs as shown in Figure 5-30. A wide variety of flowering and foliage plants, including all plants of the house plant category, are grown under lights. Fluorescent lamps in T-8 and T-12 sizes and with ordinary loadings are acceptable for this type of horticulture. Ordinary loading lamps (400 mA) can be used to grow seedlings and short plants (less than 15 cm [6 in.]) but high-output lamps (800 mA) and very high output lamps (1500 mA) are preferred for taller plants.

Commercial and Industrial Applications

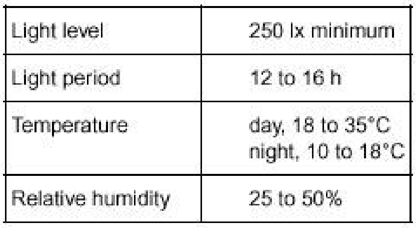
Interior spaces with live plants and trees are now commonplace in lobbies, offices, shopping malls, airport waiting rooms, banks, country clubs, restaurants, entryways of condominiums and apartments, and atria of large hotels and of government, commercial, and industrial buildings. Before any plants are chosen or plans are made for their use, the designer, plant specialist, or architect must first determine if the environment is suitable.

The photon flux in the space determines the species of plants that survive. If the photon flux due to daylight is not sufficient for live plants, then supplemental lighting should be used, provided that other factors are favorable. The amount of supplemental light is determined by the plant species having the greatest light requirement.

Professional plant specialists prefer acclimatized plants for interiorscaping. Acclimatized plants are those that have been conditioned for use in the low-humidity and low-illuminance indoor environments. These plants are taken from greenhouses that often receive full sunlight to a greenhouse with heavy shade. Here they remain for two months or more before being used for interiorscaping. Also, the watering frequency is reduced to condition the plants for indoor use. Such acclimatization prevents the shock that frequently results in rapid defoliation when plants are taken without conditioning from the bright greenhouse to the interiorscape.

The following approximate requirements serve as an initial guide in deciding if the environment is suitable for plants.

Specific requirements for each species can differ.

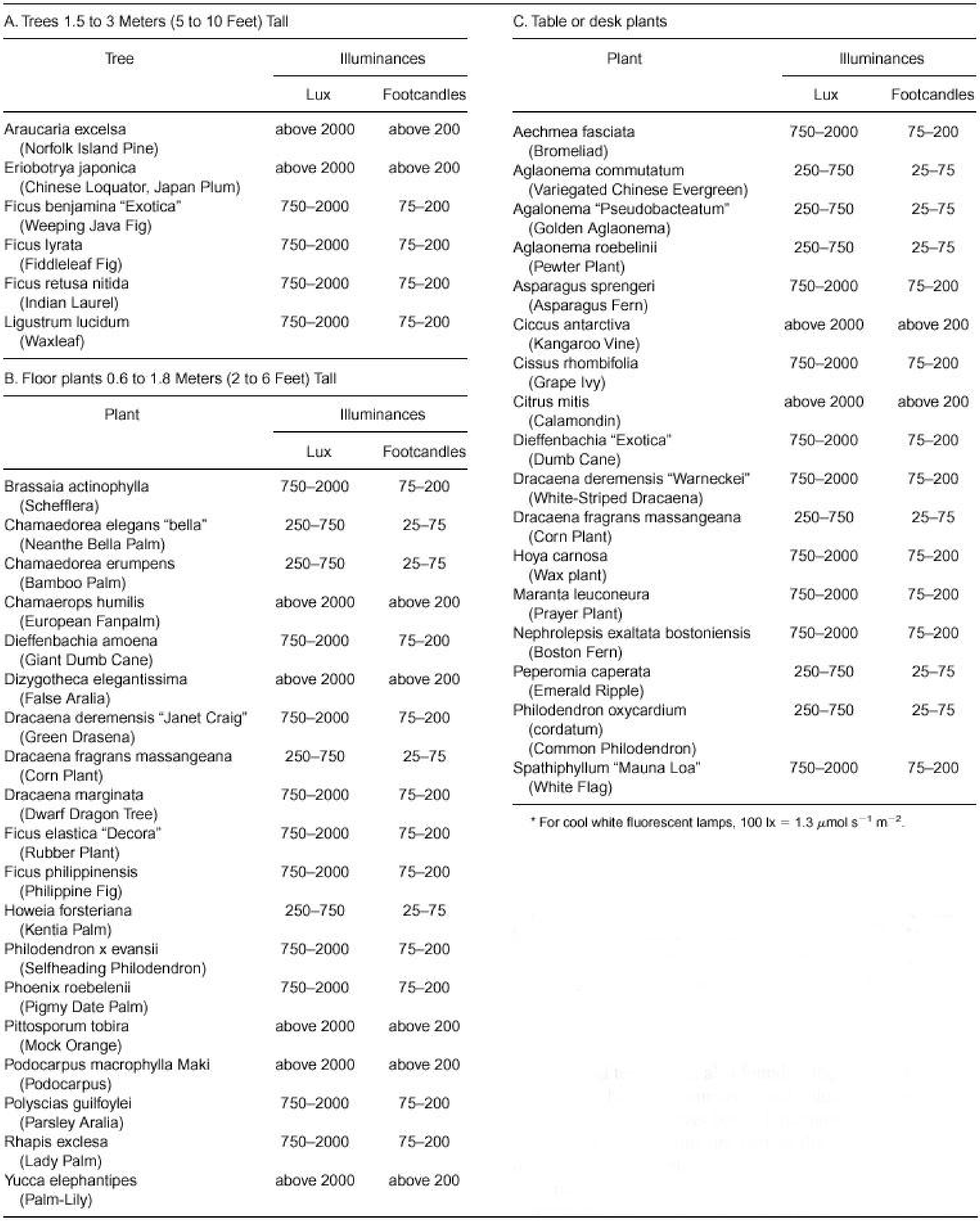


Light level	250 lx minimum
Light period	12 to 16 h
Temperature	day, 18 to 35°C night, 10 to 18°C
Relative humidity	25 to 50%

Lighting in interior occupied spaces serves a dual purpose: lighting for people and for plants. Therefore, illuminance is specified rather than irradiance, which is required for controlled growth applications.

COMMON PLANTS AND ILLUMINANCES

Approximate recommended illuminances for common plants in interiors are shown in Figure 5-31. Plants are categorized as trees, floor plants, and table or desk plants. The lower illuminances in this figure are the minimum for maintenance. Higher values are more satisfactory for good plant condition. The recommendations are for acclimatized plants receiving 14 h of light per day.



A. Trees 1.5 to 3 Meters (5 to 10 Feet) Tall

Tree	Illuminances	
	Lux	Footcandles
Araucaria excelsa (Norfolk Island Pine)	above 2000	above 200
Eriobotrya japonica (Chinese Loquator, Japan Plum)	above 2000	above 200
Ficus benjamina "Exotica" (Weeping Java Fig)	750–2000	75–200
Ficus lyrata (Fiddleleaf Fig)	750–2000	75–200
Ficus retusa nitida (Indian Laurel)	750–2000	75–200
Ligustrum lucidum (Waxleaf)	750–2000	75–200

B. Floor plants 0.6 to 1.8 Meters (2 to 6 Feet) Tall

Plant	Illuminances	
	Lux	Footcandles
Brassaia actinophylla (Schefflera)	750–2000	75–200
Chamaedorea elegans "bella" (Neanthe Bella Palm)	250–750	25–75
Chamaedorea erumpens (Bamboo Palm)	250–750	25–75
Chamaerops humilis (European Fanpalm)	above 2000	above 200
Dieffenbachia amoena (Giant Dumb Cane)	750–2000	75–200
Dizygotheca elegantissima (False Aralia)	above 2000	above 200
Dracaena deremensis "Janet Craig" (Green Drasena)	750–2000	75–200
Dracaena fragrans massangeana (Corn Plant)	250–750	25–75
Dracaena marginata (Dwarf Dragon Tree)	750–2000	75–200
Ficus elastica "Decora" (Rubber Plant)	750–2000	75–200
Ficus philippinensis (Philippine Fig)	750–2000	75–200
Howeia forsteriana (Kentia Palm)	250–750	25–75
Philodendron x evansii (Selfheading Philodendron)	750–2000	75–200
Phoenix roebelenii (Pigmy Date Palm)	750–2000	75–200
Pittosporum tobira (Mock Orange)	above 2000	above 200
Podocarpus macrophylla Maki (Podocarpus)	above 2000	above 200
Polyscias guilfoylei (Parsley Aralia)	750–2000	75–200
Rhapis exclesa (Lady Palm)	750–2000	75–200
Yucca elephantipes (Palm-Lily)	above 2000	above 200

C. Table or desk plants

Plant	Illuminances	
	Lux	Footcandles
Aechmea fasciata (Bromeliad)	750–2000	75–200
Aglaonema commutatum (Variegated Chinese Evergreen)	250–750	25–75
Agalonema "Pseudobacteatum" (Golden Aglaonema)	250–750	25–75
Aglaonema roebelinii (Pewter Plant)	250–750	25–75
Asparagus sprengeri (Asparagus Fern)	750–2000	75–200
Ciccus antarctiva (Kangaroo Vine)	above 2000	above 200
Cissus rhombifolia (Grape Ivy)	750–2000	75–200
Citrus mitis (Calamondin)	above 2000	above 200
Dieffenbachia "Exotica" (Dumb Cane)	750–2000	75–200
Dracaena deremensis "Warneckei" (White-Striped Dracaena)	750–2000	75–200
Dracaena fragrans massangeana (Corn Plant)	250–750	25–75
Hoya carnosa (Wax plant)	750–2000	75–200
Maranta leuconeura (Prayer Plant)	750–2000	75–200
Nephrolepsis exaltata bostoniensis (Boston Fern)	750–2000	75–200
Peperomia caperata (Emerald Ripple)	250–750	25–75
Philodendron oxycardium (cordatum) (Common Philodendron)	250–750	25–75
Spathiphyllum "Mauna Loa" (White Flag)	750–2000	75–200

* For cool white fluorescent lamps, 100 lx = 1.3 μmol s^{-1} m^{-2}.

Figure 5-31. Recommended Illuminances* for Acclimatized Plants (14 h of Light Per Day)

Aquarium and Terrarium Lighting[225-231]

Aquaria and terraria are also found in the home, office, and school for hobby, decorative, and educational purposes. Aquarium lighting serves both a functional and an ornamental purpose when plants are part of the aquarium environment. Through the process of photosynthesis, lighted aquarium plants increase the oxygen level essential for fish respiration and at the same time reduce the carbon dioxide level, preventing the buildup of carbonic acid, which can be harmful to fish. The light also illuminates both the fish and the aquarium. Dramatic colors of both fish and plants can be observed when fluorescent plant growth lamps (Figure 5-24) are used, because the high long- and short-wavelength output of these lamps emphasizes red and blue colors. Overall, however, colors can appear more natural with conventional rare-earth or daylight fluorescent lamps.

Both fluorescent and incandescent lamps are used, with a preference for the former because they are more efficacious. Lighting requirements for aquaria usually range from 0.25 to 0.5 lamp watts per liter of tank capacity when using fluorescent lamps.

Lighting can have important behavioral effects on fish in aquaria. Many fish rely heavily on vision for feeding and locating mates.[225] The visual sensitivity of fish differs from that of humans and other species. Some fish appear to have visual responses to UV-A radiation that might assist in locating food sources at specific times of the day.[226] Light-dark cycling of lighting conditions also can play an important role in breeding routines.[227]

Terrarium lighting usually requires both fluorescent and incandescent lighting. As a rule of thumb, fluorescent lighting is applied at approximately 200 lamp W/m^2 for the plant life while an incandescent lamp is used to light a portion of the terrarium to provide IR radiation for such animals as lizards and frogs, usually found in such environments.

Many animals commonly kept in terraria have a parietal eye,[228] a light-sensitive region that appears to be involved with circadian regulation. The mating behavior patterns of male reptiles can be disturbed if light-dark cycling is not performed regularly.[229]

Another important requirement in lighting for terraria containing reptiles or amphibia is to provide sufficient UV radiation to allow for the production of vitamin D.[230] This vitamin is essential for skeletal development as well as the visual and immune systems. Caution must be taken, however, to avoid excessive UV radiation, which has been demonstrated to hamper growth and development of eggs in several species.[231] The requirements for UV radiation depend on the species, natural habitat, and egg-laying routines.

EFFECTS ON MATERIALS[232-240]

Fading and Bleaching

Fading and bleaching of colored textiles and other materials on exposure to light and other radiant energy is of special interest because of the high illuminances now employed in merchandising. Consequently, a knowledge of some of the factors involved is important. Some of these (not necessarily in order of importance) are as follows:

- Illuminance
- Duration of exposure
- Spectral distribution of the radiation
- Moisture
- Temperature of the material
- Chemical composition of the dye or other colorant
- Saturation of the dye (tints versus saturated colors)
- Composition and weave of fabric
- Intermittency of exposure
- Chemical fumes in the atmosphere

While many studies of fading and colorfastness have been published, especially in textile journals, most of them are deficient in data on the illuminances involved. In general, these articles have dealt primarily with improvements in dyes and dyeing methods. Such tests have involved exposures to daylight in various geographical regions and to standardized types of arc lamps, called "fading lamps." The National Institute of Standards and Technology (NIST) has developed standardized methods and lamps for conducting such tests.

A long review of research in this field,[232] with extensive bibliography, summarizes the subject as follows. The rate at which a dye fades is governed by seven factors:

- Photochemistry of the dye molecule
- Physical state of the dye
- Chemistry of the substrate
- Fine structure of the substrate
- Presence of foreign substances

- Atmosphere
- Irradiance

Certain general conclusions have been derived from studies of several hundred specimens of colored textiles. In view of the fact that the tests have been limited to an infinitesimal percentage of the dyes and textiles in general use, it must be realized that such conclusions are not definitive and many exceptions can be found.

The irradiance and duration of exposure are two of the most important factors. Two studies[233,234] indicate an approximate reciprocal relationship between time and illuminance in the production of fading; that is, the fading is dependent on the product of these two factors and is substantially unaffected by variations in both as long as the product is unchanged. A third study[235] disagrees with this conclusion, indicating that at higher illuminances this relationship breaks down.

The spectral power distribution of the incident radiation used affects the rate of fading. It has been found[236] that UV-B energy is a small component in most practical light sources but can cause very rapid fading and other forms of product deterioration in some cases. Most electric light sources emit UV-A radiation and this spectral region produces more fading per unit of energy than an equal amount in the visible spectrum. Filters that absorb much of the UV-A but very little visible radiation, have been found to reduce fading somewhat,[237] but not as much as is sometimes suggested. It has been shown that fading is produced by energy throughout the entire visible spectrum shorter than approximately 600 nm. Daylight produces more fading than tungsten and fluorescent sources for the same illuminance because daylight has more energy in the short-wavelength region of the spectrum.[233] The germicidal (bactericidal) lamp, producing high energy at 253.7 nm, has been used as a potent source for accelerated fading tests[236] even though no relationship has been found between fading by germicidal lamps and fading by sunlight or commonly used electric light sources.

Figure 5-32 shows spectral reflectance curves for new and slightly faded specimens of pink silk cloth. The spectral changes indicate bleaching in regions of maximum absorption and darkening in regions of minimum absorption. These changes are typical of many specimens tested. Fading appears to be a photochemical process requiring oxygen and is inhibited or greatly reduced in a vacuum. Moisture can also enhance fading. Cellulose is particularly affected by moisture, but wool is less affected, for example.[232] Temperature appears to have little effect on the fading rate of silk and cotton at temperatures below 50°C (120°F), but the rate is approximately twice as great at 65°C (150°F) as it is at 30°C (85°F). Often it is found that a light tint is more susceptible than a higher concentration of the same dye.

Fading is of major importance to the merchandising field. In one early investigation, tests of approximately 100 textile specimens showed that approximately half of the samples faded to some degree after 500 klx × h (50,000 fc × h) of incandescent illumination. A later study[238] of 100 commercial fabrics suggests that several times that exposure is required to produce a minimum perceptible fading with incandescent and fluorescent lamps. Dyes have greatly improved in lightfastness, and fading is not as extensive a problem as it was when the fluorescent lamp was introduced.

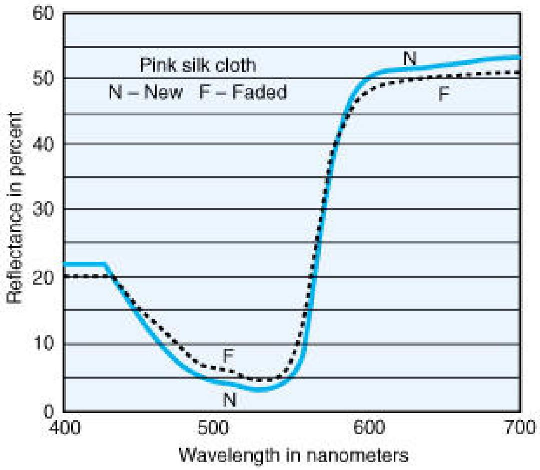


Figure 5-32. Spectral reflectance of a specimen of pink silk before and after exposure sufficient to cause moderate fading.

Fading of merchandise is most readily apparent where one area has received a high level of exposure and an adjacent area has not. Typical examples are folded neckties and socks stacked on shelves in display cases. To reduce perceptible fading, displayed goods should be rotated periodically.

Grocery stores display packaged meats in refrigerated cases under high illuminances. Fresh unprocessed meats show no appreciable color change due to light within any reasonable display period, although unwrapped meats can show color changes due to dehydration. However, many processed meats, such as bologna, receive their red color from a curing process using salt or sodium nitrate. Through a reaction with light and air, such meats return to their original gray color, and this fading takes place very rapidly in some meats. Some, especially veal loaf and bologna, can show perceptible color change in 1500 to 2000 lx×h (150 to 200 fc×h). Since the illuminance in some display cases may be as high as 1000 lx (100 fc), undesirable changes can occur in 1.5 to 2 h. The most susceptible meats should be placed as far away from the lamps as possible. Depending on the degree of original muscle pigmentation, frozen meat is considered salable for 3 to 6 days under illuminances between 500 and 2000 lx (50 and 200 fc).[239] Above 2000 lx (200 fc), shelf life is considerably reduced. Differences in the spectral power distribution of the light sources result in no apparent or statistically significant differences in the rate of color degradation.

Cigars can bleach to some degree in cases illuminated by fluorescent lamps, but the exposures must be quite high. In a test using seven brands of cigars it was found that an exposure of approximately 400 klx × h (40,000 fc × h) produced a just-noticeable change and that this exposure could be doubled before the color change reached an objectionable degree. Exposures of this magnitude are greater than typical for the merchandising of cigars.

Luminescence and Luminescent Materials

Photoluminescence (see Chapter 1, Light and Optics) occurs in many hundreds of materials when they are exposed to radiation. The most important practical application of photoluminescent materials is in fluorescent light sources, where UV radiation excites the lamp phosphors. These phosphors are oxygen-dominated inorganic crystalline materials. Other materials, such as the zinc and cadmium sulfides and a wide variety of organic compounds excited by UV-A radiation, are used extensively to achieve spectacular theatrical effects and in various signs and instrument dials and low-location emergency lighting. So-called optical bleaches are fluorescent organics used as whiteners in laundered items such as shirts and sheets; they are excited by UV-A and short-wavelength visible radiation to fluoresce, appearing bright blue. This balances for the natural yellow-white appearance of the unimpregnated cloth. Superbright orange and red organic dyes that fluoresce under UV-A excitation are widely used as identification and warning markers, for example, in high-speed aircraft to aid in rapid visual acquisition to avoid collision. Fluorescent paint, ink, and dyed fabrics are available in many colors, including red, orange, yellow, blue, and a white that appears blue under UV radiation. Because these materials transform UV and short-wavelength visible energy into light, as well as reflect incident light, their brightness under daylight is conspicuously high. Some fluorescent materials have an apparent reflectance (under daylight) of over 100%; that is, they emit more visible light than strikes them.

These colored fluorescent materials are especially useful on signal flags and signal panels because they can be identified more easily and at greater distances than nonfluorescent surfaces. The increased range over which the fluorescent flags can be identified is most apparent during the half-light conditions of dawn and twilight. Organic fluorescent dyed materials are at times used to produce spectacular signs, such as used on streetcars or buses, and very colorful clothing.

Other photoluminescence applications include X-ray- and gamma-ray-stimulable crystals, which find extensive use in scintillation counters, used for detecting and quantifying the exciting radiation. Chemical analyses often are based on the use of the characteristic luminescence of certain activator ions in known host media. Many types of glass fluoresce to some extent. This is important in certain scientific work where even a small fluorescent emission from a glass filter can ruin an experiment.

Cathodoluminescent materials find their most important application in television screens and in such scientific instruments as oscilloscopes, electron microscopes, image intensifiers, and radar screens. Here zinc and cadmium sulfides and oxygen-dominated phosphors such as the silicates, phosphates, and tungstates are used. An improvement in color television screens has resulted from the development of a rare-earth (europium) activated deep-red phosphate phosphor.

Luminescence attending chemical reactions has been observed widely in both organic and inorganic systems. One of the most interesting is the reaction between the naturally occurring chemicals luciferin, luciferase, and adenosine triphosphate (ATP) within the firefly.

Sound and friction of phosphors are phenomena of relatively little practical application. Electric field excitation of phosphors has found use in readout devices and recently in electrodeless fluorescent lamps (see Chapter 6, Light Sources).

Phosphorescent Materials.

Phosphorescent materials, excited by UV energy, daylight, or light from electric lamps, have been shown to have a high brightness of afterglow for periods of 6 to 9 h, and some of them have a noticeable brightness for as long as 24 h after the exciting source has been removed. Certain phosphorescent materials, generally combinations of zinc, calcium, cadmium, and strontium sulfides, can be incorporated into adhesive tapes (plastic overcoatings), paints, and certain molded plastics. Because of the tendency of many plastics either to transmit moisture, which decomposes the sulfide, or to react directly with the phosphor, care should be exercised in the choice of a plastic to carry the phosphorescent powders. Both vinyl and polystyrene plastics have been found to be well suited to this application.

Phosphorescent materials are suitable only for applications where it is possible to light them before they are needed. Although some materials can be used in spots where a visible brightness is necessary for about 6 to 9 h, only a few of the many phosphorescent compounds have this degree of persistence. Those manufactured from zinc sulfide have high initial brightness after extinguishing the light source, but their useful brightness period does not extend beyond 20 to 30 minutes. Before refinements in the processing of calcium and strontium phosphors were made, the useful brightness of these types did not extend beyond 2 to 3 h after activation. Today, strontium aluminate phosphors can have significantly longer usefulness. Now that long-persistence phosphors are available, phosphorescent materials are suitable for night-long use in many applications.

Brightness reduction (decay) rates are hastened by high temperatures. At very low temperatures (60 K) luminescence may be completely arrested, to recur later upon warming.

Radioactive Excitation. This is simply excitation by electrons, ions (atoms, nuclear fragments), or γ-rays, singly or in combination, resulting from the fission or radioactive decay of certain elements. For example, radium emits particles that can excite luminescence when they strike a suitable phosphor. Krypton-85 excites by emission of β-rays or high-energy electrons. The sulfide phosphors emit light not only when exposed to UV energy or light, but also under bombardment by the rays from radioactive materials. Thus, by compounding a mixture of such a radioluminescent material such as zinc sulfide and a small amount of radioactive material, a self-luminous mixture can be produced. Such a radioactive luminous compound continues to emit light without the help of external excitation for a very long time (several years) in practical applications. Radioactive-luminous materials have been used for many years on watch and clock dials and on the faces of other instruments that must be read in the dark. They are the only type of commercially available luminous materials that maintain self-luminosity for years. The power source was formerly some salt of radium or more frequently the lower-priced mesothorium. These were displaced by strontium-90, and more recently polonium, which has certain advantages with regard to cost and safety. Radioactively powered exit signs typically use tritium, a source of β-rays. See Chapter 29, Emergency, Safety, and Security Lighting, for more information on self-luminous signs.

The bombardment of the fluorescent materials by radiation causes them to decompose, which limits the life of the combination. A good-quality material is useful for a few years and appears to maintain a fairly constant brightness during this period. The life of radioactive-luminous paint is controlled to a great extent by the concentration of radioactive material in the mixture, as is the brightness. Increased radioactive content means increased brightness, but more rapid decomposition of the glowing salt. Because of the expense of the radioactive substances used to activate this material, radioactive-luminous paint seldom is used in large quantities or to cover large areas.

EFFECTS OF IR ENERGY[241-249]

Heat may be transferred from one body to another by conduction, convection or radiation, or by a combination of these processes. IR heating involves energy transfer primarily by radiation, although some convection heating can exist simultaneously due to natural or forced air movement.

Transfer of energy or heat occurs whenever radiant energy emitted by one body is absorbed by another. However, only the wavelengths longer than those of visible radiation and shorter than those of radar are used for radiant heating (770 to 100,000 nm). Energy absorption of white, pastel-colored, and translucent materials is best obtained from emissions longer than 2500 nm, whereas the majority of dark-pigmented and oxide-coated materials readily absorb the full range of emissions, visible as well as IR radiation. Water vapor, steam, and other gases absorb IR energy in specific, characteristic bands throughout the spectrum (e.g., Figure 5-1). Glass and quartz materials effectively transmit IR energy only out to about 5000 nm.

Sources of IR Energy

Many sources for producing IR energy are available (see Chapter 6, Light Sources). These can be classified generally as point, line, and area sources. Their temperatures, spectral power distribution, and life characteristics vary widely, although source selection generally is not critical unless the products to be heated are selective as to wavelength penetration or absorption, as in the case of many translucent plastics.

Tungsten-filament heaters provide essentially instant on-off response from a power source, and their radiant energy efficiency, 86% of power input, makes them a preferred source of IR radiation. Other heaters have thermal inertia varying from approximately 1 min for quartz tubes to 4 to 5 min for metal-sheath heaters. Operating efficiencies are substantially influenced by the design and maintenance of external reflector systems and to a lesser extent by the air temperature and velocity within the heating zone. Overall efficiencies of 35 to 60% are readily obtained in well-designed systems where a long holding time at the designed product temperature is not required. All quartz heat sources can accept high thermal shock. However, metal heaters are best for applications subject to mechanical shock and vibration. A variety of porcelain holders and terminals is available for these sources. Specular reflectors of anodized aluminum, gold or rhodium are recommended for directing the radiant energy to product surfaces.

By comparison, gas IR systems require far heavier and more costly construction to comply with insurance safety requirements. In calculating their operating efficiencies, one must take into account energy loss in the combustion flue products as well as other design factors affecting the ultimate energy utilization.

Product Heating with IR

IR radiant energy can be used for any heating application where the principal product surfaces can be arranged for exposure to the heat sources.[241] Modern methods of conveying materials have greatly accelerated the use of heat sources arranged in banks or tunnels. Typical applications include:

- Drying and baking of paints, varnishes, enamels, adhesives, printer's ink, and other coatings
- Preheating of thermoplastic materials for forming and tacking
- Heating of metal parts for shrink-fit assembly, forming, thermal aging, brazing, radiation testing, and conditioning surfaces for application of adhesives and welding
- Dehydrating of textiles, paper, leather, meat, vegetables, pottery, and sand molds
- Spot and localized heating for any desired objective

Rapid heating can be provided in relatively cold surroundings by controlling the amount of radiant energy, absorption characteristics of the exposed surfaces, and rate of heat loss to the surroundings.[242] Highly reflective enclosures, with or without thermal insulation, are commonly employed to assure maximum energy use. Limited amounts of air movement are often essential in portions or all of the heating cycle, to avoid temperature stratification and assure removal of water or solvent vapors.[243] Product temperature control is normally provided by varying the exposure time to IR radiation, or the heater wattage per unit area of facing tunnel area. With modern linear heaters, power densities of 5 to 130 kW/m^2 (0.5 to 12 kW/ft^2) can accommodate high automation speeds.

Where precise temperatures are needed, the design condition may then be modified by voltage or current input controls to add flexibility for a variety of product conditions, handling speeds, or chemical formulations. The temperature of moving parts can be accurately measured by scanning with a radiation pyrometer to provide indication or full automatic control of the heating cycle. Where quality standards permit small variations in temperature, an initial installation test may be made with portable instrumentation, and thereafter the cycle can repeat itself with a degree of reliability consistent with the power supply voltage. This avoids the need for the usual controls required for other types of process heating.

Spot heating of a portion of an object can eliminate the need for energy formerly required to preheat the whole object. Appropriate applications of IR heating can lead to more efficient use of energy in production facilities.

Comfort Heating with IR

The use of IR radiation for heating in commercial and industrial areas has become quite popular. The T-3 quartz lamp as a semiluminous IR source has distinguished itself for a wide variety of applications in commercial buildings, marquee areas, industrial plants, warehouses, hangars, stadiums, pavilions, and other public areas. Units are usually of the pendant or recessed type, with reflector control for the combined visible and IR radiation. In contrast, residential use (except for bathroom areas) is mostly confined to such low-temperature sources as electric baseboards and plastered radiant ceilings.

By supplying heat only when and where needed, IR heating allows thermostats of conventional heating systems to be lowered while comfort is maintained locally and energy conserved overall.

Applications. Radiant comfort heating applications fall into two broad classifications: general heating and spot heating.[244] General heating installations irradiate complete room areas. High levels of building insulation generally are recommended. The installation in this case often provides a uniform radiant power density in the range of 100 to 320 W/m^2 (10 to 30 W/ft^2) incident on the floor surface. However, some system designers prefer equipment layouts using asymmetric units to provide a somewhat higher density in the areas adjacent to outside walls to help offset the wall thermal loss. To date, like convection heating systems, overall radiant systems have had an installed capacity sufficient to hold the desired indoor temperature and overcome the building heat loss at the specified outdoor design temperature. However, performance data on some installations indicate that a heating capacity sufficient to overcome only 70 to 90% of the building thermal loss is adequate.[245] This reduction probably is due to the direct personnel heating, which elevates the mean radiant temperature in the space.

IR radiation passes through air with little absorption, and this is particularly true of the near IR. Therefore, installations involving quartz IR lamps can be mounted at much greater heights than those with far-IR sources. One can choose equipment with a narrow beam spread so the radiation can be confined primarily to the floor, where it is most beneficial, and losses through the walls are limited. By this means, the mounting height can be increased without requiring a greater installed capacity. It is good practice to keep the radiation from striking the walls at heights more than 2.4 m (8 ft) above the floor.

Although IR heating of the air is minimal, air in radiation-heated areas is warmed from energy absorption by the floor and other solid surfaces. Because the heated air rises, room temperature can be controlled with air thermostats[245] that are shielded from the IR sources.

IR heating systems have an advantage over convection air heating systems for spaces that are subject to high rates of air change (for example, where overhead doors are opened frequently). In these areas, the warm air is lost immediately and air temperature recovery can be lengthy with convection heating. With a radiant system, most objects are warmer than the air, so the air in the space recovers temperature faster.

With quartz tubes, metal-sheath heaters, and gas-fired IR units that produce no light, on-off cycling of the equipment is permissible. When lamps that produce light are used, the cycling should be from full to half voltage to prevent large changes in illumination. Certain types of incandescent heat lamps are manufactured with red glass bulbs to minimize light output and the potential for visual distraction. This typically reduces the radiant power by less than 5 percent.

Spot Heating. The greatest potential use for high-intensity radiant heating lies in spot or zone heating in exposed areas where conventional heating is impractical, for example, marquees, waiting platforms and loading docks, and such infrequently used areas as stadiums, arenas, viewing stands, houses of worship, and assembly halls. The radiation intensity needed for spot heating varies with a number of factors. The major ones are:

1. The degree of body activity as dictated by the task. The more physical effort expended by the worker, the lower the target temperature. Clothing also influences the target temperature.

2. The lowest temperature that is apt to exist in the space (or the lowest temperature at which the owner wants to provide comfort).

3. The amount of air movement at the location. Indoor drafts and slight air movements outdoors can be overcome by higher irradiances, but compensation for wind velocities of more than 2.2 to 4.5 m/s (5 to 10 mi/h) at temperatures below -1°C (30°F) is not sufficient. Wind screens are far more beneficial than increased radiation levels. For spot heating, units should be positioned to supply radiation from at least two directions, preferably above and from the side of the area to be heated. Care should be taken to avoid locating equipment directly over a person's head. In practice, levels for spot heating vary from 100 W/m^2 (10 W/ft^2) at waist level for an indoor installation supplementing an inadequate convection system to more than 1 kW/m^2 (100 W/ft^2) for a marquee or sidewalk people-heating system.

At the higher radiation levels, ice and snow are melted[246] and water on the floor is evaporated. This can reduce the safety hazard of a slippery floor and improve housekeeping by minimizing the tracking in of snow and water in inclement weather. Where snow melting is desirable, the heating units should be energized as soon as snow starts to fall to avoid any accumulation and consequent high reflection of IR energy.

IR heating installations in infrequently used areas can be often turned on before an event to preheat the room surfaces, then turned off before the event is over, with the heat stored in the surfaces and body heat maintaining the comfort level. Many of the control strategies discussed in Chapter 27, Lighting Controls, apply equally to the control of IR heating systems.

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6

Light Sources

A BRIEF HISTORY OF LIGHT SOURCES[1,2,3]

The earliest man-made light sources were fire, torches, and candles. Ancient Egyptians used hollowed-out stones filled with fat, with plant fibers as wicks. These were the first candles, and they date back to about 3000 BC. In the Middle Ages, candles were made of tallow, a type of animal fat; later they were made of beeswax or paraffin. Modern candles can still be thought of as a type of fat lamp, but their use today is almost entirely decorative.

Ancient Greeks and Romans made lamps from bronze or pottery that burned olive oil or other vegetable oils in their spouts. Many oil lamps appeared during the Middle Ages, when reflectors were added to their designs. Early American colonists used fish oil and whale oil in their Betty lamps. Many improvements were made in the design and fabrication of these lamps over the years, but none produced light efficiently until 1784, when a Swiss chemist named Argand invented a lamp that used a hollow wick to allow air to reach the flame, resulting in a bright light. Later, a glass cylinder was added to the Argand lamp allowing the flame to burn better. With the birth of the petroleum industry, kerosene became a widely used fuel in these lamps.

In the 1800s gas lamps became popular as street lights, originating in London, England. The gas lamp had no wick, but its chief drawback was an open flame that produced considerable flicker. The electric lamp replaced gas lamps in the late 1800s and early 1900s. The first electric lamp was the carbon-arc lamp, demonstrated in 1801 by Sir Humphrey Davy, but electric lights became popular only after the incandescent lamp was developed independently by Sir Joseph Swan in England and Thomas Edison in the United States. The latter patented his invention in 1879 and subsequently made the invention the commercial success that it is today. Figure 6-1 illustrates the history of different light sources.

This century has seen a huge increase in the number of available light sources in the marketplace, starting with improvements in the Edison lamp, then the introduction of mercury vapor lamps in the 1930s, followed closely by fluorescent lamps at the 1939 World Fair. Tungsten-halogen lamps were introduced in the 1950s; metal halide and high pressure sodium (HPS) lamps in the 1960s. The introduction of electrodeless lamps in the 1990s is an indication that the industry is dynamic, and the introduction of new light sources is expected to continue at least at the present rate well into the next century. Figure 6-2 lists the approximate luminance of various light sources.

This chapter describes the various light sources and control equipment now available. Fundamental information concerning the generation of light and the operating principles of electric light sources is given in Chapter 1, Light and Optics, and in other references.[1] The sun and sky as light sources are covered in Chapter 8, Daylighting. For techniques on the measurement of light and light output from light sources, see Chapter 2, Measurement of Light and Other Radiant Energy. Some specialty lamps are discussed in Chapter 15, Theater, Television, and Photographic Lighting, and data on UV radiation from some common sources are found in the museum section in Chapter 14, Lighting for Public Places and Institutions.

With such a wide selection of light sources on the market, it is likely that several different choices could be made for a given lighting application. While the general characteristics can be provided, a definitive list with absolute values for all types and manufacturers would be too extensive for this chapter. Figure 6-3 provides a comparison of significant performance characteristics of commonly used lamps. Explanation of the parameters will be provided later in this chapter.

Figure 6-4 shows shapes of commonly available lamps. Each lamp shape also includes the corresponding American National Standards Institute (ANSI) designation used by many lamp manufacturers in their catalogs. The designation is typically followed by a number, which expresses the diameter of the lamp in multiples of 1/8 inch, so that T-12 refers to a tubular fluorescent lamp with a diameter of 12/8 or 1.5 in. (38 mm), and PAR 30 is a parabolic reflector lamp with a diameter of 30/8 or 3.75 in. (95 mm). Manufacturers use a variety of bases, discussed in the individual lamp sections below.

Light sources, luminaires, controls, and system layout are closely interrelated. A light source that is appropriate for one type of application may be impractical for another. See the application chapters that follow for guidance on light source selection.

INCANDESCENT FILAMENT AND TUNGSTEN-HALOGEN LAMPS

The primary consideration of filament lamp design is that it will produce the spectral radiation desired (visible, infrared, ultraviolet) most economically for the application intended. Realization of this objective in an incandescent filament lamp requires the specification of the following: filament material, length, diameter, form, coil spacing, and mandrel size (the mandrel is the form on which the filament is wound); lead-in wires; number of filament supports; filament mounting method; vacuum or filling gas; gas pressure; gas composition; and bulb size, shape, glass composition, and finish. The manufacture of high-quality lamps requires adherence to these specifications and necessitates careful process controls.

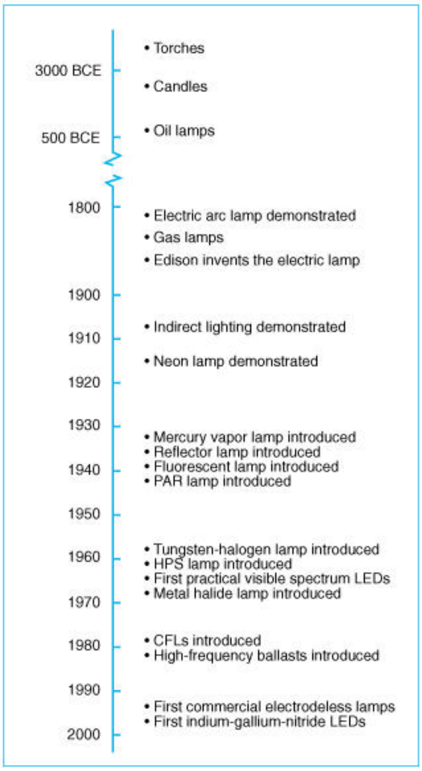


Figure 6-1. Time line of light sources.

The construction and principle of operation of incandescent filament and tungsten-halogen lamps are similar; however, the halogen regenerative cycle enables a tungsten-halogen lamp to provide the following benefits compared to a conventional incandescent lamp: longer life, higher color temperature, higher efficacy, and no bulb blackening.

Incandescent Lamp Construction

Filaments. The efficacy of light production depends on the temperature of the filament. The higher the temperature of the filament, the greater the portion of the radiated energy that falls in the visible region. For this reason it is important in the design of a lamp to keep the filament temperature as high as is consistent with satisfactory life. For example, iron is not a good filament material because it melts at a relatively low temperature (1527°C) for efficient light production. Numerous materials have been tested for filament suitability. Desirable properties of filament materials are a high melting point, low vapor pressure, high strength, high ductility, and suitable radiating characteristics and electrical resistance.

Tungsten for Filaments. Early incandescent lamps used carbon, osmium, and tantalum filaments, but tungsten has many desirable properties for use as an incandescent light source. Its low vapor pressure and high melting point, 3382°C (6120°F), permit high operating temperatures and consequently high efficacies. Drawn tungsten wire has high strength and ductility, allowing the uniformity necessary for present-day lamps. Alloys of tungsten with other metals such as rhenium are useful in some lamp designs. Thoriated tungsten wire is used in filaments for rough service applications.

Radiating Characteristics of Tungsten.[4-7] The ratio of the radiant exitance of a thermal radiator to that of a blackbody radiator is called the emissivity, and thus the emissivity of a blackbody is 1.0 for all wavelengths (see Chapter 1, Light and Optics). Tungsten is a selective radiator because its emissivity is a function of the wavelength. Figure 6-5 illustrates the radiation characteristics of tungsten and of a blackbody and shows that for the same amount of visible radiation, tungsten radiates only a percentage of the total radiation from a blackbody at the same temperature. (The intensity of curve B is approximately 76% of curve A.)

Only a small percentage of the total radiation from an incandescent source is in the visible region of the spectrum. As the temperature of a tungsten filament is raised, the radiation in the visible region increases (Figure 6-6), and thus the luminous efficacy increases. The luminous efficacy of an uncoiled tungsten wire at its melting point is approximately 53 lm/W. In order to obtain long life, it is necessary to operate a filament at a temperature well below the melting point, resulting in a loss in efficacy.

Resistance Characteristics of Tungsten. Tungsten has a positive resistance characteristic, so that its resistance at operating temperature is much greater than its cold resistance. In general-service lamps, the hot resistance is 12 to 16 times the cold resistance. Figure 6-7 illustrates the change in resistance of the tungsten filament with temperature for various lamps. The low cold resistance of tungsten filaments results in an initial in-rush of current that, because of the reactive impedance characteristic of the circuit, does not reach the theoretical value indicated by the ratio of the hot-to-cold resistance. Figure 6-8 gives the effect of the change in resistance on the current in incandescent filament lamps. The in-rush current due to incandescent filament loads is important in the design and adjustment of circuit breakers, in circuit fusing, in the design of lighting-circuit switch contacts, and in dimmer designs.

Light Source		Approximate Average Luminance (cd/m^2)
Natural light sources		
Sun (at its surface)	—	2.3×10^9
Sun (as observed from earth's surface)	At meridian	1.6×10^9
Sun (as observed from earth's surface)	Near horizon	6×10^6
Moon (as observed from earth's surface)	Bright spot	2.5×10^3
Clear sky	Average brightness	8×10^3
Overcast sky	—	2×10^3
Lightning flash	—	8×10^{10}
Combustion sources		
Candle flame (sperm)	Bright spot	1×10^4
Kerosene flame (flat wick)	Bright spot	1.2×10^4
Illuminating gas flame	Fish-tail burner	4×10^3
Welsbach mantle	Bright spot	6.2×10^4
Acetylene flame	Mees burner	1.1×10^5
Photoflash	—	1.6×10^8 to 4×10^8 peak
Nuclear sources		
Atomic fusion bomb	0.1 msec after firing—30-m dia. ball	2×10^{12}
Self-luminous paints		0.2 to 0.3
Incandescent lamps		
Carbon filament	3.15 lm/W	5.2×10^5
Tantalum filament	6.30 lm/W	7×10^5
Tungsten filament	Vacuum lamp 10 lm/W	2×10^6
Tungsten filament	Gas-filled lamp 20 lm/W	1.2×10^7
Tungsten filament	750-W projection lamp 26 lm/W	2.4×10^7
Tungsten filament	1200-W projection lamp 31.5 lm/W	3.3×10^7
RF (radio frequency)	24-mm diameter disk	6.2×10^7
Blackbody at 6500 K	—	3×10^9
Blackbody at 4000 K	—	2.5×10^8
Blackbody at 2042 K	—	6×10^5
60-W inside frosted	—	1.2×10^5
10-W inside frosted	—	2×10^4
Tungsten-halogen sources		
3000 K CCT	—	1.3×10^7
3200 K CCT	—	2.3×10^7
3400 K CCT	—	3.9×10^7
Fluorescent sources		
CFL	36-W twin tube	3×10^4
T-5	14–35 W	2×10^4
T-8	58 W	1.4×10^4
T-8	36 W	1.1×10^4
T-12 bulb	Cool white 430 mA	8.2×10^3
T-12 bulb	Cool white 800 mA	1.1×10^4
T-12 bulb	Cool white 1500 mA	1.7×10^4
T-17 grooved	Cool white 1500 mA	1.5×10^4
Electroluminescent sources		
Green color at 120 V 60 Hz	—	27
Green color at 600 V 400 Hz	—	68
Carbon arc sources		
Plain carbon arc	Positive crater	1.5×10^8
High intensity carbon arc	13.6 Rotating positive carbon	1.0×10^9
Enclosed electric arc sources		
High pressure mercury	Type H33 2.5 atm	1.5×10^8
High pressure mercury	Type H38 10 atm	1.8×10^8
High intensity short arc mercury	30 atm	2.4×10^8 (4.3×10^9 peak)
Xenon short arc	900 W dc	1.8×10^8
Electronic flash tubes	900 W dc	1×10^9 to 3×10^9

Figure 6-2. *Continued*

Light Source		Approximate Average Luminance (cd/m^2)
Photographic flash units	In beam candlepower seconds	400–6,000+
Photographic flash units	(BCPS)	400–16,000+
Clear glass neon tube	15 mm 60 mA	1.6×10^3
Clear glass neon tube	15 mm 60 mA	8×10^2
Clear glass blue tube	15 mm 60 mA	8×10^2

Figure 6-2. Approximate Luminance of Various Light Sources

Color Temperature. Often it is important to know the apparent color temperature of an incandescent lamp. Figure 6-9 expresses the approximate relationship between color temperature and luminous efficacy for a range of gas-filled lamps. The efficacy value often can be found in the literature, or it can be calculated from published lumen and wattage data. From this value it is possible to approximate the average color temperature of the filament.

Construction and Assembly. Figure 6-10 shows the basic parts and steps in the assembly of a typical incandescent, general-service filament lamp. In miniature lamps three methods of construction are typically used: flange seal, butt seal, and pinch seal (Figure 6-11).

The flange seal generally is used with lamps 20 mm (0.79 in.) and larger in bulb diameter. This construction features a glass stem with a flange at the bottom that is sealed to the neck of the bulb. When used with bayonet bases, the plane of the filament and lead wires is normally at right angles to the plane of the base pins, but a tolerance of 15°generally is permitted. The advantages of this construction are: (1) heavy lead-in wires can be used for lamp currents up to 12 A, (2) the filament can be accurately positioned, and (3) sturdy stem construction resists filament displacement and damage from shock and vibration.

The butt seal is constructed as follows. A mount consisting of lead-in wires, bead, and filament is dropped into the open end of the bulb. The lead-in wires are bent to locate the filament at the desired distance from the bulb end. An exhaust tube is then dropped down and butted against the lead-in wire and glass bulb just prior to sealing and exhausting. The base, applied later, together with the basing cement, must not only provide the lamp contacts but also protect the delicate seal. Because of seal limitations, butt seal lamps are restricted to small wire sizes with a current limit of approximately 1.0 A. The filament position varies considerably more than in flange seal lamps, since there is no definite relationship between the planes of the filament and base pins. Occasionally butt seal lamps are used without bases; these lamps should be handled carefully. When used with a base, the advantages of butt seal construction are (1) low cost and (2) small size (usually 20 mm [0.79 in.] and below).

The pinch seal is so named because glass is pinched, or formed, around the lead-in wires. Two forms are used: wire terminals and wedge base construction. For the smaller types of glow lamps, the bulb is exhausted and tipped off at the end opposite the lead-in wires. With newer wedge base lamps, the exhaust tip is at the bottom rather than the top. Pinch seal construction eliminates the need for a conventional base. Advantages are: (1) low cost; (2) small size; (3) with filament lamps, the elimination of solder and cement, which allows operation up to 300°C; and (4) small space required for wedge base lamps.

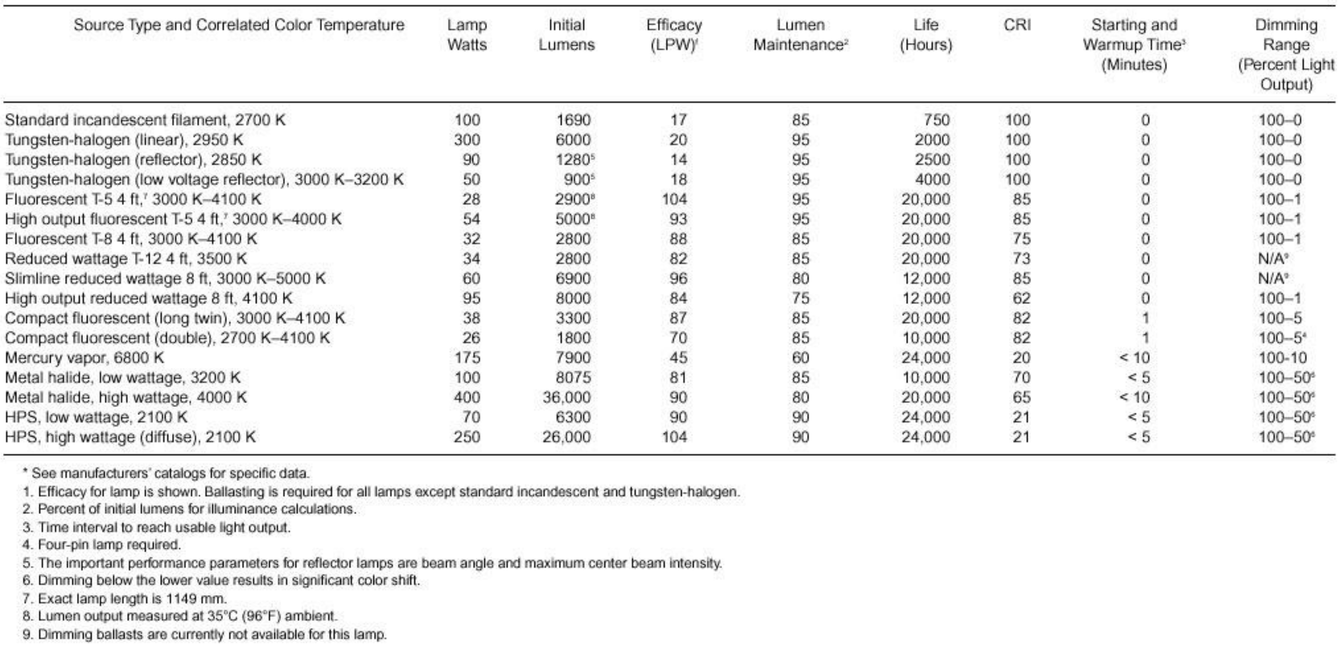
The molybdenum seal is used in some tungsten-halogen lamps, where wire seals cannot be employed, due to their thermal expansion mismatch with the fused silica envelope material. Molybdenum seals consist of thin ribbons or foils of molybdenum that are pinched in the base of the lamps to provide the required electrical lead-in. The ribbons provide a reliable seal as long as base temperature is kept below the molybdenum oxidation temperature of 350°C (662°F).

Filament Forms and Designations. Filament design involves a careful balance between light output and life. Filament forms, sizes, and support constructions vary widely with different types of lamps (Figure 6-12). Their designs are determined largely by service requirements. Filament forms are designated by a letter or letters followed by an arbitrary number. The most commonly used letters are: S (straight), meaning the wire is uncoiled; C (coiled), meaning the wire is wound into a helical coil; and CC (coiled coil), meaning the coil is itself wound into a helical coil. Coiling the filament increases its luminous efficacy; forming a coiled coil further increases efficacy. More filament supports are required in lamps designed for rough service and vibration service than for general-service lamps.

Bulbs

Shapes and Sizes. Common bulb shapes are shown in Figure 6-4.

Types of Glass. Most bulbs are made of regular lead or soda lime (soft) glass, but some are made of borosilicate heat-resisting (hard) glass. The latter withstand higher temperatures and are used for highly loaded lamps. They usually withstand exposure to moisture or luminaire parts touching the bulb. Three specialized forms of glass are also used as lamp envelopes: fused silica (quartz), high-silica, and aluminosilicate glass. These materials can withstand still higher temperatures. See the section "Bulb and Socket Temperature" below.



Source Type and Correlated Color Temperature	Lamp Watts	Initial Lumens	Efficacy (LPW)[1]	Lumen Maintenance[2]	Life (Hours)	CRI	Starting and Warmup Time[3] (Minutes)	Dimming Range (Percent Light Output)
Standard incandescent filament, 2700 K	100	1690	17	85	750	100	0	100–0
Tungsten-halogen (linear), 2950 K	300	6000	20	95	2000	100	0	100–0
Tungsten-halogen (reflector), 2850 K	90	1280[5]	14	95	2500	100	0	100–0
Tungsten-halogen (low voltage reflector), 3000 K–3200 K	50	900[5]	18	95	4000	100	0	100–0
Fluorescent T-5 4 ft,[7] 3000 K–4100 K	28	2900[8]	104	95	20,000	85	0	100–1
High output fluorescent T-5 4 ft,[7] 3000 K–4000 K	54	5000[8]	93	95	20,000	85	0	100–1
Fluorescent T-8 4 ft, 3000 K–4100 K	32	2800	88	85	20,000	75	0	100–1
Reduced wattage T-12 4 ft, 3500 K	34	2800	82	85	20,000	73	0	N/A[9]
Slimline reduced wattage 8 ft, 3000 K–5000 K	60	6900	96	80	12,000	85	0	N/A[9]
High output reduced wattage 8 ft, 4100 K	95	8000	84	75	12,000	62	0	100–1
Compact fluorescent (long twin), 3000 K–4100 K	38	3300	87	85	20,000	82	1	100–5
Compact fluorescent (double), 2700 K–4100 K	26	1800	70	85	10,000	82	1	100–5[4]
Mercury vapor, 6800 K	175	7900	45	60	24,000	20	< 10	100-10
Metal halide, low wattage, 3200 K	100	8075	81	85	10,000	70	< 5	100–50[6]
Metal halide, high wattage, 4000 K	400	36,000	90	80	20,000	65	< 10	100–50[6]
HPS, low wattage, 2100 K	70	6300	90	90	24,000	21	< 5	100–50[6]
HPS, high wattage (diffuse), 2100 K	250	26,000	104	90	24,000	21	< 5	100–50[6]

* See manufacturers' catalogs for specific data.

1. Efficacy for lamp is shown. Ballasting is required for all lamps except standard incandescent and tungsten-halogen.
2. Percent of initial lumens for illuminance calculations.
3. Time interval to reach usable light output.
4. Four-pin lamp required.
5. The important performance parameters for reflector lamps are beam angle and maximum center beam intensity.
6. Dimming below the lower value results in significant color shift.
7. Exact lamp length is 1149 mm.
8. Lumen output measured at 35°C (96°F) ambient.
9. Dimming ballasts are currently not available for this lamp.

Figure 6-3. General Characteristics of Commonly Used Light Sources*
(This table is intended to show the wide range of parameters available for lamp products. A specific example has been chosen for each source type.)

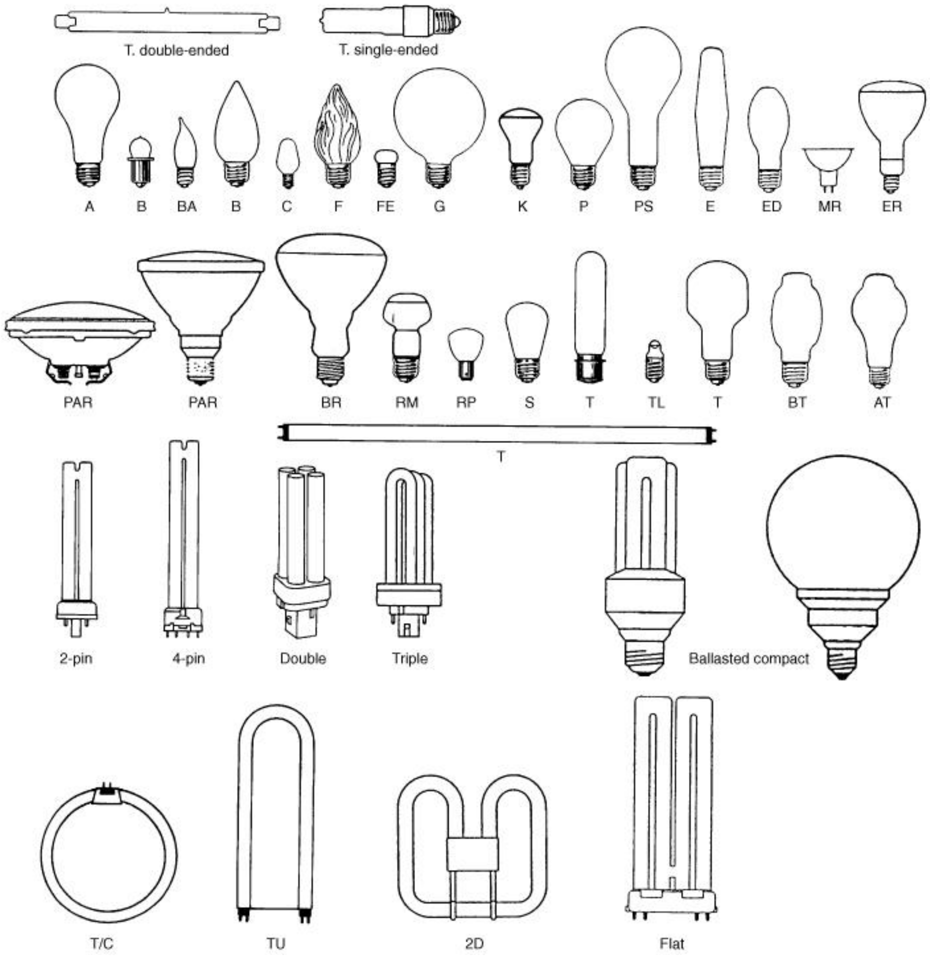


Figure 6-4. Typical bulb shapes (not to scale) and their ANSI designations. Not every ANSI designation, as key-listed here to a descriptive phrase or word, is illustrated.

A–Arbitrary spherical shape tapered to narrow neck
AT–Arbitrary tubular
B–Bulged or bullet shape; blunt tip
BA–Bulged with angular (bent) tip
BD–Bulged with dimple in crown
BR–Bulged reflector
BT–Bulged tubular
C–Conical
CA–Candle shape with bent tip
CC–Two conical shapes blended together (formerly DC)
E–Elliptical
ED–Elliptical with dimple in the crown
ER–Elliptical reflector
F–Flame shape, decorative
FE–Flat elliptical
G–Globe shape
GT–Globe/tubular combination
K–Similar to M but with conical transition
M–Mushroom shape with rounded transitions
MR–Multifaceted reflector
P–Pear shape
PS–Pear shape with straight neck
PAR–Parabolic aluminized reflector
R–Reflector
RB–Bulged reflector (see the more common BR above)
RD–Reflector with dimple in crown
REC–PAR type lamp with rectangular face
RM–Reflector, mushroom shape
RP–Reflector, pear shape
S–Straight-sided shape (compare with CA and BA)
ST–Straight-tipped shape
T–Tubular shape
TL–Tubular shape with lens in crown
T/C–Tubular circular
TU–Tubular U-shape
2D–2-dimensional

Bulb Finishes and Colors. Inside frosting is applied to many types and sizes of bulbs. It produces moderate diffusion of the light with very little reduction in output. The extremely high filament luminance of clear lamps is reduced, and striations and shadows are mostly eliminated. White lamps having an inside coating of finely powdered white silica provide a better diffusion with little absorption of light.

Daylight lamps have bluish glass bulbs that absorb some of the long wavelengths produced by the filament. The transmitted light is of a higher correlated color temperature. This color, achieved at the expense of approximately 35% reduction in light output through absorption, varies between 3500 and 4000 K. This is almost midway between tungsten filament light and daylight.

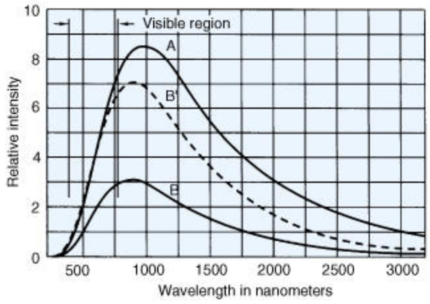


Figure 6-5. Radiating characteristics of tungsten. Curve A: radiant flux from one square centimeter of a blackbody at 3000 K. Curve B: radiant flux from one square centimeter of tungsten at 3000 K. Curve B′: radiant flux from 2.27 square centimeters of tungsten at 3000 K (equal to curve A in visible region). (The 500-watt 120-volt general service lamp operates at about 3000 K.)

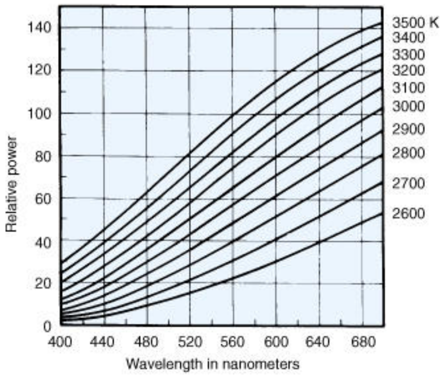


Figure 6-6. Spectral power distribution in the visible region from tungsten filaments of equal wattage but different temperatures.

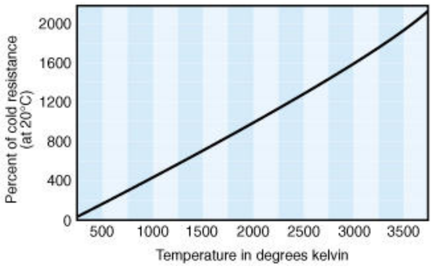
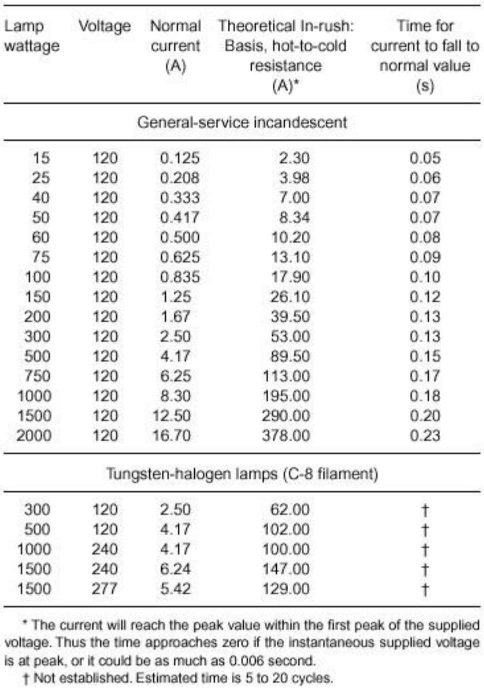


Figure 6-7. Variation of tungsten filament hot resistance with temperature.



Lamp wattage	Voltage	Normal current (A)	Theoretical In-rush: Basis, hot-to-cold resistance (A)*	Time for current to fall to normal value (s)
		General-service incandescent		
15	120	0.125	2.30	0.05
25	120	0.208	3.98	0.06
40	120	0.333	7.00	0.07
50	120	0.417	8.34	0.07
60	120	0.500	10.20	0.08
75	120	0.625	13.10	0.09
100	120	0.835	17.90	0.10
150	120	1.25	26.10	0.12
200	120	1.67	39.50	0.13
300	120	2.50	53.00	0.13
500	120	4.17	89.50	0.15
750	120	6.25	113.00	0.17
1000	120	8.30	195.00	0.18
1500	120	12.50	290.00	0.20
2000	120	16.70	378.00	0.23
		Tungsten-halogen lamps (C-8 filament)		
300	120	2.50	62.00	†
500	120	4.17	102.00	†
1000	240	4.17	100.00	†
1500	240	6.24	147.00	†
1500	277	5.42	129.00	†

* The current will reach the peak value within the first peak of the supplied voltage. Thus the time approaches zero if the instantaneous supplied voltage is at peak, or it could be as much as 0.006 second.

† Not established. Estimated time is 5 to 20 cycles.

Figure 6-8. Effect of Hot-Cold Resistance on In-rush Current in an Incandescent Filament (Laboratory Conditions)

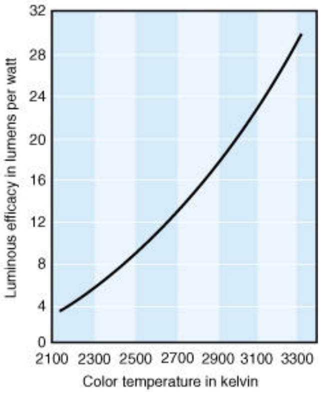


Figure 6-9. Variation of color temperature with lamp efficacy.

General-service incandescent colored lamps are available with inside- and outside-spray-coated, outside-ceramic, transparent-plastic-coated, and natural-colored bulbs. Outside-spray-coated lamps generally are used indoors and not exposed to weather. Their surfaces collect dirt readily and are not easily cleaned. Inside-coated bulbs have smooth outside surfaces that are easily cleaned; thus the pigments are more durable. Ceramic-coated bulbs have the colored pigments fused onto the glass, providing a permanent finish. They are suitable for indoor and outdoor use, as are most transparent-plastic-coated bulbs. The coating permits the filament to be observed directly. Natural-colored bulbs are made of colored glass. Colored reflector lamps use ceramic-coated bulbs, stained bulbs, plastic-coated bulbs, and dichroic interference filters to obtain the desired color characteristics.

Bases. Figure 6-13 shows the most common lamp bases. Most lamps for general lighting purposes employ one of the screw bases. Where a high degree of accuracy in positioning of light sources with relation to optical elements is important, as in the case of projection systems, bipost and prefocus bases ensure proper filament location. Lamp wattage is also a factor in determining the base type.

Most bases are secured to the bulbs by cement and are cured by heat when the lamp is manufactured. Since this cement becomes weaker with age, particularly if exposed to excessive heat, lamps intended for high-temperature service use a special heat-tolerant basing cement or bases that are mechanically fastened without the use of cement.

Gas Fill. Around 1911, attempts were made to reduce the rate of evaporation of the filament by the use of gas-filled bulbs. Nitrogen was first used for this purpose.[8] Although the fill gas reduced bulb-wall blackening, it increased heat loss, leading to even greater light loss. An incandescent filament operating in an inert gas is surrounded by a thin sheath of heated gas, to which some of the input energy is lost; the proportion lost decreases as the filament diameter is increased. When the filament is coiled in a tight helix, the sheath surrounds the entire coil so that the heat loss is no longer determined by the diameter of the wire but by the diameter of the coil, thus greatly reducing this energy loss. A coiled-coil filament has even less length for a given power rating, thus further reducing the area available for convective cooling. The use of coiled-coil filaments and gas-filled bulbs has yielded major improvement in incandescent lamp efficacies. However, general-service 120-V lamps below 25 W are usually of the vacuum type since gas filling does not improve the luminous efficacy in this wattage range.

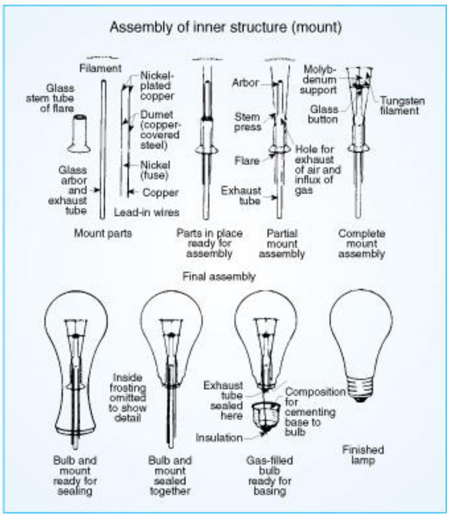


Figure 6-10. Steps in the manufacture of a typical incandescent filament lamp.

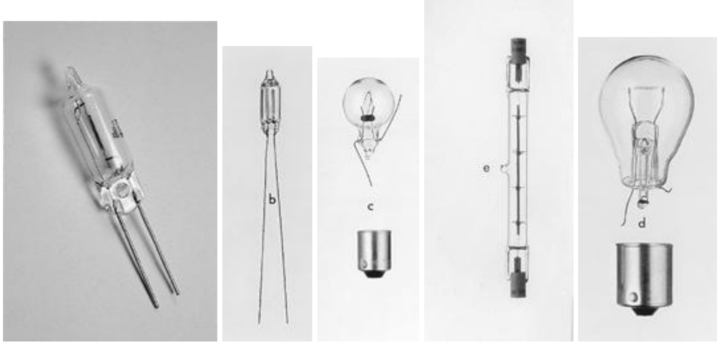


Figure 6-11. Primary type of bulb construction: (a) glass halogen capsule with pinched seal, (b) pinch seal with lead-in wire terminals, (c) butt seal, (d) flange seal, and (e) molybdenum ribbon pinch seal.

Inert gases are now preferred because they do not react with the internal parts of the lamp and because they conduct less heat than nitrogen. It was some years after the development of gas-filled lamps before argon became available in sufficient quantity and purity and at reasonable cost. Most lamps are now filled with argon and a small amount of nitrogen; some nitrogen is necessary to suppress arcing between the lead-in wires.

The proportion of argon and nitrogen depends on the voltage rating, the filament construction and temperature, and the lead-tip spacing. Typical amounts of argon in use are: 99.6% for 6-V lamps, 95% for 120-V general-service coiled-coil lamps, 90% for 230-V lamps having fused lead wires, and 50% or less for 230-V lamps when no fuses are used in the leads. Some projection lamps are 100% nitrogen filled.

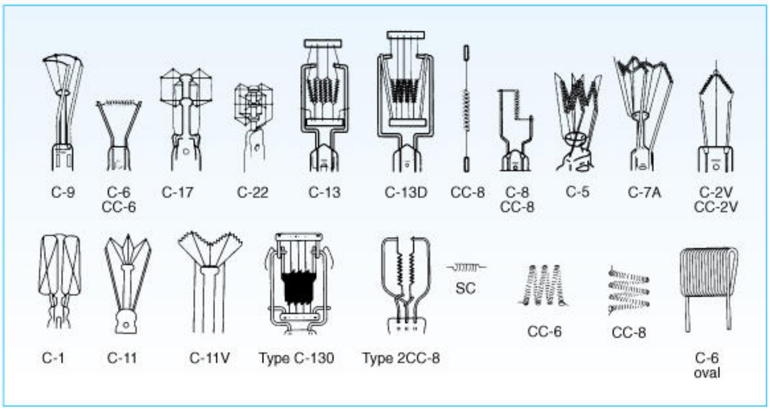


Figure 6-12. Typical lamp filament constructions (not to scale).

Krypton, although expensive, is used in some lamps where the increase in cost is justified by the increased efficacy or increased life. Krypton gas has lower heat conductivity than argon. Also, the krypton molecule is larger than that of argon and therefore further retards the evaporation of the filament. Depending on the filament form, bulb size, and mixture of nitrogen and argon, krypton fill can increase efficacy by 7 to 20%.[9,10] Krypton is used in some special lamps such as marine signal and miner's cap lamps because of the resulting high efficacy.

An even more expensive gas, xenon, is used in a number of unique applications. Xenon has lower heat conductivity and larger molecular size than krypton and thus allows even higher efficacy. However, it costs significantly more than krypton and is used only for special product applications.

Hydrogen gas has a high heat conductivity and is therefore useful for signaling lamps where quick flashing is desired.[11]

Tungsten-Halogen Lamps. The light generation mechanism of tungsten-halogen lamps is the same as that of common incandescent filament lamps, except for the halogen regenerative cycle. Halogen is the name given to a family of electronegative elements, including bromine, chlorine, fluorine, and iodine. Although the tungsten-halogen regenerative cycle has been understood for many years, no practical method of using it was established until the development of small-diameter fused quartz envelopes for filament lamps provided the proper temperature parameters. Iodine was used in the first tungsten-halogen lamp; today, other halogen compounds, predominantly bromine, are used.

The regenerative cycle starts with the tungsten filament operating at incandescence, evaporating tungsten off the filament. Normally the tungsten particles would collect on the bulb wall (Figure 6-14a), resulting in bulb blackening, common with incandescent lamps and most evident near the end of their life. However, in halogen lamps the temperature of the bulb is high enough so that the tungsten combines with the halogen. The correlated minimum temperature of the bulb must be approximately 260°C (500°F).

The resulting tungsten-halogen compound is also gaseous and continues to circulate inside the lamp until it comes in contact with the incandescent filament. Here, the heat is sufficient to break down the compound into tungsten, which is redeposited on the filament, and halogen, which is freed to continue its role in the regenerative cycle (Figure 6-14b). However, since the tungsten does not necessarily redeposit exactly where it came from, the tungsten-halogen lamp still has a finite life. Dimmed tungsten-halogen lamps should periodically be run at full power, inducing the tungsten-halogen cycle to clean the tungsten off the bulb wall, and thereby maintaining lamp efficacy over time.

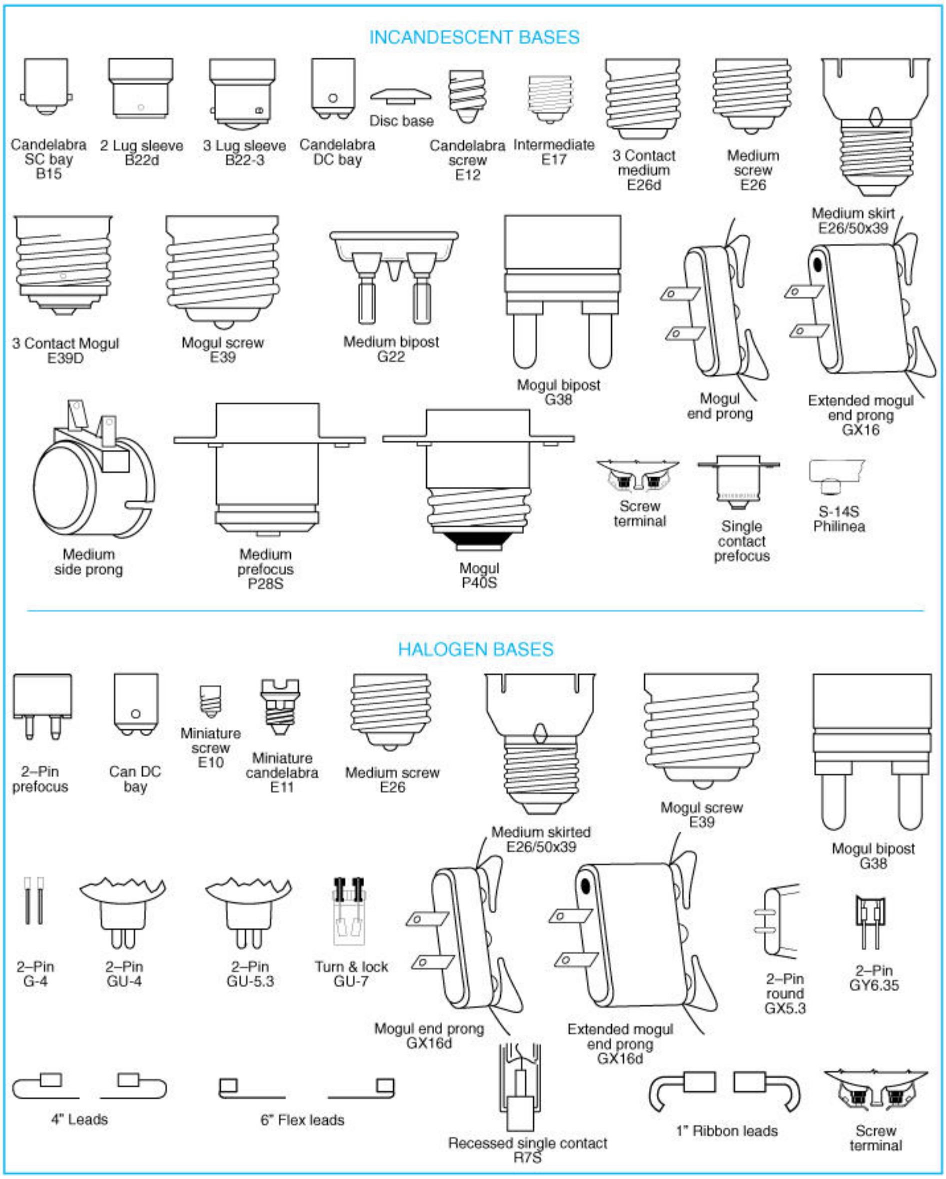


Figure 6-13. Common lamp bases (not to scale). ANSI designations are shown, where available.

The requirement of a high bulb wall temperature for the halogen regenerative cycle led to the corollary effect of producing smaller lamps. This resulted first in the development of small low-voltage reflector lamps and finally in the incorporation of halogen capsules in various PAR envelopes. These PAR envelopes have replaced both incandescent PAR and BR types.

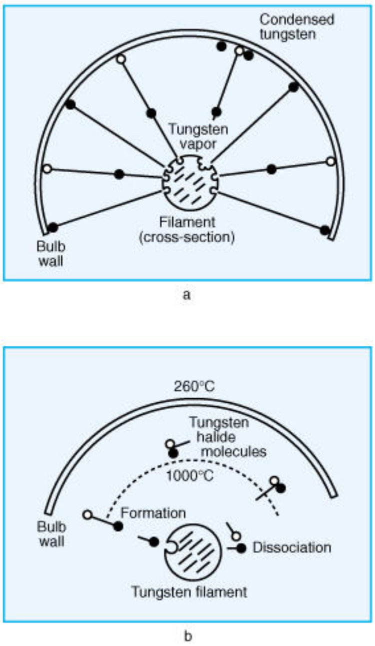
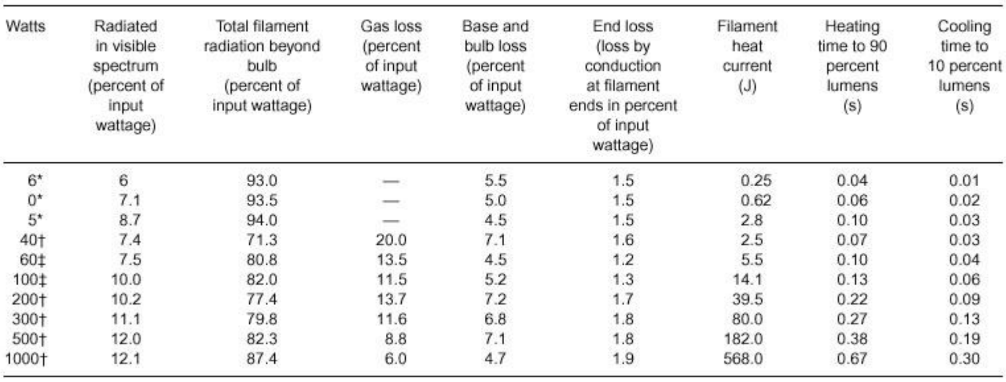


Figure 6-14. Tungsten cycle in (a) standard incandescent, and (b) tungsten-halogen.



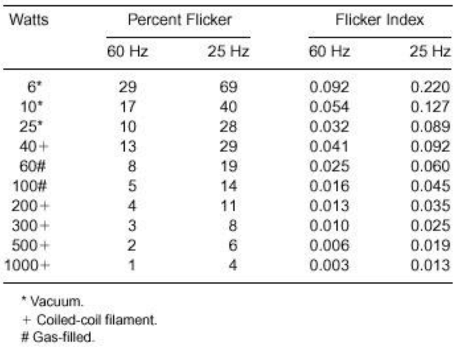
Watts	Radiated in visible spectrum (percent of input wattage)	Total filament radiation beyond bulb (percent of input wattage)	Gas loss (percent of input wattage)	Base and bulb loss (percent of input wattage)	End loss (loss by conduction at filament ends in percent of input wattage)	Filament heat current (J)	Heating time to 90 percent lumens (s)	Cooling time to 10 percent lumens (s)
6*	6	93.0	—	5.5	1.5	0.25	0.04	0.01
0*	7.1	93.5	—	5.0	1.5	0.62	0.06	0.02
5*	8.7	94.0	—	4.5	1.5	2.8	0.10	0.03
40†	7.4	71.3	20.0	7.1	1.6	2.5	0.07	0.03
60‡	7.5	80.8	13.5	4.5	1.2	5.5	0.10	0.04
100‡	10.0	82.0	11.5	5.2	1.3	14.1	0.13	0.06
200†	10.2	77.4	13.7	7.2	1.7	39.5	0.22	0.09
300†	11.1	79.8	11.6	6.8	1.8	80.0	0.27	0.13
500†	12.0	82.3	8.8	7.1	1.8	182.0	0.38	0.19
1000†	12.1	87.4	6.0	4.7	1.9	568.0	0.67	0.30

Figure 6-15. Luminous and Thermal Characteristics of Typical Incandescent Filament Lamps

Performance Parameters

Energy Characteristics. The manner in which the energy input to a lamp is dissipated can be seen in Figure 6-15 below for typical general-service lamps. The radiation in the visible spectrum (column 2) is the percentage of the input power actually converted to visible radiation. The gas loss (column 4) indicates the amount of heat lost by the filament due to the conduction through and convection by the surrounding gas in gas-filled lamps. The end loss (column 6) is the heat lost from the filament by the lead-in wires and support hooks which conduct heat from the filament. Column 3 shows the total radiation beyond the bulb, which is less than the actual filament radiation due to absorption by the glass bulb and the lamp base.

Incandescent lamps operated below 25 Hz will produce perceptible flicker and can create a stroboscopic effect. Flicker will be less from an incandescent source if it has a larger filament and is operated at a higher wattage and at a higher supply frequency. Modern incandescent light sources operated at 60 Hz do not produce noticeable flicker, nor a stroboscopic effect, to the human eye. The flicker index of several incandescent lamps operated at 25 Hz and 60 Hz is shown in Figure 6-16. Consult Chapter 2, Measurement of Light and Other Radiant Energy, for more information about lamp flicker.



Watts	Percent Flicker		Flicker Index	
	60 Hz	25 Hz	60 Hz	25 Hz
6*	29	69	0.092	0.220
10*	17	40	0.054	0.127
25*	10	28	0.032	0.089
40+	13	29	0.041	0.092
60#	8	19	0.025	0.060
100#	5	14	0.016	0.045
200+	4	11	0.013	0.035
300+	3	8	0.010	0.025
500+	2	6	0.006	0.019
1000+	1	4	0.003	0.013

* Vacuum.
+ Coiled-coil filament.
# Gas-filled.

Figure 6-16. Flicker Characteristics of Incandescent Filament Lamps

Bulb and Socket Temperatures. Incandescent filament lamp operating temperatures are important for several reasons. Excessive lamp temperature can affect lamp life, luminaire life, and the life of the electrical supply circuit. High temperatures can ignite combustible materials that form a part of the luminaire or those adjacent to the luminaire. Under certain atmosphere or dust conditions, high bulb temperatures (above 160°C [320°F]) can induce explosion or fire. Bulb and socket temperatures for a 100-W A-19 lamp and a 500-W PS-35 lamp for different operating positions are shown in Figure 6-17.

General-service incandescent filament lamp bulbs are made of regular lead or lime soft glass, the maximum safe operating temperature of which is 370°C (698°F). Some lamps for special applications, such as outdoor floodlighting lamps, have hard glass bulbs that have a safe temperature limit of 470°C (878°F). Lamps with still harder glass bulbs can be operated up to 520°C (968°F).

The maximum safe base temperature for general-service lamps is 170°C (338°F), measured at the junction of the base and the bulb. In all cases excessive temperature can cause failure of the basing cement, as well as softening of the solder used to connect the lead wires to the base. Silicone cement and high-melting-point solder permit base temperatures to approach 260°C (500°F). Bipost bases carry considerable heat to the socket through the base pins, and the parts of the socket in contact with the base pins should be capable of withstanding temperatures up to 290°C (554°F). Tubular fused quartz infrared and tungsten-halogen cycle lamps generally have a maximum seal temperature of 350°C (662°F) to prevent oxidation.

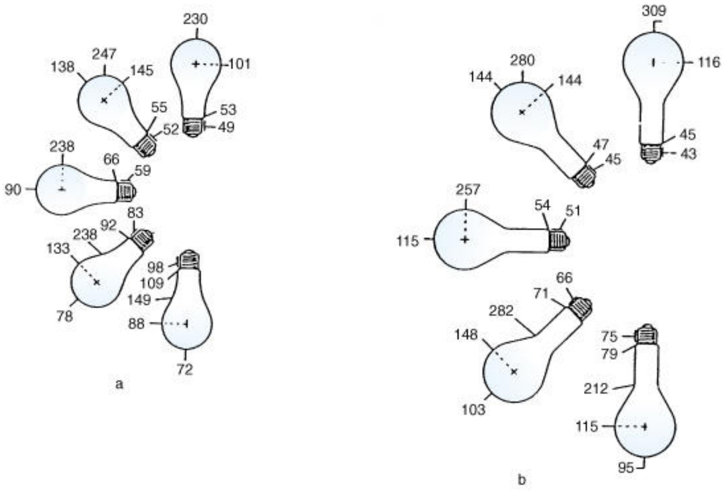


Figure 6-17. Incandescent filament lamp operating temperatures in still air at 25℃ (77℉) ambient: (a) 100-watt CC -8, A-19 lamp; (b) 500-watt CC-8, PS-35 lamp. All lamp temperatures shown are in degrees Celsius.

Some of the factors affecting base temperature are filament type, light center length, heat shields, bulb shape and size, and gas fill. Base temperature is not necessarily correlated to wattage ratings; that is, lamps of lower wattage do not necessarily have lower base temperatures. Medium-base luminaires should be capable of accepting lamp base temperatures on the order of 135-150°C (1275-1302°F). These limits are consistent with Canadian Standards Association (CSA), American National Standards Institute (ANSI), and International Electrotechnical Commission (IEC) standards for base temperature for A-type lamps. Measurements should be made in accordance with ANSI C78.25, "Lamp-Base Temperature Rise-Method of Measurements."[12] If the luminaire accepts R and PAR lamps, then the temperature capability of the luminaire should be 170 to 185°C (338 to 365°F) if reasonable electrical insulation life is desired for the luminaire. Heat-transmitting dichroic-reflector lamps should be placed only in luminaires specifically designed for them; this is normally indicated on the luminaire.

For base-up operation, and where only slight enclosing of the lamp is provided by the luminaire, base temperature is the major factor affecting luminaire temperatures, with lamp wattage being a minor consideration. As the luminaire provides more and more enclosing of the lamp, base temperature has less effect, and wattage assumes more importance.

High temperatures reduce the life of electrical insulation for lamp and luminaire parts. Figure 6-18 shows how the position of the filament affects the temperature of the bulb. This variation in temperature with position is sufficiently large to affect the life of wire insulation and other luminaire components.

Lamp Characteristics

Life, Efficacy, Color Temperature, and Voltage Relationships. If the voltage applied to an incandescent filament lamp is varied, there is a resulting change in the filament resistance and temperature, current, power, light output, efficacy, and life. These characteristics are interrelated, and not one of them can be changed without affecting the others. The following equations can be used to calculate the effect of a change from the design conditions on lamp performance (capital letters represent normal rated values; lowercase letters represent changed values):

$$\frac{\text{life}}{\text{LIFE}} = \left(\frac{\text{VOLTS}}{\text{volts}}\right)^{d}$$

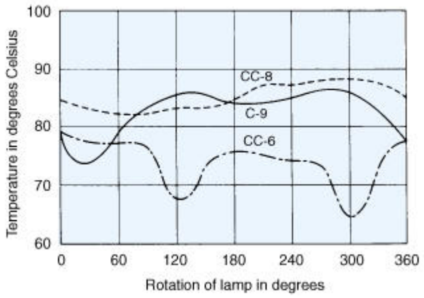


Figure 6-18. Profile temperatures vary with rotation of lamp filament; three types shown.

$$\frac{\text{lumens}}{\text{LUMENS}} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^{k}$$

$$\frac{\text{lpw}}{\text{LPW}} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^{g}$$

$$\frac{\text{watts}}{\text{WATTS}} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^{n}$$

$$\frac{\text{color temperature}}{} = \left(\frac{\text{volts}}{\text{VOLTS}}\right)^{m}$$

For approximations, the following exponents may be used in the above equations: $d = 13$, $g = 1.9$, $k = 3.4$, $n = 1.6$, and $m = 0.42$. For more accuracy, the exponents must be determined by each lamp manufacturer from a comparison of normal-voltage and over- or undervoltage tests of many lamp groups. Exponents vary for different lamp types, lamp wattages, and ranges of percentage voltage variation. The values given above are roughly applicable to vacuum lamps of approximately 10 lm/W and gas-filled lamps of approximately 16 lm/W in a voltage range of 90 to 110% of rated voltage. For information outside this range, refer to Figure 6-19.

The curves of Figure 6-19a show the effect of voltage variations on lamps in general lighting (multiple) circuits.[13,14] The effect of voltage variation on the characteristics of tungsten-halogen lamps cannot be accurately predicted outside of the voltage range of 90 to 110% of the rated voltage.

Filament Notching. Ordinarily, for laboratory test operation, normal tungsten filament evaporation determines incandescent lamp life. Where that is so, lamps should reach their design-predicted life. Another prominent factor influencing filament life is filament notching. Filament notching is the appearance of steplike or sawtooth irregularities on all or part of the tungsten filament surface after long use. These notches reduce the filament wire diameter at random points. In some cases, especially for fine-wire filaments, the notching is so deep as to almost sever the wire. Faster spot evaporation due to high temperatures at this notch and reduced filament strength become the dominant factors influencing lamp life. Predicted lamp life can be reduced by as much as one-half from this cause.

Filament notching is associated with at least three factors (primarily occurring in fine-wire filament lamps): (1) low-temperature filament operation, as in long-life lamps with 10,000- to 100,000-h designs; (2) small filament wire sizes, typically less than 0.025 mm (0.001 in.) in diameter; and (3) direct current operation.

Depreciation During Life. Over a period of time, incandescent filaments evaporate and become smaller, which increases their resistance. In multiple circuits, the increase in filament resistance reduces current, power, and light. A further reduction in light output is caused by the absorption of light by the deposit of the evaporated tungsten particles on the bulb.

In series circuits having constant-current regulators, the increase in filament resistance during life causes an increase in the voltage across the lamp and a consequent increase in wattage and generated lumens. This increase in lumens is offset to varying degrees by the absorption of light by the tungsten deposit on the bulb. In low-current lamps the net depreciation in light output during life is very small, or in the smaller sizes there may be an actual increase. In lamps of 15- and 20-A ratings, the bulb blackening is much greater, and throughout life more than offsets the increase in lumens due to the increased wattage.

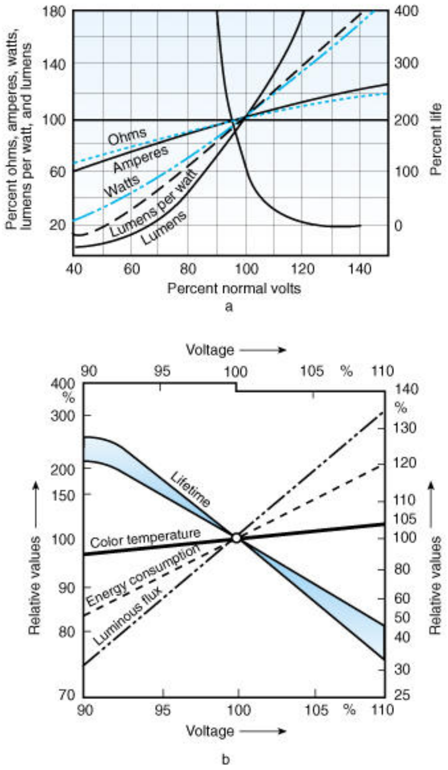


Figure 6-19. Effect of voltage and current variation on the operating characteristics of: (a) incandescent filament lamps in general lighting (multiple) circuits and (b) tungsten-halogen lamps in series street lighting circuits.

The blackening in vacuum lamps is uniform over the bulb. In gas-filled lamps the evaporated tungsten particles are carried by convection currents to the upper part of the bulb. When gas-filled lamps are burned base up, most of the blackening occurs on the neck area, where some of the light is normally intercepted by the base. Consequently, the lumen maintenance for base-up operating is better than for base-down or horizontal operating with gas-filled lamps.

In a base-up operating lamp, an appreciable reduction of lamp lumen depreciation (LLD) can be obtained through the use of a coiled-coil filament located on or parallel to the bulb axis.

To reduce blackening from traces of oxygen or water vapor in the gas fill, an active chemical, known as a getter, is used inside the bulb to combine with and absorb impurities remaining in the bulb.

Tungsten-halogen cycle lamps generally have significantly less depreciation during life due to the regenerative cycle, which removes the evaporated tungsten from the bulb and redeposits it on the filament. Figure 6-20 shows the change in light output and efficacy for typical incandescent and tungsten-halogen lamps. See the discussion on tungsten-halogen lamps earlier in this chapter.

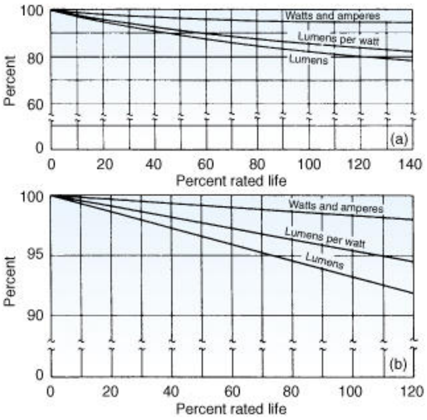


Figure 6-20. Typical operating characteristics of lamps as a function of burning time: (a) general-service lamps and (b) tungsten-halogen lamps. (Note differences in scales.)

Lamp Mortality. Many factors inherent in the manufacturing process make it impossible for every lamp to achieve the rated life for which it was designed. For this reason, lamp life is rated as the average of a large group. A range of typical mortality curves representing the performance of high-quality lamps is illustrated in Figure 6-21.

Dimming of Incandescent and Tungsten-Halogen Lamps. Dimmers today have a dual purpose: energy conservation and aesthetic lighting effects. Incandescent lamps can be dimmed simply by lowering the voltage across the lamp filament. When the voltage is lowered, less power is dissipated and less light is produced with a lower color temperature. An added benefit is an increase in the life of an incandescent lamp. For example, when an incandescent lamp is operated at 80% rated voltage using a dimmer, its life is increased by a factor of nearly 20. In a tungsten-halogen lamp, the life of the filament depends on voltage just as with standard incandescent filament lamps. However, because the regenerative halogen cycle stops when bulb wall temperature falls below 260° C (500°F), the tungsten halogen lamp blackens and its useful life is not extended by nearly the same factor as that of standard lamps. This can be partially compensated for by periodically operating the lamp near or at full light output, which helps clean the lamp of tungsten deposits.

In the 1950s, rheostats were used for dimming by regulating the lamp current in an incandescent lamp. They were large and inefficient. Today, most dimmers are electronic, using thyristor and transistor circuits that have low power dissipation. Modern dimmers are efficient and reduce power as the source is dimmed. Thyristors operate as high-speed switches that rapidly turn the voltage to the lamp on and off. This switching can cause electromagnetic interference with other electrical equipment as well as audible buzzing in the lamp filament. Magnetic coils known as chokes are usually used as filters to reduce these effects. With many wall-box dimmers, however, lamp buzzing cannot be completely eliminated because a larger choke is needed than space allows. For these cases, remotely mounted, properly sized lamp debuzzing coils or additional chokes are recommended.

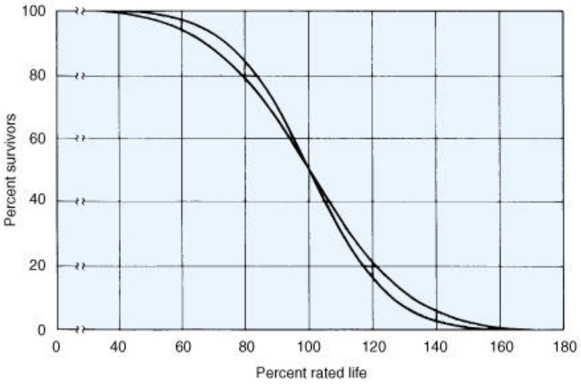


Figure 6-21. Range of typical mortality curves (average for a statistically large group of incandescent filament lamps).

Classification of Incandescent and Tungsten-Halogen Lamps

Incandescent filament lamps were historically divided into three major groups: large lamps, miniature lamps, and specialty lamps. They also were cataloged separately by lamp manufacturers. There is no sharp dividing line among the groups, and they are usually included in the same catalog by the manufacturer. The discussion below classifies lamps into four categories for the purposes of illustrating their applications: general lamps, dedicated application lamps, low-voltage miniature and sealed beam lamps, and photographic and photo-optical lamps. The following gives a brief description of a few of the many types of lamps that are regularly manufactured. More complete details are available in manufacturers' catalogs.

General Lamps (Lamps Used in a Variety of Applications)

General Service. These are large lamps made for general lighting use on 120-V circuits. General-service lamps range from 10 to 1500 W and satisfy the majority of incandescent lighting applications. All sizes are made in both clear and inside-frosted bulbs. Below 200 W, inside-white-coated finishes are also available.

High Voltage. This voltage class refers to lamps that operate directly on circuits of 220 to 300 V and represents a very small portion of the lamp demand in North America. Lampholders should be Underwriters Laboratories (UL) or CSA approved for a voltage level appropriate to the voltage rating of the lamps being used, that is, 250 V for lamps up to 250 V, 600 V for lamps above 250 V.

High-voltage lamps have filaments of small diameter and longer length and require more supports than corresponding 120-V lamps. Therefore, they are less rugged and are 25 to 30% less efficient because of greater heat losses. Due to the higher operating voltage, these lamps require less current for the same power, permitting some wiring economy.[15]

Extended Service. Extended-service lamps are intended for use in applications where a lamp failure causes significant inconvenience, nuisance, or hazard, or where replacement labor cost is high or power cost is unusually low. For such applications, where long life is most important and a reduction of light output is acceptable, lamps with 2500-h or longer rated life are available. Longer life is obtained by operating the filament at lower temperatures than normal. This, however, lowers the luminous efficacy. In most general-service use the cost of power used during the lamp life is many times the lamp life cost, and therefore efficacy is important. Where replacement of burned-out lamps is an easy, convenient operation, as in residential use, long-life lamps usually are not recommended.[16] For such use, incandescent lamps with the usual 750- or 1000-h design life give a lower cost of light than extended-service lamps.

General-Lighting Tungsten-Halogen Lamps. These lamps improve on the regular incandescent sources in several ways. Their advantages over regular incandescent lamps include low LLD and compactness. They also provide whiter light (higher color temperature) and longer life at a given light output.

Halogen lamps are available in both line voltage and low voltage designs. The line voltage products are available as single ended, double ended, and PARs. The low voltage types are generally capsules or small reflector types. For specialty applications, other voltage ratings (e.g., 84 V, 200 V) are also available.

Low voltage halogen lamps operate in the voltage range from 5 to 30 V. This voltage is supplied through a step-down transformer. The advantages of low-voltage lamps are greater resistance to vibration and shock because of their larger diameter filament wire, a more compact filament that allows better beam control, and higher efficacy than line voltage lamps.

There is more ultraviolet (UV) radiation generated from tungsten-halogen lamps than from regular incandescent lamps, due to the higher filament temperature. The amount of UV radiation emitted is determined by the envelope material. Fused quartz and most high-silica glass transmit most of the UV radiated by the filament, while other special high-silica glass and aluminosilicate glass absorb UV radiation. In general lighting applications, luminaires for tungsten-halogen lamps should have a lens or cover glass that, in addition to providing the required safety protection in case of lamp breakage, filters out most of the UV radiation. In applications where the reduction of UV radiation is critical, additional filtering might be required. Care should be taken when applying lamps operating at correlated color temperatures above 3100 K, since both ultraviolet and short-wavelength visible radiation increase with color temperature,[17] creating potential hazard for both people and objects.

The halogen regenerative cycle is very temperature sensitive. Operating lamps at voltages above or below manufacturer's recommendations can have adverse effects on the internal chemical processes. It is also important to follow manufacturer's recommendations as to operating position, bulb handling, and luminaire temperatures.

The higher pressures used allow tungsten-halogen lamps to be designed for higher efficacy and longer life than normal incandescent lamps of the same wattage. For example, the 500-W nonregenerative cycle lamp is rated at 10,600 lm for 1000 h, while the 500-W T-3 tungsten-halogen lamp is rated at 10,950 lm for 2000 h.

The development of high-performance glass tubings has led to the use of halogen glass capsules in PAR lamps, including PAR 16, PAR 20, PAR 30, and PAR 38.

Multilayer infrared reflective coatings can be applied to both quartz and glass halogen bulbs. These coatings transmit light and reflect infrared energy back to the filament. This reduces the input power required to reach a given filament temperature. Luminous efficacies of 27.0 to 35.6 lm/W are obtained with this technique without reducing life.

Reflector. Reflector lamps include those made in standard and special bulb shapes and have a reflective coating applied directly to part of the bulb surface. Both silver and aluminum coatings are used.[18] Silver coatings can be applied internally or externally, and in the latter case the coating is protected by an electrolytically applied copper coating and sprayed aluminum finish. Aluminum coatings are applied internally by condensation of vaporized aluminum on the bulb surface. The following reflector lamps are readily available: bowl reflector lamps, neck reflector lamps, reflector spot and reflector flood lamps in R-type bulbs (certain sizes of reflector lamps are available with heat-resisting glass bulbs), and ellipsoidal reflector lamps (ER types), which allow substantially improved efficiency in deep, well-shielded downlights.[19] PAR spot and PAR flood lamps use PAR bulbs, typically constructed from two molded glass parts, the reflector and the lens, which are fused together. As the names suggest, several lamp designs with different candlepower distributions are available, typically expressed in terms of beam angle. Colored R and PAR lamps are available. Cool beam PAR lamps with heat-transmitting dichroic reflectors are available where it is desirable to reduce the infrared energy in the beam. Long-neck halogen PAR-30 lamps are available for retrofitting standard R-30 luminaires without the use of socket extenders. Multifaceted pressed glass reflector lamps with tungsten-halogen capsules and infrared-transmitting dichroic reflectors, known as MR-11 and MR-16, have been adapted from projection lamp designs for display lighting applications.

Rough Service. To provide the resistance to filament breakage, rough-service lamps employ special, multiple-filament-support construction (C-22 in Figure 6-12). Because of the number of supports, the heat loss is higher and the efficacy lower than for general-service lamps.

In using miniature lamps where rough-service conditions are encountered, bayonet and wedge base lamps should be chosen instead of screw base lamps. Bayonet and wedge base lamps lock in the socket; screw base lamps tend to work loose.

Linear Incandescent. The linear incandescent lamp has a tubular bulb diameter of 26 mm (1 in.) and two metal disk bases, one at each end of the lamp, with the filament connected between them. Many have adjustable insert tabs attached to the bases, thereby simplifying insertion into their sockets. The filament, in the form of a stretched coil, is supported on glass insulating beads along a small metal channel within the bulb. The 30- and 60-W sizes are available in the 450-mm (18-in.) length. The 40-W lamp is made in a 300-mm (12-in.) length. All sizes are available in either clear or inside-frosted tubes as well as white and various color coatings.

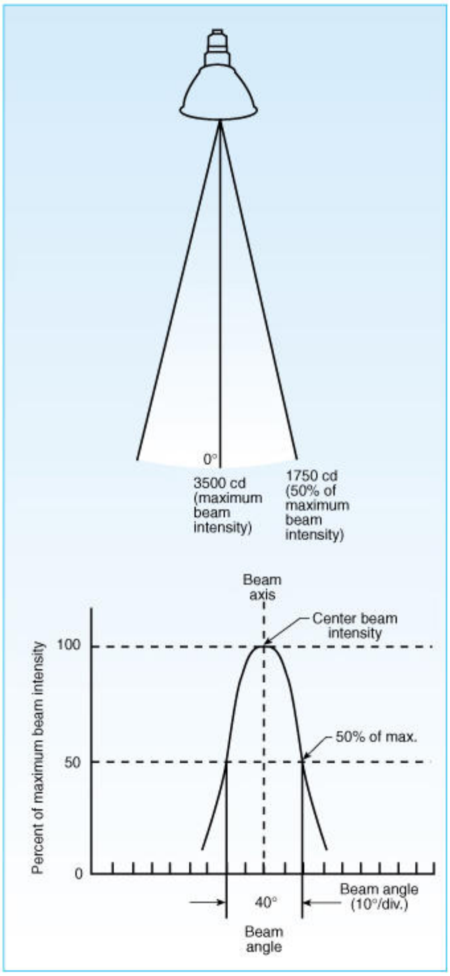


Figure 6-22. The beam angle is the angle within which the lamp produces 50% of the lamp's maximum intensity.

Another style of linear incandescent lamp, using the S14 base, is available. Versions include 35, 60, and 150 W.

Decorative. A wide variety of lamps for decorative application is available. Different bulb shapes, together with numerous colors and finishes, are used to achieve the desired appearance. Lamp manufacturers' catalogs should be consulted for information on the many decorative types.

Three-Way. These lamps employ two filaments, operated separately and in combination, to provide three light levels. The common lead-in wire is connected to the shell of the base; the other end of one filament is connected to a ring contact, and the end of the other filament to a center contact. Thus, either filament, or both together, may be used with the selection made in the socket. Three-way lamps are available in several different wattage combinations.

Energy-Saving. Most general- and extended-service lamps are now available in reduced wattages, which also have lower lumen output. The use of reflector lamps to improve directional lighting has also become popular for energy-saving applications. Better optical control with sharper cutoffs places the same illuminance on a specific area with fewer watts. A variety of reflector lamps is now available, including the BR30 and BR40. The most significant energy improvement is in the family of halogen PAR and halogen IR PAR products, which use significantly less power and provide equal or superior illuminance than incandescent PAR and BR types. In traffic signals, lamps are now being marketed with a ring mirror so as to capture lost light and redirect it through the lens.

Dedicated Application Lamps. Dedicated application lamps are those that have been designed primarily for a single application.

Spotlight and Floodlight. Lamps used in spotlights, floodlights, and other specialized luminaires for lighting theater stages, motion picture studios, and television studios, have concentrated filaments accurately positioned with respect to the base. When the filament is placed at the focal point of a reflector or lens system, a precisely controlled beam is obtained. These lamps are intended for use with external reflector systems. Because of their construction, these lamps must be burned in positions for which they are designed, to avoid premature failures.

Appliance Lamps. High-temperature types that can withstand temperatures up to 315°C (599°F) are available for ovens. Other types are designed for refrigerators, and rugged filament types are used in vacuum cleaners.

Vibration Service. Most lamps have coiled filaments made of tungsten with high sag resistance. Vibration lamps, designed for use where vibrations would cause early failure, are made with a more malleable tungsten filament. The sagging of the wire used allows the coils to open up under vibration, thus preventing short circuits between coils.

To withstand shock and vibration, low-voltage (6.3-V or less) miniature radio panel lamps incorporate mounts whose resonant frequency has been synchronized with that of the coiled filament.

Sometimes only trial and error will determine the best lamp to resist shock and vibration. Vibration-resistant sockets or equipment, using a coiled spring or other flexible material to deaden vibration, have been employed where general-service lamps are used under conditions of severe vibration.

Showcase. Display cases in retail applications commonly use tubular bulbs with conventional screw bases. The longer lamps have filaments with supports similar to linear incandescent lamps. The common sizes are 25 and 40 W, but sizes up to 75 W are available.

Sign. While large numbers of gas-filled lamps are used in enclosed and other types of electric signs, those designated particularly as sign lamps are mostly of the vacuum type. These lamps are best adapted for exposed sign and festoon service because the lower bulb temperature of vacuum lamps minimizes the occurrence of thermal cracks resulting from rain and snow. Some low-wattage lamps, however, are gas filled for use in flashing signs. Bulb temperatures of these low-wattage, gas-filled lamps are sufficiently low to permit exposed outdoor use on high-speed flashing circuits.

Traffic Signal Lamps. Lamps used in traffic signals are subjected to more severe service requirements than in most applications of incandescent lamps. Such lamps must be compatible with the design requirements of standard traffic signals.

Ribbon Filament Lamps. Incandescent lamps made with ribbons or strips of tungsten for the filaments have been used in special applications where it is desirable to have a substantial area of fairly uniform luminance.[20] Ribbon dimensions vary from 0.7 to 4 mm (0.03 to 0.16 in.) in width and up to 50 mm (1.97 in.) in length. The 5-20-A ribbon filament lamps are usually employed in recorders, instruments, oscillographs, and microscope illuminators. The 30- to 75-A lamps are used for pyrometer calibration standards and for spectrographic work. Figure 6-23 shows typical lamps.

Figure 6-23. Typical ribbon filament lamps: (a) 6-volt, 18-ampere, T-10, 2-mm, 3000-K microscope illuminator; (b) 6-volt, 9-ampere, T-8—½, 1-mm, 3000-K optical source; and (c) 3.5-volt, 30-ampere, T-24 with quartz window, 3-mm, U-shaped filament, 2300-K pyrometer and spectroscope source.

Infrared Heat Lamps. All incandescent filament lamps are effective generators of infrared (IR) radiation. Most of the incandescent filament lamp input power is radiated as IR energy. Wavelengths longer than 5000 nm are absorbed to a large extent by the glass or fused quartz envelope. Lamps for heating applications are designed for low light output and long life. Tubular fused quartz lamps are also available with a ceramic reflector that increases heat by approximately 50% directly below the center line of the lamp.

Tungsten filament IR lamps are available with ratings up to 5000 W. Generally speaking, tungsten filament lamps for industrial, commercial, and residential service operate at a filament color temperature of 2500 K. At this low operating temperature compared to lighting lamp filament temperatures, the service life is well in excess of 5000 h. Frequently, lamps using tungsten filaments have provided many years of operation because the service life is generally determined by mechanical breakage or rupture of the filament due to vibration or handling, rather than the rate of evaporation of tungsten, as is the case with lamps used for light. Lamps having heat-resisting glass bulbs or tubular fused quartz envelopes are recommended where liquids might come in contact with the bulb.

The distribution of power radiated by various infrared sources is shown in Figure 6-24. For application information, see Chapter 5, Nonvisual Effects of Optical Radiation.

Low-Voltage Miniature and Sealed Beam Lamps. The term "miniature" applied to light sources is a lamp manufacturer's designation determined by the trade channels through which these lamps are distributed, rather than by the size or characteristics of the lamps. In general, however, most miniature lamps are small and require relatively little power. The most notable exceptions to this generalization are sealed beam lamps, such as automotive headlamps and aircraft landing lamps, some of which are classed as miniature lamps, even though they can be as large as 200 mm (7.3 in.) in diameter and dissipate up to 1000 W.

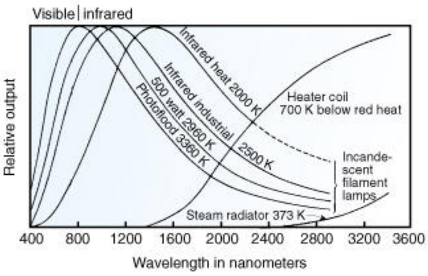


Figure 6-24. Spectral power distribution from various infrared sources.

The great majority of miniature lamps are either incandescent filament lamps or glow lamps; the latter are discussed under "Miscellaneous Discharge Lamps" later in this chapter. Also, electroluminescent lamps and light-emitting diodes (see sections below) are included in the miniature lamp family. Incandescent miniature lamps[21] and glow lamps[22] are specified completely by numbers standardized and issued by ANSI.

With the notable exception of multiple holiday lamps, miniature incandescent lamps are designed to operate below 50 V. These voltages are often obtained from batteries or generators. These miniature lamps can be operated on 120-V circuits when step-down transformers, series circuits, rectifiers, or resistors are used to reduce the voltage.

Miniature lamps are used chiefly when conditions require a small light source or little power. To insure that the lamp is as small as possible, base sizes are matched to the bulb and the application. They have many uses, principally in automobiles, aircraft, decoration, and as glow lamps in electronic circuits. Both long-life and fleet-service (heavy-duty filaments) products are replacements for standard miniature lamps in the automotive sector. Halogen miniature lamps often are used to replace incandescent miniature lamps. These halogen lamps deliver a whiter and brighter light than the incandescent lamps they replace.

Subminiature lamps have increased in popularity. They range in size from T-2 to T-1/8. The T-1-3/4 and T-1 are used extensively for instruments and indicators. The T-5/8 and smaller sizes down to T-1/8 are used chiefly in such novelty applications as tiny flashlights, jewelry, and medical instruments.

Train and Locomotive. Lamps designated for train and locomotive service are designed for several classes of low-voltage (75-V or lower) service. The power usually is provided by generators, with a battery connected in parallel so that both supply power to the lamps. Low-voltage lamps have shorter and heavier filaments than 120-V lamps of the same wattage; consequently, they are more rugged and have higher efficacy.

DC Series. Transit system voltages and some railway shop and yard voltages range from 525 to 625 V. Lamps for such service are operated with five to twenty lamps in series. The design voltages of individual lamps operated five in series are nominally 115, 120, and 125 V. Lamps of the dc series are rated in unusual wattages (36, 56, 94, or 101 W).

Gas-filled 30-V lamps are used for car lighting. The trolley voltage divided by 30 determines the number of lamps connected in series across the line. These lamps are equipped with short-circuiting cutouts that short-circuit the lamps on burnout, thus preventing arcing and leaving the remainder of the lamps in a given circuit operating. These 30-V lamps are rated in amperes, instead of in the usual watts.

Aviation. Lighting for aviation is divided into two classes: lighting on and around airports, and lighting on aircraft. In airport lighting, both multiple and series type lamps are used. Most systems use series lamps of 6.6- and 20-A designs for airport approach, runway, and taxiway lighting. Multiple lamps are used for obstruction, hazard beacon, and airport identification beacon lighting. On aircraft, small and miniature lamps are used for both interior and exterior lighting. Most lamps used in airport lighting are designed to produce a controlled beam of light complying with required standards from such regulators as the U.S. Federal Aviation Authority (FAA) and Transport Canada.

Hazard beacons and airport identification beacons, signaling the presence of high obstructions or the whereabouts of the airport, use lamps ranging from 500 to 1200 W. Lamps used on the airport proper range from 10 to 500 W. Lamps used for aircraft lighting are in the miniature classification, except for landing lamps, which can be rated as high as 1000 W. See also "Flashtubes," later in this chapter, for alternative beacon sources.

Tungsten-halogen lamps are often provided in place of many regular incandescent types because of their better lumen maintenance and longer life. See Chapter 23, Transportation Lighting, for information on the application of lamps in airports and aircraft lighting.

Indicator and Other Service Lamps. Lamps for indicator, radio, and television service usually are operated from low-voltage transformers.

Flasher Lamps. Incandescent lamps that flash automatically (Figure 6-25), because of a built in bimetal strip similar to those used in thermostats, are available in several sizes. When the lamp lights, heat from the filament causes the bimetal strip to bend away from the lead-in wire. This breaks the circuit and the lamp extinguishes. As the bimetal strip cools, it returns to its original position against the lead-in wire and lights the lamp. This alternating cooling and heating keeps the lamp flashing. An exception to this is found in a certain type of miniature screw base lamps called the shorting type. The bimetal in this type is so mounted that it shorts across the lead-in wire when hot. If these lamps, which are difficult to distinguish from the opening type, are inserted in sockets intended for the normal flasher lamps, they can drain batteries, blow fuses, overheat wires, or ruin transformers.

Figure 6-25. Typical flasher showing bimetal strip.

Typical Uses. Indicator lamps provide a visual indication of existing circuit conditions. They are widely used in fire and police signaling systems, power plant switchboards, production machinery, motor switches, furnaces, and other devices requiring warning or pilot lights.

Indicator lamps can be wired with motor or heating elements and can be used to indicate that the current is flowing to an appliance or that it is functioning properly. They often are used in other instrumentation and with photocells and relays. Flashlights, radios, clocks, bicycles, and toys account for more uses. Other applications include the use of miniature lamps for holiday and other festive occasions, and for colorful patio and garden lighting. For garden lighting, low-voltage miniature equipment is available.

Flashlight, Handlantern, and Bicycle. These lamps are commonly operated by dry-cell batteries having an open-circuit voltage of 1.5 V per cell for new batteries, dropping to approximately 0.9 V per cell at the end of battery life. This voltage drop results in a reduction in light output in a manner analogous to that shown in Figure 6-19a.

Automotive. Lamps for most passenger vehicles, trucks, and coaches operate at 12 V. The power source is a storage battery-rectified alternator system. Head lamps include sealed beam and halogen capsules.

SEALED BEAM AND TUNGSTEN-HALOGEN EPOXY SEALED BEAM LAMPS. These lamps contain filaments, lens, and reflectors in a precise, rugged optical package available in a wide variety of sizes and voltages ranging from 6 to 28 V. Sealed beam lamp lenses are made of borosilicate "hard" glass. The reflector is vaporized aluminum on glass and in the incandescent versions is hermetically sealed to the lens cover. The advantages are accurate reflector contour for accurate beam control, precise filament positioning on rugged filament supports, and high efficacy and excellent lumen maintenance. Vaporized aluminum on glass is an excellent reflector, it does not deteriorate, and the normal bulb blackening has little effect on output throughout lamp life. The sealed beam lamp is particularly suitable where a large amount of concentrated light at low voltage is required, as with automotive head lamps. Tungsten-halogen epoxy-sealed beam lamps contain a small bulb of aluminosilicate glass, surrounding the filament. The bulb also contains a high-pressure, rare-gas atmosphere with small additions of halogen compounds as required for operation of the tungsten-halogen cycle.

REPLACEABLE AUTOMOTIVE HALOGEN HEAD LAMPS. Changes in automotive styling have led to the creation of replaceable halogen capsules. These lamps meet the current Society for Automotive Engineers (SAE) standards while allowing the designer to use additional shapes of head lamps. Special automotive bases have the advantage that only the light source, rather than the entire assembly, can be replaced when necessary.

Sealed beam lamps are made in a number of rectangular and round versions to allow for automotive design flexibility. They are also available in both single and dual filament designs.

Photo-optical and photographic applications

Photo-Optical Lamps. Lamps designed specifically for photo-optical applications typically require tighter tolerances on the positioning of the filament and very often have special prefocus bases to ensure proper alignment in application. In the typical photo-optical application, the prime objective is to collect and direct the lamp's output through an aperture or film gate. In some applications, such as video projection and fiber-optic illuminators, collimation of the light is also needed. In many cases low-voltage filaments are used to provide the smallest but highest luminance source possible, resulting in the greatest optical efficiency. Life is often sacrificed for efficacy and source flex. Typical applications are film, slide, overhead, and video projection, microfilm viewers, and microscope and fiber-optic illuminators.

Tungsten-halogen lamps have nearly replaced conventional incandescent lamps for most photo-optical applications. Their small size allows for more efficient optical control. See "Tungsten-Halogen Lamps" earlier in this chapter for additional information.

One of the principal developments has been the adoption of halogen lamp types with integrated external dichroic mirrors. By carefully positioning the lamp filament in ellipsoidal or parabolic dichroic reflectors, good beam control is possible. This obviates bulky and expensive external condensers and reflectors. The dichroic mirror is constructed to transmit most of the infrared radiation and reflect light through the film plane. This results in a lower film gate temperature or aperture temperature leading to longer film and optical component life.

Photographic. Lamps used specifically for photographic service are adapted to the response or sensitivity of several classes of film emulsions. Some lamps are specified in terms of color temperature, which serves as a basic rating for film exposure data. Lamp life is less important. Lamps of various size often are matched for color temperature, and rated life varies as necessary with wattage to achieve the specified color temperature. Typical color temperature-rated lamps of conventional construction can drop by 100 K throughout life. There is negligible change in the color temperature of tungsten-halogen lamps during their life.

Photoflood. These are high-efficacy sources similar to other incandescent filament lamps for picture taking, with color temperatures ranging from 3200 to 3400 K. Because of their high filament temperature, these lamps generally produce approximately twice the luminous flux and three times the photographic effectiveness of similar wattages of general-service lamps. Relatively small bulb sizes are employed. The 250-W No. 1 photoflood, for example, is the same size as the 60-W general-service lamp. These lamps can be conveniently used in less bulky reflecting equipment or for certain effects in ordinary residential or commercial luminaires.

The photoflood family includes reflector and projector (PAR) lamps with various beam spreads. Some of these have tungsten-halogen sources; some have integral 5000-K daylight filters. In addition, tungsten-halogen lamps in several sizes and color temperatures are classed as photofloods and used in specially designed reflectors.

FLUORESCENT LAMPS

The fluorescent lamp is a low-pressure gas discharge source, in which light is produced predominantly by fluorescent powders activated by UV energy generated by a mercury arc. The lamp, usually in the form of a long tubular bulb with an electrode sealed into each end, contains mercury vapor at low pressure with a small amount of inert gas for starting. The inner walls of the bulb are coated with fluorescent powders commonly called phosphors. When the proper voltage is applied, an arc is produced by current flowing between the electrodes through the mercury vapor. This discharge generates some visible radiation, but mostly invisible UV radiation, the principal lines being approximately 254, 313, 365, 405, 436, 546, and 578 nm. The UV in turn excites the phosphors to emit light. The phosphors are generally selected and blended to respond most efficiently to 254 nm,[23,24] the primary wavelength generated in a mercury low-pressure discharge. See Figure 6-26 and the discussion of fluorescence in Chapter 1, Light and Optics.

Like most gas discharge lamps, fluorescent lamps must be operated in series with a current-limiting device. This auxiliary, commonly called a ballast, limits the current to the value for which each lamp is designed. It also provides the required starting and operating lamp voltages and may provide dimming control.

Lamp Construction

Bulbs. Linear fluorescent lamps are commonly made with straight, tubular bulbs varying in diameter from approximately 6 mm (0.25 in. T-2) to 54 mm. (2.125 in. T-17) and in overall length from a nominal 100 to 2440 mm (4 to 96 in.). The bulb is historically designated by a letter indicating the shape, followed by a number indicating the maximum diameter in eighths of an inch. Hence T-8 indicates a tubular bulb 8/8 in., or 1 in. (26 mm), in diameter. The nominal length of the lamp includes the thickness of the standard lampholders and is the back-to-back dimension of the lampholders with a seated lamp.

Fluorescent lamps also come in shapes other than straight tubes. U-shaped tubes are formed by bending tubes in half. They are commonly used in 0.61 m (2 ft) square luminaires. Circular (circline) lamps are tubes bent in a circle with the two ends adjacent to each other. In increasing use are smaller diameter, single-ended, compact fluorescent lamps consisting of multiple shaped tubes joined together to form a continuous arc path (Figure 6-26). They are designed to approach the size of the incandescent lamp.

Commonly used lamp designations are shown in Figure 6-27. The 32 W T-8 lamp is used as an example, but the designations for most fluorescent lamps follow the same principles.

Nomenclature of Fluorescent Lamps. Fluorescent lamps can be designated as illustrated in Figure 6-27. This is only one example; often manufacturers will adopt variations. The specifier should consult with the manufacturer to ensure correct nomenclature for design purposes.

Electrodes. Two electrodes are hermetically sealed into the bulb, one at each end. These electrodes are designed for operation as either cold or hot cathodes, more correctly called glow or arc modes of discharge operation.

Electrodes for glow (cold cathode) operation can consist of closed-end metal cylinders, generally coated on the inside with an emissive material. Cold cathode lamps operate at a few hundred milliamperes, with a high value of the cathode fall (the voltage required to create ion and electron current flow) in excess of 50 V.

The arc mode (hot cathode) electrode generally is constructed from a single tungsten wire, or a tungsten wire around which another very fine tungsten wire has been uniformly wound. The larger tungsten wire is coiled, producing a triple-coil electrode. When the fine wire is absent, the electrode is referred to as a coiled-coil electrode. The coiled-coil or triple-coil tungsten wire is coated with a mixture of alkaline earth oxides to enhance electron emission. During lamp operation, the coil and coating reach temperatures of approximately 1100°C (2012°F), at which point the coil-and-coating combination thermally emits large quantities of electrons at a low cathode fall, in the range of 10 to 12 V. The normal operating current of arc mode lamps is approximately 1.5 A or less. As a consequence of the lower cathode fall associated with the hot cathode, more efficient lamp operation is obtained, and therefore most fluorescent lamps are designed for such operation.

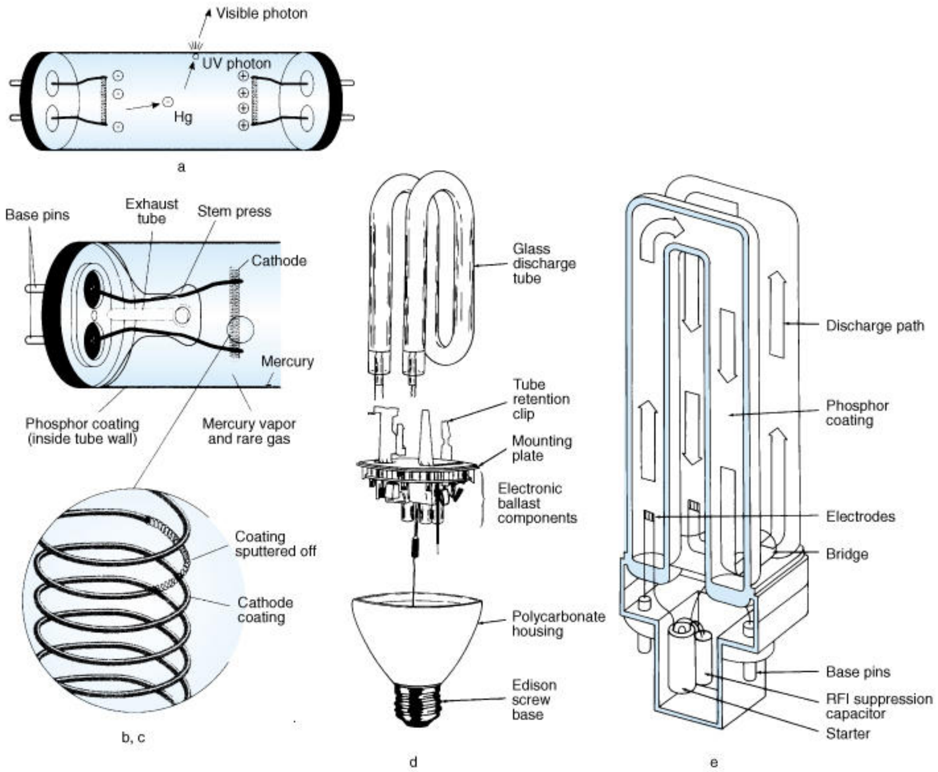


Figure 6-26. Cutaway view of some common fluorescent lamps: (a) A typical rapid-start fluorescent lamp and the production of light; (b) lamp electrode construction; (c) detail of the electrode; (d) a screw-in compact fluorescent lamp with built-in ballast; (e) a 2-pin plug-in compact fluorescent lamp with built-in starter.

F	32	T8	RE735	/ES/HO
(a)	(b)	(c)	(d)	(e)

(a) Lamp type. "F" is used for fluorescent lamps. "FB" or "FU" is used for U-bent lamps, while "FT" is used for twin-tube lamps.
(b) Wattage for preheat and rapid start lamps; or lamp length (in.) for slimline and HO lamps.
(c) Diameter of tube (in eighths of an inch). "T8" is a 1-in. diameter tube, and "T12" is a 1.5-in. diameter tube.
(d) Lamp color (sometimes omitted). "RE" indicates a rare earth phosphor; "7" represents the first digit of the CRI (between 70 and 79); "35" represents the first two digits of the CCT (between 3500 and 3599). For halophosphate lamps, the color might be represented as in these examples: "CW" for cool white or "WW" for warm white.
(e) Optional modifiers. "ES" represents an energy saving lamp; "HO" is high output; "VHO" is very high output. These are often preceded with a slash ("/").

Figure 6-27. Nomenclature of Fluorescent Lamps

Gas Fill. The operation of the fluorescent lamp depends on the development of a discharge between the two electrodes sealed at the extremities of the lamp bulb. This discharge is developed by ionization of mercury gas contained in the bulb. The mercury gas is typically maintained at a pressure of approximately 1.07 Pa (0.00016 lb/in.^{2}), which is the vapor pressure of liquid mercury at 40°C (104°F), the optimum bulb wall temperature of operation for which most lamps are designed (see the section "Temperature Effect on Operation" below). In addition to the mercury, a rare gas or a combination of gases at low pressure, from 100 to 400 Pascals (0.015 to 0.058 lb/in.^{2}), is added to the lamp to facilitate ignition of the discharge. Standard lamps employ argon gas; energy-saving types, a mixture of krypton and argon; others, a combination of neon and argon or of neon, xenon, and argon.

Phosphors. The color of the light produced by a fluorescent lamp depends on the blend of phosphors used to coat the wall of the tube (see Figure 1-12 for a list of important phosphors). Many different white and colored fluorescent lamps are available, each having its own characteristic spectral power distribution (Figure 6-28). These types have a combination of continuous and line spectra.

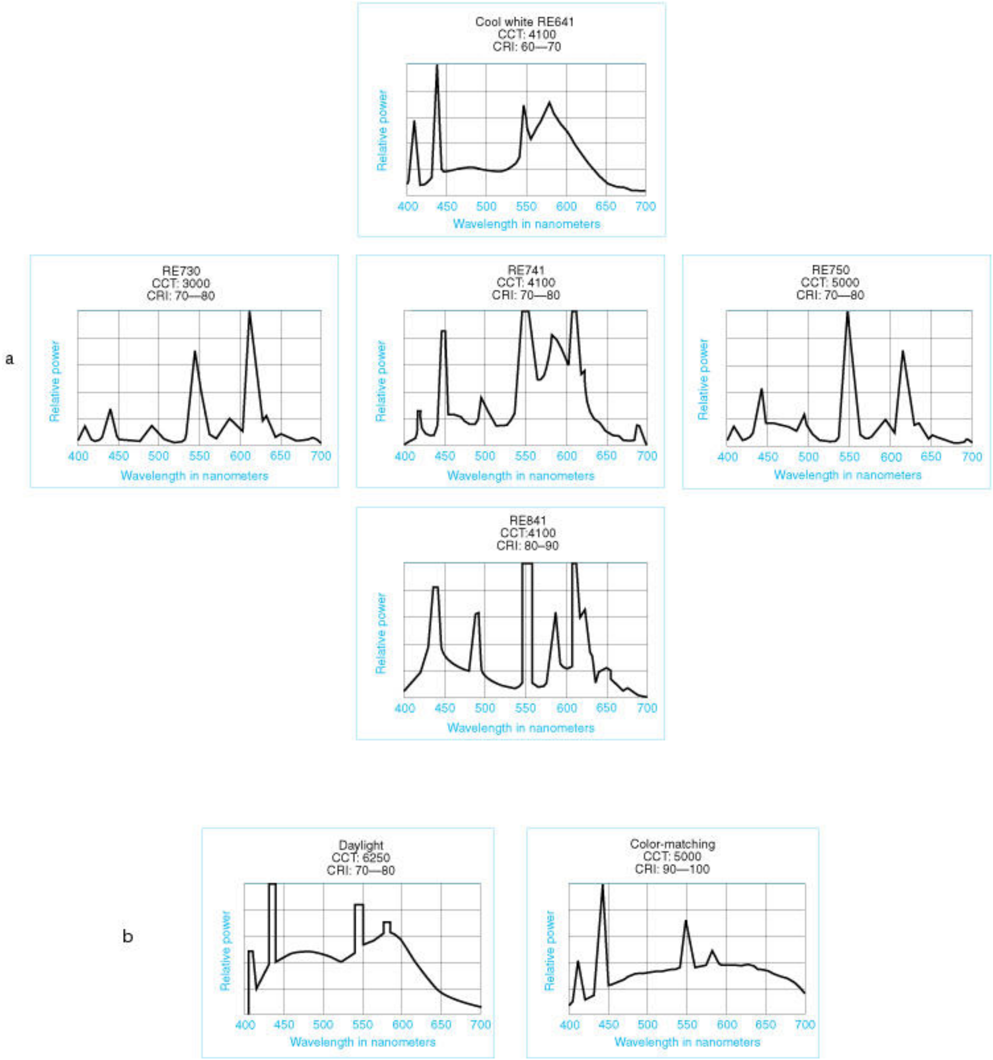


Figure 6-28a and b. Approximate spectral power distribution charts for various types of fluorescent lamps.

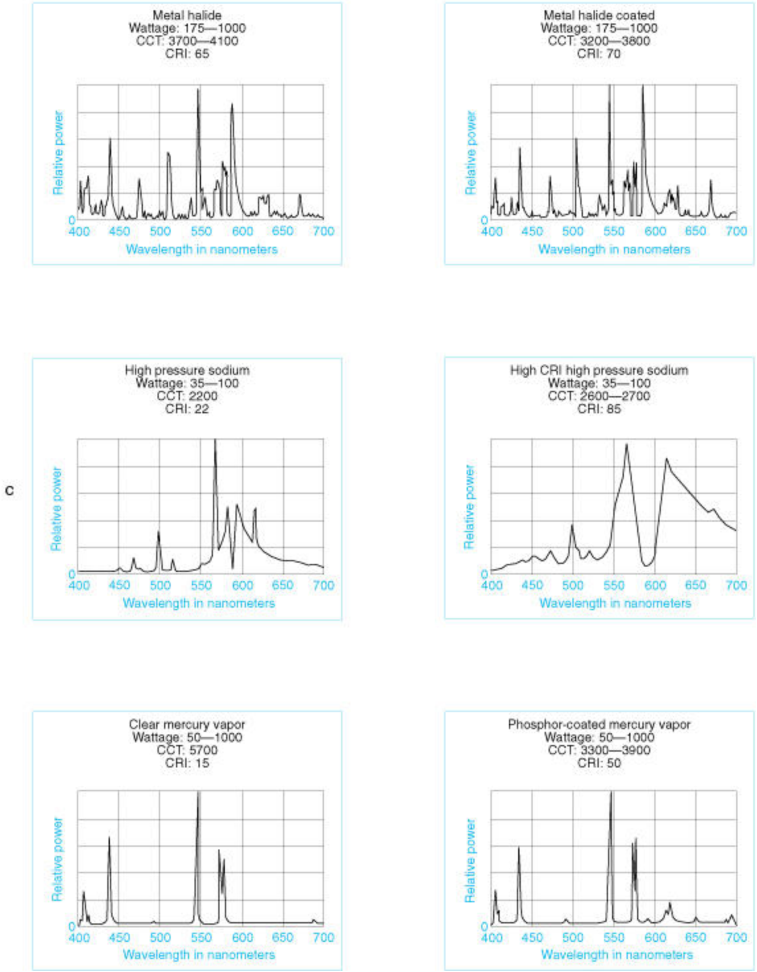


Figure 6-28c. Approximate spectral power distribution charts for various types of HID lamps.

Popular fluorescent lamps use three highly efficient narrow-band, rare-earth activated phosphors with emission peaks in the short-, middle-, and long-wavelength regions of the visible spectrum. These triphosphor lamps can be obtained with high color rendering, improved lumen maintenance, and good efficacy with correlated color temperatures between 2500 and 6000 K relative to halophosphate lamps.[25,26]

Since the rare-earth phosphors are expensive, the longer T-5, T-8, T-10, and T-12 triphosphor lamps typically employ a two-coat system consisting of a less expensive halophosphate phosphor applied with the rare-earth type. The rare-earth activated phosphor is closest to the mercury discharge and, as a result, the spectral power distribution of the lamp is more influenced by these phosphors. Common commercial types have correlated color temperatures of 3000, 3500, and 4100 K.

A variety of lamp types is available that radiate in particular wavelength regions for specific purposes, such as plant growth, merchandise enhancement, and medical therapy. Various colored lamps, such as blue, green, and gold, are obtained by phosphor selection and filtration through pigments.

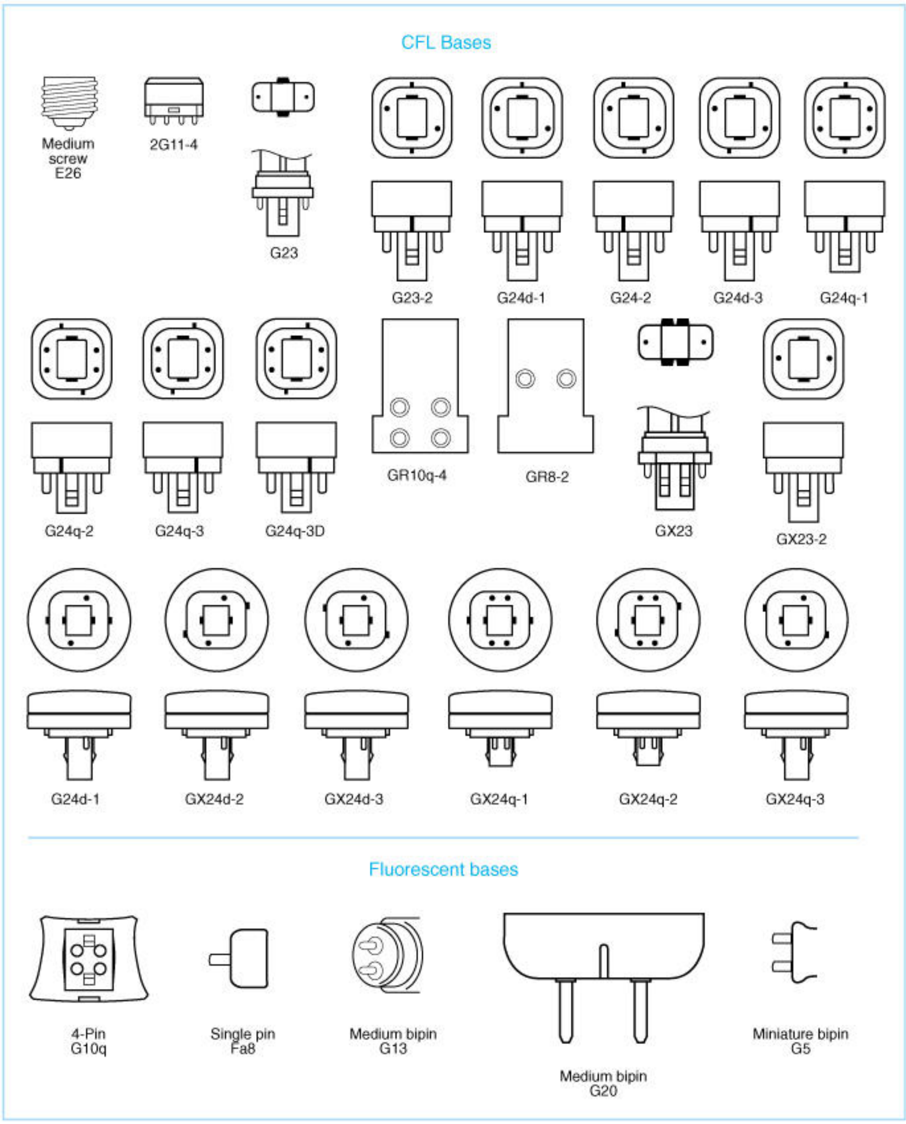


Figure 6-29. Typical bases for linear and compact fluorescent lamps (not to scale). ANSI designations are shown.

Bases. For satisfactory performance, a fluorescent lamp must be connected to a ballasted electrical circuit with proper voltage and current characteristics for its type. Several fluorescent lamp base designs are used. The bases physically support the lamp in most cases and provide a means of electrical connection (Figure 6-26).

Straight tube lamps designed for instant-start operation (see the section "Instant-Start Lamp and Ballast Operation" below) generally have a single connection at each end. As a consequence, a single-pin base is satisfactory.

Preheat and rapid-start lamps (see the section "Lamp Starting" below) have four electrical connections, two at each end of the tube, and therefore require dual-contact bases. In the case of the circline lamp, a single four-pin connector is required. Many compact fluorescent lamp bases have unique designs to help ensure their use with the correct ballast.

Single-ended compact fluorescent lamps with integral starters have plastic bases containing a glow switch and a noise reduction filter capacitor. These bases have two connection pins. Some lamp wattages are available without the starting components mounted within the bases and have four connection pins (Figure 6-29). Only four-pin lamps are dimmable. For incandescent lamp retrofit applications, self-ballasted compact fluorescent lamps have medium screw bases.

Common Fluorescent Lamp Families

T-12 Fluorescent Lamps. Until the National Energy Policy Act of 1992 (EPACT), the most commonly applied fluorescent lamp in the United States and Canada was the T-12, 40-W, 4-ft (1.22-m), rapid-start lamp with a cool white or warm white phosphor. EPACT banned the production of these type lamps after 1995. EPACT also impacted the T-12, 8-ft (2.44 m) lamps. As with 4-ft lamps, only reduced wattage or improved color rendition lamps are currently produced for U.S. consumption. For many new installations, the more efficient T-8 lamps are often specified.

Legislation similar to EPACT exists in Canada, where energy efficiency standards for fluorescent lamp ballasts, fluorescent lamps, and incandescent reflector lamps have been established under the Energy Efficiency Act. Regulated products cannot be imported into Canada or traded between its provinces unless they meet the regulatory requirements.

Energy-Saving Fluorescent Lamps. In response to the energy crisis of the 1970s, lamp companies introduced halophosphate T-12 lamps filled with an argon-krypton gas mixture, rather than argon only. The 4-ft (1.22 m) lamps can be operated suitably on a ballast designed for 4-ft (1.22 m) 40-W lamps, but because of the different gas mixture they dissipate approximately 34 W per lamp. Any of the energy-saving ballasts that operate standard lamps at full light output can be used, provided the ballast is listed for use with the lamps; this information is stated on the ballast label. These lamps may not be used with any ballast that provides reduced wattage and thus reduced light output in a standard lamp, nor with any ballast that does not list the lamp on its label. A transparent conductive coating is applied to these energy-saving lamps, resulting in a lower required starting voltage and less lumen output. By using these lamps as a retrofit in overilluminated spaces, a saving of 5 to 6 W per lamp can be achieved.

Whether operated on standard or energy-efficient magnetic ballasts, energy-saving fluorescent lamps generate approximately 87% of the light generated by a standard (40-W T-12) lamp at 25°C (77°F). This lamp-ballast system is less efficient than the standard argon gas lamp-ballast system, since it generates fewer lumens per watt. This is due to increased ballast losses. In addition, these lamps cannot be dimmed as easily as standard T-12 lamps, and they are more sensitive to temperature, especially in regard to starting, and should not be started or operated at low temperatures.

T-8 Fluorescent Lamps.[27,28] T-8 fluorescent lamps are a family of 1-in.-diameter (25.4 mm) straight tube lamps manufactured in some of the same lengths as T-12 lamps. The 4-ft version of the lamp is designed to consume approximately 32 W. It is also available in 2-, 3-, 5- and 8-ft. (0.16-, 0.91-, 1.52-, and 2.44-m) lengths. The smaller diameter makes it economical to use the more efficient and more expensive rare-earth phosphors. Although the T-8 and T-12 lamps are physically interchangeable, they cannot operate on the same ballast. T-8 lamps are designed to operate on line-frequency rapid-start ballasting systems at approximately 265 mA, or on high-frequency electronic ballasts at slightly less current. Due to the higher efficacies that can be reached with T-8 systems, they have replaced the conventional T-12 lamps in many applications.

T-5 Fluorescent Lamps. T-5 fluorescent lamps are a family of smaller diameter straight tube lamps employing triphosphor technology. Available only in metric lengths and mini bipin bases, the T-5 lamps provide a higher source brightness than T-8 lamps and better optical control. The lamps provide optimum light output at an ambient temperature of 35°C (95°F) rather than the more typical 25°C (77°F), allowing for the design of more compact luminaires. Also available are high-output versions providing approximately twice the lumens at the same length as the standard versions. T-5 lamps are designed to operate solely on electronic ballasts. Their unique lengths, special lampholder, and ballast requirements make them unsuitable for most retrofit applications. These lamps are used in shallower luminaires than the T-8 lamps, which are more efficient over all than luminaires for T-8 lamps.

Compact Fluorescent Lamps. The rare-earth activated phosphor has led to the development of a growing variety of multitube or multibend single-ended lamps known as compact fluorescent lamps (CFLs). The lamps originally were designed to be interchangeable with conventional 25- to 100-W incandescent lamps, but now this lamp type includes sizes that replace conventional fluorescent lamps in smaller luminaires.

T-4 and T-5 tubes typically are used in compact fluorescent lamps. There are many techniques of adding, bending, and connecting the tubes to obtain the physical size and lumen output desired. The tube portion of the lamp is sometimes enclosed in a cylindrical or spherical outer translucent jacket made of glass or plastic. Some lamps contain the lamp starter, while others contain both the starter and the ballast, which can take the form of a simple magnetic choke or an electronic ballast.

Present compact lamp wattages vary from 5 to 55 W, and rated lumen output ranges from 250 to 4800 lm. Overall lamp length varies from 100 to 570 mm (3.93 to 22.4 in.), depending on lamp wattage and construction. Some designs with self-contained ballasts are equipped with Edison-type screw-in bases for use in incandescent sockets (Figure 6-26d), while other designs use special pin-type bases for dedicated use with mating sockets designed for lamps of a particular wattage (Figure 6-26e). Because of the high power density in these lamps, high-performance phosphors are used extensively in order to enhance brightness, lumen maintenance, and color rendering ability. Amalgams can be added to some versions to enhance performance under a range of operating temperatures.

Special Fluorescent Lamps: Subminiature, Reflector, Cold Cathode, and Electrodeless. In addition to the lamps described above, four families of fluorescent lamps are designed and constructed for special applications: subminiature, reflector, cold cathode fluorescent, and electrodeless fluorescent lamps.

Subminiature fluorescent lamps are extremely small. They were first used in the backlighting of liquid crystal displays. They are two basic types: hot cathode and cold cathode. The lamps all have bulb diameters of 7 mm (approximately T-2-1/2).

The cold cathode series ranges from 1 to 3 W, having an output of 15 to 130 lm, respectively. Standard lamp lengths range from 10 to 50 mm (0.4 to 2.0 in.). These low-power light sources have a low bulb wall temperature, which is important when backlighting displays where space is limited and components must be kept cool. The lamps have a rated life of 20,000 h.

The hot cathode family of subminiature fluorescent lamps ranges from 4 to 13 W, with lumen output packages ranging from 95 to 860 lm, respectively. The lumen output is similar to T-5 preheat fluorescent lamps of comparable length. The hot cathode lamps have a rated life of 10,000 h. Their high light output lends them to such general lighting applications as display lighting, valance lighting, furniture-mounted task lighting, and other applications requiring small-diameter, linear light sources.

The triphosphor blends in both hot and cold cathode products provide for improved efficacy at the higher wattages and good color rendering (CRI of about 80).

Reflector fluorescent lamps are designed for applications requiring directional light output distribution patterns. They have a white powder reflective layer between the phosphor and the bulb that covers a major angular portion of the envelope wall. The major portion of the light is emitted through the strip coated with just the fluorescent phosphor. A cross-sectional diagram and a relative candlepower distribution for a 235° reflector lamp are shown in Figure 6-30. Reflector lamps with other angular widths are available. As a consequence of the reflector layer, absorption of generated light is somewhat higher than in standard fluorescent lamps, producing a somewhat reduced total light output.

Cold cathode fluorescent lamps often are used in decorative, sign lighting, and other architectural applications. Due to their high energy losses associated with electrode operation, they are not as efficacious as the more widespread hot cathode lamps for lengths up to 2.44 m (8 ft). The lamps can be custom manufactured in special shapes and sizes. They are frequently manufactured with small diameter tubing so they can be bent into various shapes and sizes. Cold cathode lamps with color phosphors can replace neon tubes in many applications where exposed sources are acceptable. Other advantages of cold cathode lamps include immediate starting, even under cold conditions, and long life unaffected by the number of starts.

Neon lamps are cold cathode lamps lacking a phosphor coating. The color of the nonfluorescent neon lamps is determined primarily by the fill gas. Neon emits red, whereas argon mixed with mercury vapor emits blue. Combined with colored glass, these and other gas fills create additional colors.

Other special lamps are available for extreme ambient temperatures. One family, designed for low temperatures, incorporates a jacket to conserve heat. Another, for high temperatures, incorporates a mercury amalgam. In both cases, these lamps are designed to optimize the mercury vapor pressures at unusual temperatures.

Electrodeless Lamps. Electrodeless lamps have begun to appear on the general lighting market because of advances in the electronics industry and changes in electromagnetic interference (EMI) standards over the last 30 years.

Electrodeless lamps use an electromagnetic (EM) field, instead of an electric current passing through electrodes, to excite the gas in a bulb. Electrodeless lamps can be categorized according to the method by which they produce EM fields: either inductive discharge or microwave discharge.

Inductive discharge lamps (Figure 6-31), also known as induction lamps, operate using the principle of induction. These lamps also are called electrodeless fluorescent lamps because their EM fields produce light by exciting the same phosphors found in conventional fluorescent lamps. They operate as follows:

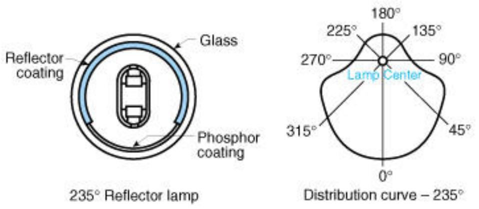


Figure 6-30. Cross-section diagrams and relative candlepower distribution curves for 235-degree reflector lamp.

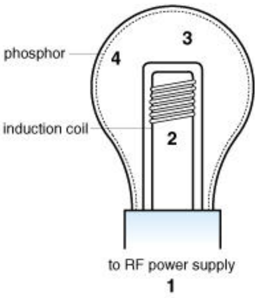


Figure 6-31. Diagram of an induction lamp.

1. The radio frequency (RF) power supply sends an electric current to an induction coil (a wire wrapped around a plastic or metal core).
2. The current passing through the induction coil generates an EM field.
3. The EM field excites the mercury in the gas fill, causing the mercury to emit ultraviolet (UV) energy.
4. The UV energy strikes and excites the phosphor coating on the inside of the glass bulb, producing light.

Microwave discharge lamps (Figure 6-32) generate microwaves, which excite the plasma. They operate as follows:

1. A magnetron generates a microwave field.
2. The microwaves travel through a waveguide into a cavity.
3. In the cavity, a hollow glass or quartz ball rotates at high speed to stabilize the fill in the ball (necessary for a uniform light distribution).
4. The excited fill forms a plasma that emits light.

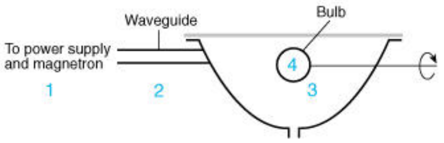
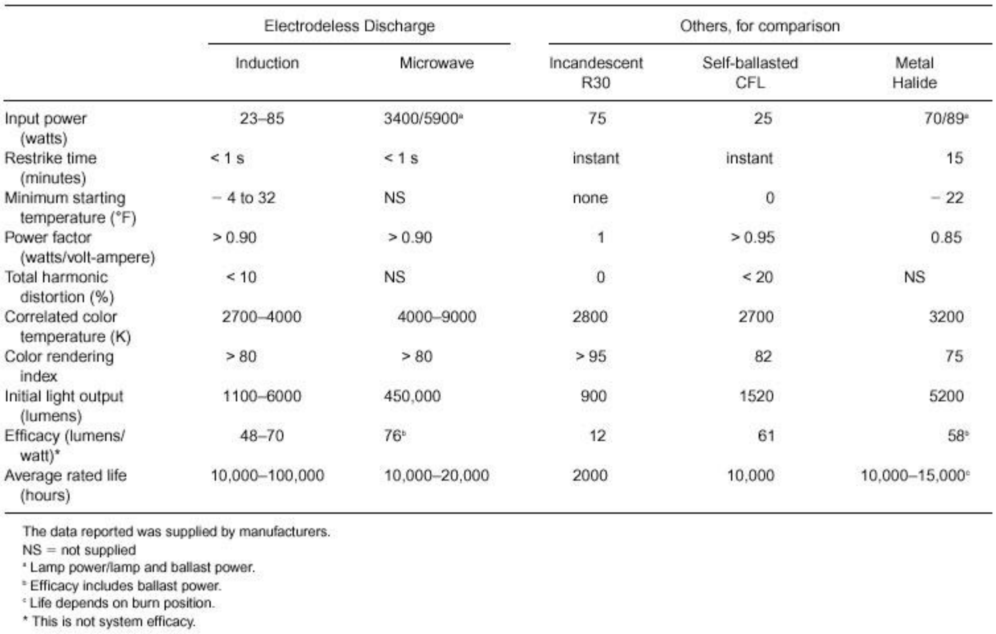


Figure 6-32. Operation of the microwave discharge lamp.



	Electrodeless Discharge		Others, for comparison		
	Induction	Microwave	Incandescent R30	Self-ballasted CFL	Metal Halide
Input power (watts)	23–85	3400/5900[a]	75	25	70/89[a]
Restrike time (minutes)	< 1 s	< 1 s	instant	instant	15
Minimum starting temperature (°F)	− 4 to 32	NS	none	0	− 22
Power factor (watts/volt-ampere)	> 0.90	> 0.90	1	> 0.95	0.85
Total harmonic distortion (%)	< 10	NS	0	< 20	NS
Correlated color temperature (K)	2700–4000	4000–9000	2800	2700	3200
Color rendering index	> 80	> 80	> 95	82	75
Initial light output (lumens)	1100–6000	450,000	900	1520	5200
Efficacy (lumens/watt)*	48–70	76[b]	12	61	58[b]
Average rated life (hours)	10,000–100,000	10,000–20,000	2000	10,000	10,000–15,000[c]

The data reported was supplied by manufacturers.
NS = not supplied
[a] Lamp power/lamp and ballast power.
[b] Efficacy includes ballast power.
[c] Life depends on burn position.
* This is not system efficacy.

Figure 6-33. Performance Characteristics of Typical Electrodeless Lamps

The efficacies of electrodeless lamps are like those of CFLs or HID lamps of comparable light output. Electrodeless lamps use rare-earth phosphors, giving them color properties similar to those of higher-end fluorescent lamps.

Electrodeless lamps are electronic devices, and like all electronic devices they generate EM waves. Electromagnetic interference (EMI) occurs when unwanted EM signals, which can travel through wiring or radiate through the air, interfere with desirable signals from other devices. In the United States, the Federal Communications Commission (FCC) regulates EM emissions in the communication frequencies of 450 kHz to over 960 MHz. Canada also regulates EM emissions over these frequencies through Industry Canada. Manufacturers must comply with FCC regulations to sell products in the United States. However, manufacturer compliance does not assure that EMI will not occur in unregulated frequencies. The International Special Committee on Radio Interference develops standards for EMI from lighting devices, which are accepted by the European community.

Of the available induction lamps, one operates at 13.56 MHz and meets FCC requirements without shielding. It is approved for both commercial and residential use. Others operate at 2.65 MHz, which meets the European community's standard for induction lighting. Sometimes, appropriate luminaires must be used to meet shielding requirements; some lamps meet the FCC's EMI requirements for commercial use but not for residential use because their reflectors offer some shielding. Figure 6-33 gives the performance characteristics of typical electrodeless lamps in comparison to other lamps.

The microwave lamp operates at 2.45 GHz for regulatory and economic reasons. That frequency is approved for consumer electronics; for example, microwave ovens operate at 2.45 GHz. Because of the popularity of the microwave ovens, magnetron parts are produced in large quantities and are relatively inexpensive.

Performance Parameters

Figure 6-3 lists several performance parameters for many common fluorescent lamps. These parameters are discussed in more detail below.

Luminous Efficacy: Light Output. Three main energy conversions occur in a fluorescent lamp. Initially, electrical energy is converted into kinetic energy by accelerating charged particles. These in turn yield their energy during particle collision to electromagnetic radiation, particularly UV. This UV energy in turn is converted to visible energy by the lamp phosphor. During each conversion some energy is lost, so that only a small percentage of the input is converted into visible radiation. Figure 6-34 shows the approximate energy distribution in a typical cool white fluorescent lamp.

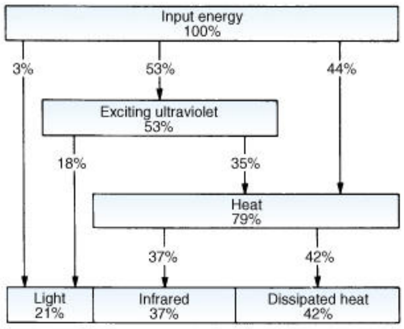


Figure 6-34. Energy distribution in a typical cool white fluorescent lamp.

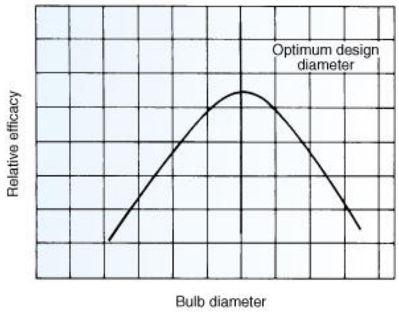


Figure 6-35. Efficacy of typical fluorescent lamps as a function of bulb diameter, holding gas fill pressure with arc current constant.

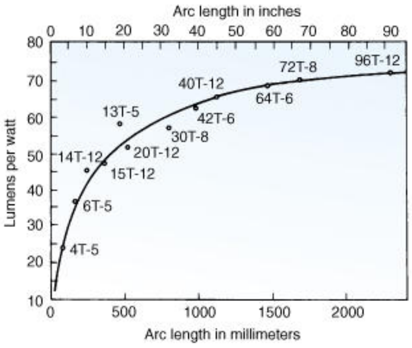


Figure 6-36. Efficacy of a typical halophosphate fluorescent lamp as a function of lamp length.

The geometric design and operating conditions of a lamp influence its efficacy. Figures 6-35 and 6-36 show the effect of the bulb design on lamp operation. Figure 6-35 shows that at a constant current, as the lamp diameter increases, the efficacy increases, reaches a maximum, and then decreases.[29] The reasons for this phenomenon are two-fold. In lamps of small diameter, an excessive amount of energy is lost by recombination of electrons with ions at the bulb wall. As the bulb diameter is increased, this loss decreases, but losses due to imprisonment of radiation become correspondingly larger.

As shown in Figure 6-36, the length of a lamp also influences its efficacy; the greater the length, the higher the efficacy. This is based on two separate energy losses within the lamp: the energy absorbed by the electrodes, which do not generate any appreciable light, and the energy losses directly associated with the generation of light. The electrode losses are essentially constant, whereas the loss associated with light generation depends on lamp length. As lamp length increases, electrode loss decreases relative to the total losses.

The operating voltage of a lamp, like its efficacy, is a function of its length, as shown in Figure 6-37. The characteristic electrode voltage drops for the hot and cold cathode T-8 lamps are indicated by the intersection of the curves with the ordinate corresponding to zero arc length.[30]

Lamp Life. The lamp life of hot cathode lamps is determined by the rate of loss of the emissive coating on the electrodes (Figures 6-26b and c). Some of the coating is eroded from the filaments each time the lamp is started. Emissive coating also is lost by evaporation during normal lamp operation. Electrodes are designed to minimize both of these effects. The end of lamp life is reached when either the coating is completely removed from one or both electrodes, or the remaining coating becomes nonemissive.

Because some of the emissive coating is lost from the electrodes during each start, the frequency of starting hot cathode lamps influences lamp life. The rated average life of fluorescent lamps usually is based on three hours of operation per start (3 h/start). The estimated effect of burning cycles on lamp life normalized to 100% at 3 h/start is presented in Figure 6-38. Cold cathode lamps are not appreciably affected by starting frequency because of the type of electrode used.

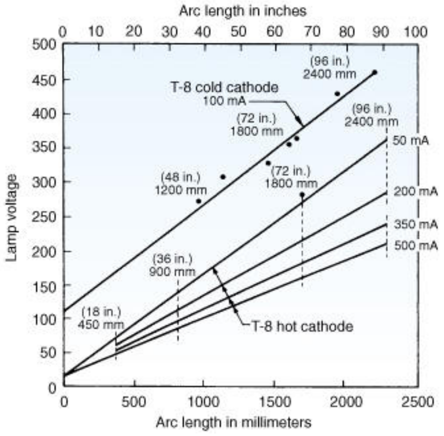


Figure 6-37. Operating voltage of typical hot and cold-cathode 26-mm (T-8) fluorescent lamps as a function of arc length.

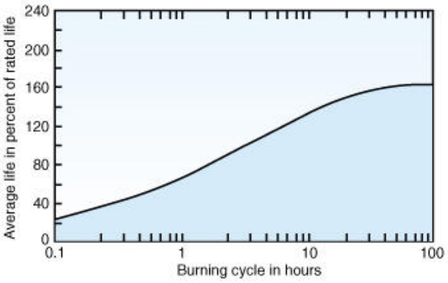


Figure 6-38. Effect of burning cycles on average lamp life for most popular types of rapid-start fluorescent lamps. All fluorescent lamps follow similar functions depending on the specific lamp and ballast used.

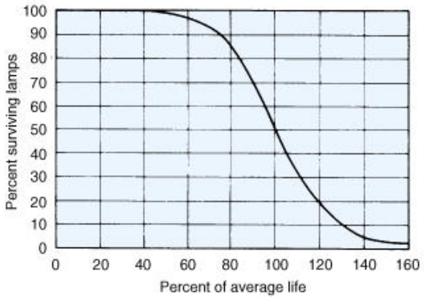


Figure 6-39. Typical mortality curve for a statistically large group of fluorescent lamps (at 3 operating hours per start).

Some electronic ballasts have been designed to instant start rapid-start T-8 and T-12 lamps. Typically there is a 25% reduction in lamp life based upon 3 h/start. Many other conditions affect lamp life. Ballast characteristics and starter design are key factors for preheat circuits. Ballasts that neither provide specified starting requirements nor operate lamps at proper voltage levels can greatly affect lamp life. For preheat circuits, starters also must be designed to meet specified characteristics.

The electrode heating current in rapid-start lamps is critical and is affected not only by ballasts but also by poor lamp-to-lampholder contact or improper circuit wiring. Improper seating of a lamp in a lampholder can prevent electrode heating. Lamps operating in this mode typically fail within 50 to 500 h. Another factor in lamp life is line voltage. If the line voltage is too high, it can cause instant starting of lamps in preheat and rapid-start circuits. If it is low, slow starting of rapid-start or instant-start lamps, or the recycling of starters in preheat circuits, can result. All of these conditions adversely affect lamp life. A typical mortality curve for a large group of fluorescent lamps is given in Figure 6-39. This curve has recently been validated, on a first order basis, for rapid-cycle switching.

Ballasts are available for low-temperature starting of rapid-start lamps. At higher temperatures, lamps operating on these ballasts will start before the electrodes are properly heated, shortening lamp life. Time delay relays are available to ensure proper electrode heating prior to application of ignition voltage to the lamp.

R_h/R_c ratio is correlated with fluorescent lamp life for rapid-start electronic ballasts. R_c is the cold lamp electrode resistance at room temperature (25°C [77°F]). R_h is the hot lamp electrode resistance at the end of the preheat period but before the glow to arc transition. The average electrode temperature before the lamp glow to arc transition (T_h) can be calculated using the equation

$$T_h = T_c \times (R_h/R_c)^{0.814}$$

where T_c is 25°C. This equation is based on the resistance-temperature relationship for tungsten wire. Lamp manufacturers recommend that approximately 700°C is needed to assure minimum sputtering during lamp starting. This electrode temperature correlates to an R_h/R_c ratio of approximately 4.25. For values less than 4.25, sputtering increases and lamp life decreases.

In summary, the R_h/R_c ratio appears to be correlated with lamp life based on lamp starting. A low R_h/R_c ratio indicates that the lamp electrodes have not been heated sufficiently during lamp starting, resulting in reduced lamp life. The data shown here support previous recommendations that for rapid-start electronic ballasts, the R_h/R_c ratio should be equal to or higher than 4.25, representing an average electrode temperature of 700°C.

Lumen Depreciation. The light output of fluorescent lamps decreases with accumulated operating time because of photochemical degradation of the phosphor coating and glass tube and the accumulation of light-absorbing deposits within the lamp. The rate of phosphor degradation increases with arc power and decreases with increased coating density. Lamp lumen depreciation (LLD) curves for different fluorescent lamps are shown in Figure 6-40.[31,32] Protective coatings are sometimes used to reduce the phosphor degradation. Triphosphors are more stable and allow higher loading levels, as for example in T-5, T-8, compact, and subminiature lamps.

The deposit of electrode coating material evaporated during lamp operation causes end darkening. This reduces UV radiation into the phosphors, thereby reducing light output near the ends.

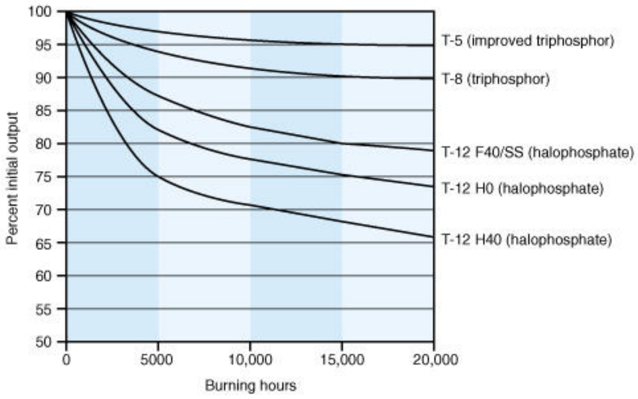


Figure 6-40. Fluorescent lamp lumen depreciation (based on operating on suitable ballast at 3 hr per start).

Spectral Power Distribution and Chromaticity. Spectral power distribution data for several fluorescent lamps are shown in Figure 6-28. For a discussion of color and color rendering index, see Chapter 4, Color.

Temperature Effect on Operation. The luminous performance, light output, and color of a fluorescent lamp are dependent on the mercury vapor pressure within the lamp, which depends on temperature (Figure 6-41).

A fluorescent lamp contains a larger quantity of liquid mercury than will become vaporized at any one time. The excess liquid mercury condenses at the coolest point or points on the lamp. The mercury pressure within the lamp depends on the temperature of the coldest point or points. Lamp construction, design, and wattage, as well as luminaire design, ambient temperature, and wind or draft conditions, affect the cold point.

Lamps using mercury amalgams are available for extending the usable ambient temperatures to higher values. An amalgam is an alloy of mercury and other metals. The amalgam stabilizes and controls the mercury pressure. Placed in a fluorescent lamp, it determines the mercury vapor pressure in the discharge by absorbing or releasing mercury. Amalgams typically are used with compact fluorescent lamps where the bulb wall gets so hot that conventional temperature control techniques are less effective.

An amalgam keeps mercury pressure in the discharge close to its optimal value as the lamp temperature changes. As a result, an amalgam lamp can produce more than 90 percent of its maximum light output over a wide temperature range. Amalgam lamps also tend to maintain relatively constant light output at different operating positions compared to non-amalgam lamps. However, amalgam lamps can take longer to reach their full light output when turned on.[33]

The internal temperature of a luminaire can adversely affect the life of some types of fluorescent lamps. High ambient temperatures not only lower the lamp's lumen output but also can change the lamp's electrical characteristics, bring these characteristics outside the design range of the ballast, and therefore allow more than rated current to flow. Long-term operation at higher currents shortens the life of the lamp.

As the temperature of the cold point changes, both the light output and the active power also change. Both active power and light output have optimum temperatures. Lamp efficacy, defined as light output divided by active power, is typically maximized at approximately 40°C (104°F) (Figure 6-41). Since temperatures within luminaires are typically above the optimum temperature for the lamps and since light loss beyond the optimum temperature is nearly linear, a rule of thumb can be used to estimate light loss as a function of high ambient temperatures. There will be a 1% loss in light output for every 1.1°C (2°F) increase in the ambient temperature above 38°C (100°F).[33]

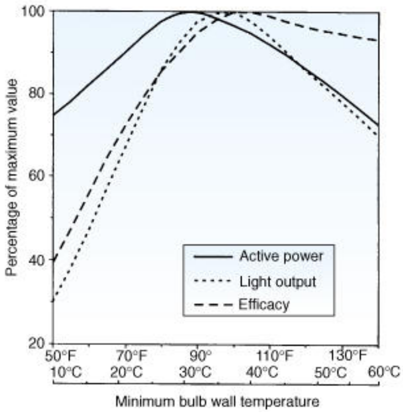


Figure 6-41. Typical fluorescent lamp temperature characteristics. Exact shape of curves will depend on lamp and ballast type; however, all fluorescent lamps have curves of the same general shape, since this depends on mercury vapor pressure.

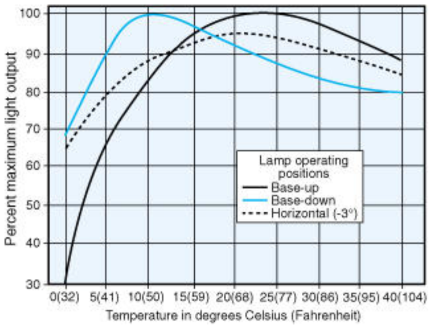


Figure 6-42. The light output characteristics for a nonamalgam compact fluorescent lamp show that the cool zone designed into the lamp geometry to help lower the minimum bulb wall temperature is most effective when the lamp operates base-up.

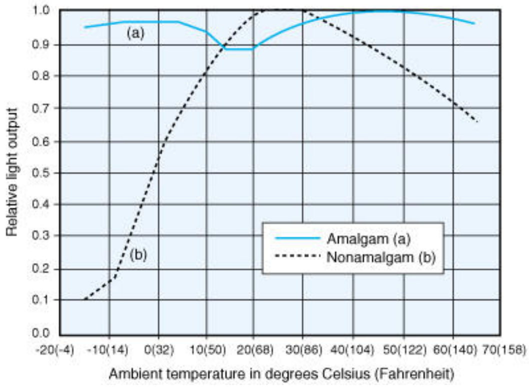


Figure 6-43. Comparison of relative light output vs. ambient temperature for two compact fluorescent lamp designs: one with amalgam (curve a) and one nonamalgam (curve b) in a base-up burning position.

Compact fluorescent lamps often are more sensitive to the temperature of the operating environment than the standard straight tube lamps. In some cases the increased temperature inside the luminaire results in lower than rated light output. Additionally, the performance of many types of compact fluorescent lamps depends on their operating position. Figure 6-42 shows the influence of operating position on typical compact lamps. Some compact fluorescent lamps employ amalgam technology that reduces the lamp sensitivity to burning position and lumen loss due to high and low temperature (Figure 6-43).

Most T-8 and T-12 lamps, which are intended primarily for indoor use, have been designed for their light output and luminous efficacy to reach optimum values at a minimum bulb wall temperature of 38°C (100°F). In well-designed luminaires, this temperature is typically reached when the lamps are operated at rated power under usual indoor temperatures.

Curves for an 800-mA high-output fluorescent lamp are shown in Figure 6-44 (left). As these curves indicate, the light output falls to very low values at temperatures below freezing. Lamps intended for indoor operation display poor low-temperature performance unless protected by suitable enclosures. Figure 6-44 (right) shows the relationship between ambient temperature and light output for a typical outdoor floodlight using 800-mA high-output lamps. While considerable variation occurs with temperature change, satisfactory illumination is obtained for most winter temperatures.

Each lamp-luminaire combination has its own distinctive characteristic of light output as a function of ambient temperature. In general, the shape of the curve is quite similar for all luminaires, but the temperature at which the highest light output is reached can be different.

Effects of Temperature on Color. The color of light from a fluorescent lamp depends on the phosphor coating and also the mercury arc discharge. Each of these components reacts differently to temperature changes. Figure 6-45 shows a typical color shift characteristic of a halophosphate fluorescent lamp.

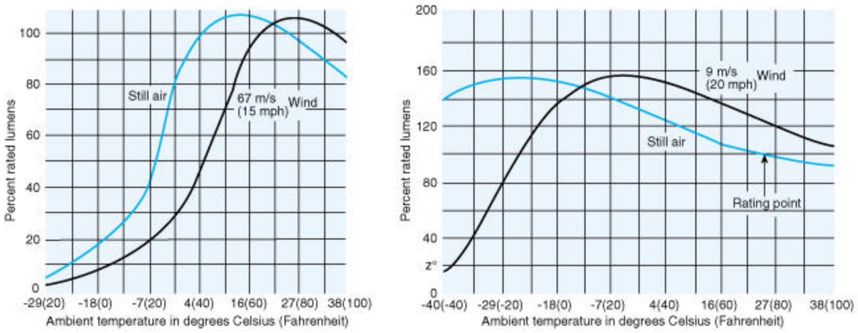


Figure 6-44. Light output versus ambient temperature. (*Left*) F96T12/HO fluorescent lamp. Light output falls to low values at temperatures below freezing. Loss in light at high ambient temperatures is much less. (*Right*) Two F72T12/HO lamps mounted in a typical floodlight. Performance of lamps designed for indoor application is considerably improved when operated in a suitable enclosure.

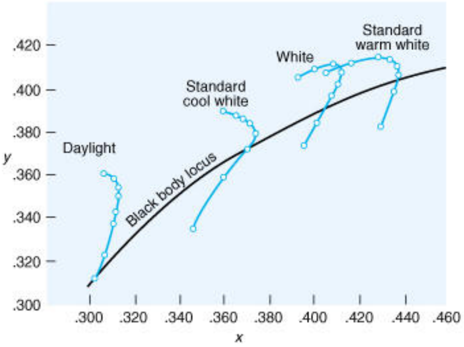


Figure 6-45. This CIE chromaticity diagram contains data for four different halophosphate fluorescent lamps. It shows that the color each lamp produces shifts toward the blue/green with increasing temperature. The lowest point on each curve is at −20℃ (−4℉). Following each curve up and to the left as it bends over, the furthest point is at 120℃ (248℉). Intermediate points are 20℃ (36℉) apart. The chromaticity coordinates of any point are obtained from the x and y axis.

Color shift can be a concern when substantial differences in internal temperature exist between adjacent luminaires. This can arise from the proximity of certain luminaires to air diffusers or open windows; differences in ceiling cavity conditions or ceiling material with surface and recessed equipment; differences in the tightness of enclosures with enclosed equipment; differences in lamp loading or number of lamps in identical luminaires; and use of some of the luminaires as air diffusers in the air-conditioning system.

High-Frequency Operation of Fluorescent Lamps. High-frequency electronic ballasts generally provide power to the fluorescent lamp in the range of 10 to 50 kHz from a 50- to 60-Hz power supply. The primary advantage of high-frequency electronic ballasts for fluorescent lighting systems is higher efficacy relative to the 60-Hz magnetic ballast systems.

As shown in Figure 6-46, efficacy increases rapidly with high-frequency operation until 20 kHz; in the range from 20 to 100 kHz, efficacy is constant. The improved performance of the fluorescent lamp at high frequencies has been attributed to two factors. First, a reduction in end losses is achieved by elimination of the oscillation on the anode half of the operating cycle. Second, an increase in efficiency of the lamp's positive column (major portion of the arc stream) is achieved by operating at lower wattage. In order to save energy, fluorescent lamps normally are operated at lower than rated wattage with high-frequency electronic ballasts while maintaining the lamp's rated lumen output.

In order to avoid audible noise, most electronic ballasts operate the lamp above 20 to 30 kHz. Another consideration in high-frequency operation of fluorescent lamps is radiated and conducted radio-frequency (RF) noise. The electronic ballast must have filter circuitry to constrain the conducted RF to within government regulations. In addition, the lamp current waveform must be chosen to limit RF intensity.

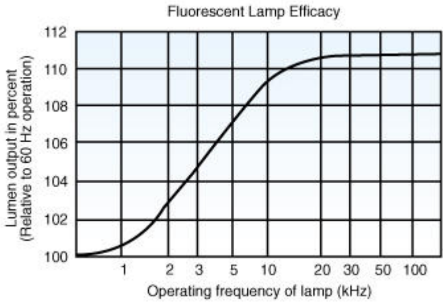


Figure 6-46. Lamp efficacy gain at constant lumen output vs. operating frequency for a 40-watt, T-12 rapid-start lamp.

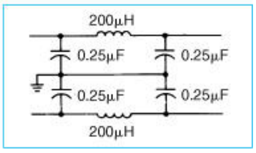


Figure 6-47. Typical radio interference filter.

Radio Interference. The mercury arc in a fluorescent lamp emits electromagnetic radiation. This radiation can be received by nearby radios, causing an audible noise. Radio noise reaches the receiver either by radiation to the antenna or by conduction over the power lines. Because of the frequencies generated by the fluorescent lamp, radiated interference is ordinarily limited to the AM broadcast band and nearby amateur and communications bands. Radiated interference can be eliminated by moving the antenna farther from the lamp. A distance of 3 m (9.8 ft) is usually sufficient. Where this is not practical, shielding media, such as electrically conducting glass or certain louver materials, can suppress the noise below the interference level. FM, television, and higher frequencies rarely are affected by radiated interference but can be affected by conducted interference. Conducted interference can be suppressed by an electric filter in the line at the luminaire. Figure 6-47 shows a typical design. Luminaires with this type of filtering and appropriate shielding material have been qualified under pertinent military specifications for sensitive areas. Most instant-start ballasts and starters for preheat circuits have capacitors for reducing radio interference.

Infrared Interference with Compact Fluorescent Lamps. The use of infrared (IR) radiation for transmitting data and control signals has increased in popularity for equipment such as television and video cassette recorders, computers, and medical devices. Such equipment generally uses IR receivers that, in North America, operate at carrier frequencies from 33 kHz to 40 kHz, and some at 56 kHz. With the increased use of compact fluorescent lamps operated on electronic ballasts, more interference problems have been reported. If the operating frequency of the compact fluorescent ballast or its second harmonic, which is the power supply frequency, is within the frequency band of the appliance IR receiver, interference can occur. To reduce or eliminate this interference, one should move the lamp to a new position or use other lamp and ballast combinations where frequency matching does not occur. Current electronic ballast designs take into account this potential interference by using operating frequencies that minimize this interaction. Additionally, IR receivers now contain improved coding that is less sensitive to stray IR radiation.

Flicker and Stroboscopic Effect. The light output of a fluorescent lamp varies with instantaneous power input. Operating on a magnetic ballast with a 60-Hz power input frequency, the resulting 120-Hz variation coupled with phosphor persistence makes the fluctuating light output too rapid for most people to perceive. This assumes, however, that the power input is free of electrical noise. The presence of electrical noise from other equipment can result in frequencies that manifest themselves as visible flicker. Under noise-free operating conditions, the flicker index for typical fluorescent lamps operated with electromagnetic ballasts ranges from 0.01 to approximately 0.1, and is much lower when operated with high frequency electronic ballasts. For a discussion about flicker and the stroboscopic effect, including the definition of the flicker index, see Chapter 2, Measurement of Light and Other Radiant Energy.

Lamp Operation and Auxiliary Equipment

General. Like most arc discharge lamps, fluorescent lamps have a negative volt-ampere characteristic and therefore require an auxiliary device to limit current flow. This device, called a ballast, might also provide a voltage sufficient to start the arc discharge. This voltage can vary between 1.5 to 4 times the normal lamp operating voltage.

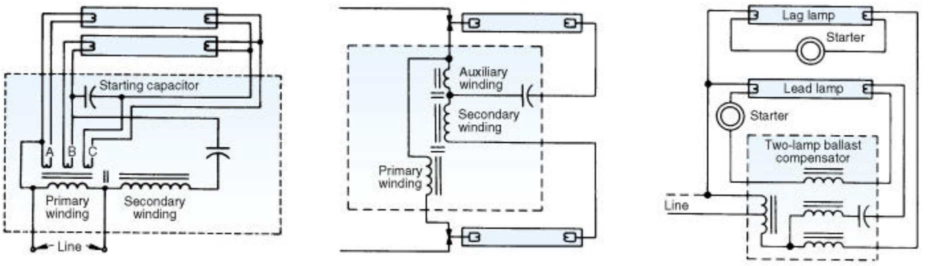
The life and light output ratings of fluorescent lamps are based on their use with ballasts providing proper operating characteristics, which have been established in the ANSI standards for dimensional and electrical characteristics of fluorescent lamps (C78 Series). Ballasts that do not provide proper electrical values might reduce either lamp life or light output or both. This auxiliary equipment requires electrical power and therefore reduces the system efficacy below that based on the power requirements of the lamp.

Lamp Starting. The starting of a fluorescent lamp occurs in two stages. First, the electrodes must be heated to their emission temperatures. Second, a sufficient voltage must exist across the lamp to ionize the gas in the lamp and develop the arc. In some starting systems, a voltage is applied between one of the electrodes and ground to help ionization.

As the ambient temperature is reduced, it becomes more difficult to start fluorescent lamps. Higher voltages are required to reliably start lamps at low temperatures. For efficient lamp and ballast operation, specific ballasts are generally available for each of the following temperature ranges: above 10°C (50°F) for indoor applications, above − 18°C (0°F) for outdoor temperature applications, and above − 29°C (− 20°F) for outdoor temperature applications.

Three different means of starting lamps with magnetic ballasts have been developed. Preheat starting requires an automatic or manual starting switch. Instant starting requires a high ballast open circuit voltage. Rapid starting, the most commonly used starting circuit, continuously heats the electrodes, obviating high voltages and starting switches. Several magnetic circuits are shown in Figure 6-48. In general, for operation on magnetic ballasts, there are differences between lamp designs for different starting methods; therefore, it is important to match the lamp to the starting circuit. The lamp description normally identifies the proper circuit, that is, preheat, rapid, or instant start.

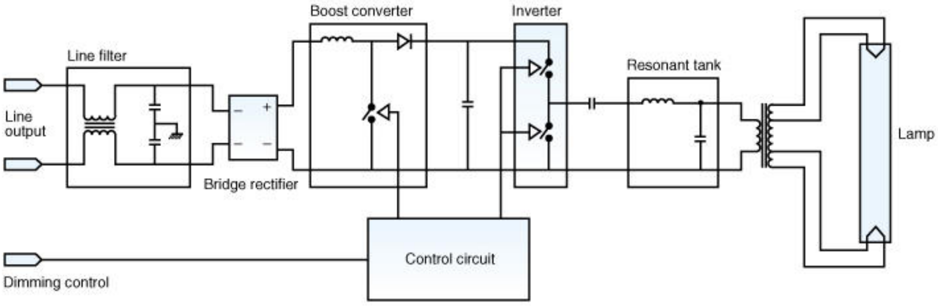
For electronic ballasts, new techniques for starting fluorescent lamps have been developed. Electronic ballasts have been introduced that can instant start most rapid-start fluorescent lamps. Additionally, hybrid electronic starting methods are available that combine characteristics of rapid and preheat starting. Electronic ballasts are also available with a soft starting sequence, which is designed to minimize damage to the electrodes during starting and therefore to lengthen lamp life.



(a) Two-lamp rapid-start high power factor. Used for rapid-start, high output, and extra high output lamps, for both indoor and low temperature applications. The small capacitor shunted across one lamp momentarily applies nearly all of the ballast secondary voltage across the other lamp. The lamp cathodes are continuously heated by the cathode heating windings (A, B, and C) in the ballast.

(b) Two-lamp series-sequence instant-start high power factor. Used in instant (slimline) indoor units. Lamps start in sequence with auxiliary winding helping to start first lamp. Note disconnect lamp-holder connection that removes power from the ballast primarily when lamps are being changed, thus preventing electric shock.

(c) Two-lamp lead-lag preheat, high power factor. Used in 40-watt and 90-watt pre-heat-type general luminaires. Note compensator winding, which is needed to produce sufficient preheat current in the lead circuit.



(d) Hot cathode rapid-start lamps with electronic ballasts

Figure 6-48. Typical fluorescent lamp circuits.

Preheat Lamp and Ballast Operation. In preheat circuits, the lamp electrodes are heated before application of the high voltage across the lamp. Lamps designed for such operation have bipin bases to facilitate electrode heating. Many preheat-starting compact fluorescent lamps have the starting devices built into the lamp base.

The preheating requires a few seconds, and the necessary delay usually is accomplished by an automatic switch that places the lamp electrodes in series across the output of the ballast. Current flows through both electrode filaments, heating them. Subsequently, the switch opens, applying the voltage across the lamp. Due to the opening of the switch under load, a transient voltage (an inductive spike) is developed in the circuit, which aids in ignition of the lamp. If the lamp does not ignite, the switch closes and reheats the filaments. In some systems, preheating is accomplished by a manual switch.

The automatic switch is commonly called a starter. It can incorporate a small capacitor (0.006 µF) across the switch contacts to shunt high-frequency oscillations that might cause radio interference.

Ballasts are available to operate some preheat lamps without the use of starters. These ballasts use the rapid-start principle of lamp starting and operating and popularly are called trigger start ballasts.

Starters For Preheat Circuits. The operation of a preheat circuit requires heating of the electrodes prior to application of voltage across the lamp. Preheating can be effected by use of a manual switch or a switch that is activated by application of voltage to the ballast circuit. A number of automatic switch designs are commercially available. Diagrams for two designs are presented in Figure 6-49.

Thermal Switch Starter. A diagram of a thermal switch starter is presented in Figure 6-49a. Initially the silver-carbon contact of the thermal starter is closed, placing the electrodes in series with the parallel combination of the bimetal and the carbon resistor. Upon closing the ballast supply circuit, the output voltage of the ballast is applied to this series-parallel wiring combination. The current heats the bimetallic strip in the starter, causing it to open the silver-carbon contact. The time of opening is sufficient to raise the temperature of the electrodes to approximately its normal operating value. Upon opening the circuit, the ballast output voltage in series with an inductive spike (kick) voltage is applied to the lamp. If the lamp ignites, its normal operating voltage maintains a low current through the carbon resistor, developing and transferring sufficient heat to the bimetal to hold its contact open thereafter.

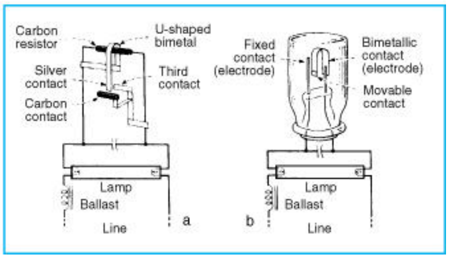


Figure 6-49. Starter switches for preheat cathode circuits: (a) thermal type; (b) glow switch type.

Should the lamp fail to start on the first attempt, the ballast open-circuit voltage applied to the carbon resistor heats the bimetal sufficiently to cause the silver contact to move against the third contact. This short-circuits the carbon resistor, permitting preheating current to flow through the electrodes. As the bimetal cools, the circuit through the third contact is opened, resulting in the application of the circuit voltage to the lamp again. This making and breaking of the circuit through the third contact continues until the lamp ignites. The bimetal circuit is held open thereafter as noted above. The carbon contact circuit functions only when the line voltage is initially applied to the ballast.

Thermal-switch starters require some power (0.5 to 1.5 W) during lamp operation, but their design ensures positive starting by providing an adequate preheating period, a high induced starting voltage, and characteristics inherently less susceptible to line voltage variations. For these reasons they give good all-around performance under adverse conditions, such as direct-current operation, low ambient temperature, and varying voltage.

Glow-Switch Starter. The circuit for this starter is presented in Figure 6-49b. The bulb is filled with an inert gas chosen for the voltage characteristics desired. On starting, the line switch is closed. There is almost no voltage drop in the ballast, and the voltage at the starter is sufficient to produce a glow discharge between the contacts. The heat from the glow distorts the bimetallic strip, the contacts close, and electrode preheating begins. This short-circuits the glow discharge so that the bimetal cools, and in a short time the contacts open. The open-circuit voltage in series with an inductive spike voltage is applied to the lamp. If the lamp fails to ignite, the ballast open-circuit voltage again develops a glow in the bulb, and the sequence is repeated until the lamp ignites. During normal operation, there is not enough voltage across the lamp to produce further starter glow, so the contacts remain open and the starter requires no power.

Cutout Starter. This starter resets either manually or automatically. It is designed to prevent repeated blinking or attempts to start a deactivated lamp. This type of starter should be good for at least ten or more renewals.

Lamp Failure in Preheat Circuit. Starters that provide no means for deactivation when a lamp fails will continue to attempt to start the lamp. The lamp might repeatedly blink on and off, and the ballast or starter will eventually fail. Thus it is important to remove a failed preheat lamp immediately.

Instant-Start Lamp and Ballast Operation. Arc initiation in instant-start lamps depends solely on the application of a high voltage across the lamp. This voltage (400 to 1000 V) ejects electrons from the electrodes by field emission. These electrons flow through the tube, ionizing the gas and initiating an arc discharge. Thereafter, the arc current provides electrode heating. Instant-start lamps need only a single contact at each end. A single pin is used on most instant-start lamps. These are commonly called slimline lamps. A few instant-start lamps use bipin bases with the pins connected internally. In the case of lamps designed for instant starting at 400 to 1000 V open circuit, it is necessary to provide some means of counteracting the effect of humidity on the capacitive lamp-ground current that initiates the necessary glow discharge. Most manufacturers coat the outside of bulbs of this type of lamp with a transparent, nonwetting material; others apply a narrow conducting strip along the bulb. A grounded conducting plate, such as a metal reflector near the lamp, commonly known as a starting aid, is necessary to obtain the lowest lamp starting voltage.[34]

Rapid-Start Lamp and Ballast Operation.[35-38] Lamps designed for rapid-start operation typically have low-resistance cathodes. Normally, the cathodes are heated continuously by the application of cathode voltage while the lamps are in operation. In some energy-saving circuits, the cathode voltage is reduced or disconnected after the starting of the lamps. Heating is accomplished through low-voltage windings built into the ballast or through separate low-voltage transformers designed for this purpose. This results in a starting-voltage requirement similar to that of preheat lamps. Lamps usually start in approximately one second, which is the time required to heat the filaments to their proper temperature.

A starting aid, consisting of a grounded conducting plate, is required for reliable starting. For lamps operating at 500 mA or less, the nominal distance between the lamp and a 25 mm (1-in.) wide conducting plate is 13 mm (0.5 in.); for lamps operating at currents greater than 500 mA, the nominal distance to the conducting strip is 25 mm (1 in.).

Rapid-start lamps are coated with a transparent nonwetting material to counteract the adverse effect of humidity in lamp starting. All 800-mA and most 1500-mA lamps operate on the rapid-start principle. Forty-watt and circline lamps designed for rapid-start service also can be used in comparable preheat circuits.

Electronic Ballast Starting. All three starting methods are employed in electronic ballasts. When applied to electronic ballasts, the differences between the rapid-start and the preheat technique become less significant. The preheat designs use internal timing components that delay the full open-circuit voltage while applying power to the electrodes for preheating. After starting, the power to the electrodes is reduced to almost zero. Most of the rapid-starting systems do not rely on a potential to ground to aid the start as with the magnetic ballast. The starting method is similar to the preheat technique except that the electrode voltage usually remains after the lamp starts. Electronic ballasts have been designed to "instant-start" rapid-start fluorescent lamps. Typically there may be a reduction in expected life when operated in this manner.

Ballasts

Magnetic Ballasts. The construction of a typical thermally protected rapid-start magnetic ballast is shown in Figure 6-50. The components include a transformer-type core and coil. A capacitor might be included. These components are the heart of the ballast, providing sufficient voltage for lamp ignition and lamp current regulation through their reactance.

The core-and-coil assembly is made of laminated transformer steel wound with copper or aluminum magnet wire. The assembly is impregnated with a nonelectrical insulation to aid in heat dissipation and, with leads attached, is placed in a case. The case is filled with a potting material (e.g., hot asphalt) containing a filler such as silica. This compound completely fills the case, encapsulating the core and coil and the capacitor. The base is then attached.

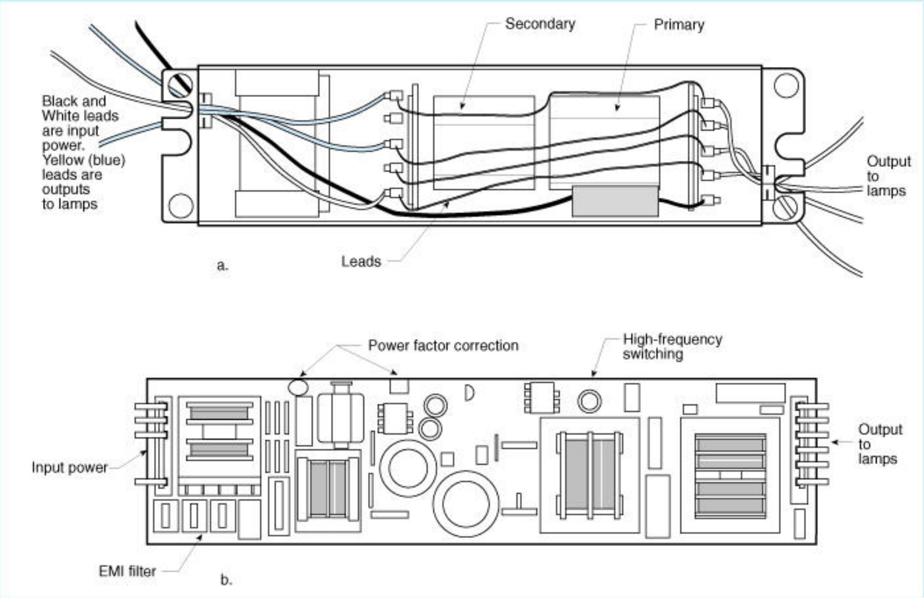


Figure 6-50. Components of a magnetic ballast (a) and high-frequency electronic ballast (b) for a linear fluorescent lamp.

The average ballast life at a 50% duty cycle and a proper ballast operating temperature is normally estimated at twelve years. Ballast life is reduced by higher temperatures or longer duty cycles.

Most fluorescent lamp ballasts used indoors should have an internal thermal protection device. This prevents misapplication of the ballast in high-temperature applications and protects against failure and undesirable conditions that can occur at end of ballast life. In the United States the thermally protected ballast approved by Underwriters Laboratories is known and marked or labeled as "Class P."

Because of the magnetic components in most ballasts, including some electronic ballasts, vibrations can cause audible noise. The noise depends on several factors, including the construction, mounting, number, and spacing of the ballasts and luminaires, and the acoustical characteristics and use of the room.

Ballast manufacturers publish sound ratings that indicate the relative sound-producing potential of their different models. These ratings are based on the experience of the model in different ambient conditions, operating in places ranging from a quiet school room, church, or office to a relatively noisy business office, store, or factory. An A rating means the ballast/luminaire hum probably will not be noticeable in quiet spaces. A B rating is borderline in the quiet applications, but will not be a problem in the noisier places. The C rating should be used only in noisy places like factories.

Electronic Ballasts.[39] The operating frequency of electronic ballasts is chosen to be high enough to increase the lamp efficacy and to make ballast noise inaudible, but not so high as to cause electromagnetic interference (EMI). Electronic ballasts also provide a level of light output regulation that is unavailable in totally passive, magnetic ballasts. Designs are available for the rapid- and instant-start of lamps. Some electronic ballasts are designed to operate up to four lamps each. Many are made in the same size and shape as magnetic units in order to ease direct replacement. Some designs have circuits that keep the line-current harmonic distortion below 20% and provide a power factor in excess of 90%. Some ballasts also employ circuits to limit the current in-rush when power is applied to the ballast. This in-rush, which is a result of the electrolytic capacitors of an electronic ballast charging up, occasionally had been reported as a problem for switches and relays used to turn power to the ballasts on and off. Electronic ballasts also can be designed to operate with dc and low-voltage systems for applications in buses, airplanes, trailers, and battery-operated emergency systems.

In addition, it has been reported that some T-5 and smaller fluorescent lamps have problems at the end of life in field applications. When a fluorescent lamp fails, typically one of the electrodes becomes an open circuit. This can create an asymmetric lamp current operating condition that can produce high local heating, which in turn can crack the lamp bulb or overheat and deform the lamp base. ANSI specifications for magnetic ballasts[40] have been revised to address the end-of-life operation of these lamps.

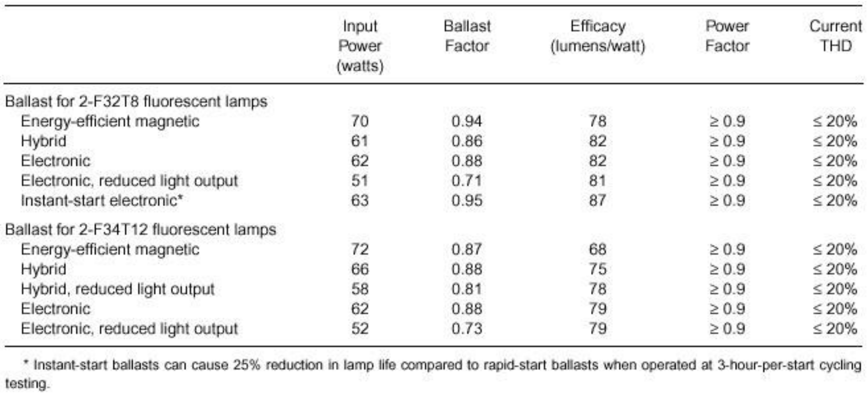
Reduced-Wattage Ballasts. Ballasts are available that operate standard lamps at 50 to 80% of their rated wattage. Energy-saving lamps should not be used in combination with these ballasts, since the arc will tend to waver.

Energy-Saving Ballasts. Energy-saving ballasts have lower power losses than the more common magnetic ballasts. These may be rated by Certified Ballast Manufacturers (CBM) and are used either with common lamps or with reduced-wattage lamps. For example, power losses in two-lamp 40-W rapid-start ballasts have been reduced by 4 to 5 W per lamp over common magnetic ballasts. A typical two-lamp 40-W unit with a low-loss energy-saving ballast dissipates approximately 86 W, compared to approximately 95 W for most magnetic ballasts.

Energy-Saving Systems. Specialized lamp-and-ballast combinations are available to achieve energy savings. These include a 32-W T-8 (4-ft) lamp with a high-efficiency ballast and a 28-W T-12 lamp, also with a high-efficiency ballast, having internal solid-state switches that turn off the usual rapid-start cathode heater voltage. These ballasts can also operate a 34-W reduced-wattage lamp. Power reducers are also available for saving energy. These solid-state electronic devices are wired in series with the lamp ballast to reduce operating wattage. Note that a reduction in light output results.[41]

Ballast Power Factor. The power factor is defined as the ratio of input wattage to the product of root mean square (rms) voltage and rms current. It represents the amount of current and voltage that the customer is actually using as a fraction of what the utility must supply. High power factor is defined as being above 90%. A ballast with low power factor draws more current from the power supply and therefore, larger supply conductors might be necessary. Low-power-factor ballasts are more common with compact fluorescent systems than for 4-ft and 8-ft fluorescent systems. Some public utilities have established penalty clauses in their rate schedule for installations with low power factor. Some utilities require high power factor equipment.

Ballast Factor and Ballast Efficacy Factor. The ballast factor is defined by ANSI (ANSI C82.2-1984)[40] as the relative light output of a lamp operated on the ballast with respect to the same lamp on a reference ballast, usually expressed in percent. The reference ballasts are discussed in detail for each fluorescent lamp type in the applicable ANSI lamp standards. The ballast efficacy factor (BEF) is defined as the ballast factor in percent, divided by the total input power in watts. In the United States, federal regulation sets limits on the BEF of some ballasts for 1.22 m (4-ft) and 2.44 m (8-ft.) fluorescent lamps, summarized in the following table:



	Input Power (watts)	Ballast Factor	Efficacy (lumens/watt)	Power Factor	Current THD
Ballast for 2-F32T8 fluorescent lamps					
Energy-efficient magnetic	70	0.94	78	≥ 0.9	≤ 20%
Hybrid	61	0.86	82	≥ 0.9	≤ 20%
Electronic	62	0.88	82	≥ 0.9	≤ 20%
Electronic, reduced light output	51	0.71	81	≥ 0.9	≤ 20%
Instant-start electronic*	63	0.95	87	≥ 0.9	≤ 20%
Ballast for 2-F34T12 fluorescent lamps					
Energy-efficient magnetic	72	0.87	68	≥ 0.9	≤ 20%
Hybrid	66	0.88	75	≥ 0.9	≤ 20%
Hybrid, reduced light output	58	0.81	78	≥ 0.9	≤ 20%
Electronic	62	0.88	79	≥ 0.9	≤ 20%
Electronic, reduced light output	52	0.73	79	≥ 0.9	≤ 20%

* Instant-start ballasts can cause 25% reduction in lamp life compared to rapid-start ballasts when operated at 3-hour-per-start cycling testing.

Figure 6-51. General Characteristics of Commonly Used Ballasts

Lamp Description	Bulb Diameter (in.)	Bulb Watts	Base (End Caps)	Normal Length		Min. Required RMS Voltage Across Lamp for Reliable Starting (V)	Operating Current (mA)	Operating Voltage (V)	Cathode Heaters (Low Resistance)	
				(mm)	(in.)				Volts	Maximum Watts
F32T8	1	32	Med. Bipin	1200	47.25	200	265	137	3.6	1.7
FT36W/2G11RS	5/8	38.1	2G11	419	16.49	230 single lamp	430	110	3.6	continuous
CFL26	1/2	26	G24d-3	169	6.65	198	325	105	preheat >10 sec	420mA
T5	5/8	28	Min. Bipin	1200	47.25	375	210	107	preheat <2 sec	210mA
T5/HO	5/8	54	2G11	830	32.6	425	400	135	preheat <2 sec	700mA
40T12/SS	1	34–35	Med. Bipin	1200	47.25	1 = 200; 2 = 256	460	79	3.6	—
96T12/SS (Slimline)	1	60	Single pin	2400	94.48	565	440	157	none	continuous
96T12/HO/SS (Rapid start)	1	97	Recess D. C.	2400	94.48	296 2 lamps	830	126	3.6	continuous
			G5 Min. Bipin	1149	45.25					
			G5 Min. Bipin	1149	45.25					

Figure 6-52. Fluorescent Lamp Electrical Characteristics

In addition to the federal regulation, some states might impose additional restrictions on the above or on additional lamp types. Specifically excluded are dimming ballasts, ballasts intended for use in ambient temperatures of − 17.8°C (0°F) or lower and ballasts with power factor less than 90% that are designed for residential use (in buildings up to three stories). Moreover, some utility companies have specified a minimum BEF and ballast factor in their rebate programs for energy-efficient equipment. They generally pertain to the same lamps as the U.S. federal regulation.

Harmonics. Line-current harmonics are those components of the line current that oscillate at low integer multiples of the fundamental frequency of the power supply. For instance, in North America, the fundamental frequency is 60 Hz, the second harmonic is 120 Hz, the third harmonic is 180 Hz, and so forth. Switching in modern solid-state electronic ballasts can cause substantial line-current harmonics when corrections are not implemented in the ballast. This can be especially harmful in three-phase installations if the third-harmonic current is large. The third harmonic and its multiples add in the neutral wire, while the fundamental currents tend to cancel one another there. If the third harmonic is 33.3% of the fundamental, then the total third harmonic in the neutral wire is equal to the fundamental in the phase wires. This can cause problems, including overheating, if the neutral wire is not properly sized.

For these reasons, ANSI C82.11[42] places limits on the harmonic content in the line current for electronic ballasts employed in commercial and residential lighting applications. In the United States, several utility companies have included harmonics as an issue in their rebate programs intended for customers who purchase energy-efficient equipment. Early electronic ballasts typically had high total harmonic distortion (THD) content, which led to the development of these standards. Figures 6-51 and 6-52 list THD and electrical characteristics of fluorescent lamps, respectively.

Fluorescent Lampholders. Lampholders are designed for each lamp base style. Typically several versions of each are available to allow various spacings and mounting methods in luminaires (Figure 6-53). Proper spacing should be maintained between lampholders in luminaires to ensure satisfactory electrical contact. Manufacturers' catalogs should be consulted for dimension and spacing information on any particular lampholder type.

When fluorescent lamps are used in circuits providing an open-circuit voltage in excess of 300 V, or in circuits that permit a lamp to ionize and conduct current with only one end inserted in the lampholder, electrical codes usually require some automatic means for opening the circuit when the lamp is removed. This usually is accomplished by the lampholder so that on lamp removal, the ballast primary circuit is opened. The recessed contact bases on 800- and 1500-mA fluorescent lamps eliminates the need for this disconnect feature in lampholders for these lamps.

Figure 6-53. Typical lampholder designs.

Lamp bases for many compact fluorescent lamps are constructed with unique pin-and-keyway systems to prevent installing the wrong lamp. Universal lampholders that allow lamps of any wattage to fit should be avoided.

Dimming of Fluorescent Lamps.[43-45] Many types of fluorescent lamps are suitable for dimming. Dimming fluorescent lamps differs from dimming incandescent lamps in two key ways. First, fluorescent dimmers do not provide dimming to zero light as do incandescent dimmers. However, products are available to dim to as low as 0.5 to 25% of maximum light output. Second, when dimming fluorescent lamps, the correlated color temperature varies substantially less over the dimming range than incandescent lamps.

Dimming is achieved by reducing the effective lamp current. When doing so, it is necessary to supply the full starting voltage and to maintain the restriking voltage necessary at each 60-Hz half cycle. This is especially true when operating the lamp at low light output. It is also necessary to provide filament heating for all except cold cathode lamps in order to maintain the required electron emissions from the electrodes at all intensities.

Early magnetic dimming ballasts achieved dimming by lowering the primary voltage to the ballast transformer. Such a dimming system can be used with two-pin cold cathode fluorescent lamps in a series circuit as shown in Figure 6-54. With this arrangement, it is possible to reduce the luminous intensity to approximately 10% of maximum light output. The performance of magnetic dimming ballasts can be improved by adding one or more of the following features: filament transformers to provide filament heat, pulse networks to provide the required restriking voltage at low intensities, and high-frequency keep-alive current to maintain the discharge when the line current is interrupted during part of the 60-Hz cycle. These components can be packaged together with the magnetic ballast or be separately installed in the luminaires as dimming adapters.

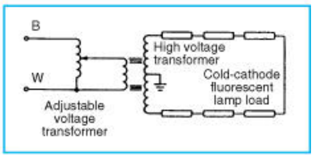


Figure 6-54. Typical dimming circuit for series-connected cold-cathode lamps.

Controls for the magnetic dimming ballasts are available in two-wire and three-wire configurations. The two-wire systems have a limited dimming range, typically 25% light output at the low end, but can be retrofitted with existing wiring in most cases. The three-wire configurations bring a control wire to an external control, such as a wall station. This flexibility allows for a substantial improvement in the dimming performance.

For electronic dimming ballasts, there are several control schemes available. Some manufacturers use a three-wire scheme as described above, so that electronic dimming ballasts can directly replace magnetic dimming ballasts without affecting the control unit. Other three-wire implementations also require the control to be changed. Yet other manufacturers use four-wire systems where two of the wires are used for the dimming signal and the other two to carry the main lamp current.

Most currently available fluorescent lamp dimming systems incorporate electronic ballasts that use high-frequency (typically 20 to 50 kHz) switching of the lamp current. They are designed to be used with four-pin, rapid-start, and compact fluorescent lamps and are available for several lamp diameters and lengths. Electronic dimming ballasts generally are more efficient and less bulky than their autotransformer predecessors. Furthermore, lamp flicker can be substantially reduced with electronic dimming ballasts.

Most electronic ballasts offer energy savings approximately proportional to the reduction in light output (Figure 6-55). This is particularly true at dimmer settings above 25 to 50% luminous output. Furthermore, four-pin construction allows cathode heating when dimming. This is important since it extends lamp life and eliminates flicker when properly implemented. It is also advisable to select premium-quality knife-edge sockets rather than leaf-spring contacts. This ensures that cathode heating is reliably supplied. Finally, solid-state dimmers are substantially quieter (less humming) than their magnetic predecessors.

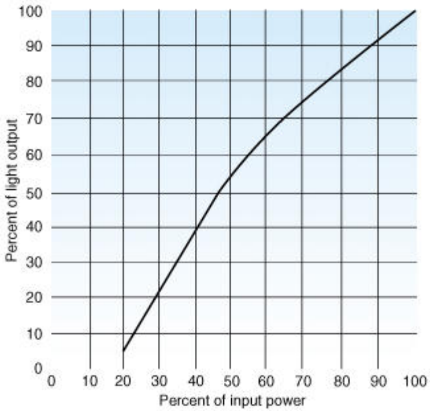


Figure 6-55. Light output vs. input power for a typical 40-watt 120-volt rapid-start fluorescent dimming system.

The performance of a fluorescent dimming system might not be satisfactory if the lamp is not correctly matched with the dimming ballast and the controller. In particular, reduced wattage, energy-saving retrofit lamps should not be used in dimming systems, unless so recommended by the dimmer manufacturer. Doing so might shorten the life of the lamp and ballast.

Flashing of Fluorescent Lamps.[46,47] Cold cathode and rapid-start or preheat-start hot cathode fluorescent lamps can be flashed and still maintain good performance. Cold cathode lamps are flashed through control of either the transformer primary or secondary voltage. Hot cathode lamps can be flashed by means of a special ballast that turns the arc current on and off but keeps the cathode heating on. An external flashing device is required with either system. This unit must be rated for the voltage and current involved, and it is recommended that separate contacts be used for each ballast to prevent circulating currents between ballasts. Flashing of fluorescent lamps is sometimes used in advertising.

HIGH-INTENSITY DISCHARGE LAMPS

High-intensity discharge (HID) lamps include the groups of lamps commonly known as mercury, metal halide, and high-pressure sodium. The light-producing element of these lamp types is a wall-stabilized arc discharge contained within a refractory envelope (arc tube) with wall loading in excess of 3 W/cm^2 (19.4 W/in.^{2}).

Lamp Construction and Operation

All high-intensity discharge lamps produce light by means of an electrical arc discharge contained in an arc tube inside the bulb. The arc tube contains tungsten electrodes that terminate the arc discharge at each end of the arc tube. The arc tube also contains a starting gas that is relatively easy to ionize at low pressure at normal ambient temperatures. This starting gas is usually argon or xenon or a mixture of argon, neon, or xenon, depending on the type of HID lamp. The arc tube also contains metals or halide compounds of metals that, when evaporated into the arc discharge, produce characteristic lines of radiant energy. Each type of HID lamp produces light related to the type of metal that is contained in the arc. Mercury vapor lamps produce light by exciting mercury atoms; high-pressure sodium lamps produce light by exciting sodium atoms; and metal halide lamps produce light by exciting several different atoms and molecules, primarily sodium, scandium, thulium, holmium, and dysprosium.

The arc tube is contained inside a soft or hard glass outer bulb to protect the arc tube and internal electrical connections from the environment. The outer bulb absorbs the majority of UV energy radiated by the arc tube while allowing light to pass through. The outer glass bulb can be coated with a diffusing material to reduce the source brightness of the lamp. In mercury vapor and metal halide lamps, this diffusing coating can be a color-correcting phosphor that uses UV energy radiated by the arc tube to improve the lamp's overall color rendering properties.

Within the outer bulb there are wires suitable for high temperatures to conduct electricity to the arc tube and structural components to support the arc tube. There might be other components, including resistors or diodes used to help start the arc discharge, and devices called getters to purify the atmosphere in the outer lamp. The atmosphere in the outer bulb might be a low-pressure gas (usually nitrogen) or, in many cases, a vacuum.

HID lamps have screw bases (medium or mogul) made from brass, nickel, or special alloys to minimize corrosion. Some HID lamps have special bipin bases or pairs of single contact bases at each end of the lamp to provide electrical connections (Figure 6-56).

If the outer bulb is broken and the arc tube continues to operate, the lamp emits a significant amount of UV energy. Exposure to people beyond about 15 minutes can produce severe erythemal effects (skin reddening) or eye damage (see Chapter 5, Nonvisual Effects of Optical Radiation, for more details). Self-extinguishing lamps usually contain a tungsten filament in place of a portion of nickel wire that will oxidize quickly and separate, extinguishing the electrical arc and turning the lamp off. The lamp is then inoperative and needs to be replaced.

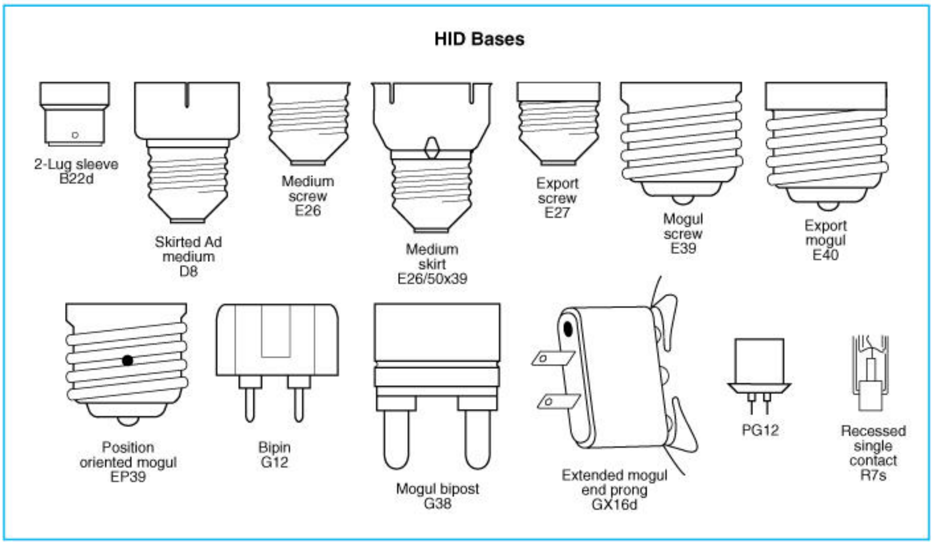


Figure 6-56. Common HID lamp bases (not to scale). ANSI designations are shown.

Mercury Lamps.[48-52] In mercury lamps, light is produced by the passage of an electric current through mercury vapor. Since mercury has a low vapor pressure at room temperature, and even lower when it is cold, a small amount of more readily ionized argon gas is introduced to facilitate starting. The original arc is struck through the ionization of this argon. Once the arc strikes, its heat begins to vaporize the mercury, and this process continues until all of the mercury is evaporated. The amount of mercury in the lamp essentially determines the final operating pressure, which is 200 to 400 kPa (29 to 58 lb/in.^{2}) in the majority of lamps.

The electrodes of mercury lamps usually are made of tungsten, in which the emission material, composed of several metallic oxides, is embedded within the turns of a tungsten coil protected by an outer tungsten coil. The electrodes are heated to the proper electron-emissive temperature by bombardment energy received from the arc.

Most mercury lamps are constructed with two envelopes: an inner envelope (arc tube) that contains the arc, and an outer envelope that (1) shields the arc tube from outside drafts and changes in temperature; (2) usually contains a stable, low-pressure gas (generally nitrogen) that prevents oxidation of internal components and also increases the breakdown voltage across the outer bulb parts; (3) provides an inner surface that will accept phosphor coatings; and (4) normally acts as a filter, removing most of the UV radiation produced by the arc. Phosphors placed inside the outer envelope can convert some of this UV energy to light, as in fluorescent lamps.

Typically, the mercury lamp's inner envelope (arc tube) is made of fused silica with thin molybdenum ribbons sealed into the ends as current conductors. The outer envelope (bulb) is usually made of hard (borosilicate) glass but also can be of other glasses for special transmission or where pollution and thermal shock are not problems.

The essential construction details shown in Figure 6-57 are typical of lamps with fused silica (quartz) inner arc tubes within an outer envelope. Other lamps, such as those for special photochemical application and self-ballasted types, have different constructions.

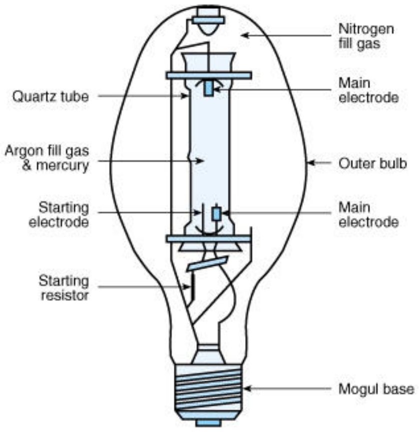


Figure 6-57. Mercury vapor lamp construction.

The pressure at which a mercury lamp operates accounts in large measure for its characteristic spectral power distribution. In general, higher operating pressure tends to shift a larger proportion of emitted radiation into longer wavelengths. At extremely high pressure there is also a tendency to spread the line spectrum into wider bands. Within the visible region the mercury spectrum consists of five principal lines (404.7, 435.8, 546.1, 577, and 579 nm), which result in greenish-blue light at efficacies of 30 to 65 lm/W, excluding ballast losses. While the light source itself appears to be bluish-white, there is a deficiency of long-wavelength radiation, especially in low- and medium-pressure lamps, and most objects appear to have distorted colors. Blue, green, and yellow are emphasized; orange and red appear brownish. Clear mercury lamps generally have a CRI value of approximately 15, and are not desirable for use where people will occupy the space. They are, however, quite suited to landscape lighting (see Chapter 21, Exterior Lighting).

A significant portion of the energy radiated by the mercury arc is in the UV region. Through the use of phosphor coatings on the inside surface of the outer envelope, some of this UV energy is converted to visible radiation. The most widely used lamps of this type are coated with a vanadate phosphor (4000 K, designation DX) that emits long-wavelength radiation (orange-red); this improves efficacy and color rendering. This phosphor also is blended with others to produce cooler or warmer colors. Figure 6-28 shows the spectral power distributions of a clear lamp and ones using these phosphors.

Metal Halide Lamps.[53-61] Metal halide lamps are similar in construction to mercury lamps, the major difference being that the metal halide arc tube contains various metal halides in addition to the mercury and argon. When the lamp attains full operating temperature, the metal halides in the arc tube are partially vaporized. When the halide vapors approach the high-temperature central core of the discharge, they are dissociated into the halogen and the metals, with the metals radiating their spectrum. As the halogen and metal atoms move near the cooler arc tube wall by diffusion and convection, they recombine, and the cycle repeats.

The use of metal halides inside the arc tube presents two advantages. First, metal halides are more volatile at arc tube operating temperatures than pure metals. This allows the introduction of metals with desirable emission properties into the arc at normal arc tube temperatures. Second, those metals that react chemically with the arc tube can be used in the form of a halide, which does not readily react with fused silica.

The efficacy of metal halide lamps is greatly improved over mercury lamps. Commercially available metal halide lamps have efficacies of 75 to 125 lumens/watt (excluding ballast losses). Almost all varieties of white-light metal halide lamps have color rendering properties as good as or superior to phosphor-coated mercury lamps.

The radiating metals introduced as halides in these lamps have characteristic emissions that are spectrally selective. Some metals principally produce visible radiation at a single wavelength, while others produce a multitude of discrete wavelengths. Still others provide a continuous spectrum of radiation. In order to obtain a desired spectrum, blends of metal halides are used. Two typical combinations of halides used are scandium and sodium iodides, and dysprosium, holmium, and thulium rare-earth (RE) iodides. Their spectral power distributions are shown in Figure 6-28. Other metals, such as tin, when introduced as halides, radiate as molecules, providing a continuous band spectra across the visible spectrum. The scandium-sodium system, for example, can produce CCTs between 2500 to 5000 K by varying the blend ratio and arc tube operating temperature. The rare-earth system, on the other hand, has a characteristic CCT of approximately 5400 K, which, when augmented by the inclusion of sodium iodide, may be lowered to 4300 K. A rare-earth system augmented with cesium and sodium iodides can achieve a CCT of 3000 K. The rare-earth system provides a somewhat higher general color rendering index than the scandium-sodium system; lithium iodide additions look promising for enhancing the color rendering properties of the scandium-sodium system.

Selected colors also can be produced using single elements in the arc tube: sodium for orange, thallium for green, indium for blue, and iron for UV. Luminous efficacy and lamp life tend to be greater for scandium-sodium lamps, but thallium can be used to improve the efficacy of RE lamps. These trade-offs should be considered in selecting a lamp type for each particular application. Metal halide lamps are also available with phosphors applied to the outer envelopes (Figure 1-13). These phosphors lower the CCT of the lamps by approximately 300 K. The main use of the phosphor coating is to create a more diffuse light source.

Metal halide lamp construction is similar to that of a mercury lamp (Figure 6-58). One significant design characteristic is that the arc tubes usually are smaller for equivalent wattages. The metal halide arc tube has a white coating applied to the ends to increase vaporization of the metal halides.

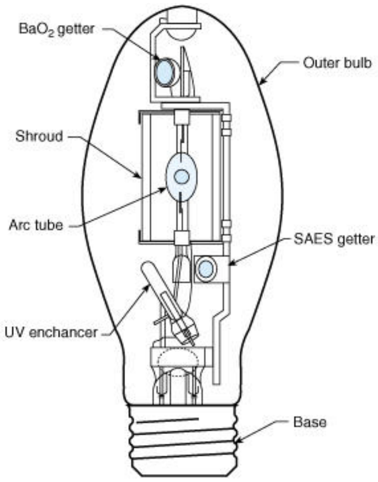


Figure 6-58. Metal halide lamp construction.

Another design characteristic of metal halide lamps is that the arc tubes often are custom shaped. Most metal halide lamps are life- and lumen-rated in the vertical operating position. For instance, a universal operation lamp has its best performance in the vertical position. When a universal lamp is operated horizontally, the arc bows upward due to convection currents. At the same time, the metal halide pool (which is liquid) moves to the center of the arc tube. The bowed arc moves farther from the metal halides than when the lamp is vertical, causing them to cool. This lowers the vapor pressure of the metal halide chemicals and decreases the concentration of metals in the arc with a resulting loss in light. In addition, the bowed arc moves closer to the top of the arc tube wall, causing its temperature to increase. The higher wall loading on the arc tube material results in a decrease in life rating by approximately 25%.

Since many applications require horizontal lamp orientation, a number of arc tube designs have been developed. There are two common configurations for horizontal high output arc tubes as shown in Figure 6-59. The first is a bowed arc tube shaped to follow the natural bowing of the horizontal arc. In this design, the chemicals are confined to the ends of the arc tube as the shape prevents migration. The second design is an asymmetric arc tube with the electrodes lower in the arc tube body such that the arc bows to the center line of the arc tube. Both of these designs provide increased light (approximately 25%) and longer life (approximately 33%) over the universal lamps operated horizontally.

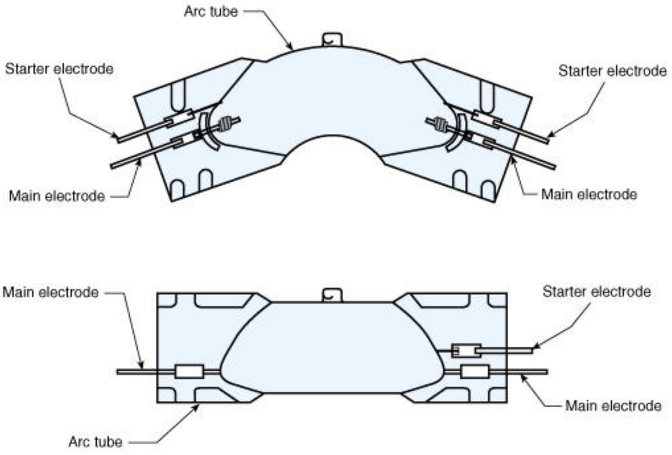


Figure 6-59. Common configurations for horizontal metal halide lamps.

Since the horizontal high-output arc tubes are designed to accommodate the upward bow of a horizontally operating arc, the arc tube must be operated horizontally to prevent overheating of the arc tube walls, which dramatically shortens lamp life and increases the probability of violent failures. A special base and socket are always used with horizontal high-output lamps to help ensure proper arc tube orientation (Figure 6-60). Lamp operating position is much less important for mercury and high-pressure sodium lamps.

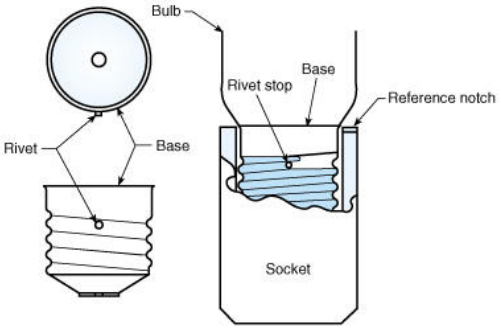


Figure 6-60. Base and socket configuration for some horizontal high-output metal halide lamps.

Some arc tubes have been designed with ovoid shapes (Figure 6-61a). These arc tubes are actually formed in a mold using high-pressure gas. They are commonly referred to as formed body arc tubes. The older style of arc tubes are referred to as pinched body arc tubes (Figure 6-61b). The molding process ensures a highly repeatable and accurate shape for each arc tube. The actual contour and shape of the arc tube gives some excellent benefits in performance. The walls of the arc tube are contoured to better follow the shape of the arc, thereby allowing for a more uniform thermal profile for the arc tube. This shape also allows the metal halide chemicals to heat up more rapidly than those in the conventional pinched body arc tube. On average, formed body arc tubes warm up three times faster than pinched body arc tubes of the same wattage. Formed body arc tubes have much smaller pinch seal areas. These areas serve to cool the arc tube end chambers and thereby reduce lamp efficacy by lowering the temperature of the metal halide pool. This undesirable cooling is more of a problem in lower-wattage lamps in which the pinch seal area comprises a greater part of the total thermal mass of the arc tube than for the higher wattage lamps.

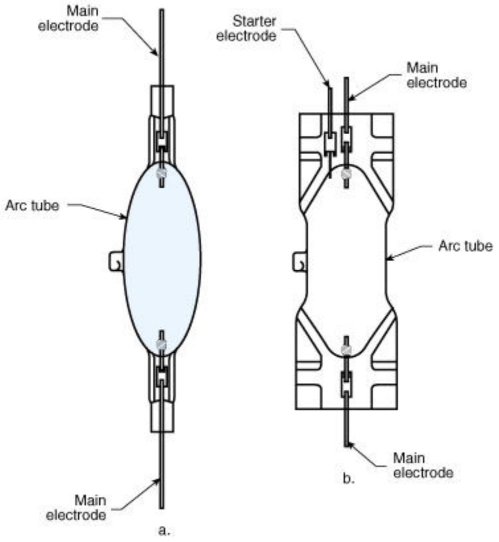


Figure 6-61. Common arc tubes: (a) ovoid, and (b) pinched body.

The smaller pinch seal area has an effect on lamp starting. The older pinch seal designs use a secondary starter electrode that helps to initiate breakdown of the arc tube gases. In formed body arc tubes, there is no room for the secondary electrode. Consequently the arc is initiated by a high-voltage pulse (typically 3,000 V minimum) applied directly across the main electrodes. Devices called ignitors are used to provide these starting pulses. Ignitor starting has been found to have additional performance features. In general, lamps start faster when ignitors are used. They start more reliably, and the fill pressure inside the arc tube can be increased over standard starter electrode systems. This higher fill pressure helps to retard tungsten evaporation from the electrode, which causes lumen depreciation due to arc tube wall darkening.

The classic pinched body metal halide lamps that use a starter electrode must also contain a system that provides for either shorting of the starter electrode to the main electrode or opening the starter electrode circuit after the lamps have started. This is required to prevent electrolysis in the fused silica between the starting and operating electrodes, especially when a halide such as sodium iodide is used in the lamp. Failure to short or open the starter electrode circuit will result in very short lamp lives. These starter circuits typically use a bimetal switch. The location and type of switch can restrict the lamp operating position as the bimetal must achieve a certain temperature to function.

In some metal halide lamps the electrical connection to the electrode at the dome of the lamps is made by a small nonmagnetic wire remote from the arc tube. This prevents diffusion of sodium through the arc tube by electrolysis caused by a photoelectric effect when the current lead is near the arc tube. Most metal halide lamps above 150 W require a higher open-circuit voltage to start than mercury lamps of corresponding wattage. Therefore, they require specific ballasts. Certain metal halide lamps designs, however, can be operated on some types of mercury ballasts in retrofit situations.

Most metal halide lamps use getters to overcome impurities that, if present in the outer jacket of a metal halide lamp in sufficient concentrations, can compromise performance. The predominant problems arise from hydrogen and carbon contamination.

Special metal halide lamps are available that automatically extinguish the arc should the outer envelope break or puncture. They can be used in locations where exposure to UV radiation should be avoided.[62]

Low-wattage metal halide lamps[63-65] (below 175 W) come in many varieties for different applications, such as displays, recessed lighting, and track lighting. They produce brilliant white light in a small arc capsule enclosed in a small outer jacket. Such lamps include single-ended lamps with medium or E27 bases (32 to 175 W), single-ended lamps with bipin bases (35 to 150 W), and double-ended lamps with recessed single contact bases (70 to 150 W).

Some single-ended lamps use a transparent sleeve surrounding the arc tube called a shroud. A thin-walled shroud is useful as a heat shield because it helps achieve a more uniform arc tube temperature; it also retards sodium loss. A heavy shroud is used in lamps suitable for open luminaires. These shrouds prevent the outer jacket of the lamp from breaking in case of an arc tube violent failure. When relamping an open luminaire it is important to use only open luminaire rated lamps (those with shrouds). To prevent user misapplication the industry has developed unique socket and base combinations for both medium and mogul base lamps.

Certain metal halide lamps must be operated in enclosed luminaires designed to contain any hot quartz fragments that might result from an arc tube rupture. Some metal halide lamps do not have a hard glass outer jacket. These lamps can have either no outer jacket or an outer jacket that is made from fused silica that transmits UV energy. In these designs, the luminaire must have a cover glass providing the UV filtration.

High-Pressure Sodium Lamps.[66] In high-pressure sodium lamps, light is produced by electric current passing through sodium vapor. These lamps are constructed with two envelopes, the inner arc tube being polycrystalline alumina, which is resistant to sodium attack at high temperatures and has a high melting point. Although translucent, this material provides good light transmission (more than 90%). The construction of a typical high-pressure sodium lamp is shown in Figure 6-62.

Polycrystalline alumina cannot be fused to metal by melting the alumina without causing the material to crack. Therefore, an intermediate seal is used. Either solder, glass, or metal can be used. Ceramic plugs also can be used to form the intermediate seal. The arc tube contains both xenon as a starting gas and a small quantity of sodium-mercury amalgam, which is partially vaporized when the lamp attains operating temperature. The mercury acts as a buffer gas to raise the gas pressure and operating voltage of the lamp.

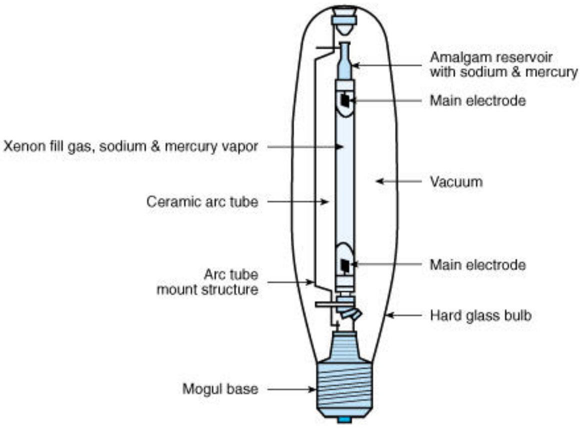


Figure 6-62. High-pressure sodium lamp construction.

The outer borosilicate glass envelope is evacuated and serves to prevent chemical attack of the arc tube metal parts. It also helps to maintain arc tube temperature by isolating the metal from ambient temperature effects and drafts.

Most high-pressure sodium lamps can operate in any position. The operating position has no significant effect on light output. Lamps are also available with diffuse coatings on the inside of the outer bulb to increase source luminous size or reduce source luminance.

High-pressure sodium lamps radiate energy across the visible spectrum. This is in contrast to low-pressure sodium lamps, which radiate principally the doublet D lines of sodium at 589 nm. Standard high-pressure sodium lamps, with sodium pressures in the 5 to 10 kPa (40 to 75 Torr) range, typically exhibit color temperatures of 1900 to 2200 K and have a CRI of 22. At higher sodium pressures, above approximately 27 kPa (200 Torr), sodium radiation of the D line is self-absorbed by the gas and is radiated as a continuous spectrum on both sides of the D line. This results in the dark region at 589 nm as shown in the typical spectrum in Figure 6-28. Increasing the sodium pressure increases the CRI to at least 65 at somewhat higher correlated color temperatures; however, life and efficacy are reduced. White high-pressure sodium lamps have been developed with correlated color temperatures of 2700 to 2800 K and a CRI between 70 and 80. Higher-frequency operation is one method of providing white light at reduced sodium pressure. High-pressure sodium lamps have efficacies of 45 to 150 lm/W, depending on the lamp wattage and desired color rendering properties.

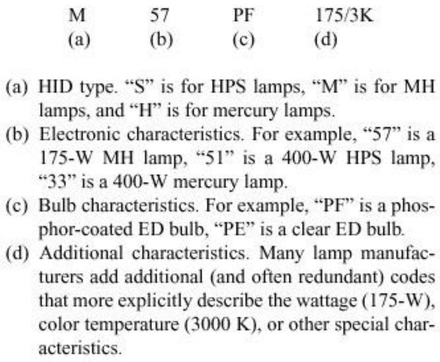
Because of the small diameter of a high-pressure sodium lamp arc tube, no starting electrode is included as in the mercury lamp. Instead, a high-voltage, high-frequency pulse is provided by an ignitor to start these lamps. Some special high-pressure sodium lamps use a specific starting-gas mixture (a combination of argon and neon that requires a lower starting voltage than either gas alone) and a starting aid inside the outer bulb. These lamps can start and operate on many mercury lamp ballasts.

High-pressure sodium lamps are also available with two identical arc tubes contained within the outer bulb. These arc tubes are connected in parallel inside the lamp, but only one arc tube is started with the ignitor pulse. In the event of a momentary power outage, this dual arc tube lamp restrikes immediately when power is restored. Within about one minute, the lamp returns to full light output.

Lamp Designations

The current identifying designations of high-intensity discharge lamps generally follow a system that is authorized and administered by ANSI. All designations start with a letter (H for mercury, M for metal halide, S for high-pressure sodium). This is followed by an ANSI-assigned number that identifies the electrical characteristics of the lamp and ballast. After the number there are two letters that identify the size, shape, and finish of the bulb. After this sequence, the manufacturer may add special letters or numbers to indicate information not covered by the standard sequence of the designation, such as lamp wattage or color.

An example HID lamp designation is as follows:



M	57	PF	175/3K
(a)	(b)	(c)	(d)

(a) HID type. “S” is for HPS lamps, “M” is for MH lamps, and “H” is for mercury lamps.
(b) Electronic characteristics. For example, “57” is a 175-W MH lamp, “51” is a 400-W HPS lamp, “33” is a 400-W mercury lamp.
(c) Bulb characteristics. For example, “PF” is a phosphor-coated ED bulb, “PE” is a clear ED bulb.
(d) Additional characteristics. Many lamp manufacturers add additional (and often redundant) codes that more explicitly describe the wattage (175-W), color temperature (3000 K), or other special characteristics.

Lamp Starting

Mercury Lamps. Some special two-electrode mercury lamps, and many photochemical types, require a high open-circuit voltage to ionize the argon gas and permit the arc to strike. In the more common three-electrode lamps an auxiliary starting electrode placed near one of the main electrodes makes it possible to start the lamp at a lower voltage. Here, an electric field is first established between the starting electrode, which is connected to the opposite main electrode through a current limiting resistor, and the adjacent main electrode. This causes an emission of electrons, which develops a local glow discharge and ionizes the starting gas. The arc then starts between the main electrodes. The mercury gradually vaporizes from the heat of the arc and draws current. During this process the arc stream changes from the bluish glow of the argon arc to the blue-green of mercury, increasing greatly in luminance and becoming concentrated along the axis of the tube. At the instant the arc strikes, the lamp voltage is low. Normal operating values are reached after a warmup period of several minutes, during which the voltage rises until the arc attains a stabilization vapor pressure; the mercury is then entirely evaporated.

If the arc is extinguished, the lamp will not relight until it is cooled sufficiently to lower the vapor pressure to a point where the arc will restrike with the voltage available. The time from initial starting to full light output at ordinary room temperatures, with no enclosing lighting unit, and also the restriking time (the cooling time required before the lamp will restart), vary between 3 and 7 min, depending upon the lamp type.

Metal Halide Lamps. The method of starting most metal halide lamps above 150 W is through an auxiliary starter electrode similar to that used in mercury lamps. The presence of the metal halides causes the starting voltage to be higher than it needs to be for mercury lamps. Therefore, higher-wattage metal halide lamps generally are not operated on mercury control gear. Sometimes people operate 400-W metal halide lamps on standard mercury ballast. This is not good practice since aged lamps require higher starting voltages, if they start at all.

The newer formed body arc tubes do not have room to accommodate the starter electrode in the pinched body arc tube lamps (Figure 6-61b), and therefore a different method of starting is employed. These lamps use an ignitor, a high voltage-low current generating device, as part of the external control circuit. The ignitor provides enough voltage across the main electrodes to initiate an arc. Most lamps below 150 W use an ignitor for starting.

A metal halide lamp does not reach full light output immediately but instead must warm up over a period of several minutes (time to reach full light output is longer for higher lamp wattages). During this phase, the color of the discharge changes as the metal halides warm up, evaporate, and incorporate into the arc. Upon full warm up, the lamp color and electrical characteristics stabilize. Since a metal halide arc tube is smaller than that of a mercury lamp of equivalent wattage, it operates at a higher temperature. Hence, the time to cool down is longer and the time to reignite is longer. The hot restrike time in a conventional pinched body arc tube can be 15 min or longer. Lamps that use ignitor starting restrike much faster than the conventional pinched body arc tube designs with starter electrodes due to higher pulse voltages.

High-Pressure Sodium Lamps. Since the high-pressure sodium lamp does not contain a starting electrode, a high-voltage, high-frequency pulse is used to ionize the starting gas. Once started, the lamp warms to full light output in approximately 10 min, during which time the color changes.

Because the operating pressure of a high-pressure sodium lamp is lower than that of a mercury lamp, the restrike time is shorter. It usually restrikes in less than 1 min and warms up in 3 to 4 min (see also Figure 6-63).

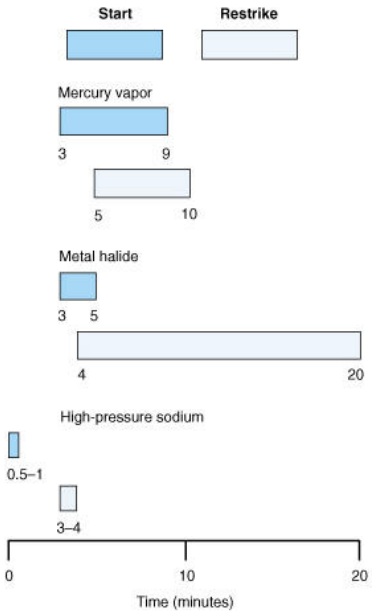


Figure 6-63. Starting and restrike times among different HID lamps.

Lamp Life and Lumen Depreciation

Average rated lamp life is defined as that time after which 50% of a large group of lamps are still in operation. The procedure prescribes operating cycles for HID lamps of 11 h on, 1 h off.[67] For certain lamp types and applications, criteria other than failure to light may be considered, such as rapid cycling, drastic color change, or significant reduction in lumen output. Lamp life is generally based on the prescribed operating cycle. HID lamp life and lumen maintenance are affected by changes in the operating cycle, however. As a rule of thumb, as the operating period is shortened by 50%, lamp life is reduced by approximately 25%. Contact lamp manufacturers for further information about shorter operating cycles and reduced lamp life.

HID lamps usually are rated for initial lumens after 100 h of operation. Figure 6-64 illustrates light losses for three types of 400-W HID lamps over time.

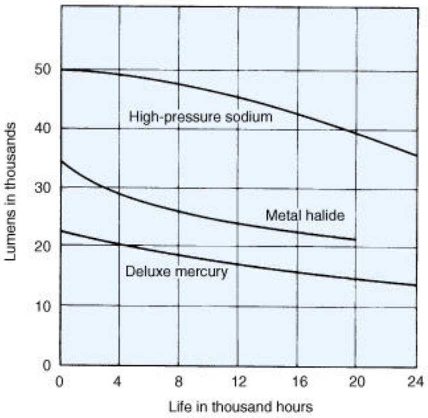


Figure 6-64. Typical lumen maintenance curves for 400-W high-intensity discharge lamps.

Mercury Lamps. General-service mercury lamps have a long average rated life. They usually employ an electrode with a mixture of metal oxides embedded in the turns of tungsten coils from which the electrode is assembled. During the life of the lamp, this emission material is very slowly evaporated, or sputtered, from the electrode and is deposited on the inner surface of the arc tube. This process results first in a white deposit on the inner surface of the arc tube, eventually in a blackening of the arc tube, and ultimately in exhaustion of the emission material in the electrodes and the end of lamp life when the starting voltage exceeds the open-circuit voltage.

Metal Halide Lamps. Chemical reaction between the iodine in a metal halide lamp and the emission materials included in mercury lamp electrodes prevents the use of mercury electrodes in a metal halide lamp. Because the electrodes used with metal halide lamps evaporate more rapidly than mercury lamp electrodes, they generally have shorter life ratings. In addition, some metal halide lamps experience strong color changes toward the end of normal life. Where the color appearance of the lamps is critical, the useful life of the lamps ends when the color shift becomes objectionable.

High-Pressure Sodium Lamps. High-pressure sodium lamps employ electrodes very similar to those used in mercury lamps. This fact, combined with the smaller diameter of the arc tube, gives high-pressure sodium lamps excellent lumen maintenance.

Lamp type	Ballast	Flicker Index
Mercury		
250W Warm Deluxe	Reactor	.127
250W Cool Deluxe	Reactor	.137
250W Deluxe White	Reactor	.131
250W Deluxe White	CWA (M-H type)	.172
100W Deluxe White	CW-Premium	.142
100W Deluxe White	CW	.183
400W Deluxe White	Reactor	.121
400W Deluxe White	CWA (M-H type)	.144
High Pressure Sodium		
250W Deluxe	Reactor of CWA	.131
250W Standard	Reactor or CWA	.200
Metal Halide		
250W High Color Quality	Reactor	.080
250W High Color Quality	HPS-CWA	.102
175W Coated	CWA	.083
175W Clear-Vertical	CWA	.078
175W Clear-Horizontal		.092
250W Coated (A)	CWA	.070
250W Clear-Vertical	CWA	.102
250W Clear-Horizontal		.121
250W Coated (B)	CWA	.092
250W Clear-Vertical	CWA-Premium	.088
250W Clear-Horizontal		.097
400W Clear-Vertical	CWA	.086
400W Clear-Horizontal		.095
1000W Clear (vert)	CWA	.067
175W (3200K)	CWA	.090

Figure 6-65. Flicker Index for HID Lamps Operated on Different Ballast Types

The life of a high-pressure sodium lamp is limited by a slow rise in operating voltage that occurs over the life of the lamp. This rise is principally caused by arc tube end blackening from electrode sputtering. The blackening absorbs radiation, which heats up the arc tube ends and vaporizes additional sodium amalgam. This increases the arc tube pressure and consequently the arc voltage. Other reasons for arc tube voltage rise are the diffusion of sodium through the arc tube end seals and the removal of sodium from the arc stream by combination with impurities in the arc tube.

When the ballast can no longer supply enough voltage to reignite the arc during each electrical half-cycle, the lamp extinguishes. When it cools down, the lamp will again ignite and warm up until the arc voltage rises so that the ballast cannot support the arc. This cycling process occurs until the lamp is replaced.

Effect of Ambient Temperature

The light output of a typical double-envelope HID arc tube is little affected by the ambient temperature. These lamps are generally satisfactory for temperatures down to − 29°C (− 20°F) or lower. On the other hand, single-envelope lamps, intended primarily for use as UV sources, are critically affected by low temperatures, particularly if the surrounding air is moving. They are not considered suitable for use below 0°C (32°F) without special protection, since they do not give full output. Ambient temperature affects the striking voltage of all discharge lamps, and in some cases higher starting voltages for indoor use are recommended for roadway and floodlighting installations in cold climates. Ballasts for roadway lighting service and other low-temperature applications are designed to provide the necessary voltage to start and operate each particular lamp at temperatures as low as − 29°C (− 20°F). Recommendations for starting voltages have been developed by ANSI.[68]

Lamp Operating Temperature

Excessive envelope and base temperatures may cause failures or unsatisfactory performance due to softening of the glass, damage to the arc tube by moisture driven out of the outer envelope, softening of the basing cement or solder, or corrosion of the base, socket, or lead-in wires. Maximum bulb and base temperatures are prescribed by various standards associations. The use of reflecting equipment that concentrates heat and energy on either the inner arc tube or the outer envelope should be avoided. In the case of metal halide and high-pressure sodium lamps in which all the material is not vaporized, concentrated heat on the arc tube can affect the color of illumination as well as electrical characteristics and lamp life.

Flicker and Stroboscopic Effect

The light output of all HID lamps varies to some degree with cyclic changes of the line voltage. This flicker depends on the lamp type and the ballast circuit. Flicker can be an important consideration for HID lamps. In many lighting applications the stroboscopic effect from HID sources is not a problem. It can, however, be annoying to spectators in games such as tennis or Ping-Pong. Operators of rotating machinery can find it distracting. To minimize the stroboscopic effect, systems with a flicker index of 0.1 or less are suggested, or luminaires can be wired alternately on different phases of a three-phase system.

Figure 6-65 illustrates the variation in flicker index for mercury, metal halide, and high-pressure sodium lamps for several ballast types operated at 60 Hz. The flicker index is considerably higher in 50-Hz power systems. The flicker effect can be effectively eliminated by using electronic ballasts having high-frequency or rectangular wave characteristics.

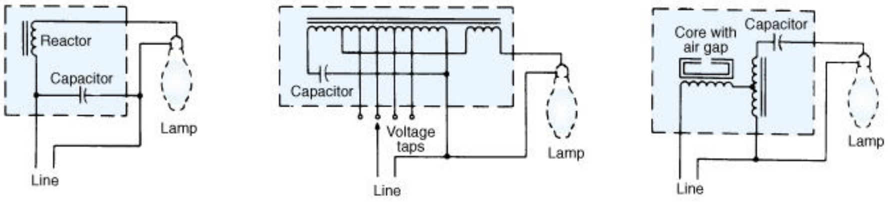
In addition to the above, some flicker sometimes can be seen from the end of the lamp when viewed peripherally by the retina (see Chapter 3, Vision and

Perception). This flicker is a result of the arc being initiated at alternate electrodes during positive and negative half cycles, and has a frequency that is equal to line frequency. It is also eliminated in high-frequency operation.

Auxiliary Equipment

HID lamps have negative volt-ampere characteristics, and therefore a current-limiting device, usually in the form of a transformer and reactor ballast, must be provided to prevent excessive lamp and line currents. The lamps are operated on either multiple or series circuits. Figure 6-66 gives schematic diagrams of several typical ballast types. Figure 6-67 summarizes the characteristics of the most common combinations of HID lamps and ballasts.

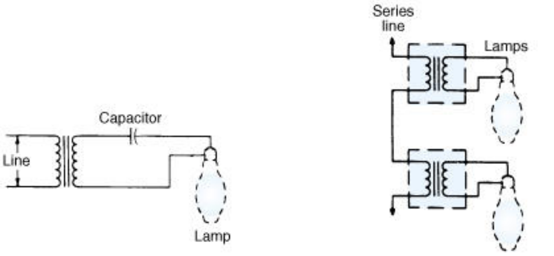
A distinction must be made between lag circuit and lead circuit ballasts. The lamp current control element of a lag circuit ballast consists of an inductive reactance in series with the lamp. The current control element in lead circuit ballasts consists of both inductive and capacitive reactances in series with the lamp; however, the net reactance of such a circuit is capacitive in mercury and metal halide ballasts, and inductive in high-pressure sodium ballasts.



(a) High power factor reactor mercury lamp ballast

(b) High power factor autotransformer mercury lamp ballast

(c) Constant wattage autotransformer ballast for mercury lamps or peak-lead ballast for metal halide lamps



(d) Constant wattage (isolated circuit) ballast for mercury lamps

(e) Constant current series regulator ballast for mercury lamps

Figure 6-66. Typical circuits for operating high-intensity discharge lamps.

Ballast/lamp	Input Power (watts)	Ballast Factor	Efficacy (lumens/ watt)	Power Factor	Current THD
Ballast for 70-W metal halide lamp	95	1	58	≥ 0.9	≤ 30%
Electronic ballast for 70-W metal halide lamp	82	0.95	64	≥ 0.9	≤ 30%
Ballast for 400-W metal halide lamp	458	1	79	≥ 0.9	≤ 30%
Ballast for 70-W high pressure sodium lamp	94	1	68	≥ 0.9	≤ 30%
Ballast for 250-W high pressure sodium lamp	300	1	87	≥ 0.9	≤ 30%
Ballast for 175-W mercury vapor lamp	205	1	39	≥ 0.9	≤ 30%

Figure 6-67. Characteristics of Common Combinations of HID Lamps and Ballasts

There are a number of ballasts in use for operating mercury lamps. Wattage losses in ballasts are usually in the order of 5 to 15% of lamp wattage.

Lag Reactor. The simplest lag circuit ballast is a reactor consisting of a single coil wound on an iron core placed in series with the lamp. The only function of the reactor is to limit the current delivered to the lamp. Such a reactor can be used only when the line voltage is within the specified lamp starting voltage range. The power factor of this circuit is approximately 50% lagging; this is commonly referred to as normal or low power factor. The line current under starting conditions is approximately 50% higher than normal operating current; therefore, it is recommended that supply wiring be sized for approximately twice the normal operating current.

High-power-factor versions are available where a capacitor is installed in the circuit to increase the power factor of the system to better than 90%. This is generally the preferred system, since it also reduces the input current under starting and operating conditions almost 50% below that of the low-power-factor system, allowing full utilization of the circuit.

Since a lag reactor performs only the function of current control, it is the smallest, most economical, and most efficient ballast. However, it has shortcomings that should be considered in application. The reactor provides little regulation for fluctuations in line voltage; for example, a 3% change in line voltage can cause a 6% change in lamp wattage. Therefore, the reactor is not recommended where line fluctuations exceed 5%.

High-Reactance Autotransformer. Where the line voltage is below or above the specified lamp starting voltage range, a transformer is used in conjunction with the reactor to provide proper starting voltage. This normally is accomplished with the combination of primary and secondary coils forming a one-piece single high-reactance autotransformer. The power factor of this circuit is approximately 50% lagging and has the same advantages and shortcomings as the normal power factor of a reactor lag circuit. High-power-factor versions are available in which a capacitor is installed in the circuit to increase the power factor of the system to better than 90%. The effect on input current is the same as in the high-power-factor reactor. Regulation and lamp performance are unchanged.

Constant-Wattage Autotransformer (CWA). This type of lead circuit ballast is the most widely used in mercury lighting systems. It consists of a high-reactance autotransformer with a capacitor in series with the lamp. The capacitor allows the lamp to operate with better wattage stability when the voltage on the branch circuit fluctuates. This ballast is used when line voltage is expected to vary by more than 5%. For example, a 10% change in line voltage would result in only a 5% change in lamp wattage. Other advantages with the CWA ballast are high power factor, low line extinguishing voltage, and line starting currents that are lower than normal line currents. The CWA ballasts allow for maximum loading on branch circuits and provide an economical and efficient mercury lighting system.

The capacitor used with the CWA ballast performs an important ballasting function, as in all lead-type circuits. The capacitor used in lag-type high-power-factor reactor and high-power-factor autotransformer ballasts is purely a power factor correction component and has no ballasting function.

Constant Wattage (CW). This type of ballast, also referred to as regulated or stabilized, has operating characteristics similar to the CWA. The light output and wattage vary less than 2% with up to a 13% change in line voltage. The CW ballast, like the CWA ballast, uses a lead circuit; it differs in that the lamp circuit is completely isolated from the primary winding. It also has the same advantages as the CWA ballast, such as high power factor, low line extinguishing voltage, and low line starting currents.

Two-Lamp Lead-Lag Circuit. The lead-lag ballast design approach is commonly used to operate two 250-, 400-, or 1000-W mercury or metal halide lamps in two independent circuits. A current-limiting reactor operates one lamp, and a combination reactor and capacitor connected in series operates the second. The lamps operate independently, so that the failure of one has no effect on the other. The input current of the combination of capacitors and reactors is lower than the sum of the two individual operating currents. These elements provide a high power factor and reduce flicker. This circuit can be used only when the line voltage is within the specified lamp starting voltage range. It is the most economical two-lamp system with regulation similar to the normal-power-factor reactor and autotransformer ballasts. A lag reactor may be used in one luminaire and a lead reactor in the next luminaire. An equal number of each in a branch circuit will result in a high branch circuit power factor.

Two-Lamp Series (Isolated) Constant Wattage. This circuit is essentially the same as single-lamp constant wattage, except that it operates two lamps in series. The most effective use of this circuit is in applications where the ambient temperature is − 18°C (0°F) or above. It is most popular for indoor 400-W applications.

Constant-Current Series Regulators. Mercury lamps also are operated in series on constant-current series regulators. The most commonly used method employs a current transformer for each lamp. It differs in design from the more common multiple type of ballast. The usual design is a two-winding transformer as illustrated in Figure 6-66e. Since the series circuit regulator reactance limits the current in the circuit, the individual lamp current transformer is not designed to limit current, but rather to transform it from the regulator secondary current to the rated lamp current. In addition, the transformer is made to limit the secondary open-circuit voltage so that no cutout is necessary when a lamp fails. Series transformers are available for the more popular lamps to operate from either 6.6-, 7.5- or 20-A series circuits and can be operated on all types of constant-current transformers. These circuits usually are satisfactory for metal halide lamps and high-pressure sodium lamps designed for operation on reactor-type mercury ballasts.

Two-Level Mercury Ballasts. Two-level operation of mercury lamps can be accomplished by switching capacitors on lead circuit ballasts. Such ballasts that operate 125-, 250- and 400-W mercury lamps at two levels are available. For example, a 400-W mercury lamp may be operated at either 400 or 300 W by switching leads at the ballast. These two-level mercury ballasts are used for energy saving. Similar designs are available for high-pressure sodium and metal halide lamps. Both lamp manufacturer and ballast manufacturer should be contacted for specific information.

This control technique is presently limited to horizontal operation above 10°C (50°F). The warmup time is 50% longer on low level.

Metal Halide Lamps. Metal halide lamps operate well on many different types of control gear. The control gear selection depends on the operating environment of the lamp and the degree of voltage regulation provided by the local utility. In the United States, the common type of control gear for lamps over 150 W is the lead peaked autotransformer. This control gear provides moderately good voltage regulation, yielding a change in lamp wattage of 7 to 10% for a line voltage change of 10%. The lead peaked autotransformer performs much like the CWA ballast and has similar operating features. In Europe and many other countries where high open-circuit voltages are available from the mains, lag-reactor ballasts plus an ignitor are more commonly used. Where voltage regulation is good, the use of lag-reactor ballasts can save significant energy over the more common multi-tap lead peaked autotransformer.

For metal halide lamps below 175 W, the most common control gear is the lag reactor or high-reactance autotransformer. Power correcting capacitors typically are employed. Using the lag reactor ballast to regulate lamp wattage causes the least line voltage variations. A 5% change in line voltage can result in a 12% change in lamp wattage. Long-term operation of lamps under high line conditions shortens lamp life. For starting, an ignitor is used that provides a high voltage-low current pulse of between of between 3 and 5 kV. There are three types of ignitors in use today. The most common is the impulser or parallel ignitor, which uses a ballast winding as the ignitor's pulse transformer. Another type is the superimposed or series ignitor, which contains a pulse transformer that is independent of the ballast windings. Finally, there is the two-wire ignitor, which provides a lower pulse voltage directly across the lamp leads.

High-Pressure Sodium Lamps. Unlike mercury and metal halide lamps, which exhibit relatively constant lamp voltage with changes in lamp wattage, the high-pressure sodium lamp voltage varies with lamp wattage. Therefore, operating parameters for maximum and minimum permissible lamp wattage and voltage have been established.[66] The latest ANSI recommendations for high-pressure sodium lamps should be followed. Figure 6-68 shows the lamp voltage and wattage limits for 400-W high-pressure sodium lamps.

Lag or Reactor Ballast. This ballast type is similar to the mercury lamp reactor ballast. It is a simple reactor in series with the lamp, designed to keep the operating characteristics within the trapezoid. A starting circuit is incorporated to provide the starting pulse. Step-up or step-down transformers are provided where necessary to match the line voltage. In most cases, a power-factor-correcting capacitor is placed across the line or across a capacitor winding on the ballast primary. This type of ballast usually provides good wattage regulation for variations in lamp voltage, but rather poor regulation for variations in line voltage. It is the least costly ballast with the lowest power loss among ballasts for high-pressure sodium lamps.

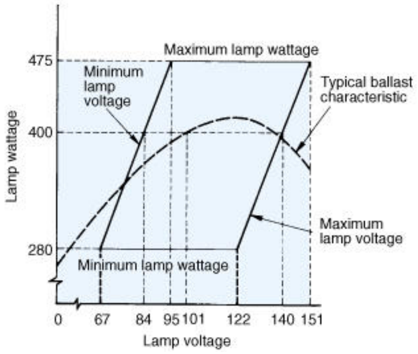


Figure 6-68. Wattage and voltage limits for 400-W high pressure sodium lamps.

Magnetic Regulator or Constant-Wattage Ballast. This ballast consists essentially of a voltage-regulating section that feeds a current-limiting reactor and the pulse starting circuit. It provides good wattage regulation for changes in line voltage, as a result of the voltage-regulating section, and good regulation for changes in lamp voltage, which is the main characteristic of the reactor ballast.

The magnetic regulator is a high-cost ballast, having the greatest power losses, but it generally provides good wattage regulation under all conditions of line and lamp voltage. A power-factor-correcting capacitor usually is included. It should be noted that this circuit differs from constant-wattage mercury ballast circuits.

Lead Circuit Ballast. This circuit is similar to that of the CWA mercury-lamp ballast. It operates with a combination of inductance and capacitance in series with the lamp. It differs in design from the CWA mercury-lamp ballast in that it does not maintain a constant lamp current but rather decreases the current as the lamp voltage increases, so as to keep the lamp operating wattage within the trapezoid limits. This ballast type provides wattage regulation for changes in both line voltage and lamp wattage. For a change of no greater than 10% in line voltage it maintains the lamp wattage within the trapezoid. It is intermediate in cost and power losses.

Ignitors. Ignitors are used in the ballast circuit for most high-pressure sodium lamps, some metal halide lamps and some specialty arc lamps. The ignitor starts cold lamps by first providing a high enough voltage for ionization of the gas to produce a glow discharge. To complete the starting process, enough power must then be provided by the starting pulses to sustain an arc through a glow-to-arc transition. The range of pulse voltages to start cold lamps is 1 to 5 kV, usually provided by an electronic resonant circuit which applies multiple pulses to the lamp when the circuit is energized. The circuit turns itself off after the lamp starts by sensing the reduction in open-circuit voltage or, with some ignitors, after a fixed period of time.

Instant restarting of hot lamps is accomplished by increased ignition voltage. Voltage pulses of 10 to 70 kV are required by most HID lamps, and these are provided by resonant circuits. To halve the voltage to ground values, ignitor circuits are available to apply opposing pulses simultaneously to the ends of the lamp. Most instant-restart lamps are of double-ended construction to minimize arc-over between lead wires, internal supports, or base contacts. These high-voltage starting pulses normally are applied in one or several short bursts, using the open-circuit voltage reduction on restart to turn off the ignitor.

Dimming of High-Intensity Discharge Lamps

Although HID lamps are optimized to operate at full power, some energy savings can be obtained through dimming. In energy management applications, savings of 50% or more might be obtained where available daylight is used with a photosensor and dimming control system. Daylight tends to compensate for the color changes of dimmed HID lamps. Additional controls for HID lighting can be employed for lumen maintenance and with time-of-day and demand reduction programs as administered by a computer or a simple time clock. Simple manual control for an HID dimming system can provide flexibility in multipurpose room applications and improved efficiency by tuning the light output for a specific task (see Chapter 27, Lighting Controls).

Some light sources are more suitable for dimming than others. Therefore, when considering a particular HID light source for dimming, it is suggested that the manufacturers of the lamp and the dimming system be contacted for information or performance characteristics in the dimmed state. In some cases, the lamp manufacturer's warranty is limited when dimming. In a properly designed dimming system, however, lamp life is unaffected by dimming.

The slow warmup and hot restrike delay, which are characteristic of HID sources, also apply to dimming. HID lamps respond to changes in dimmer settings much more slowly than incandescent or fluorescent sources; delays between minimum and maximum light output vary 3 to 10 min. Instantaneous dimming is available, however, over a limited range for some lamps.

HID lamps should be started at full power and the dimming delayed until the lamp is fully warmed up. Properly designed dimming systems ensure this occurs.

In addition to speed, the range of response is not comparable to that of incandescent or fluorescent dimming; however, in most cases the lamp efficacy and color are reasonably good down to 50% dimming or less. While not well suited to dramatic lighting or theatrical effects, they are quite satisfactory for many energy management applications. In these applications, the slow response of HID lamps provides additional system stability and minimal occupant distraction.

Typical curves of lumen output versus input power are shown in Figure 6-69. These curves describe general trends; the dimming system manufacturer should be consulted for more details.

Clear mercury lamps change very little in color from 100 to 25% light output; the blue-green color that is characteristic of clear mercury sources is present at all dimmer settings (Figure 6-70). Color-improved mercury lamps generally perform well down to approximately 30% light output.

The color appearance, color consistency from lamp to lamp, and color rendering of some clear, low-wattage metal halide lamps can begin to change at 80% lumen output. For higher wattages, the color of the clear lamps begins to change at approximately 60% light output, where a blue-green color (characteristic of mercury vapor) starts to appear. The effect is somewhat less with phosphor-coated lamps.

The color appearance of typical high-pressure sodium lamps does not appreciably change until approximately 50% light output. Below 50%, a strong yellow color, characteristic of low-pressure sodium, begins to prevail. In the case of the higher-color-rendering high-pressure lamps, the lamp manufacturer should be consulted on dimming performance.

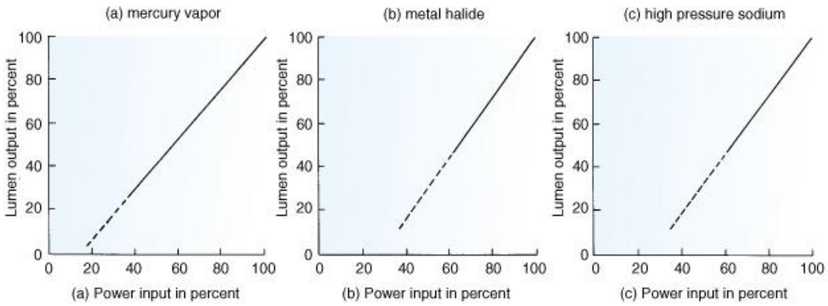


Figure 6-69. Lumen output vs. power input for high-intensity discharge lamps: (a) mercury vapor, (b) metal halide, and (c) high-pressure sodium. The dotted lines represent operating areas where significant color changes in the lamp occur.

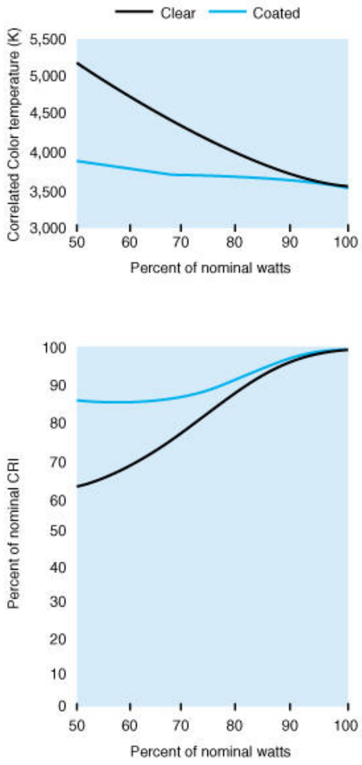


Figure 6-70. Correlated color temperature and CRI shift with dimming. Clear metal halide lamps can experience a shift in color temperature of over 1000 K and a drop of 35% in CRI when dimmed to 50% of rated output. Phosphor-coated lamps are much less vulnerable to this color shift.

Self-Ballasted Lamps

Self-ballasted mercury lamps are available in various wattages. These lamps have a mercury vapor arc tube in series with a current-limiting tungsten filament. In some types, phosphors coated on the outer envelope provide additional color improvement. The overall efficacy is lower than that of other mercury lamps because of the resistive losses of the tungsten filament. As the name denotes, these lamps do not require an auxiliary ballast.

SHORT-ARC LAMPS

Short-arc or compact-arc lamps characteristically provide a source of very high luminance. They are primarily used in searchlights, projectors, display systems and optical instruments (e.g., spectrophotometers and recording instruments) and for simulation of solar radiation. They also can be used as sources of modulated light, generated through current modulation.

Short-arc lamps are high-pressure gas discharge lamps characterized by an electrode-stabilized arc that is short compared with the size of the envelope. Depending on rated wattage and intended application, their arc length may be from about 0.01 to 0.47 in. (0.3 to 12 mm). These arcs have the highest luminance and radiance of any continuously operating light source and are the closest to being a true point source.[69-82]

Some typical short-arc lamps are shown in Figures 6-71 and 6-72. These lamps have optically clear fused silica (quartz) bulbs of spherical or ellipsoidal shape with two diametrically opposite seals. Four types of seal are used in short-arc lamps. The graded seal and the molybdenum foil seal are current-carrying seals, while the molybdenum-and-Kovar cup seal and the elastomer (mechanical) seal are separated from the current conductor by a cup or a flange. For applications requiring ozone-free operation, the lamp envelopes are fabricated from quartz, which does not transmit wavelengths below 210 nm.

Most short-arc lamps are designed for dc operation. The better arc stability and substantially longer life of the dc lamps have limited the use of ac short-arc lamps to special applications.

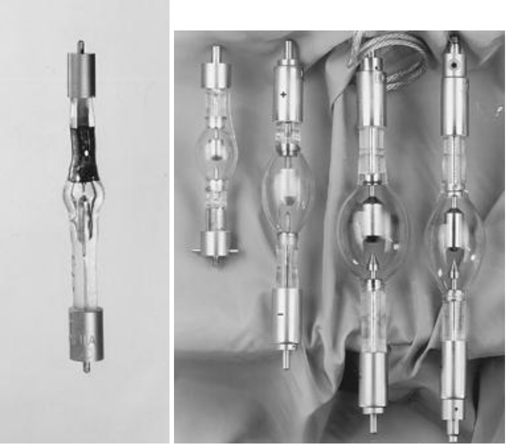


Figure 6-71. Typical short-arc lamps: (a) low-wattage mercury-argon lamps (100-W at left, 200-W at right), and (b) medium-wattage xenon lamps (from left: 1.6, 2.2, 4.2, 3.0 kW).

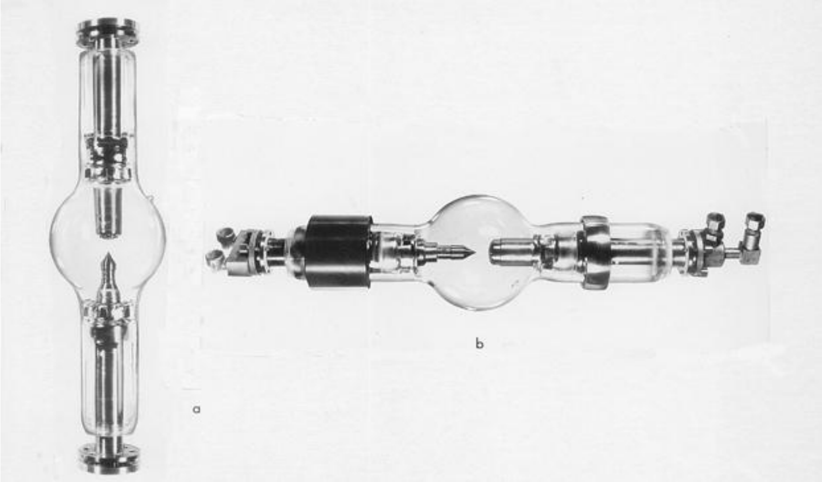


Figure 6-72. Typical high-power xenon compact arc lamps with liquid-cooled electrodes: (a) 30-kW lamp for solar simulators (principal operating position is vertical), and (b) 20-kW lamp for military searchlights (principal operating position is horizontal).

Starting of Short-Arc Lamps

Like most vapor discharge lamps, short-arc lamps require auxiliary devices to start the arc and limit the current. For ac lamps, either resistive or inductive ballasts are used. Direct-current lamps are best operated from specifically designed power systems that provide, with good efficiency, the high-voltage pulses (up to 50 kV) required to break down the gap between the electrodes, ionize the gas, and heat the cathode tip to thermionic emitting temperatures. Further, they provide enough open-circuit dc voltage to assure the transition from the low-current, high-voltage spark discharge initiated by the starter to the high-current, low-voltage arc. With a properly designed system, a short-arc lamp will start within a fraction of a second. Many power supplies are regulated so that lamp operation is independent of line voltage fluctuation. Four basic types of sensors for power regulation are presently in use: current, voltage, power, and optical regulators. The type of power system used depends on the specifics of the application.

Mercury and Mercury-Xenon Lamps[69,70,72,76]

To facilitate lamp starting, short-arc mercury lamps contain argon or another rare gas at pressures of 1 to 4 kPa (0.15 to 0.58 lb/in.^{2}), the same as standard mercury lamps. After the initial arc is struck, the lamp gradually warms up, and the voltage increases and stabilizes as the mercury is completely vaporized. Mercury lamps require several minutes to achieve full operating pressure and light output. This warmup time is reduced by approximately 50% if xenon at greater than atmospheric pressure is added to the mercury. Lamps with this type of fill are known as mercury-xenon short-arc or compact-arc lamps. The spectral power distribution in the visible region is essentially the same for both types, consisting mainly of the five mercury lines and some continuum due to the high operating pressure (Figure 6-73). The luminous efficacy of these lamps is approximately 50 lm/W at 1000 W and approximately 55 lm/W at 5000 W. Mercury and mercury-xenon lamps are available from 30 to 7000 W and are usually operated in the vertical position.

Xenon Lamps[71,74-82]

Xenon short-arc lamp are filled with several atmospheres of xenon gas. They reach 80% of the final output immediately. The CCT of the arc is approximately 5000 K. The spectrum is continuous from the UV through the visible into the infrared (Figure 6-74). Xenon lamps exhibit strong emission lines in the near infrared between 800 and 1000 nm and some weak lines in the short-wavelength visible region.

Xenon short-arc lamps range from 5 to 32,000 W, and they are available for operation in vertical or horizontal positions. Lamps designed for operation above 10 kW typically require liquid cooling of the electrodes. The luminous efficacy of the xenon short-arc lamp is approximately 30 lm/W at 1000 W, 45 lm/W at 5000 W, and over 50 lm/W at 20 kW and above.

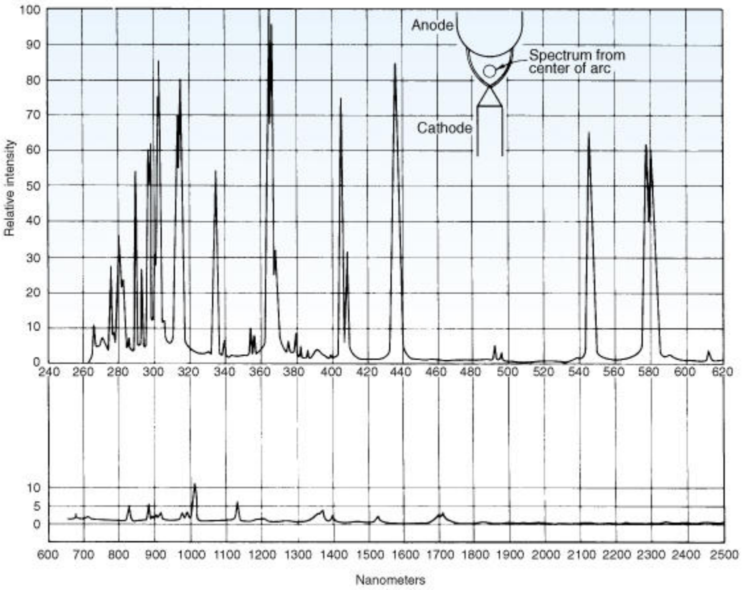


Figure 6-73. Spectral power distribution of a 2.5-kW mercury-xenon lamp from 240 to 2500 nm.

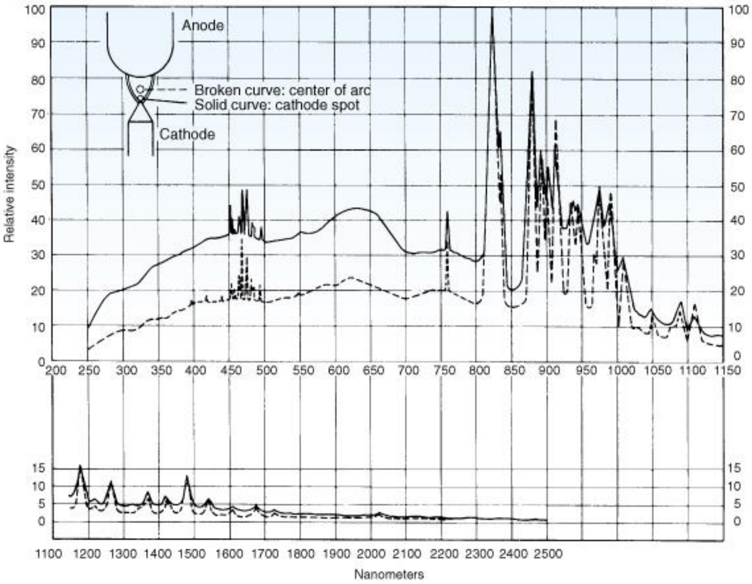


Figure 6-74. Spectral power distribution of a 2.2-kW xenon lamp from 200 to 2500 nm.

Ceramic Reflector Short-Arc Xenon Lamps

Ceramic reflector xenon (CRX) lamps combine the basic technology of short-arc lamps and an internal reflector that focuses the arc's energy through a sapphire window in the ceramic-to-metal housing. The window transmits energy in both the IR and UV regions of the spectrum. These devices have the advantages of increased output, safety, and ease of handling and installation. They also obviate some peripheral equipment such as optical focusing components needed in many applications where short-arc lamps are used. CRX lamps are available with inputs from 175 to 1000 W. Their spectral power distributions can be varied for special applications by altering the reflector material or its coating.

Lamp Operating Enclosure

Short-arc mercury, mercury-xenon, and xenon lamps are under considerable pressure during operation (up to 5000 kPa [726 lb/in.^{2}] for small lamps and approximately 1000 kPa [145 lb/in.^{2}] for large ones) and therefore must be enclosed during operation. In addition, precaution must be taken to ensure protection from the powerful UV radiation emitted from these lamps. See Chapter 5, Nonvisual Effects of Optical Radiation.

In general, short-arc lamps up to approximately 1 kW are designed to operate with convection cooling. Special ventilation is not required unless critical components of the lamps are subjected to excessive temperatures, caused by confined enclosures, excessive ambient temperatures, or infrared radiation.

For safety during shipment, storage, or handling of xenon or mercury-xenon lamps, special protection cases are provided. These cases are made of metal or plastic and are so arranged around the bulb that the lamp can be electrically connected without removing the case. The case should not be removed until immediately before the lamp is energized.

Compact-Source Metal Halide Lamps

Compact-source, or medium-arc, metal halide lamps[83,84] are based on a combination of the short-arc lamp and the metal halide lamp technology. Their arc discharge is predominantly electrode stabilized and operates between tungsten electrodes spaced 2.5 to 35 mm (0.1 to 1.4 in.) apart in ellipsoidal or almost spherical quartz bulbs. They are filled with mercury and argon as basic elements for starting the arc, and, as in some standard metal halide lamps, rare-earth metal iodides and bromides are added in order to obtain a broad spectral power distribution. Both a high luminous efficacy and excellent color rendering with a correlated color temperature close to that of daylight are achieved, together with a small source size.

These lamps are available in various single-ended and double-ended constructions typically ranging from 70 to 1800 W. In special cases, higher wattages (up to 18,000 W) may be achieved. They typically are designed to operate on alternating current and require unique power supplies or ballasting equipment with high-voltage starting devices. Most lamps can be instantly restarted when hot.

Some lamps are available with the arc tubes mounted in integral ellipsoidal reflectors that can focus the light through small apertures or fiber-optic bundles. Other lamps are available in PAR configurations for applications that require concentrated beams.

Compact-source lamps are used for motion picture and television lighting, outdoor location lighting, theatrical lighting, sports lighting, fiber-optic illuminators, liquid crystal displays (LCD), and video projectors. If used in projectors, careful attention must be given to the modulation if the lamp output and the projector's shutter speed (frame rate) to avoid unintentional stroboscopic effects.

MISCELLANEOUS DISCHARGE LAMPS

Low-Pressure Sodium Lamps

In low-pressure sodium discharge lamps, the arc is carried through vaporized sodium. The light produced by the low-pressure sodium arc is almost monochromatic, consisting of a double line at 589.0 and 589.6 nm. The starting gas is neon with small additions of argon, xenon, or helium. In order to obtain the maximum efficacy of the conversion of the electrical input to the arc discharge into light, the vapor pressure of the sodium must be approximately of 0.7 Pa ($1/10^{-4}$ lb/in.^{2}), which corresponds to an arc tube bulb wall temperature of approximately 260°C (500°F). Any appreciable deviation from this pressure degrades the lamp efficacy. To maintain the operating temperature for this pressure, the arc tube is normally enclosed in a vacuum flask or in an outer bulb at high vacuum.

The run-up time to full light output is 7 to 15 min (Figure 6-75). When first started, the light output is the characteristic red of the neon discharge, and this gradually gives way to the characteristic yellow as the sodium is vaporized. The hot re-ignition is good, and most low-pressure sodium lamps restart immediately after interruption of the power supply.

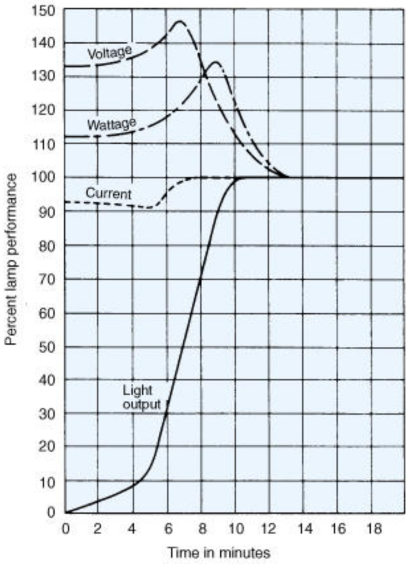


Figure 6-75. Low pressure sodium lamp performance during starting.

Efficacy. Low current density is vital to efficient generation of light. High densities result in excitation of atoms to higher energy levels and thus a loss of efficacy in converting electricity to light. Thermal insulation increases efficacies to above 180 lm/W for the 180-W U-type low-pressure sodium lamp, or approximately 150 lm/W including ballast losses. The thermal insulation consists of a light-transparent, IR-reflecting layer on the inside of the outer envelope. It is generally made of indium oxide; previously tin oxide and internal glass sleeves were used.

Construction. There are two types of low-pressure sodium lamps: the linear and the hairpin, or U tube. The linear lamp has a double-ended arc tube, similar to a fluorescent lamp, with preheat electrodes sealed into each end. Its arc tube, made of a special sodium-resistant glass, is sealed into an outer vacuum jacket with a medium bipin base at each end.

The hairpin type has the arc tube double back on itself, with its limbs very close together (Figure 6-76). Two versions are available, based on different approaches to maintaining even distribution of sodium in the arc tube throughout life. Excess metallic sodium condenses at the coolest part of the lamp, generally at the bend of the arc tube. If not controlled, very low sodium concentrations will produce a neon-argon arc in the tube. This is known as "operating bare."

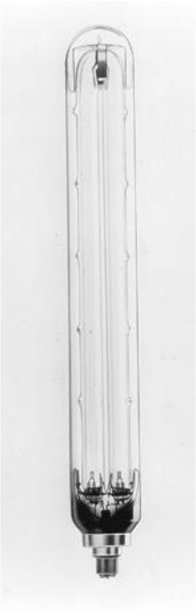


Figure 6-76. Construction of low pressure sodium lamps (U-tube or hairpin type).

One hairpin design provides dimples in the outer surface of the arc tube; these serve as alternative cool points for the metallic sodium condensation. The dimples also inhibit migration of sodium due to vibration or gravitational effects. The alternative design uses a graded heat-reflecting film along the inside of the outer envelope, with the greatest amount of reflected heat at the bend.

Auxiliary Equipment. The low-pressure sodium arc, in common with all discharge lamps, has a negative volt-ampere characteristic. A current-limiting device, usually a transformer and reactor ballast, must be provided to prevent excessive lamp and line currents.

High-power-factor autotransformer ballasts are most commonly used. The required lamp starting voltages ranging between 400 and 550 V. A capacitor wired in parallel on the primary side increases the power factor to 90% or better. On this type of ballast, lamp regulation is excellent: lamp wattage and lumen output remain within 5% for a varying line voltage range of 20%. Constant-wattage ballast designs are also available.

Glow Lamps

These are low-wattage, long-life lamps designed primarily for use as indicator or pilot lamps, night lights, location markers, and circuit elements. They range from 0.06 to 3 W and have an efficacy of approximately 0.3 lm/W. A group of typical glow lamps is shown in Figure 6-77. These emit light having the spectral character of the gas with which they are filled. The most commonly used gas is neon, having a characteristic orange color. The glow is confined to the negative electrode. Glow lamps have a critical starting voltage, below which they are, in effect, an open circuit.

Figure 6-77. Typical glow lamps with ANSI numbers (old trade numbers).

Like other discharge lamps, glow lamps require a current-limiting resistance in series. Glow lamps with screw bases have this resistor built into the base, while for unbased lamps or lamps with bayonet bases a resistor of the proper value must be employed external to the lamps.

Glow lamps filled with an argon mixture rather than neon radiate chiefly in the near UV region around 360 nm and are therefore used mainly to excite fluorescence in minerals and other materials as well as for some photographic applications.

Zirconium Concentrated Arc Lamps, Enclosed Type

These lamps use a direct-current arc constituting a concentrated point source of light of high luminance, up to 45 million cd/m^2. They are made with permanently fixed electrodes sealed into an argon-filled glass bulb. The light source is a small spot, 0.13 to 2.8 mm (0.005 to 0.11 in.) in diameter (depending on the lamp wattage), which forms on the end of a zirconium oxide-filled tantalum tube that serves as the cathode. The spectral power distribution is similar to that of a blackbody with a correlated color temperature of 3200 K. These lamps produce a candela distribution characterized by the cosine law. They require special circuits that generate a high-voltage pulse for starting and a well-filtered and ballasted operating current. Suitable power supplies are recommended by the manufacturer. Figure 6-78 illustrates various examples of side- and end-emission lamps.

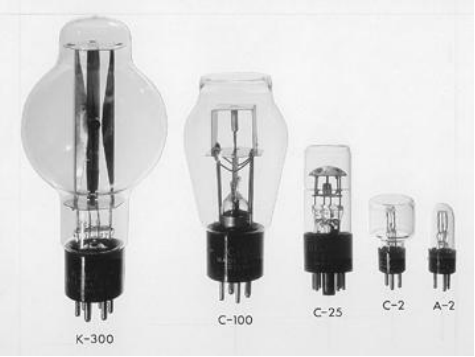


Figure 6-78. Side and end-emission concentrated arc lamps.

Pulsed Xenon Arc (PXA) Lamps

These are ac xenon lamps with two active electrodes (a polarized xenon lamp has current flowing in only one direction and one active electrode). A switching reactor in series with the low-pressure lamp forces 50 to 100 peak amperes (120 pulses per second) through the lamp. The reactor also supplies a continuous current of 2 to 3 A to keep the lamp operating between pulses. The spectrum produced is characteristic of xenon, typically 6000 K. PXA lamps are available in linear and helical types.

The efficacy of these sources is approximately 35 to 40 lm/W. Available lamp wattages range from 300 to 8000 W, and forced-air cooling is required during operation.

PXA lamps are used in the graphic arts industry for applications requiring instant start; high-intensity, stable light output; and daylight-quality color temperature.

Flashtubes

These light sources are designed to produce high-intensity flashes of extremely short duration. They are primarily used for photography; viewing and timing of reciprocating and rotating machinery; airport approach lighting systems, including navigation aids, obstruction marking, and warning and emergency lights; laser pumping; and entertainment applications.

A conventional flashtube consists of a transparent tubular envelope of glass or fused silica (quartz) that has its main discharge electrodes internally located near the extremities and usually has an external electrode of wrapped wire for triggering. It generally contains very pure xenon gas at a pressure below atmospheric, usually in the range of 25 to 80 kPa (3.63 to 11.6 lb/in.^{2}). Sometimes other gases such as argon, hydrogen, and krypton are added to the xenon to obtain different spectral power distributions or different electrical, thermal, and deionization characteristics. With a voltage applied across its main electrodes, the tube acts as a high impedance or open circuit until a trigger pulse ionizes the gas within the tube. A trigger pulse induces ionization and thereby causes the xenon gas to become conductive. A discharge then occurs between the main electrodes, whereupon the gas becomes highly luminescent.

A xenon flashtube converts up to 35% of the input energy to light. The luminous efficacy ranges from 30 to 60 lm/W. The spectral quality is close to that of daylight, having a correlated color temperature of approximately 6000 K, so that the radiation encompasses the entire visible spectrum and extends into the UV and near IR (Figure 6-79). Flashtubes are available in many sizes and shapes to suit the user and the type of optical system employed. The most common types are straight (linear), wound (helix), and U shape. Other configurations are available for special applications. Figure 6-80 shows some typical commercially available flashtubes.

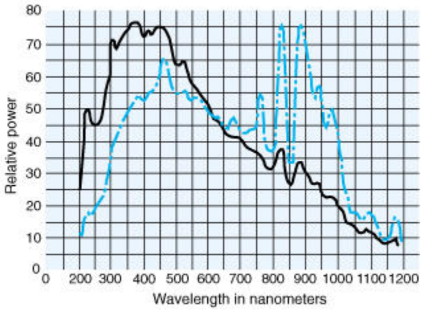


Figure 6-79. Spectral power distribution of a typical xenon-filled flashtube for two different discharge conditions: (a) high voltage, low capacitance (solid line), and (b) low voltage, high capacitance (dashed line).

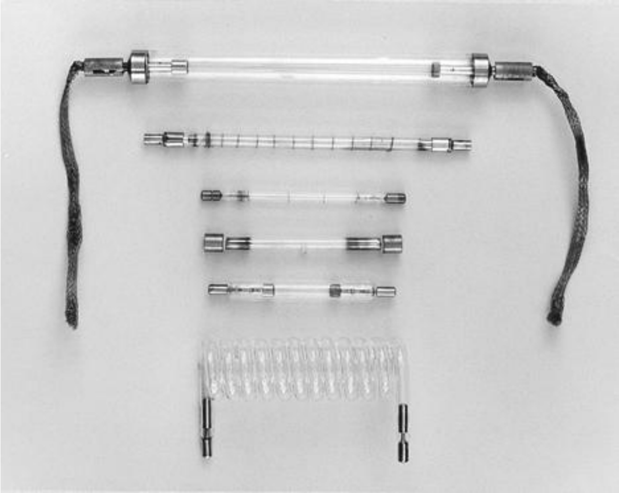
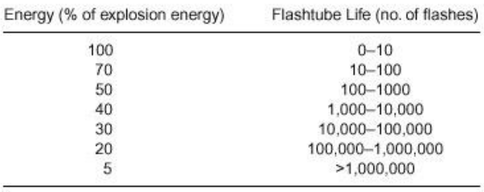


Figure 6-80. Typical flashtubes.

Energy and Life. For single-flash operation the limit to the amount of energy that can be consumed depends on the desired tube life measured in useful flashes. This life is affected by the rate of envelope wall blackening and destruction of the tube or its parts. Flashtubes designed for very high loading have envelopes made of fused silica, which can withstand high thermal shock. The peak power encountered during a discharge produces a thermal shock that could shatter the envelope; hence, to maximize the energy per flash the thermal shock must be limited. This can be done by reducing the peak current, which also lengthens the flash duration. To limit peak current and thermal shock as well as control the pulse duration, inductance is added in series within the discharge loop.

Normally, the life expectancy of a flashtube can be related to the percentage of explosion energy expended by a flash in a particular application. The explosion energy is defined by manufacturers as the energy level at a given flash duration that will cause the tube to fail within ten flashes, usually by disintegration of the envelope. The life can be approximated as follows:



Energy (% of explosion energy)	Flashtube Life (no. of flashes)
100	0–10
70	10–100
50	100–1000
40	1,000–10,000
30	10,000–100,000
20	100,000–1,000,000
5	>1,000,000

Limits of Power Input. The average power input is a product of the energy per flash and the flash rate. The maximum power that any flashtube can dissipate is determined by the envelope area, the type of envelope material, and the method of cooling, such as free air convection, forced air convection, or use of a liquid coolant. For fused silica envelopes the maximum input power can be approximated as follows: free air convection, 5 W/cm^2 (32.3 W/in.^{2}); forced air convection, 40 W/cm^2 (258 W/in.^{2}); liquid cooling, 200 W/cm^2 (1290 W/in.^{2}).

Energy Storage Banks. The electrical energy that subsequently is discharged through the flashtube to produce light is stored in a capacitor bank. This bank must be capable of rapid discharge into a very low impedance load. Therefore, it must have a rather low inductance as well as a very low equivalent series resistance. It must also be capable of storing energy at a high voltage without significant leakage. Typical voltages vary from about 300 to 4000 V. Current banks use aluminum electrolytic, paper-oil or metalized paper capacitors designed specifically for energy storage applications. All are highly efficient in delivering energy to the flashtube. The type selected depends upon the voltage, temperature, and life, as well as size and weight limitations.

Electronic Circuitry. In addition to discharge circuitry, a conventional xenon flash system has a charging circuit and a trigger circuit (Figure 6-81). The charging circuit accepts primary electrical power at low voltage, transforms and rectifies it to higher voltage, and applies it to the capacitor bank, where it is stored as potential energy. The luminance of the flashtube depends upon its loading, which in turn depends on the capacitance of the energy storage capacitor and the voltage across it, in accordance with the formula:

$$\text{loading in joules} = CV^2$$

where

C = capacitance in µF
V = voltage across the tube (and capacitor) in kV.

The trigger circuit used for producing the high-voltage ionizing pulse consists of a low-energy capacitor discharge system driving a pulse transformer. The pulse transformer establishes an electric field that starts the ionization process and causes the gas to conduct. This pulse usually is applied to the external trigger wire (external electrode), but in some applications it is applied across the main discharge electrodes by a pulse transformer with a very low secondary impedance in series with the flashtube discharge circuit.

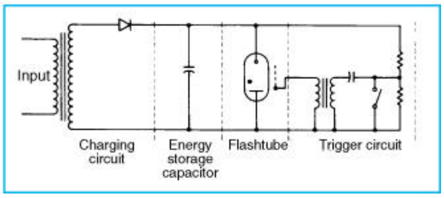


Figure 6-81. Basic elements of a typical flashtube power supply.

By varying the voltage to the capacitor bank and hence its capacitance, and by the insertion of inductance in the discharge circuit, it is possible to vary both the light output and the flash duration of the system. The flash duration is dependent on the value of the capacitor, the inductance of the discharge circuit, and the effective impedance of the flashtube. Although the flashtube is a nonlinear circuit element, its effective impedance can be approximated according to the formula:

$$\text{flashtube impedance} = \rho L/A$$

where

ρ = plasma impedance in $\Omega \times$ cm,
L = arc length in cm,
A = cross-sectional area of the arc in cm^2.

At current densities encountered in usual practice, ρ has a value of approximately 0.02 Ω-cm.

Flashtubes with their associated circuitry can be designed to operate with flash energies from fractional watt-seconds to 20,000 watt-seconds, with durations from approximately one microsecond to many milliseconds, and with repetition rates from a single flash up to 1000 flashes per second. Even higher repetition rates can be attained with special circuitry and flashtube design.

Linear-Arc Lamps

Linear-arc quartz envelope lamps are available for both continuous wave and pulsed operation. Lamps operated in the pulsed mode are discussed above under flashtubes. Forced-air-cooled long-arc xenon lamps are made with arc lengths up to 1.2 m (4 ft), bore diameters up to 12 mm (0.47 in.), and wattages up to 6 kW. These lamps are used for special illumination requirements and solar simulation and have an efficacy of approximately 30 lm/W.

Water-cooled long-arc xenon and krypton lamps are made with arc lengths up to 0.3 m (1 ft.), bore diameters up to 10 mm (0.39 in.) and wattages up to 12 kW. Their main application is for laser pumping; krypton arc lamps are especially suitable for pumping neodymium-doped yttrium-aluminum garnet (Nd:YAG) lasers.

Forced-air-cooled mercury and halide-doped long-arc lamps are available in lengths up to 1.2 m (4 ft), bore diameters up to 10 mm (0.39 in.), and wattages up to 5 kW. They are used for UV photochemical applications, including the curing of paints, varnishes, and coatings.

Mercury capillary lamps are made with arc lengths up to 150 mm (6 in.), bore diameters from 0.08 in. (2 mm), and wattages up to 6 kW. They are used for UV photoexposure in the semiconductor and other industries. They are also finding use in the rapid thermal processing of silicon wafers.

All linear arc lamps use special ballasts and high-voltage starting devices. Manufacturers' recommendations for operation should be carefully followed.

ELECTROLUMINESCENT LAMPS[85-88]

An electroluminescent lamp is a thin (typically less than 1.2 mm [0.05 in.]), flat-area source in which light is produced by a phosphor excited by a pulsating electric field. These lamps are used in decorative lighting, instrument panels, switches, emergency lighting and signs, and for backlighting liquid crystal displays (LCDs).

An electroluminescent lamp is a plate capacitor with a phosphor embedded in its dielectric and with one or both of the electrode plates translucent or transparent (Figure 1-20). Green, blue, amber, yellow, or white light is produced by choice of phosphor. The green phosphor has the highest luminance. Lamps are available in rigid ceramic or flexible plastic and are easily fabricated into simple solid or complex multisegmented shapes in lengths as long as 1500 ft. The lamps have thin profiles, light weight, and generate little heat. Some can operate in exterior conditions from −40°C to 121°C (− 40°F to 250°F).

The longevity of these lamps depends on isolating the plates and dielectric from humidity during manufacture and use. Their luminance varies with applied voltage, frequency, temperature, and time as well as with the type of phosphor and lamp construction. Electroluminescent lamps can be dimmed. The relationship between voltage and luminance for ceramic and plastic electroluminescent lamps is shown in Figure 6-82. Unlike that of some light sources, the color does not change as the voltage is increased or decreased. At 120 V, 60 Hz, the luminance of the ceramic form with the green phosphor is approximately 0.33 cd/ft^2 (3.5 cd/m^2); the luminance of the plastic form can be as high 2.5 cd/ft^2 (27 cd/m^2) under these conditions, or up to 11.6 cd/ft^2 (125 cd/m^2) at 120 V, 400 Hz. With the ceramic form at 600 V, 400 Hz, a luminance of 6.5 cd/ft^2 (70 cd/m^2) has been achieved.

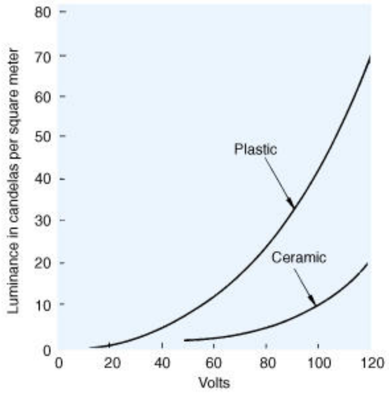


Figure 6-82. Luminances of green ceramic and plastic electroluminescent lamps operated at 400 Hz as a function of voltage.

Electroluminescent lamps have long life and low power requirements. They usually do not fail abruptly, and because of this, useful life is taken as the number of operating hours after which luminance falls below a specified level. Some electroluminescent lamps using long-life phosphor have operated continuously for more than ten years while powered at 115 V, 400 Hz. The number of operating hours after which the luminance falls to 50% of initial has been used for comparing lamp performance, but this can vary greatly depending on the drive voltage and frequency and the type of phosphor used (Figure 6-83). The value of the time to half luminance for flexible-type lamps operated at 115 V, 400 Hz can vary from 1000 to 30,000 h, depending on the type of phosphor. Typical initial current and power at these parameters are 1.2 mA and 40 mW/in.^{2}

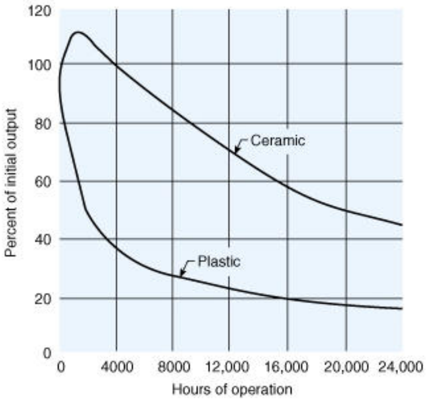


Figure 6-83. Light output versus hours of operation for green ceramic and plastic electroluminescent lamps.

The types of electroluminescent devices explained above require high-voltage drivers, which could be a negative feature for use in certain applications. A new type of electroluminescent material known as light emitting polymer (LEP) that operates at low voltage was discovered in 1990. LEPs are organic semiconducting materials that exhibit light emitting characteristics similar to conventional inorganic semiconductors such as light emitting diodes (LEDs) (see section below). In addition, they possess the desirable processing and mechanical characteristics of plastics. A key feature of LEP is that it emits light in a way that is similar to conventional LEDs; in addition, the emitted light can be patterned like LCDs. Therefore, this technology lends itself to the creation of ultrathin lighting displays that operate at low voltage. LEP technology is still in its infancy. Monochromatic devices that are suitable for small display lighting, such as digital readouts on electronic devices, are beginning to emerge commercially.

LIGHT-EMITTING DIODES

AlInGaP and InGaN Light-Emitting Diodes[89-96]

Aluminum indium gallium phosphide (AlInGaP) and indium gallium nitride (InGaN) are the two most common light emitting diode (LED) technologies, displacing older gallium arsenide phosphide (GaAsP), gallium phosphide (GaP), and aluminum gallium arsenide (AlGaAs) LEDs. The following is an overview of these technologies from the perspective of illuminating engineering. Additional information is available for AlInGaP LEDs (References 89-92) and InGaN LEDs (References 93-94), and for LEDs in general (References 95-96). Details on the physics of LEDs is available in Chapter 1, Light and Optics.

Intensity and Color

Manufacturers commonly test and bin each LED for luminous intensity and color. Like incandescent reflector lamps, the luminous intensity of LED devices is specified in terms of its beam angle. However, LED manufacturers refer to this as the viewing cone angle or the $2\theta_{\_\_12\_\_}$ angle (in degrees). Typically, all LEDs within a bin do not vary in luminous intensity by more than an factor of two. Because of the difficulty in measuring luminous intensity accurately, there is an expected 10% overlap between adjacent bins.

The color of an LED device is specified in terms of the dominant wavelength emitted, λ_d (in nanometers). Amber AlInGaP and InGaN blue and blue-green LEDs are binned by dominant wavelength, λ_d. Mixing two color bins in the same pixel matrix can produce an uneven color appearance and is not recommended. Dominant wavelengths for the colors produced by AlInGaP and InGaN LED devices are plotted on the 1931 CIE chromaticity diagram, shown in Figure 6-84. AlInGaP LEDs produce the colors red (626 to 630 nm), red-orange (615 to 621 nm), orange (605 nm), and amber (590 to 592 nm). InGaN LEDs produce the colors green (525 nm), blue green (498 to 505 nm), and blue (470 nm).

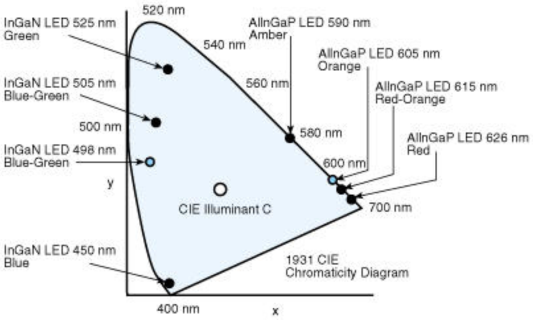


Figure 6-84. Dominant wavelengths, λ_d (nm), plotted on the 1931 CIE Chromaticity Diagram.

Typical spectral half-bandwidths are usually specified on LED lamp data sheets as $\Delta\lambda_{1/2}$. For AlInGaP LEDs, the typical half-bandwidth is approximately 17 nm, and for InGaN LEDs it is approximately 35 nm.

The luminous intensity, color, and forward voltage of AlInGaP LEDs are affected by the temperature of the LED p-n junction. As the temperature of the LED p-n junction increases, the luminous intensity decreases, the dominant wavelength shifts towards longer wavelengths, and the forward voltage drops. The variation in luminous intensity of InGaN LEDs with operating ambient temperature is small (about 10%) from − 20°C to 80°C. The small variations are not readily visible and need not be taken into account for most applications. The dominant wavelength of InGaN LEDs does vary with LED drive current; as the LED drive current increases, dominant wavelength moves toward shorter wavelengths.

Dimming

LEDs may be dimmed to 10% of maximum by reducing the drive current and still have even luminous intensity across an LED matrix. Pulse width modulation (PWM) is the preferred method for dimming LEDs. LEDs may be dimmed to 0.05% of maximum by using PWM. With PWM, the peak pulse current and the pulse rate remains constant while the duration of the on-time pulse is shortened.

Reliability

The rated maximum junction temperature (T_{JMAX}) is the most critical parameter on an LED device data sheet. Temperatures exceeding this value usually result in catastrophic failure of a plastic encapsulated LED device. T_{JMAX} is actually a limitation related to packaging rather than to the LED chip.

Lamp life for LED devices is based on the mean time between failures (MTBF). MTBF is determined by operating a quantity of LED devices at rated current in an ambient temperature of 55°C and recording when half the devices fail.

Lumen depreciation for AlInGaP LED devices is shown in Figure 6-85. The dotted line is an extrapolation from currently available data. The same information for InGaN LED devices is shown in Figure 6-86. Fewer data are available for this technology, and those data were collected at 25°C (77°F). The dotted line is extended for currently available data.

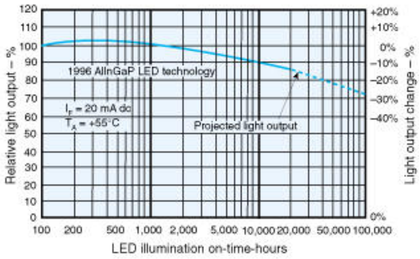


Figure 6-85. Projected long-term light output degradation for AlInGaP LED technology at 55¡C.

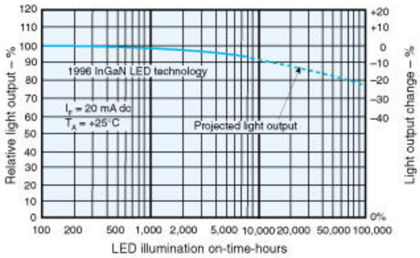


Figure 6-86. Projected long-term light output degradation for InGaN LED technology at 25¡C.

AlInGaP and InGaN LED Package Configurations

Amber, orange, and red AlInGaP plastic T-1 3/4 LED lamps (Figure 6-87a) with circular radiation patterns have been the preferred package for high-luminance applications such as traffic signals, variable message signs, commercial advertising signs, and EXIT signs. InGaN blue-green plastic T-1 3/4 LED lamps are used in green traffic signals. InGaN blue and green and AlInGaP amber and red plastic T-1 3/4 oval LED lamps with elliptical radiation patterns are used in color graphical commercial LED advertising signs and large scale outdoor full color video displays. Higher intensity AlInGaP amber and red LEDs (Figure 6-87b) were designed primarily for automotive exterior lighting, such as tail lights and turn signals. Now other high-luminance designs are incorporating these LED devices. New plastic package configurations (Figure 6-87c) incorporating both AlInGaP and InGaN LED devices, have been designed to illuminate large areas.

AlInGaP amber and red plastic LED surface mount (SMT) emitters (Figure 6-88a and b) are popular on PC board assemblies. The brightness of chip LED devices is low and useful only for applications where the ambient light level is also low. The subminiature LED devices provide higher brightness and can be used in more applications.

White LED Devices

Efforts have been undertaken to develop LED devices that produce white light. One method is to combine red, green, and blue LED chips in the same package to produce white light. However, individuals with color deficiencies may not see the emitted light as white.

Recently InGaN LED devices have been combined with photoluminescent phosphors (see Chapter 1, Light and Optics, for information on photoluminescence). The short-wavelength energy from the InGaN LED device induces fluorescence in the phosphor that is encapsulated in the epoxy surrounding the LED chip. The photoluminescent phosphor emits a broad spectral distribution, which in combination with the spectrum of a blue LED, produces a blue-white color (Figure 6-89). Color deficient individuals will still see the combined spectral distribution as blue-white light.

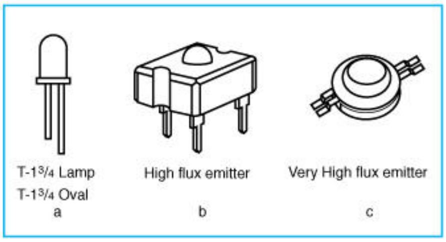


Figure 6-87. Plastic package high-performance LED devices.

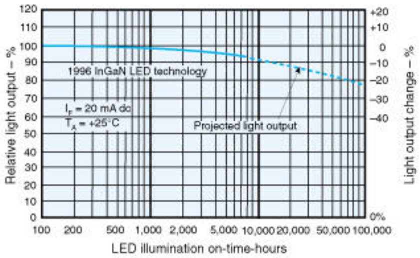


Figure 6-86. Projected long-term light output degradation for InGaN LED technology at 25¡C.

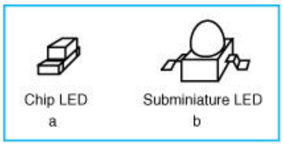


Figure 6-88. Plastic package surface-mount (SMT) LED devices.

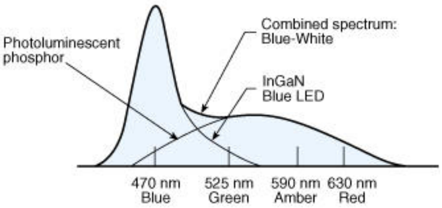


Figure 6-89. Spectral distribution of a blue-white LED/photoluminescent phosphor device.

Photometric and Electrical Characteristics of LEDs

Because they are highly directional light sources, LEDs often are specified in terms of their peak intensity, in millicandelas (mcd). Depending on their viewing cone angle, peak intensities of high-output AlInGaP LEDs range from 100 to 650 mcd for red lamps, and from 120 to 1100 mcd for amber ones. Blue InGaN LEDs with narrow viewing cone angles can have peak intensities greater than 500 mcd.

Typical operating voltages for LEDs can range from 1.5 to 4 V. With a typical current of 20 mA, the input power of a single LED can range from approximately 0.03 to 0.08 W. A single red traffic signal head might contain from 20 to 200 individual LED components and have an input power of 10 to 15 W.

Luminous efficacy of LEDs is defined as the emitted luminous flux (in lm) divided by the emitted radiant power (in W). This is commonly called internal efficacy. Using this definition, blue LEDs can have a rated internal efficacy in the order of 75 lm/W; red LEDs, approximately 155 lm/W; and amber ones, 500 lm/W. Taking into consideration losses due to internal re-absorption, the luminous efficacy is on the order of 20 to 25 lm/W for amber and green LEDs. This definition of efficacy is called external efficacy and is analogous to the definition of efficacy typically used for other light source types. See Chapter 1, Light and Optics, for definitions of these terms most relevant to illuminating engineering.

LASERS

The word "laser" is an acronym for "light amplification by stimulated emission of radiation." Invented in 1960, a laser is a device that concentrates light waves on an intense, low-divergence beam. Even though the light source is an inefficient converter of electrical energy to light energy, a single laser becomes incredibly efficient when applied to a very large-scale lighting requirement (Figure 6-90).

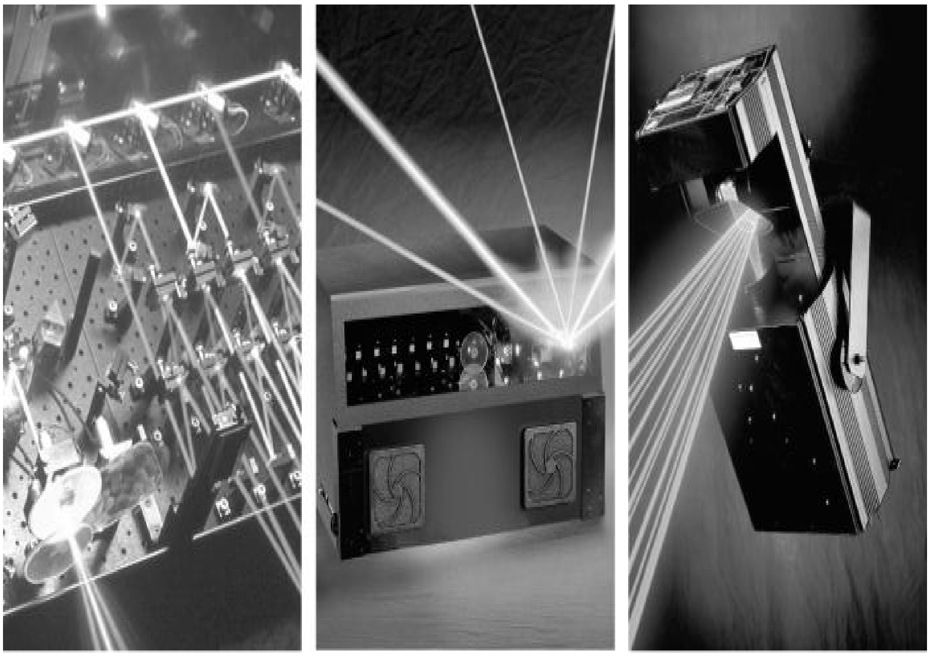


Figure 6-90. Laser display equipment (left, optical components; center, laser head; right, display unit mounted for remote control).

What is collectively referred to as a laser is really a complete lighting system comprised of three main parts: the laser tube, a gas-filled tube that emits the light; the projector that manipulates or scans the beam; and the computer hardware and software that stores and controls the performance. Chapter 1, Light and Optics, gives details on laser physics.

Lasers are used in hundreds of different applications ranging from corporate theater and major concert tours to surveying and construction. Industrial business theater presentations use sophisticated laser graphics and animation to augment multi-image slide and video productions. Laser effects highlight or emphasize a corporate message or speaker with dramatic flair. Many large corporations use lasers at their conventions and special events. Performers have incorporated lasers in their performances and music videos. Large-scale uses have included theme parks.

The laser tube filled with either argon or krypton gas emits the visible light to be manipulated into spectacular light sculptures and paintings. Argon lasers emit light in the blue-green range. For aerial projections to be visible, all the light energy from large-frame 20-watt lasers must be used. For projected images, however, the argon beam can be divided into its component wavelengths of blue and green to create beam colors that can be manipulated separately. Krypton lasers emit red light, which provides important color contrast and spectrum expansion for facade projections.

Laser installations and performances are regulated by federal, state, and local regulations designed to protect public health and safety. The concentrated energy in the low-divergence beam (within a determinable distance from the beam origin) could cause retinal damage if projected directly into the eye. Consequently, various regulations call for minimum separation distances (e.g., 3-meter vertical, 2.5-meter lateral) between beam projections and humans.

NUCLEAR LIGHT SOURCES

Nuclear light sources are self-contained and require no power supply. They typically provide illumination for instrument panels, controls, clocks, and exit signs (see Chapter 29, Emergency, Safety, and Security Lighting).

These sources consist of a sealed glass tube or bulb internally coated with a phosphor and filled with tritium gas. Low-energy beta particles (electrons) from the tritium, an isotope of hydrogen, strike the phosphor, which in turn emits light of a color characteristic of the type of phosphor used. Thus, the mechanism of light production is very similar to that in a conventional television tube. The higher the ratio of the quantity of tritium to the phosphor area, the greater the luminance. The luminance can range up to 7 cd/m^2 (0.65 cd/ft^2), with a typical average of 1.7 cd/m^2 (0.16 cd/ft^2) (this level is approximately that of an illuminated car instrument panel), and the sources can be supplied in a variety of colors. Highest luminances are obtained in the green and yellow phosphors, and green is the usual color supplied. Since tritium has a half-life of 12.3 yr, one might expect the brightness of the source to decay likewise. In reality, the half luminance typically is reached in 6 to 7 yr, and the useful life of these lamps is currently about 15 yr. These light sources can be supplied in very small sizes, down to 5 mm (0.2 in.) in diameter by 2 mm (0.079 in.) in length.

The glass wall is impervious to tritium and completely absorbs any beta radiation not already absorbed by the phosphor. The unit is thus a completely sealed source and does not present any radiation hazard. Glass capsules can be produced in a wide variety of shapes and sizes and are usually made to normal glassworking tolerances. All applications of these lamps are monitored by the Nuclear Regulatory Commission in the United States and by Atomic Energy Canada in Canada.

CARBON ARC LAMPS

Carbon arc lamps were the first commercially practical electric light sources. They were used for many years in applications where extremely high luminance, high correlated color temperature, and/or high color rendering were necessary, such as in motion picture projection lamphouses and for theatrical followspots, searchlights, and film production daylight supplemental lighting. In most of those applications, xenon short arc and metal halide light sources have replaced carbon arc.

Carbon arcs are operated in lamphouses that shield the outside from stray radiation. These lamphouses incorporate optical components such as lenses, reflectors, and filters for eliminating undesired parts of the spectrum.

For more information about different types of carbon arc lamps, their operating characteristics, and power sources, see previous editions of the IESNA *Lighting Handbook*.

GASLIGHTS

Gaslights use gaseous fuels for light and decorative purposes. They use open gas flames or incandescent mantles of the upright and inverted types. For more information, see previous editions of the IESNA *Lighting Handbook*.

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7

Luminaires

A luminaire is a device to produce, control, and distribute light. It is a complete lighting unit consisting of the following components: one or more lamps, optical devices designed to distribute the light, sockets to position and protect the lamps and to connect the lamps to a supply of electric power, and the mechanical components required to support or attach the luminaire.

This chapter provides information for both specifiers and manufacturers of luminaires. It describes most common types of luminaires, how they are used, and how their performance is evaluated, and gives a general classification system useful for understanding their application. With the exception of lamps (light sources), the characteristics, design, and manufacture of luminaire components are described. Detailed information for the specific applications of luminaires can be found in the appropriate application chapters.

GENERAL DESCRIPTION

Light Sources

Luminaires are designed and manufactured for all common types of electric lamps. Luminaires are commonly available for these lamps:

- Incandescent filament including tungsten halogen and infrared (heating) lamps
- Fluorescent
- Compact fluorescent
- Induction or electrodeless lamps, including fluorescent and sulfur lamps
- High-intensity discharge lamps, including metal halide, high-pressure sodium, and mercury
- Low-pressure sodium lamps

Luminaires are less common for xenon arc and carbon arc lamps.

The size, materials, thermal properties, photometric performance, and power requirements of a luminaire depend on the type of lamp used. For example, lamps that produce a large amount of infrared (IR) radiation (heat) require luminaires that are vented for convection, and fluorescent lamps that are sensitive to environmental temperature must be protected from low air temperatures.

Light Control Components

The lamps used in some luminaires have integrated light control components. These are usually incandescent and tungsten-halogen lamps with a reflective coating and/or refracting prisms on the bulb. These integral lamp components produce useful beams and patterns of light without any auxiliary optical control. In these cases, most of the light control is provided by the lamp; the luminaire is simply an appliance to hold the lamp, deliver electric power, and perhaps permit the lamp to be aimed in different directions.

Most lamps emit light in virtually all directions, and their efficient application requires light control components to collect and distribute the light. Four types of light control components are commonly used: reflectors, refractors, diffusers, and louvers or shields. See the sections "Optical Control" in Chapter 1, Light and Optics, and "Materials Used in Luminaires" in this chapter for detailed discussion of optical control by reflection and refraction.

Reflectors. A reflector is a device, usually of coated metal or plastic, that has a high reflectance and is shaped to redirect by reflection the light emitted by the lamp. The surface finish of luminaire reflectors usually is classified as specular, semi-specular, spread, or diffuse. For more information, see "Optical Control" in Chapter 1, Lighting and Optics.

Some applications require the reflector to control the light very precisely, so specular or semi-specular reflecting material is used. Metal reflectors are formed and then polished or chemically coated to produce a specular finish. In some cases, metal reflectors are manufactured from metal stock that has already been treated to produce a specular finish. Plastic reflectors are molded and then coated with aluminum by vaporization. Examples of specular reflectors are those used to control the light from a metal halide lamp to produce a narrow beam of light for sports lighting, and the parabolic louvers in fluorescent lamp troffers.

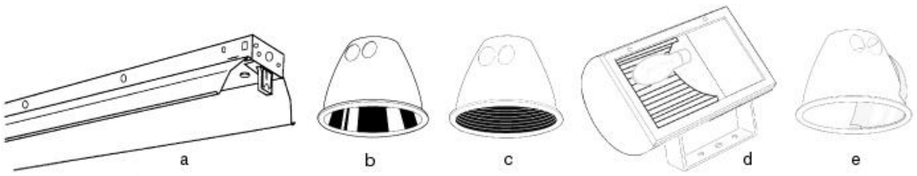


Figure 7-1. Examples of reflectors: (a) linear faceted, coated steel reflector in a strip fluorescent lamp luminaire, (b) and (c) spun specular and grooved aluminum reflectors for a compact fluorescent downlight luminaire, (d) faceted reflector for a floodlight luminaire, and (e) reflector with "kicker" to direct light for wall-wash luminaire.

In some luminaires the reflector does not have to control the light very precisely, and it is sufficient for the reflector to have a high but nondirectional reflectance. An example of this is the white, slightly specular, coated metal reflectors in some large fluorescent lamp luminaires. On the other hand, diffuse reflectors have very little effect on the distribution of light and are uncommon in luminaires. Other applications and lamps require reflectors with special surface finishes, such as semi-specular or peened materials, or coatings to reduce color separation upon reflection (iridescence) when using certain fluorescent lamps. Examples of reflectors are shown in Figure 7-1.

In some cases, reflectors have properties varying with wavelength. Alternating layers of materials with differing indices of refraction are applied to glass. These layers have a thickness approximately that of the wavelength of light (500 nm). Interference effects produce reflection that changes with wavelength. This is useful if it desirable to reflect light but not reflect long-wavelength thermal radiation or, conversely, to reflect the long wavelength radiation and pass light. These reflectors are used when it is necessary to direct light and control the heat generated by the lamps.

Refractors. Refractors are light control devices that take advantage of the change in direction that light undergoes as it passes through the boundary of materials of differing optical density (index of refraction), such as air to glass or air to plastic (see Figure 7-2). A material, usually glass or plastic, is shaped so that light is redirected as it passes through it. This redirecting can be accomplished with linear (extruded, two-dimensional) prisms or with three-dimensional pyramidal-shaped prisms. These prisms can be either raised from the surface of the material or embossed into it. They are usually small enough to become a type of surface treatment on one side of an otherwise flat sheet of glass or plastic. The entire sheet is referred to as a prismatic lens.

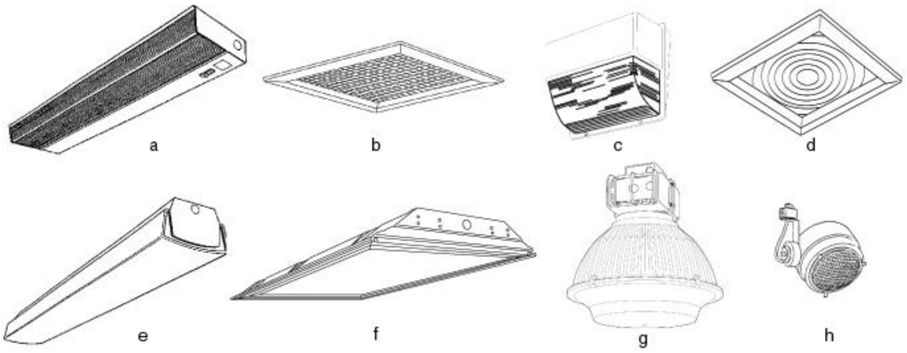


Figure 7-2. Examples of refractors: (a) prismatic lens on surface-mounted fluorescent lamp luminaire, (b) recessed luminaire with spread lens, (c) glass refractor on an outdoor area luminaire, (d) Fresnel refractor, (e) wraparound prismatic lens on a fluorescent lamp luminaire, (f) prismatic lens on recessed flourescent lamp luminaire, (g) low-bay industrial luminaire with prismatic refractor, and (h) track luminaire with spread lens refractor.

A collection of small prisms, acting in concert, can be used to control the directions from which light leaves a luminaire. This redirection can be used to partially destroy images and therefore to obscure lamps and reduce luminance by increasing the area over which the light leaves the luminaire. In some cases the sheet containing prisms is shaped to provide additional control. In specialized applications, such as the refractors used for some street lighting luminaires, the prisms are on both surfaces of the material.

Another application of refracting material takes advantage of total internal reflection. In this case the refracting material is shaped so that light passes into it through its first surface and mostly is reflected from the second surface back into the material and out the first surface. Some glass and plastic industrial luminaires use this type of light control. This is also the basis for the operation of light pipes and fiber-optic luminaires.

For some luminaires, the lamp and application require a transparent cover to block ultraviolet (UV) radiation or prevent broken lamp components from falling out of the luminaire. Though providing little optical control, these cover plates often are referred to as lenses.

Diffusers. Diffusers are light control elements that scatter (redirect) incident light in many directions. This scattering can take place in the material, such as in bulk diffusers like white plastic, or on the surface as in etched or sandblasted glass. Diffusers are used to spread light and, since scattering destroys optical images, obscure the interior of luminaires, suppress lamp images, and reduce high luminances by increasing the area over which light leaves a luminaire. Examples of diffusers are shown in Figure 7-3.

Shades, Shields, Louvers, and Baffles. Shades and shields are opaque or translucent materials shaped to reduce or eliminate the direct view of the lamp from outside the luminaire (Figure 7-4). Shades are usually translucent and are designed to diffuse the light from the lamp and provide some directional control.

Blades, usually opaque and highly reflective, can be shaped and positioned to eliminate the direct view of the lamp from certain directions outside the luminaire and to control the direction from which the light leaves.

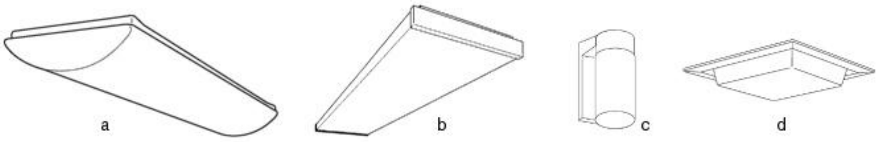


Figure 7-3. Examples of diffusers: (a) and (b) wrap-around white diffusers for fluorescent lamp luminaires, (c) jelly jar diffuser for compact fluorescent lamp luminaire, and (d) drop glass diffuser for metal halide lamp luminaire.

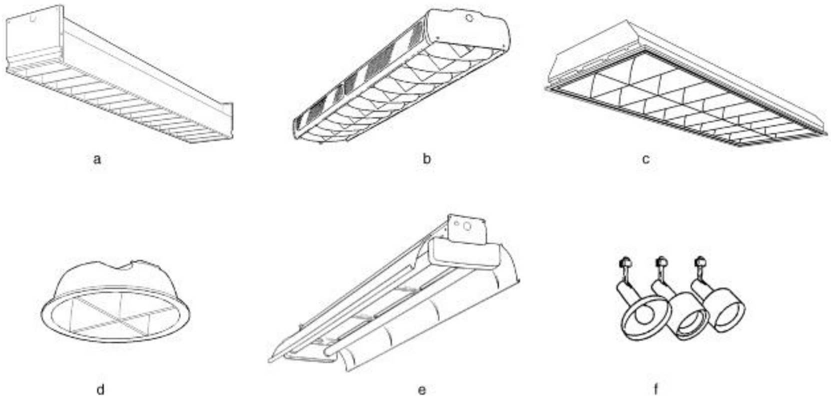


Figure 7-4. Examples of baffles, louvers, and shields: (a), (b), and (c) louvers for fluorescent lamp luminaires; (d) cross baffles for compact fluorescent lamp luminaires; (e) shield for industrial fluorescent lamp luminaire; and (f) hoods and cowls for track luminaires.

If arranged in a rectangular grid, producing cells, they are called louvers. If arranged linearly they are called baffles. In large fluorescent lamp luminaires, louvers are designed so that the lamps are directly above the center of the cells formed by the louvers. In long narrow fluorescent lamp luminaires, baffles extend across the axis of the lamps.

Louvers and baffles often are made of specularly reflecting metal, though some are of coated plastic. Though intended to eliminate the direct view of the lamp at some angles, specular louvers and baffles can provide lamp images at other viewing angles by reflection. In turn, these images may produce images in the screen of computer VDTs. See Figure 7-4 for examples of baffles and louvers.

Fiber-Optic Luminaires. A fiber-optic illumination system is a distributed lighting system allowing remote source illumination of areas and objects. A fiber-optic lighting system has a light source or illuminator, optical fiber, and various output fixtures selected to illuminate specific areas or objects. These systems can be used in lighting applications requiring the light source and light output to be separated, as in hazardous environments, wet locations, or in temperature-sensitive spaces. They also can be used when it is desirable to have sizes, shapes, or light output characteristics different from conventional luminaires.

Virtually all of the IR and most of the UV radiation from lamps, as well as the electrical connections needed to power the system, are absent from the illuminated space. The separation of source from output allows the use of various components within the source enclosure that can provide interesting optical effects at the output. Such components can include color or effects wheels and filters.

Illuminator. The illuminator is an assembly that houses the light source and positions the optical fibers within an output port, or ports, with respect to the source. It may include other components such as a cooling fan, various optical elements, filters, and color wheels or effects devices.

Since lamps are not point sources, the light is collected with a combination of reflecting and/or refracting optics. The collection efficiency is a function of both the size and shape of the light source (e.g., arc or filament) and the chemical as well as the physical characteristics of the fiber(s) receiving the light. Proper use of conventional nonimaging optical design methods enable the collection of 10 to 40% of the light into light guides.

The most commonly used lamps in optical fiber systems are tungsten-halogen and metal halide. Illuminators that incorporate halogen sources almost always includes a cooling fan. Applications that require greater light output and longer lamp life use metal halide high lamps. Other light sources (xenon, xenon metal halide, and sulfur lamps) occasionally are used in optical fiber illumination systems. These lamps have advantages that make them appropriate for certain specialized applications.

The illuminator often contains various accessories that affect the output. These include permanent filters such as IR, UV, or dichroic; rotating wheels that provide a variety of colors; and mechanical dimming or twinkling. Many tungsten-halogen illuminators are available with electronic dimming.

Optical Fiber. The principal function of optical fiber is to deliver light from the illuminator to the exit port. A fiber consists of at least two and often three concentric regions. These regions are the core, which is the light transmission medium; the cladding, which confines the light to the core, and the sheathing, which is an outer coating protecting the fiber from handling or interaction with the environment. In side lighting applications, the fiber is designed so that light is emitted uniformly from the sides. For end lighting applications, light propagates down the fiber by totally internally reflecting at the core-cladding interface. Since this reflectance is very nearly 1.0, light loss through the fiber is due almost solely to absorption and scattering. The absorption and scattering characteristics of the fiber material determine the attenuation. Total internal reflection requires a high incidence angle to the core-cladding interface, and this requires that light enter the fiber end within a certain acceptance angle. The acceptance angle is a function of the indices of refraction of the core and cladding. In general, the acceptance angle also defines the angle with which the light exits an optical fiber.

Output Optics. The nature of the optics placed on the output end of the fibers depends on the details of the application. The angular distribution of the light depends on the spread of the system's input illumination, and is typically between 60° and 80°. A wide array of fixtures that house shaped plastic or glass diffusers and/or lenses with different distribution characteristics is available to achieve many effects. In addition, numerous decorative fiber end fittings are available to create interesting display and decorative effects.

Optical fiber output fixtures typically are smaller and more lightweight than conventional luminaires because the fibers approach the characteristics of a directional point source and heat is of no concern. This allows many fixtures to be composed of plastic.

Mechanical Components

The mechanical components of a luminaire consist of a housing or general structure to support other components of the luminaire, and a mounting mechanism for the attachment of the luminaire to its support (Figure 7-5). In some luminaires the reflector is a separate component that is attached to the housing, as in a compact fluorescent lamp downlight. In other luminaires, the housing serves as the reflector, as in a fluorescent lamp troffer.

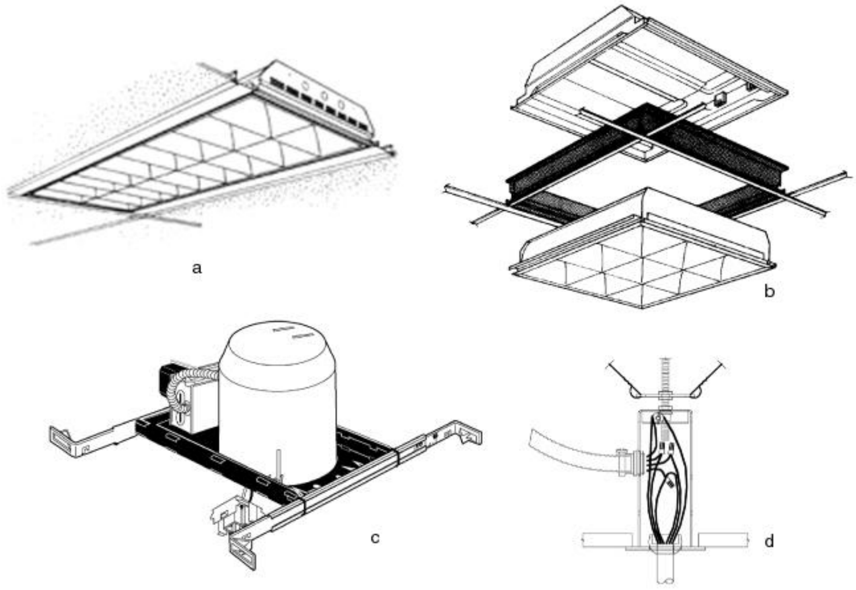


Figure 7-5. Examples of mechanical components of luminaires: (a) and (b) fluorescent lamp troffers showing housing and mounting to inverted-T ceiling system; (c) compact fluorescent lamp downlight showing housing, mounting for ballast, and mounting brackets; and (d) mounting and electrical connection for a pendant-mounted luminaire.

If the luminaire uses a refractor or transparent cover, then hinged frames or doors often are provided to hold the lens. Access for cleaning and relamping is through this door.

In damp or wet applications it is necessary to provide adequate seals to prevent migration of water into the luminaire. In some hazardous locations the housing and seals must keep explosive or flammable vapors from contact with high lamp surface temperatures or electric spark. These luminaires are said to be explosion proof.

Many recessed luminaires are vented to dissipate heat that can degrade lamp performance. In some applications, the luminaire is used as part of the building's heating, ventilating, and air conditioning system. Air is supplied to or removed from the room using the luminaire. In this case, airways are provided within the luminaire as well as attachments for air ducts and slots through which air enters or leaves the room.

Electrical Components

The electrical components of the luminaire operate the lamp (Figure 7-6). One or more sockets provide mechanical support for the lamp and furnish necessary electrical connections. For some lamps, usually single-ended, mechanical support is required in addition to the socket.

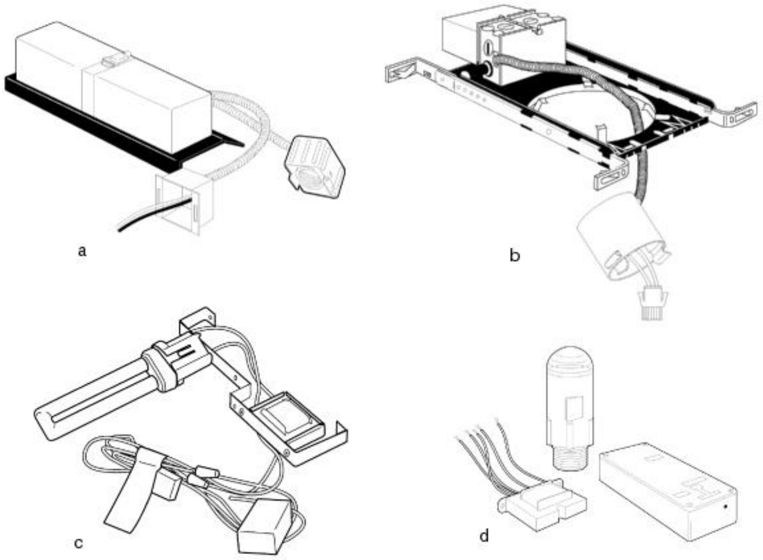


Figure 7-6. Electrical components, showing junction box, ballast, and lamp socket for (a) metal halide and (b) compact fluorescent lamp luminaires; (c) compact fluorescent lamp, socket, magnetic ballast, and connectors; and (d) photocell, transformer, and ballast for controlling outdoor luminaires.

If required, the luminaire contains and supports ballasts, starters, igniters, capacitors, or emergency lighting devices. The size and power handled by these components often determine the size of the luminaire and the requirements for proper thermal performance. In a few applications, these components are too heavy, too loud, or too large to be in the luminaire. In these cases, the ballast and other auxiliary equipment are mounted remotely from the luminaire and lamp. The luminaire also contains wiring and connectors to connect the lamp socket and, if present, the ballast to the external wiring that brings electrical power to the luminaire.

Figures 7-7 through 7-12 show cross sections of typical luminaires with most of the major components shown. Even apparently simple luminaires contain many components.

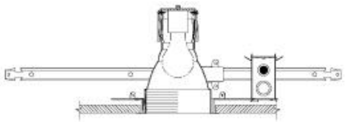


Figure 7-7. Incandescent lamp downlight showing housing, mounting, reflector, wiring, socket, and lamp.

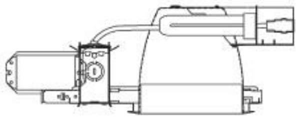


Figure 7-8. Compact fluorescent lamp downlight showing housing, mounting, reflector, wiring, socket, and lamp.

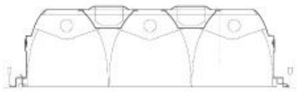


Figure 7-9. Fluorescent lamp troffer showing housing, mounting, reflector, lamps, and ballast.

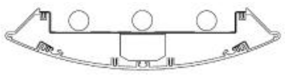


Figure 7-10. Suspended fluorescent lamp luminaire showing extruded aluminum housing, reflector, lamps, and ballast.

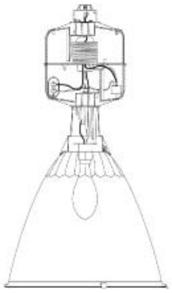


Figure 7-11. High-bay HID lamp luminaire showing housing, reflector, lamp, socket, magnetic ballast and capacitor, and mounting.

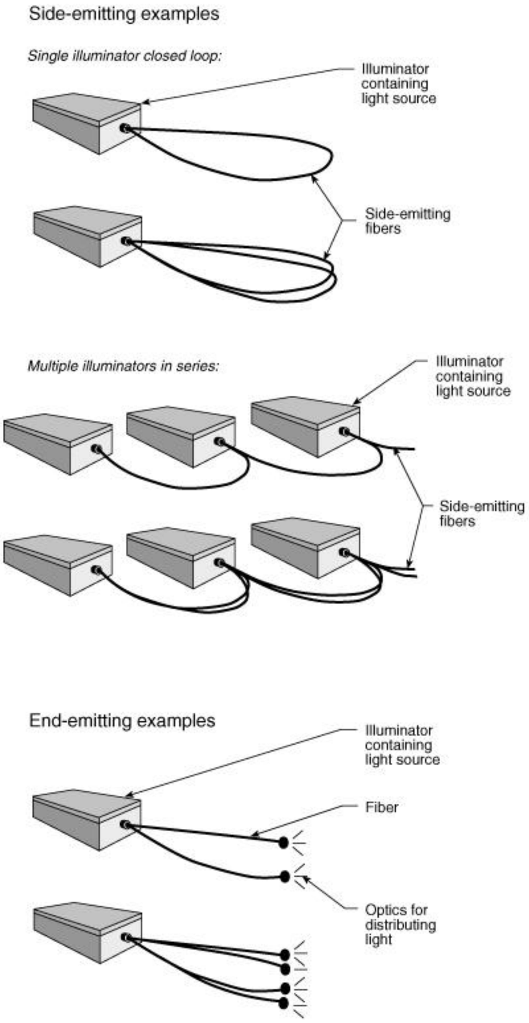


Figure 7-12. Fiber-optic luminaires.

LUMINAIRE TYPES AND CLASSIFICATION

Purpose of Classification

Luminaire classification helps specifiers and manufacturers describe, organize, catalog, and retrieve luminaire information. The nature of luminaire classification has changed with the advance of computer and information technology. Modern lighting design and specification practice relies on computer-based luminaire databases, accessed on CD-ROM or over the Internet. This technology allows luminaire data to be updated frequently and easily. In such systems, a luminaire can be known by all of its characteristics, with any one being the path by which a search finds the luminaire in a database.

Methods for Classification

Luminaires can be classified according to source, mounting, construction, application, and/or photometric characteristics. Classifications by application and photometric characteristics are discussed in the next two sections.

Classification by Application. A common form of classification organizes luminaires by application. Many luminaire characteristics are determined by application, so this distinction proves useful in organizing luminaire information. Three application areas are usually distinguished: residential, commercial, and industrial. Within each application, luminaires can be classified by source, mounting, and con struction. Examples of these include residential ceiling-mounted room luminaires using incandescent lamps, recessed fluorescent lamp troffer luminaires, and high bay suspended metal halide lamp luminaires.

Classification by Photometric Characteristics. Another form of classification uses the luminous intensity or flux distribution of the luminaire. For luminaires used indoors, a method specified by the International Commission on Illumination (CIE) is commonly used. For luminaires used outdoors, the NEMA and

IESNA methods are used.

The CIE Classification System. The International Commission on Illumination provides a classification system based on the proportion of upward and downward directed light output. This system is usually applied to indoor luminaires.

- Direct lighting. When luminaires direct 90 to 100% of their output downward, they form a direct lighting system. The distribution may vary from widespread to highly concentrated, depending on the reflector material, finish, and contour and on the shielding or optical control media employed.
- Semidirect lighting. The distribution from semidirect units is predominantly downward (60 to 90%) but with a small upward component to illuminate the ceiling and upper walls.
- General diffuse lighting. When the downward and upward components of light from luminaires are about equal (each 40 to 60% of total luminaire output), the system is classified as general diffuse. Direct-indirect is a special (non-CIE) category within this classification, in which the luminaires emit very little light at angles near the horizontal.
- Semi-indirect lighting. Lighting systems that emit 60 to 90% of their output upward are classified as semi-indirect.
- Indirect lighting. Lighting systems classified as indirect are those that direct 90 to 100% of the light upward to the ceiling and upper side walls.

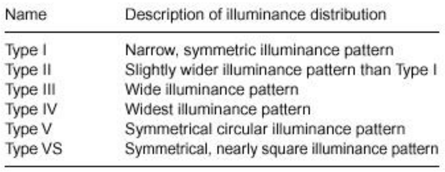
Indoor Luminaire Classifications By Cutoff. There are several characteristics of indoor luminaire intensity distributions that are important for classification. This information can appear in the photometric report for a luminaire. See the section "Luminaire Photometric Report" later in this chapter.

- Physical cutoff. The angle measured from nadir at which the lamp is fully occluded.
- Optical cutoff. The angle measured from nadir at which the reflection of the lamp in the reflector is fully occluded.
- Shielding angle. The angle measured from the horizontal at which the lamp is just visible.

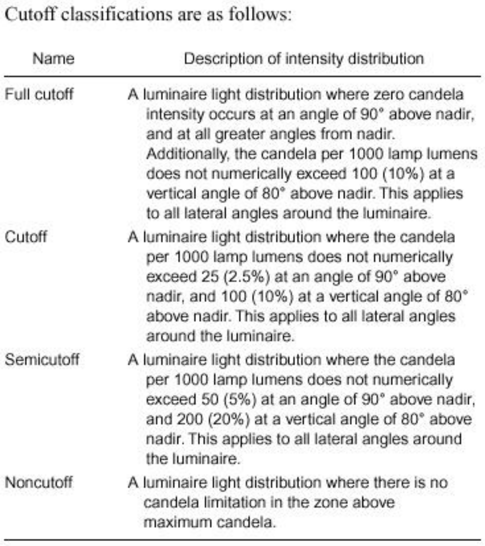
The NEMA Classification System. This system is based on the distribution of flux within the beam produced by the luminaire. It is used primarily for sports lighting and floodlighting luminaires. Seven distributions are defined, types 1 through 7, from narrowest to widest beams (see Figure 20-10 in Chapter 20, Sports and Recreational Area Lighting).

The IESNA Classification System For Outdoor Luminaires. This system is based on the shape of the area that is primarily illuminated by the luminaire. It is used for roadway and area lighting luminaires. Though these luminaires can differ in the manner in which they are mounted, by the type of intensity distribution they exhibit, and by the degree to which they provide cutoff, these luminaires often are specified by the way in which they illuminate an area.

Following are the IESNA outdoor luminaire classifications by intensity distribution (see Figure 22-6 in Chapter 22, Roadway Lighting). More detailed information on these luminaire types is found in Chapter 22, Roadway Lighting.



Name	Description of illuminance distribution
Type I	Narrow, symmetric illuminance pattern
Type II	Slightly wider illuminance pattern than Type I
Type III	Wide illuminance pattern
Type IV	Widest illuminance pattern
Type V	Symmetrical circular illuminance pattern
Type VS	Symmetrical, nearly square illuminance pattern



Cutoff classifications are as follows:

Name	Description of intensity distribution
Full cutoff	A luminaire light distribution where zero candela intensity occurs at an angle of 90° above nadir, and at all greater angles from nadir. Additionally, the candela per 1000 lamp lumens does not numerically exceed 100 (10%) at a vertical angle of 80° above nadir. This applies to all lateral angles around the luminaire.
Cutoff	A luminaire light distribution where the candela per 1000 lamp lumens does not numerically exceed 25 (2.5%) at an angle of 90° above nadir, and 100 (10%) at a vertical angle of 80° above nadir. This applies to all lateral angles around the luminaire.
Semicutoff	A luminaire light distribution where the candela per 1000 lamp lumens does not numerically exceed 50 (5%) at an angle of 90° above nadir, and 200 (20%) at a vertical angle of 80° above nadir. This applies to all lateral angles around the luminaire.
Noncutoff	A luminaire light distribution where there is no candela limitation in the zone above maximum candela.

Principal Types of Luminaires

Commercial and Residential

Portable Luminaires. These are completely self-contained luminaires designed to be moved and placed near the task to be lighted. They have a plug and outlet connection to electric power and usually contain integral switching and/or dimming. They usually contain low-wattage incandescent, tungsten-halogen, or compact fluorescent lamps. Examples of portable luminaires are floor and table luminaires, desk luminaires, and partition-mounted luminaires (Figure 7-13).

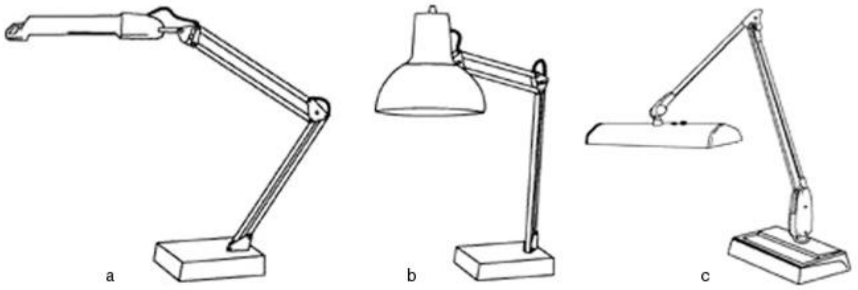


Figure 7-13. Examples of portable luminaires using (a) compact fluorescent lamp, (b) incandescent lamp, and (c) straight fluorescent lamps.

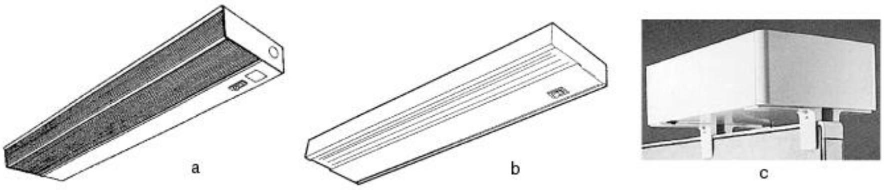


Figure 7-14. Examples of furniture-mounted luminaires: (a) under-cabinet luminaire with wrap-around prismatic lens, (b) under cabinet luminaire with extruded lens, and (c) partition-mounted luminaire with metal halide lamp.

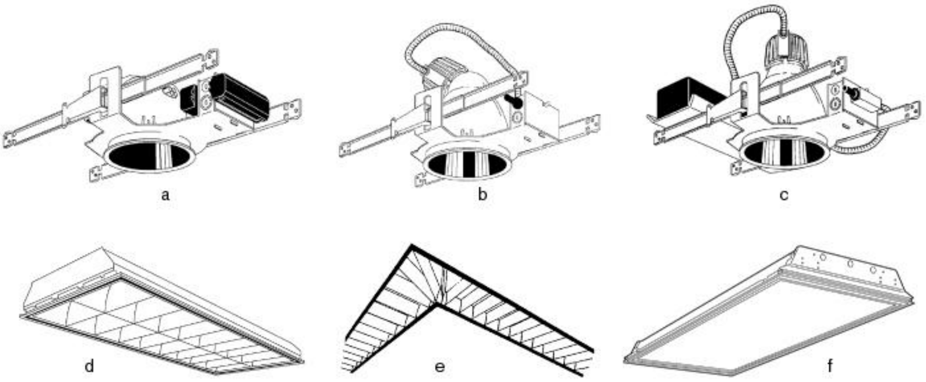


Figure 7-15. Examples of downlight luminaires using (a) compact fluorescent, (b) incandescent, and (c) metal halide lamps; (d) fluorescent lamp recessed troffer with parabolic louvers; (e) continuous linear; and (f) fluorescent lamp recessed troffer with prismatic lens.

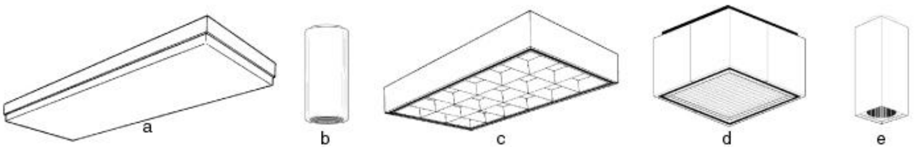


Figure 7-16. Examples of ceiling surface mounted luminaires; (a) wrap-around lens, (b) incandescent lamp downlight, (c) troffer, (d) metal halide lamp area light, and (e) metal halide lamp downlight.

Furniture Mounted. Permanently attached to furniture or other equipment surface, these luminaires are designed to be in close proximity of the task and produce localized lighting. They can be found under kitchen cabinets and in bathroom vanities (Figure 7-14).

Recessed Downlights. These are general-purpose luminaires designed to provide general or ambient lighting in a space. They are recessed into the ceiling and are designed to produce illuminance on a floor or workplane. Certain types have concentrated luminous intensity distributions designed for spaces with computer VDTs. It is often necessary to augment these luminaires with other types that raise wall luminances and add vertical illuminance to the space. Recessed downlights can be grouped by size.

There are two types of recessed downlights (Figure 7-15). Incandescent, compact fluorescent, and metal-halide lamp downlights usually have modest apertures and can exhibit very low luminances at high viewing angles. Fluorescent lamp troffers use large fluorescent lamps and are usually used with a suspended tile ceiling system. Sizes range from 6 in. × 48 in. to 48 in. square.

Ceiling Surface Mounted. These luminaires can provide general or ambient lighting with the addition that some of the light can be emitted upward to produce a higher ceiling luminance than recessed or surface-mounted downlights. Examples include fluorescent troffers, compact fluorescent downlights, incandescent and tungsten-halogen downlights for task lighting on kitchen counter tops, and wrap-around lens luminaires (Figure 7-16).

Wall Washer. These luminaires are used to produce a distribution of illuminance/luminance on a wall that, though not necessarily uniform, changes gradually from high values at the top of the wall to lower values down the wall. Many wall-wash luminaires are designed to achieve an illuminance ratio from the top to the bottom of the wall of 10:1 or less. Wall-wash luminaires can be recessed or surface mounted. These can be grouped by size.

There are two basic types of wall washers (Figure 7-17). Linear fluorescent wall washers usually have a reflector that allows them to be placed close to the wall, and are available recessed or surface-mounted. Other wall washers, including compact fluorescent, incandescent, halogen, or compact metal halide lamp luminaires, are smaller units that, if recessed, have a modest aperture and therefore can appear like other downlights in the space. They also can be surface mounted.

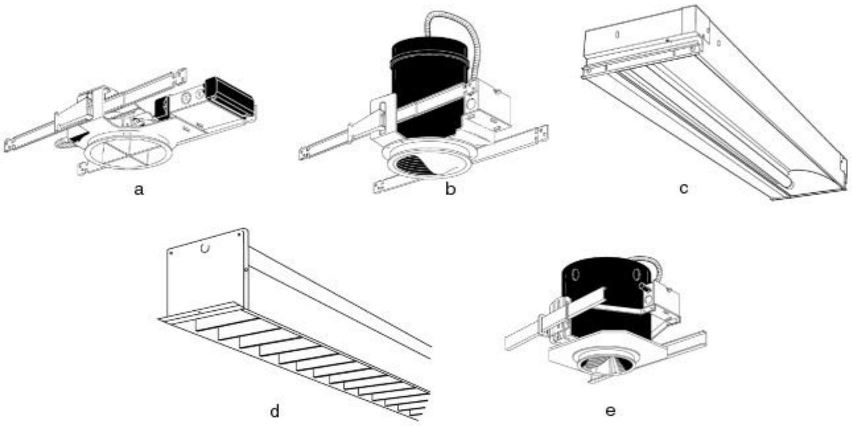


Figure 7-17. Examples of wall-wash luminaires: (a) compact fluorescent lamp luminaire with baffles, (b) incandescent lamp luminaire with eyelid, (c) recessed linear fluorescent lamp, (d) continuous linear fluorescent lamp with baffles, and (e) incandescent lamp wall washer with spread lens.

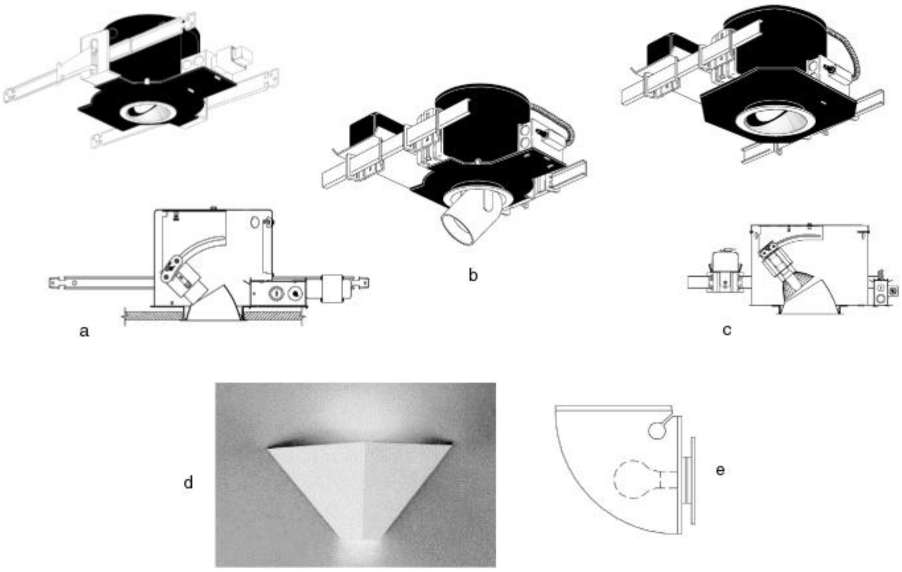


Figure 7-18. Examples of accent luminaires: (a), (b), and (c) recessed adjustable accent luminaires for reflector incandescent lamps, for tungsten-halogen lamps, and HID lamps; (d) and (e) front and side view of wall sconce luminaires using compact fluorescent and incandescent lamps.

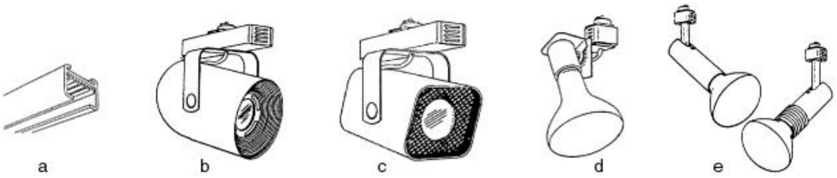


Figure 7-19. Examples of track luminaires: (a) close-up of multicircuit track, (b) and (c) track-mounted luminaires with optical control, and (d) and (e) track luminaires for holding and aiming lamps.

Accent. These luminaires are either themselves ornamental or are designed to produce patterns of light that are ornamental. They can be ceiling recessed or surface mounted, or wall mounted (Figure 7-18).

Ceiling-mounted accent luminaires use incandescent, tungsten-halogen, compact fluorescent, or low-wattage metal halide lamps. The lamps are adjustable or fixed.

Sconces and other wall-mounted accent luminaires use incandescent, tungsten-halogen, or compact fluorescent lamps. Since they are often mounted low, they are often in the field of view, and therefore the designer should be aware of the potential for glare. Translucent shields, which vary in size or shape, are often used for lighting hallways, stairways, doorways, and mirrors.

Wall-mounted luminaires with opaque shielding completely conceal the source from normal viewing angles and are strongly directional in light distribution. Downlight luminaires often are mounted on the wall for accent and display lighting, whereas uplight luminaires can be used for general, indirect lighting. The extent to which wall-mounted luminaires protrude from the wall is often subject to code restrictions such as the Americans with Disabilities Act.[1]

Track. This refers to a system that includes luminaires and a track or rail that is designed to both provide mounting and deliver electric power (Figure 7-19). Track is generally made of linear extruded aluminum, containing copper wires to form a continuous electrical raceway. Some varieties can be joined or cut, and others set into a variety of patterns with connectors. Track is available in line or low-voltage, with remote transformers available for the low-voltage equipment.

Track can be mounted at or near the ceiling surface, recessed into the ceiling with special housing or clips, or mounted on stems in high-ceiling areas. It also can be used horizontally or vertically on walls. Mechanical considerations may limit certain mounting arrangements, particularly for wall-mounted installations.

Track can be hardwired at one end or anywhere along its length. Flexibility can be added with a cord-and-plug assembly to supply power rather than with hardwiring.

A variety of adjustable track-mounted luminaires are available for attachment at any point along the track. These luminaires come in many shapes and styles, housing a large assortment of lamps, including line and low-voltage. In addition, a number of luminaires are designed to create special effects for decorative applications. Track luminaires use incandescent, tungsten-halogen, compact fluorescent, metal halide, or high-pressure sodium lamps.

Point Indirect. These luminaires are designed to provide general or ambient lighting by illuminating the ceiling with compact fluorescent, metal halide, or even high-pressure sodium lamps (Figure 7-20). They contain reflectors that help produce a wide distribution so that they can be mounted close to the ceiling. Pendants or cable usually suspends them, but some types are post-mounted from the floor.

Linear Indirect. These luminaires are designed to use linear or compact fluorescent lamps to provide general or ambient lighting by illuminating the ceiling (Figure 7-20). Reflectors are used to produce wide distributions and permit short suspension distance. Linear indirect luminaires can be suspended from the ceiling by pendants or cable or, in the case of modest spans, mounted by their ends. They can also be mounted on the walls to form a perimeter lighting system. Suspended linear indirect luminaires usually have a luminous intensity distribution that is symmetric about the lamps' axis, whereas wall-mounted linear indirect luminaires typically have an asymmetric distribution.

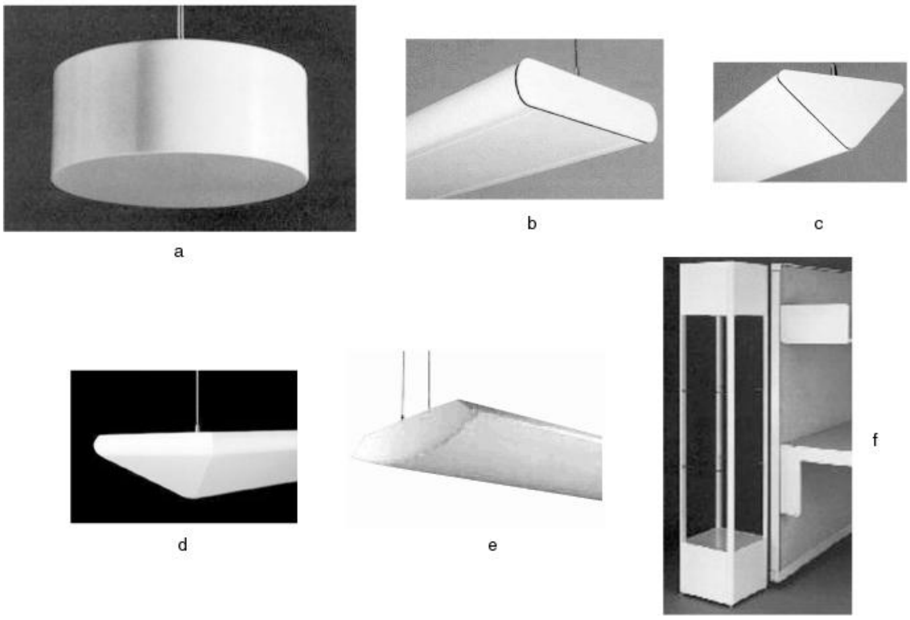


Figure 7-20. Examples of indirect luminaires: (a) pendant-mounted point indirect luminaire with metal halide lamp, (b) and (c) linear two-lamp fluorescent indirect luminaires, (d) linear single fluorescent indirect luminaire, (e) linear two-lamp fluorescent luminaire, and (f) floor-mounted point indirect luminaire.

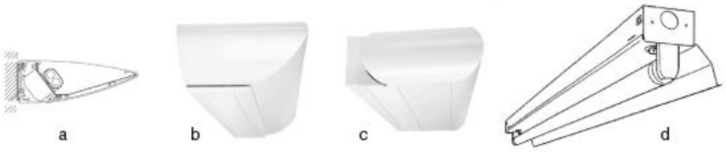


Figure 7-21. Examples of cove luminaires: (a) cove forming luminaire with biaxial fluorescent lamp, (b) and (c) cove forming luminaires with linear fluorescent lamps, and (d) fluorescent lamp strip luminaire with asymmetric reflector for mounting in a cove.

Linear Direct-Indirect. These luminaires are similar to the suspended indirect but provide some downward directed light. Variations are available for changing the proportion of upward and downward light.

Cove. These luminaires are designed to be placed in an architectural cove or to have a shape such that when mounted on the wall they produce a cove and its lighting effect (Figure 7-21). The simplest form of this luminaire is a fluorescent lamp strip, providing ballast and lamp sockets. More elaborate forms provide reflectors to control near-wall and ceiling luminance.

Stage. These luminaires are designed to produce tight optical control and provide maximum flexibility (Figure 7-22). They are common in theaters and television studios for lighting stage sets and people.

Industrial

Linear Fluorescent. These luminaires are often designed for high-output fluorescent lamps, with the reflector often being part of the housing (Figure 7-23). A refractor or lens is uncommon. These luminaires are designed to minimize accumulation of dirt by providing for convection; in areas with large amounts of airborne particles, dust-tight covers are used. Diffusers with gasketing are often used in wet locations.

Strips. These luminaires have one or more fluorescent lamps mounted to a small housing large enough to hold ballasts and sockets (Figure 7-24). Reflectors are uncommon since these luminaires are used in areas where a large amount of general diffuse lighting is required and efficiency and budget are a concern.

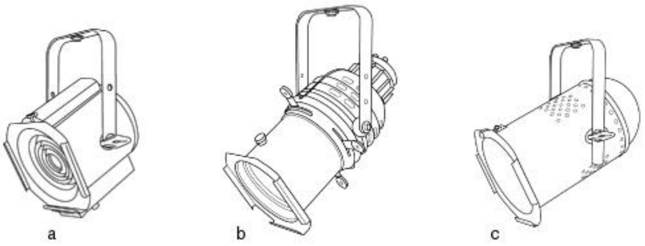


Figure 7-22. Examples of theatre luminaires: (a) Fresnel spot, (b) ellipsoidal spot, and (c) border spot.

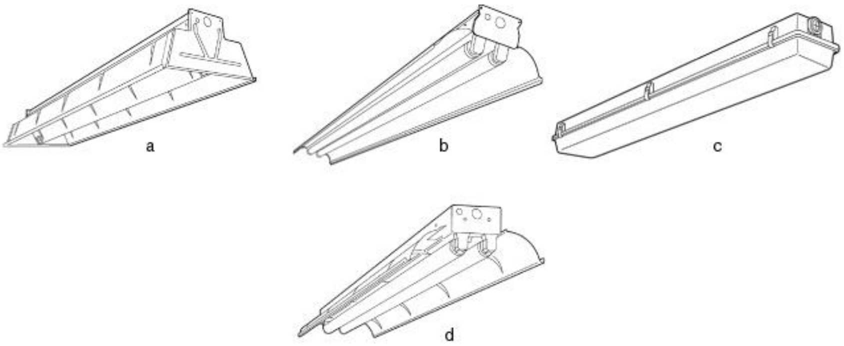


Figure 7-23. Examples of linear fluorescent lamp industrial luminaires with (a) parabolic reflector, (b) specular reflector and shield, (c) diffuser and gasketing for wet locations, and (d) open enamel reflector.

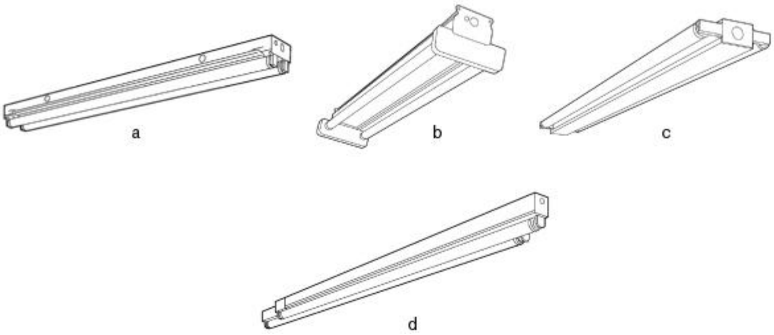


Figure 7-24. Examples of fluorescent lamp industrial strip luminaires: (a) tandem lamp strip, (b) two-lamp channel strip, (c) side-mounted lamps, and (d) staggered lamps for continuous row applications.

High Bay. These luminaires use HID lamps to produce general lighting in an industrial area (Figure 7-25). They are for applications with spacing-to-mounting height ratios of up 1.0. They are surface or pendant mounted, depending on the structure and openness of the area. These luminaires use reflectors and refractors to produce luminous intensity distributions that vary from narrow to wide, depending on the application and the need for vertical illuminance.

Low Bay. These luminaires use HID lamps to produce general lighting in an industrial area (Figure 7-26). They are for applications with spacing-to-mounting height ratios greater than 1.0. As with high bay luminaires, they are surface or pendant mounted. These luminaires usually have wide luminous intensity distributions to provide greater horizontal and vertical illuminances in areas with restricted ceiling heights.

Emergency and Exit. Emergency lighting luminaires are designed to provide enough light for egress in emergent situations. They may operate from power provided by batteries. Under normal conditions the batteries are continuously charged from line voltage. These luminaires contain circuitry that turns them on whenever line voltage is not present. Some HID luminaires contain auxiliary light sources that provide light while HID lamps cool off and restrike when line voltage is temporarily disrupted.

Exit luminaires help building occupants identify directions to an exit. They can be considered a type of illuminated signage that is useful under normal conditions but designed to provide critical help in emergent situations. Like emergency lighting luminaires, exit luminaires often operate on batteries. Compact fluorescent lamps and light-emitting diodes are commonly used in exit luminaires. Examples of emergency and exit luminaires are presented in Figure 7-27.

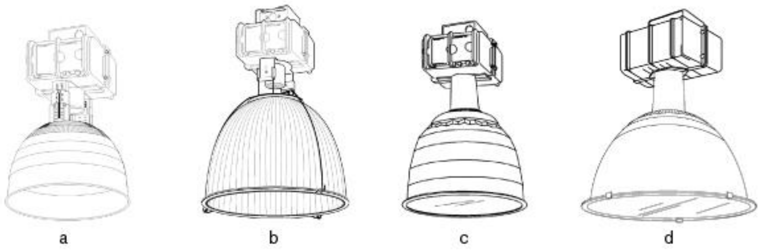


Figure 7-25. Examples of high-bay industrial luminaires: (a) open metal reflector, (b) open injection molded acrylic reflector/refractor, and (c) and (d) enclosed reflector.

Figure 7-26. Examples of low-bay industrial luminaires.

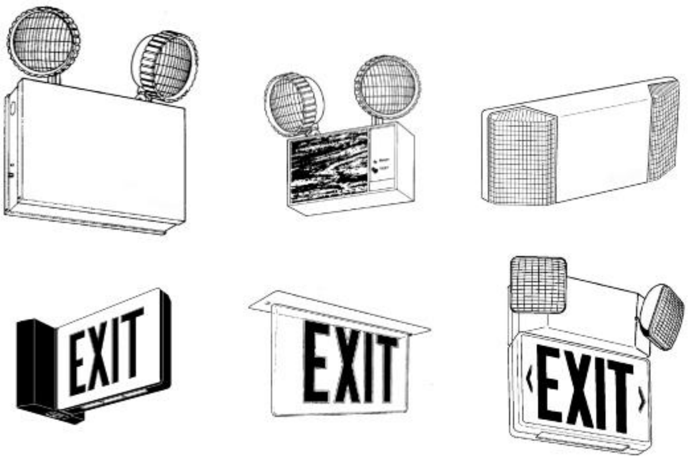


Figure 7-27. Examples of emergency and exit luminaires.

Outdoor

Floodlight. These luminaires are often used for building lighting and other special applications (see Chapter 20, Sports and Recreational Area Lighting, and Chapter 21, Exterior Lighting). These applications can require luminous intensity distributions that range from very narrow to very wide, depending on the angular size of the object being illuminated and the effect to be achieved. The luminous intensity distributions usually are not symmetric. Most types of HID lamps are used in floodlight luminaires. Lamp orientation and reflector arrangement normally determine beam characteristics. Examples of floodlight luminaires are presented in Figure 7-28.

Exterior building lighting uses luminaires with narrow and wide distributions, depending on the portion of the building being illuminated and its distance from the luminaire mounting location. Column lighting, accent lighting and distant mounting locations require narrow distributions. Lighting large areas with near mounting locations requires very wide distributions. Floodlight luminaires often have luminous intensity distributions that produce a square or rectangular illuminance pattern (see Chapter 21, Exterior Lighting).

Sports Lighting. Some sport lighting luminaires have very narrow luminous intensity distributions and typically are mounted to the side and well above the playing area. Others have medium distributions and sharp cutoff and are mounted over the playing area. Metal halide lamps are common for sports lighting luminaires. Reflectors are used to produce the required luminous intensity distribution. Refractors are not used. Use of the narrow-intensity-distribution luminaires almost always requires careful design to ensure proper overlapping of beams as well as proper horizontal and vertical illuminances. Since aiming is a critical part of their application, these luminaires are usually provided with special aiming and locking gear. Internal or external louvers also may be provided to control glare and light trespass and to improve observer comfort. Examples of sports lighting luminaires are shown in Figure 7-29.

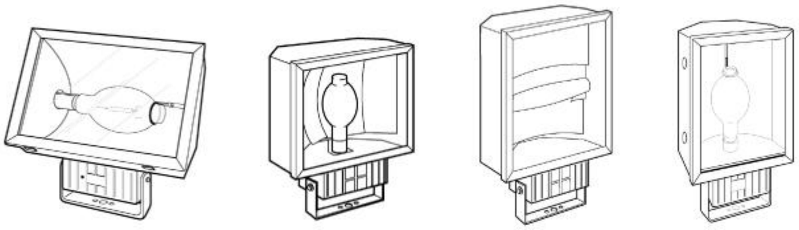


Figure 7-28. Examples of floodlight luminaires.

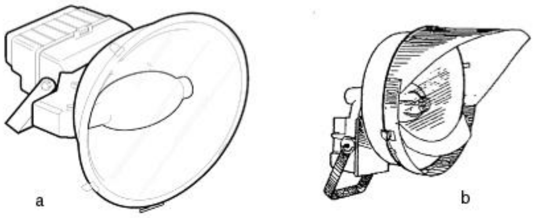


Figure 7-29. Example of sports lighting luminaires: (a) wide distribution with lamp base to the side, and (b) narrow distribution with hood and baffles to control spill light

Sports lighting luminaires are usually classified using the NEMA field angle designation. Seven categories from very narrow to very wide are used to describe the luminous intensity distribution of these luminaires (see Figure 20-10 in Chapter 20, Sports and Recreational Area Lighting).

Street and Roadway. These luminaires are designed to produce reasonably uniform illuminance on streets and roadways. They usually are mounted on arms on a pole, or are post-top mounted. All types of HID lamps are used in street and roadway luminaires. Low-pressure sodium lamps are used only occasionally. Reflectors and refractors are used to produce the various types of luminous intensity distributions required in these applications. Wide distributions permit large pole spacing. Minimum horizontal illuminance and uniformity of horizontal illuminance are typical design criteria. For this reason, the luminous intensity distributions can sometimes have maximum values at angles above 75° from the nadir.

Luminaires with dropped-dish, or ovate, refractors are commonly used in roadway applications. Because of their appearance these luminaires are referred to as "cobra head" luminaires (Figure 7-30). Poles for roadway applications are usually mounted well back from the roadside to avoid damage to both the luminaire and oncoming traffic. Modifications to the typical design of cobra heads may reduce glare and light trespass.

Pathway. Walkway and grounds lighting is often accomplished with bollards (Figure 7-31). These luminaires are mounted in the ground and have the form of a short thick post similar to that found on a ship or wharf, hence the name. The optical components are usually at the top, producing an illuminated area in the immediate vicinity. Bollards are used for localized lighting. Their size is appropriate for the architectural scale of walkways and other pedestrian areas.

Small sharp cutoff luminaires are also used on small poles to provide pathway lighting. Additionally, luminaires for lighting outdoor stairs and ramps are used. These can be mounted on poles or recessed into the structure near the stairs or ramp.

Parking Lot and Garage.[2] Parking lot lighting often uses cutoff or semi-cutoff luminaires with flat-bottomed lenses. These luminaires are mounted on post-top brackets or on short arms and can be arranged in single, twin, or quad configurations. Symmetric and asymmetric intensity distributions and mounting configurations are used to provide the necessary flexibility in pole placement for parking lots. Examples of parking lot and garage luminaires are presented in Figure 7-32.

Wall-mounted luminaires are often used for small parking lots immediately adjacent to a building or in parking structures. Often referred to as "wall packs," wall-mounted luminaires have an asymmetric distribution necessary for lighting adjacent parking lots. There is significant potential for glare and light pollution with these luminaires. Glare and light pollution can be controlled using cutoff versions of wall packs, but this decreases luminaire spacing.

Figure 7-30. Example of a roadway luminaire: a cobra head roadway luminaire with drop-dish refractor.

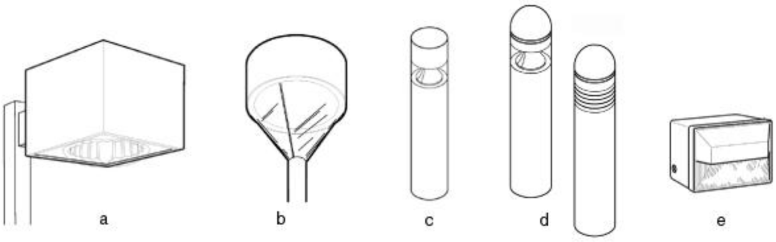


Figure 7-31. Examples of pathway luminaires: (a) and (b) post-top luminaires for pathway and area lighting, (c) and (d) bollards for pathway lighting, and (e) recessed stair and ramp luminaire.

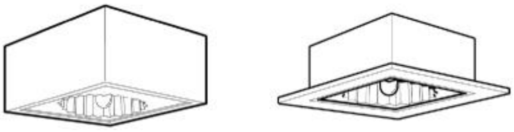


Figure 7-32. Examples of parking lot and garage luminaires.

Surface-mounted luminaires in parking structures are mounted on walls or ceilings. These are designed to produce a considerable amount of interreflected light in the structure.

Security. Security luminaires are typically outdoor luminaires designed to help visually secure an area. This can mean providing sufficient illuminance for visual surveillance or security camera surveillance. These luminaires are typically mounted in inaccessible places and have particularly strong housings and lenses to help make them vandal proof. In conjunction with some security camera systems, infrared (IR) sources can also be used that are invisible to potential trespassers. Examples of security luminaires are presented in Figure 7-33.

Landscape. Landscape luminaires are designed for use outdoors to light buildings, planting, water features, and walkways (Figure 7-34). The can be mounted in the ground, on poles, on trees, or underwater. Typically they have special housing, gasketing, lenses, and electrical wiring hardware that protects against the effects of water and corrosion.

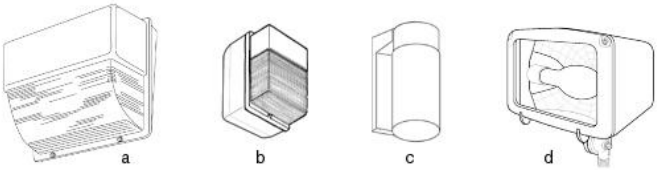


Figure 7-33. Examples of security luminaires: (a) wall-mounted HID lamp luminaire, (b) wall-mounted metal halide lamp luminaire, (c) compact fluorescent lamp jelly jar luminaire, and (d) HID lamp luminaire.

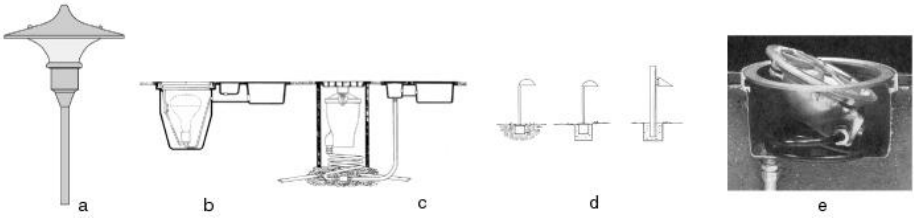


Figure 7-34. Examples of landscape luminaires: (a) ground and path luminaire, (b) and (c) direct burial and well-mounted landscape luminaires, (d) bollards for lighting pathways, and (e) underwater luminaire.

LUMINAIRE PERFORMANCE

Luminaire performance can be considered a combination of photometric, electrical, and mechanical performance. Photometric performance of a luminaire describes the efficiency and effectiveness with which it delivers the light produced by the lamp to the intended target. This performance is determined by the photometric properties of the lamp, the design and quality of the light control components, and to some extent any auxiliary equipment required by the lamp.

The electrical performance of a luminaire describes the efficacy with which the luminaire generates light and the electrical behavior of any auxiliary equipment such as ballasts. Luminaire efficacy is determined by lamp efficacy and, if present, the ballast and its interaction with the lamp. Electrical behavior, such as power factor, waveform distortion, and various forms of electromagnetic interference, are properties of the lamp and ballast.

The mechanical performance of a luminaire describes its behavior under stress. This can include extremes of temperature, water spray or moisture, mechanical shock, and fire.

Components of Photometric Performance

Luminaire Photometric Report. Luminaire photometric performance is summarized in a photometric report (Figures 7-35 and 7-36). Luminous intensity values are determined from laboratory measurements and are reported as the luminaire's luminous intensity distribution. Electrical and thermal measurements are made and often reported. These include input watts, input volts, and ambient air temperature. In addition, some calculated application quantities are usually reported. These include zonal lumens, efficiency, and coefficients of utilization. See "Luminaire Photometry" in Chapter 2, Measurement of Light and Other Radiant Energy, for a description of measurement procedures, and Chapter 9, Lighting Calculations, for a description of the calculation procedures that produce the application data.

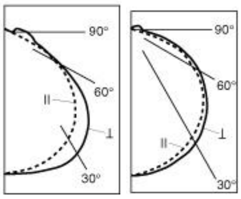
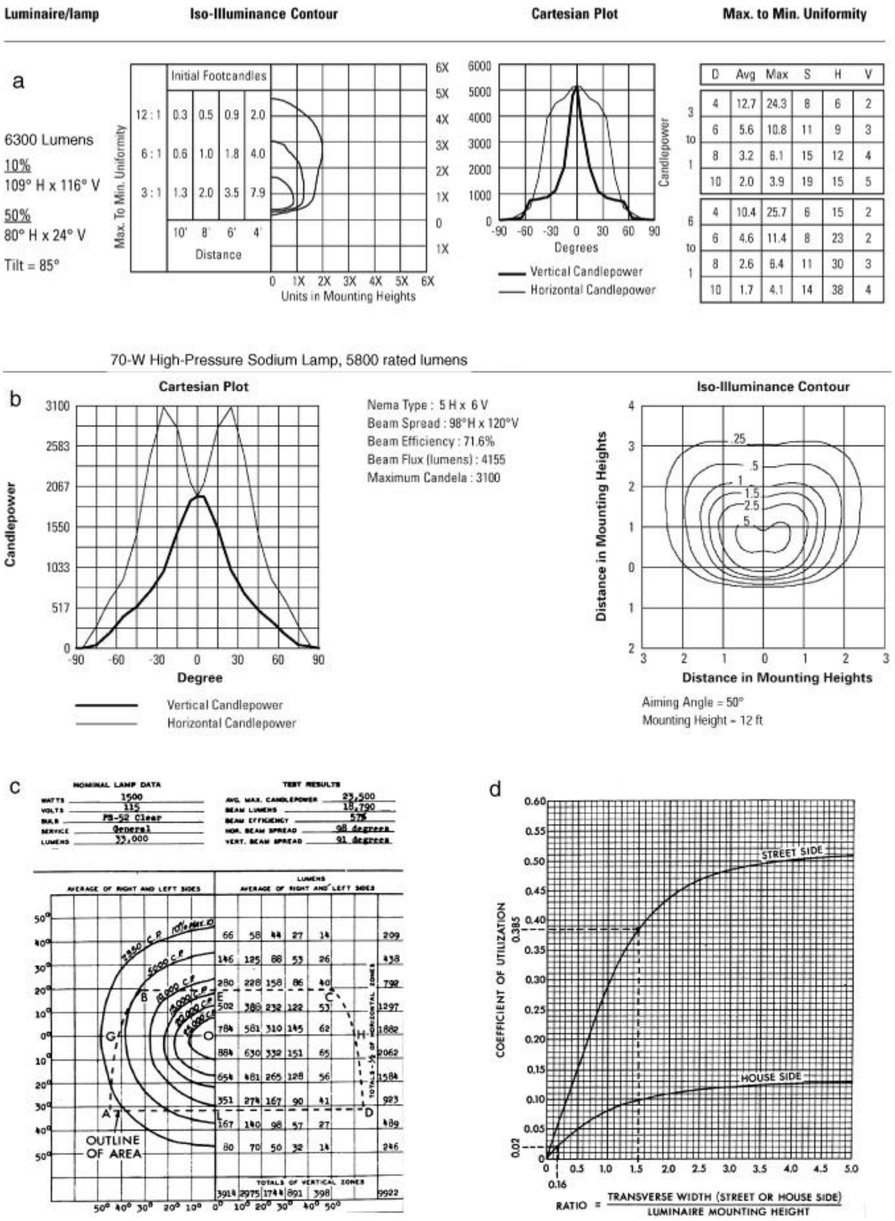


Figure 7-35. Data from an indoor luminaire photometric report. See Figure 11-12 in Chapter 11, Office Lighting, for a full indoor luminaire photometric report.



Candlepower	D	Avg	Max	S	H	V
3 to 1	4	12.7	24.3	8	6	2
	6	5.6	10.8	11	9	3
	8	3.2	6.1	15	12	4
	10	2.0	3.9	19	15	5
6 to 1	4	10.4	25.7	6	15	2
	6	4.6	11.4	8	23	2
	8	2.6	6.4	11	30	3
	10	1.7	4.1	14	38	4

Nema Type : 5 H x 6 V
Beam Spread : 98°H x 120°V
Beam Efficiency : 71.6%
Beam Flux (lumens) : 4155
Maximum Candela : 3100

NOMINAL LAMP DATA
WATTS 1500
VOLTS 115
BULB PS-52 Clear
SERVICE General
LUMENS 33,000

TEST RESULTS
AVG. MAX. CANDLEPOWER 23,500
BEAM LUMENS 18,790
BEAM EFFICIENCY 57%
HOR. BEAM SPREAD 98 degrees
VERT. BEAM SPREAD 91 degrees

66	58	44	27	14	209
146	125	88	53	26	438
280	228	158	86	40	792
502	388	232	122	53	1297
784	581	310	145	62	1882
884	630	332	151	65	2062
654	481	265	128	56	1584
351	274	167	90	41	923
167	140	98	57	27	489
80	70	50	32	14	246
3914	2975	1744	891	398	9922

Figure 7-36. Examples of outdoor luminaire photometric reports: (a) and (b) floodlight reports, (c) zonal lumens for a floodlight, and (d) coefficients of utilization for a street lighting luminaire.

Components of Luminaire Photometric Reports

Luminous Intensity Distribution. The luminous intensity distribution of a luminaire specifies its light distribution characteristics. Luminous intensities in various directions are specified in an angular coordinate system appropriate for the luminaire and its customary application. Most luminaires have luminous intensity distributions specified by luminous intensity values in directions given by angles in a spherical coordinate system. For indoor luminaires, the origin is down (nadir) (Figure 7-37). This is Type C photometry. The elevation (vertical) angle θ has the range 0° ≤ θ ≤ 180°. The azimuthal (horizontal) angle ψ has the range 0° ≤ ψ ≤ 360°. For some outdoor luminaires, usually floodlights, the origin is the primary aiming axis (Figure 7-38). This is Type B photometry. In this case the range of the two angles is -90° to 90°.

For indoor luminaires, the range of elevation (vertical) angles, θ, depends on the distribution of the luminaire. The range is usually 0° ≤ θ ≤ 90°, 90° ≤ θ ≤ 180°, or 0° ≤ θ ≤ 180°, depending on whether the luminaire emits light only downward, only upward, or both. Increments of 5° in θ are usually reported, though smaller steps are usually measured and sometimes reported if the luminous intensity distribution changes rapidly with elevation angle.

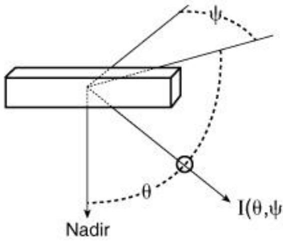


Figure 7-37. Coordinate system for indoor luminaire photometry; Type C.

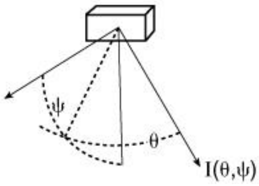


Figure 7-38. Coordinate system for outdoor luminaire photometry; Type B.

Indoor luminaires that exhibit axial symmetric distributions have luminous intensity reported for $\psi = 0°$. An incandescent downlight with lamp base up is a luminaire with an axially symmetric distribution. If the luminaire exhibits quadrilateral symmetry in the azimuthal angle, ψ, it is customary to report luminous intensity values for $0° \le \psi \le 90°$. A fluorescent troffer with a prismatic lens is a luminaire with a quadrilaterally symmetric distribution. If the luminaire exhibits bilateral symmetry in ψ, then data are reported for $0° \le \psi \le 180°$. A wall-mounted fluorescent indirect is a luminaire with a bilaterally symmetric distribution. In all cases the increments in ψ are usually 22.5°. For outdoor luminaires the range and increments are variable, the limits of each depending on the angular size of the beam.

The luminous intensity values reported for a luminaire are almost always from relative photometry, that is, lamps in the luminaires are assumed to be emitting their rated lumens. Light loss factors can be applied to account for actual field conditions.

The measurements are always far-field, that is, the distance at which measurements are made is large enough to consider the luminaire to be a point source. It is assumed that all of the luminaire lumens are emitted from the luminaire photometric center. This point is usually at the center of the opening of the luminaire, in the center of its lens, or at the geometric center of its lamps.

For many small luminaires, such as incandescent and fluorescent downlights, far-field measurements are not an issue. This is true also when the distance between luminaire and illuminated point is large compared to luminaire dimensions, as in flood lighting. But for large luminaires located near to illuminated surfaces, calculating illuminances with these luminous intensity values must be done with care. Examples of this situation are under cabinet luminaires or task lights. For more information see "Photometry as the Basis for Calculations" in Chapter 9, Lighting Calculations.

In either case, the luminous intensity distribution always gives a general idea of how light is distributed by the luminaire. A convenient way to convey this information graphically is to produce a polar plot of the luminous intensity values. The azimuthal (horizontal) angle in the spherical coordinate system is kept fixed and the elevation (vertical) angle is allowed to move from 0° to 90° or to 180°, with the luminous intensity value at each elevation angle being plotted. This data line represents one plane of luminous intensity distribution data. Similar data lines can be plotted for other planes. Cutoff, uniformity of illuminance, and light patterns can be inferred from such plots.

For indoor luminaires, luminous intensity distributions are reported usually in two ways: as an array of values and as a polar plot. In the polar plot, luminous intensities in an azimuthal plane are plotted with a single line, labeled with the azimuthal angle or the plane's orientation. Each azimuthal plane is plotted as a separate line (see the polar plot in Figure 7-35). For outdoor luminaires, luminous intensity distributions are usually reported in Cartesian plots. Luminous intensities in horizontal and vertical planes are reported (see the section labeled "Cartesian Plot" in Figure 7-36a).

Average Luminance in Various Viewing Directions. The definition of luminance can be extended to determine the average luminaire luminance, L_{ave}:

$$L_{ave}(\theta, \psi) = \frac{I(\theta, \psi)}{A'}$$

where $I(\theta,\psi)$ is the luminous intensity from the entire luminaire in direction (θ,ψ) and A' is the luminous area of the luminaire visible from that direction. This luminance gives a general idea of the luminaire's luminance and appearance but is meaningful only if the luminaire is homogeneous. In this case L_{ave} can be used to assess the potential for discomfort glare.

If the luminaire exhibits large inhomogeneities in luminance, this value can significantly underestimate the luminance of some parts of the luminaire. Average luminance is reported in indoor luminaire photometric reports.

Zonal Lumens. For indoor luminaires, nested conic solid angle cones can be established with apexes at the luminaire photometric center. Given the size of these cones and the luminous intensity values in them, the number of lumens in each cone can be determined. Each cone defines a conic zone, and the lumens within each are the luminaire zonal lumens. Any azimuthal asymmetry present in the luminous intensity distribution is not apparent, since only the number of lumens in each zone is reported.

Many outdoor luminaires have intensity distributions that are very asymmetric. In terms of Type B photometry, the distribution in the vertical is very different than that in the horizontal. In addition, the change in intensity with angle can be very great, often having a gradient exceeding 1000 cd/degree. For these reasons the zones used to report zonal lumens are small and usually of different angular size in the horizontal and vertical.

Efficiency. The total number of lumens emitted by the luminaire can also be calculated from the luminous intensity distribution. Dividing this value by the total number of lumens emitted by the lamps in the luminaire gives the efficiency. This is a measure of how effectively the lamp and the reflector and/or refractor work to get the lamp lumens out of the luminaire.

Coefficients of Utilization. As described in Chapter 9, Lighting Calculations, coefficients of utilization for indoor luminaires describe the effectiveness with which the luminaire puts lamp lumens onto the horizontal workplane of a rectangular room. Tables of these values for a range of room surface reflectances and room shapes are part of a photometric report for an indoor luminaire that can be used for general or ambient lighting. The values of coefficients of utilization typically are between 0 and 1. The coefficients may be reported as decimal values, or they may be reported as integers that must be divided by 100 before being used in the lumen method to predict average illuminance.

Some indoor luminaires are not designed or intended to produce general lighting, and coefficients of utilization are not provided. Accent and wall-wash luminaires are examples.

Spacing Criterion. Spacing criterion is a low-precision indicator of how far apart general lighting luminaires can be spaced while providing acceptable uniformity of horizontal illuminance.

Glare Assessment. For some indoor, direct, general lighting luminaires, values of Visual Comfort Probability (VCP) are reported. If present, the table gives VCP values for a range of room sizes and luminaire mounting heights. VCP values are provided only for luminaires with significant down light and with luminances no higher than that produced by a fluorescent lamp. These limitations come from the limited applicability of VCP (see Chapter 9, Lighting Calculations).

Other Components. Some luminaire photometric reports provide additional information depending on the application. Examples include wall illuminances for wall-wash luminaires, iso-illuminance contours for outdoor area luminaires, and roadway coefficients of utilization for roadway luminaires (see sections labeled "Iso-Illuminance Contour" and "Max. to Min. Uniformity" in Figure 7-36).

Effects of Luminaire Photometrics

Luminaires and Their Lighting Effects. Luminaires light architecture, people, and visual tasks. Revealing architecture is often one of the most important purposes of lighting. Curves, coves, soffits, arches, vaults, coffers, and other architectural forms require light and shadow to be seen. A luminaire with the proper luminous intensity distribution is necessary for successful lighting in such cases.

Luminaires can produce patterns of light that are interesting and important to the appearance of the space being lighted. Scalloping, wall washing, and accenting are examples. A proper luminous intensity distribution is essential. Size of scallops, uniformity of wall washing, and sharpness of accenting depend on the distribution of the luminaire and to some extent on the lighted surface's texture and color.

Luminaires are also used to light visual tasks. The requirement for contrast and luminance determine the luminous intensity distribution and placement of luminaires. For direct lighting, computer VDTs usually require luminaires with a sharp cutoff luminous intensity distribution and very careful positioning if screen images are to be avoided. If sufficient contrast of glossy horizontal tasks is to be achieved, veiling reflections must be avoided. This requires light from the side. A luminaire with a wide luminous intensity distribution can be used to achieve this. For more information on lighting spaces containing VDTs, see Chapter 11, Office Lighting.

The lighting effect produced by a luminaire is determined largely by its intensity distribution. Choosing the appropriate luminaire often means choosing the appropriate intensity distribution. In a room lighted exclusively by table or floor lamps, the type of shade and location of the light sources becomes more critical. Deep, narrow, or opaque shades do not provide useful task lighting; they restrict the spread of both downward and upward light. Figure 7-39 illustrates the difference in performance between a 360-mm (14-in.) and a 410-mm (16-in.) shade. Listed here are common forms of lighting, characterized by the intensity distribution of the luminaires, their placement, and the resulting effects.

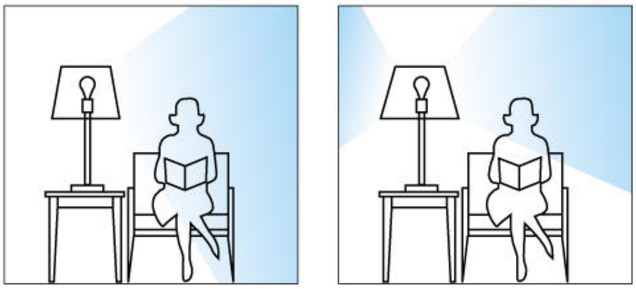


Figure 7-39. Influence of shade dimensions on light distribution of portable luminaires. Shade on the left is 360 mm (14 in.) wide. Shade on the right is 410 mm (16 in.) wide.

Direct Lighting. The distribution may vary from widespread to highly concentrated, depending on the reflector material, finish, and contour and on the shielding or optical control media employed. Concentrated distributions can cause sharp shadows.

Semidirect Lighting. The characteristics are essentially the same as for direct lighting except that the upward component tends to soften shadows and improve room brightness relationships. Care should be exercised with close-to-ceiling mounting of some types to prevent overly bright spots directly above the luminaires. Efficiencies can approach and sometimes exceed those of well-shielded direct units.

Direct-Indirect Lighting. Very little light is emitted at angles near the horizontal. Since this characteristic results in lower luminances in the direct-glare zone, direct-indirect luminaires are usually more suitable than general diffuse luminaires, which distribute the light almost equally in all directions.

Indirect Lighting. In a well-designed installation the entire ceiling becomes the primary source of light, and shadows in the space are virtually eliminated. Also, since the luminaires direct very little light downward, both direct and reflected glare are minimized if the installation is well planned. It is also important to suspend the luminaires a sufficient distance below the ceiling to obtain reasonable uniformity of ceiling luminance without excessive luminance immediately above the luminaires.

Semi-Indirect Lighting. The characteristics of semi-indirect lighting are similar to those of indirect systems except the downward component usually produces a luminaire luminance that closely matches that of the ceiling. However, if the downward component becomes too great and is not properly controlled, direct or reflected glare may result. An increased downward component improves the utilization of light over that for indirect lighting. This factor makes higher illuminances possible with fewer semi-indirect luminaires and without excessive ceiling luminance.

Luminous Intensity Distribution Forms and Resulting Effects. Depending on the intended application and the lamp used, luminaires can have luminous intensity distributions that range from the completely nondirectional or diffuse, through wide- and narrow-spread distributions, to very narrow beams. Between these extremes are distributions for uniformly illuminating horizontal surfaces, producing a smooth gradient of luminance on a wall, or producing a high-luminance scallop on a wall. Some luminous intensity distributions are asymmetric as in the case of a wall washer, where more light is sent to illuminate the wall than the room. Figures 7-40 through 7-46 give examples of luminaires, luminous intensity distributions, and the illuminances and luminances they produce. In each case, the effect of only a single luminaire is shown. The calculations for these tables assume that the intensity distribution across the luminous area of the luminaire is uniform (see Chapter 9, Lighting Calculations).

Indoor luminaires are depicted in Figures 7-40 through 7-45. For these luminaires, the horizontal illuminance is that produced in the middle of a small room (6 m × 6 m × 3 m) with typical reflectances of 0.80, 0.50, 0.20 for the ceiling, walls, and floor respectively. For the horizontal illuminance the luminaire is in the center of the room. For the vertical illuminance, the luminaire is placed close to one wall. In both cases, room surface luminances are calculated and displayed as a computer-generated image of the room. These depictions are not meant to show a luminaire in its intended mounting, but rather to show the nature of its intensity distribution. Outdoor luminaires are depicted in Figure 7-46. In this case the illuminated area is 15 m × 15 m × 15 m and some of the reflectances of the surfaces are zero.

Thermal Performance of Luminaires

In general, the thermal performance of luminaires cannot be isolated from the way in which they are used. In most interior applications and some exterior applications, luminaires are thermally coupled to their environment. However, there are some thermal issues that can be essentially isolated. Three of these are the effect of the luminaire on the operating temperature of the lamp, the effect of lamp heat on luminaire materials, and the effects of air handling.

Lamp Operating Temperature. The performance of many lamp types is dependent on the bulb wall temperature. This is particularly true for fluorescent lamps, for which both light output and electrical power input--and thus luminous efficacy--vary with the temperature of the coldest spot on the bulb wall. The lamp temperature in turn is a function of the heat balance between the lamp and its surroundings. Electrical energy provided to the lamp is partly converted into light, the balance being dissipated through the mechanisms of thermal (infrared) radiation, convection, and conduction.

Even the most efficient lamps convert only a moderate percentage of their electrical power input into visible light, as shown in Figures 7-47, 7-48, and 7-49. The efficacy varies from a low of 10% for incandescent lamps, to approximately 19% for fluorescent lamps, to a high of 28% for low-pressure sodium lamps. With the exception of low-pressure sodium lamps, the greatest percentage of energy converted by most lamps is dissipated as infrared radiation. The relative energy dissipation by convection and conduction depends on airflow conditions and the temperature around the lamp, and on the details of the lamp mounting and luminaire design.

Effects on Luminaire Materials. Since lamps emit energy at infrared as well as visible wavelengths, it is useful to examine the radiant properties of materials used in luminaires. The transmittance and reflectance of most materials are wavelength dependent. Thus, for example, a lens material can be selected that has high visible transmittance but low infrared transmittance, thereby reducing the amount of heat radiated from the luminaire. However, the heat that is trapped in the luminaire causes the lamp temperature to be greater than it would be otherwise. This may be desirable if higher lamp temperatures are needed to boost efficiency, but consideration should be given to the possibility of increased thermal stresses within the luminaire. Figure 7-50 lists the radiant properties of several materials that are commonly used in lighting systems, including the percentage reflectance and transmittance at selected wavelengths.

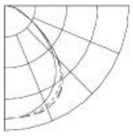
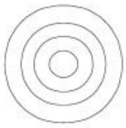
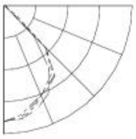
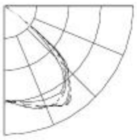
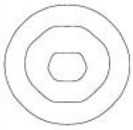
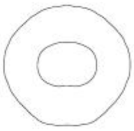
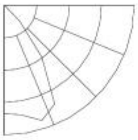
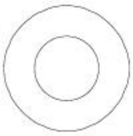
Air Handling. The thermal performance of an indoor luminaire can also include its ability to deliver or extract air from a space. These heat-transfer luminaires often are referred to as air-handling luminaires and are constructed to add or remove heat from a space by moving air. They are constructed to minimize the effect of the air on the lamp bulb temperature.

Testing and Compliance

Luminaires should be installed in accordance with regional safety regulations and be certified for safety by an organization that is accredited in the region in which the luminaire is installed. National and local electrical codes sometimes determine the type of lighting equipment that can be used and the method of installation. Typically, luminaires are tested in accordance with national or international safety standards. These establish a minimum level of safety to reduce the likelihood of fire or electric shock.

United States. Luminaire installation practices in the United States are dictated by the National Electric Code (NEC),[3] which is sponsored by the National Fire Protection Association. This code is revised every three years. The NEC requires that equipment be listed as meeting minimum safety standards by an organization that is acceptable to the municipal authority having jurisdiction over the installation. This authority is typically the local electrical inspector. The American National Standards Institute (ANSI) has accredited Underwriters Laboratories (UL) as the standards-making organization for luminaires in the United States. Virtually all local authorities require luminaires to be UL listed. They sometimes require other certifications as well.

The Occupational Safety and Health Administration (OSHA) accredits some laboratories to evaluate products using ANSI/UL standards. Such a laboratory is designated as a National Recognized Testing Laboratory.

Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Recessed troffer with two fluorescent lamps prismatic lens. Used for general lighting.					
Recessed troffer with two fluorescentlamps and louvers. Sharp cutoff for lighting spaces where VDTs are used.					
Downlight using a compact fluorescent lamp and baffles for general lighting.					
Downlight using a compact fluorescent lamp for general lighting.					
Downlight using a 100-W A-19 lamp for general lighting.					

"Sharp cutoff" refers to an abrupt fall off, usually to zero, of the intensity in a distribution. Essentially no light is emitted above this cutoff angle.

Figure 7-40. Interior downlight luminaire luminous intensity distributions.

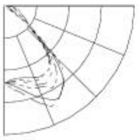
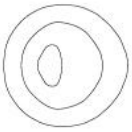
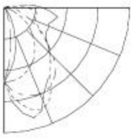
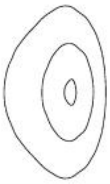
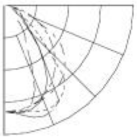
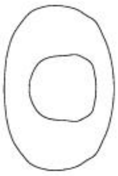
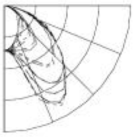
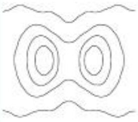
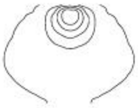
Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Recessed wall washer with a compact fluorescent lamp, spun reflector, and "kicker" to produce an asymmetric distribution.					
Ceiling surface-mounted linear wall washer with single fluorescent lamp.					
Recessed cove wall washer using one fluorescent lamp.					
Recessed linear wall washer using one T-8 fluorescent lamp.					
Downlight using a compact fluorescent lamp and asymmetric reflector for lighting corridors.					

Figure 7-41. Interior wall-wash luminaire luminous intensity distributions.

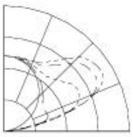
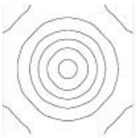
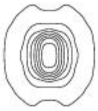
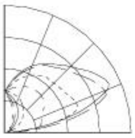
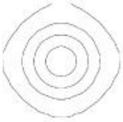
Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Pendant-mounted linear indirect with two fluorescent lamps. Suspended 0.3 m from ceiling.					
Pendant-mounted linear indirect with two fluorescent lamps. Suspended 0.6 m from ceiling.					
Linear cove mounted with one fluorescent lamp. Suspended 0.6 m from ceiling.					
Pendant-mounted indirect with one 175-W metal halide lamp. Suspended 0.6 m from ceiling.					

Figure 7-42. Interior indirect luminaire luminous intensity distributions.

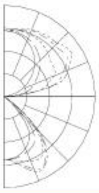
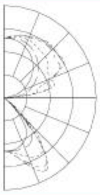
Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Pendant-mounted exhibiting 70% uplight and 30% downlight. With two T-8 fluorescent lamps suspended 0.3 m from the ceiling.					
Pendant-mounted exhibiting 70% uplight and 30% downlight. With two T-5 fluorescent lamps suspended 0.3 m from the ceiling.					

Figure 7-43. Interior direct/indirect luminaire luminous intensity distributions.

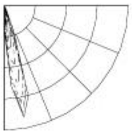
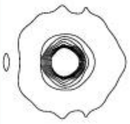
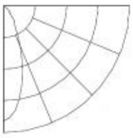
Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Recessed accent luminaire mounted 0.6 m from wall with 50-W MR16 tungsten-halogen lamp.					
Track and four luminaires with 50-W MR16 tungsten-halogen lamps, having beams of 10°, 20°, 40°, and 60°, aimed at the wall.					

Figure 7-44. Interior accent luminaire luminous intensity distributions.

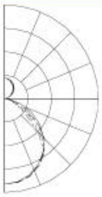
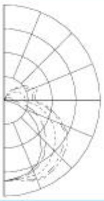
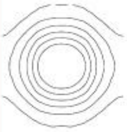
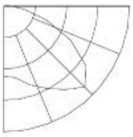
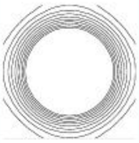
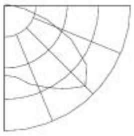
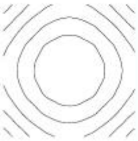
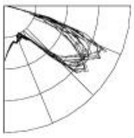
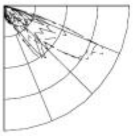
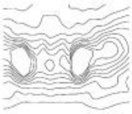
Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire in Center of Ceiling)	Visual Effect (Luminaire at Edge of Ceiling)
Surface-mounted luminaire with reflector and two T-12 fluorescent lamps.					
Strip luminaire with two T-12 high output (HO) fluorescent lamps.					
High-bay luminaire with 400-W metal halide lamp.					
Low-bay luminaire with 400-W metal halide lamp.					

Figure 7-45. Interior industrial luminaire luminous intensity distributions.

Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire Mounted Away from the Wall)	Visual Effect (Luminaire Mounted Near the Wall)
Post-top luminaire for area lighting. With 250-W metal halide lamp.					
Parking lot lighting luminaire having a sharp cutoff luminous intensity distribution. With 400-W metal halide lamp.					
Floodlight for building lighting. With beam and 400-W metal halide lamp.					
Floodlight for building lighting. Narrow beam and 400-W metal halide lamp.					

"Sharp cutoff" refers to an abrupt fall off, usually to zero, of the intensity in a distribution. Essentially no light is emitted above this cutoff angle.

Figure 7-46. Exterior luminaire luminous intensity distributions

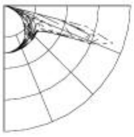
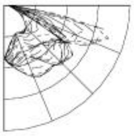
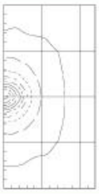
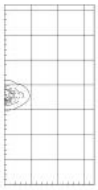
Luminaire Description	Luminous Intensity Distribution	Horizontal Illuminance	Vertical Illuminance	Visual Effect (Luminaire Mounted Away from the Wall)	Visual Effect (Luminaire Mounted Near the Wall)
Cobra head luminaire for street lighting. Cutoff luminous intensity distribution, flat lens and 200-W metal halide lamp.					
Cobra head luminaire for street lighting. Drop lens and 200-W metal halide lamp.					
Sports lighting luminaire with wide beam and 1000-W metal halide lamp.					
Sports lighting luminaire with narrow beam and 1000-W metal halide lamp.					

Figure 7-46 (continued). Exterior luminaire luminous intensity distributions.

Canada. Luminaire installation practices in Canada are dictated by the Canadian Electric Code (CEC),[4] published by the Canadian Standards Association (CSA). This code is revised every five years. The CEC requires that equipment be submitted for examination and testing by an acceptable certification agency. The CSA is the standards-making organization for luminaires in Canada. The Standards Council of Canada accredits laboratories in Canada to evaluate luminaires using CSA standards. The accredited laboratory labels equipment that meets these standards.

Mexico. Luminaire installation practices in Mexico are dictated by the Mexican government through a series of Mexican Governmental Obligatory Safety standards. Products that comply with the Mexican requirements bear the mark NOM. Laboratories are accredited by the Mexican Board of Accreditation for Testing Laboratories.

European Community. Luminaires that are exported to the European Community are required to bear the CE mark indicating that the manufacturer is in compliance with all assessment procedures required for luminaires. Essentially, luminaires are required to comply with applicable International Electrotechnical Commission requirements.

SPECIFYING AND USING LUMINAIRES

The successful use of luminaires requires an understanding of the lighting task they accomplish and the environment in which they operate. An appropriate luminaire for the lighting task has the proper photometric characteristics and is compatible with the environment. (Photometric characteristics are considered in the sections above.) Electrical, thermal, mechanical, acoustical, and maintenance aspects of a luminaire's environment can affect its performance.

Electrical

Every luminaire, as part of a lighting system, should also be considered part of an electrical wiring system. Branch-circuit panel boards and the feeders that serve them must be designed to carry the lighting electrical load. The characteristics of the electrical system, such as voltage, phases, and capacity, must be known in order to design circuits or to choose any controls such as switches, dimmers, or occupancy sensors.

Designers should know the fundamentals of electrical systems design to ensure that they can optimize flexibility and cost. All electrical systems in the United States must be designed and installed in accordance with the provisions and requirements of the NEC[3] as well as state and local codes. To assure that these requirements are met, the electrical system should always be designed by a licensed professional engineer.

The first step in the design of a coordinated lighting and electrical system is to determine the utilization voltage of the system. For new buildings, this information may be obtained from the utility company or from the engineer. In existing buildings, the information may be obtained from the maintenance engineer by measurement or by reading the name plate data on existing panel boards.

The electrical characteristics most often encountered in the United States are 120/240 V, single phase, three wire for residential buildings; 120/208 V, three phase, four wire for older or small commercial buildings; and 277/480 V, three phase, four wire for many newer and large commercial buildings. In Canada, the voltages are 120/240 V, single phase, three wire for residential buildings; 347/600 V, three phase, four wire for commercial buildings; and 277/480 V, three phase, four wire for commercial buildings in some provinces and areas. In Mexico, the electrical characteristics are 127/220 V, three phase, four wire for residential and commercial buildings and 220/440 V, three phase, four wire for industrial buildings. It should be noted, however, that branch-circuit wiring for lighting in residential and commercial applications in Mexico uses 127 V, single phase.

When the engineer is faced with a 277/480-V source of power, step-down transformers (to obtain 120/208 V) are required for use with incandescent sources. The designer must exercise caution with step-down transformers because they may also be used for power to appliance and receptacle circuits, leaving little or no power for incandescent lighting. If involved in a project early enough, the designer may wish to request that a portion of the transformer capacity be held in reserve for special lighting.

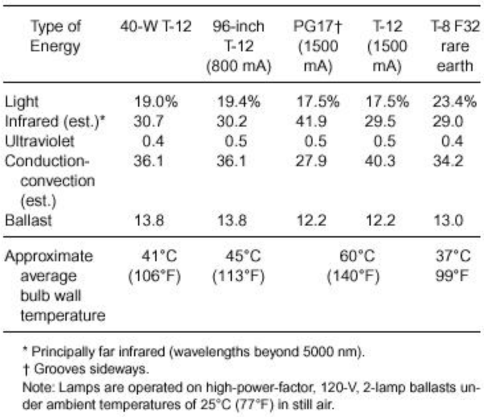
The location(s) of the panel boards and transformers are probably dictated by the architecture of the building. To exemplify, a high-rise office building probably has one electrical room per floor, with vertical electrical distribution of 277/480 V and a step-down transformer for 120/208 V on each floor.

Often the lighting designer is requested to state the power density prior to the completion of the design process. There are several sources of information available to assist in obtaining an answer; they include, in addition to past experience, the NEC,[3] ASHRAE/ANSI/IESNA 90.1,[5] and state and local codes.

In response to the need for effective energy utilization, controls have become a more integral part of lighting design. Various techniques for control are at the disposal of designers. These lighting control tools include two- or three-level switching of three- or four-lamp fluorescent lighting luminaires, and photoelectric control for daylight and occupancy/motion sensors. For a discussion of control strategies see Chapter 27, Lighting Controls.

High-power-factor ballasts are recommended for compact fluorescent lamp luminaires and the use of 208 or 480 V for HID sources both indoors and outdoors. There are code restrictions on the use of 480-V lighting equipment. The importance of using high-power-factor ballasts can be demonstrated by comparing them with normal-power-factor ballasts with the help of an example. Using two 26-W quad compact fluorescent lamps operating at 120 V, the electrical characteristics and hence the electrical circuit data are as indicated in the following table:

Figure 7-47. Energy Output for Some Fluorescent Lamps of Cool White Color



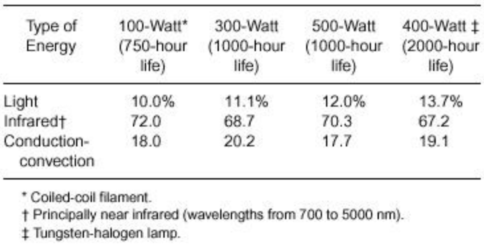
Type of Energy	40-W T-12	96-inch T-12 (800 mA)	PG17† (1500 mA)	T-12 (1500 mA)	T-8 F32 rare earth
Light	19.0%	19.4%	17.5%	17.5%	23.4%
Infrared (est.)*	30.7	30.2	41.9	29.5	29.0
Ultraviolet	0.4	0.5	0.5	0.5	0.4
Conduction-convection (est.)	36.1	36.1	27.9	40.3	34.2
Ballast	13.8	13.8	12.2	12.2	13.0
Approximate average bulb wall temperature	41°C (106°F)	45°C (113°F)	60°C (140°F)		37°C 99°F

* Principally far infrared (wavelengths beyond 5000 nm).

† Grooves sideways.

Note: Lamps are operated on high-power-factor, 120-V, 2-lamp ballasts under ambient temperatures of 25°C (77°F) in still air.

Figure 7-48. Energy Output for Some Incandescent Lamps



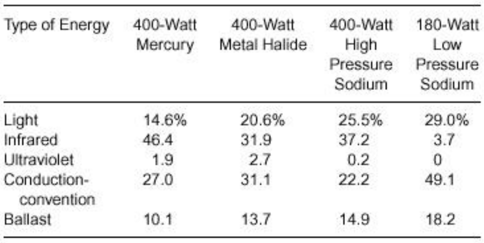
Type of Energy	100-Watt* (750-hour life)	300-Watt (1000-hour life)	500-Watt (1000-hour life)	400-Watt ‡ (2000-hour life)
Light	10.0%	11.1%	12.0%	13.7%
Infrared†	72.0	68.7	70.3	67.2
Conduction-convection	18.0	20.2	17.7	19.1

* Coiled-coil filament.

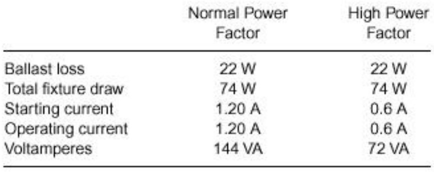
† Principally near infrared (wavelengths from 700 to 5000 nm).

‡ Tungsten-halogen lamp.

Figure 7-49. Energy Output for LPS and Three High Intensity Discharge Lamps



Type of Energy	400-Watt Mercury	400-Watt Metal Halide	400-Watt High Pressure Sodium	180-Watt Low Pressure Sodium
Light	14.6%	20.6%	25.5%	29.0%
Infrared	46.4	31.9	37.2	3.7
Ultraviolet	1.9	2.7	0.2	0
Conduction-convention	27.0	31.1	22.2	49.1
Ballast	10.1	13.7	14.9	18.2

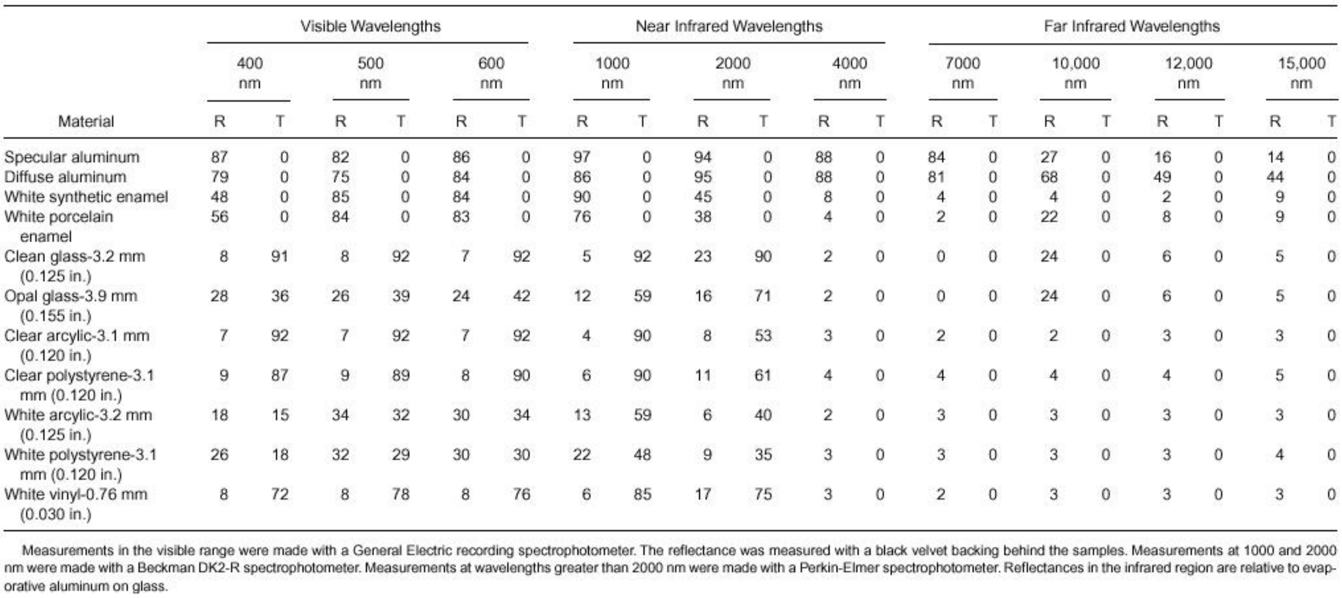


	Normal Power Factor	High Power Factor
Ballast loss	22 W	22 W
Total fixture draw	74 W	74 W
Starting current	1.20 A	0.6 A
Operating current	1.20 A	0.6 A
Voltamperes	144 VA	72 VA

Although the total fixture draw remains constant, the operating current increases and therefore the voltamperes increase. The net result in this example is that using normal-power-factor ballasts allows a maximum of 13 luminaires on a 20-A, 120-V circuit. Using a high-power-factor ballast allows a maximum of 20 luminaires on the same circuit.

Caution is required in the use of square wave inverters for emergency power with high-power-factor, compact fluorescent ballasts. The power-factor-correcting capacitor used in the ballast may look like a short circuit to the square wave output of the inverter and create circuit breaker problems.

Electronic ballasts have an inherent harmonic distortion that may damage the neutral conductor(s) of the electrical system. In some cases, it may become necessary to oversize the neutral conductor. For further information on electronic ballasts, see Chapter 6, Light Sources.



	Visible Wavelengths						Near Infrared Wavelengths						Far Infrared Wavelengths							
	400 nm		500 nm		600 nm		1000 nm		2000 nm		4000 nm		7000 nm		10,000 nm		12,000 nm		15,000 nm	
Material	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T	R	T
Specular aluminum	87	0	82	0	86	0	97	0	94	0	88	0	84	0	27	0	16	0	14	0
Diffuse aluminum	79	0	75	0	84	0	86	0	95	0	88	0	81	0	68	0	49	0	44	0
White synthetic enamel	48	0	85	0	84	0	90	0	45	0	8	0	4	0	4	0	2	0	9	0
White porcelain enamel	56	0	84	0	83	0	76	0	38	0	4	0	2	0	22	0	8	0	9	0
Clean glass-3.2 mm (0.125 in.)	8	91	8	92	7	92	5	92	23	90	2	0	0	0	24	0	6	0	5	0
Opal glass-3.9 mm (0.155 in.)	28	36	26	39	24	42	12	59	16	71	2	0	0	0	24	0	6	0	5	0
Clear arcylic-3.1 mm (0.120 in.)	7	92	7	92	7	92	4	90	8	53	3	0	2	0	2	0	3	0	3	0
Clear polystyrene-3.1 mm (0.120 in.)	9	87	9	89	8	90	6	90	11	61	4	0	4	0	4	0	4	0	5	0
White arcylic-3.2 mm (0.125 in.)	18	15	34	32	30	34	13	59	6	40	2	0	3	0	3	0	3	0	3	0
White polystyrene-3.1 mm (0.120 in.)	26	18	32	29	30	30	22	48	9	35	3	0	3	0	3	0	3	0	4	0
White vinyl-0.76 mm (0.030 in.)	8	72	8	78	8	76	6	85	17	75	3	0	2	0	3	0	3	0	3	0

Measurements in the visible range were made with a General Electric recording spectrophotometer. The reflectance was measured with a black velvet backing behind the samples. Measurements at 1000 and 2000 nm were made with a Beckman DK2-R spectrophotometer. Measurements at wavelengths greater than 2000 nm were made with a Perkin-Elmer spectrophotometer. Reflectances in the infrared region are relative to evaporative aluminum on glass.

Figure 7-50. Properties of Materials Used in Luminaires (*T* = Percent Transmittance and *R* = Percent Reflectance at the Selected Wavelength)

Thermal

The interactions between building systems as well as the response of the building to exterior conditions and occupant activities influence the performance of each of the building components. In this regard, lighting system performance is dependent on the building's thermal environment.

The major thermal considerations related to the performance of a lighting system are the dependence of its light output and efficiency on lamp temperature, and the cooling load due to energy dissipated by it. The effects of the thermal environment on light output and efficiency fall primarily within the realm of the lighting designer; the cooling load due to lighting is of more interest to the mechanical systems designer.

Essentially all of the electrical power provided to the lighting system is dissipated into the building space as heat, with the exception of any light radiated directly out of the building through transparent surfaces. The heat gain from the lighting system either contributes to the cooling load or helps to satisfy the heating requirements, depending on the building conditions. Most large commercial buildings have large interior heat sources, such as computers and other electrical equipment, and need to be cooled throughout the year. Exterior zones in large buildings, and smaller buildings with high ratios of surface area to volume, may require heating in winter. In buildings without air conditioning, the heat from lighting systems can overheat occupant spaces.

Lighting can account for 25 to 50% of building electrical energy usage. Electrical energy to meet the cooling loads imposed by lighting can add another 10 to 20%. Another important factor is that the time of day when the lighting load is greatest corresponds to the time of peak building cooling load demand and electric utility demand and of greatest electrical energy unit cost. Thus, any improvement in lighting system efficiency can save lighting energy, cooling energy, and energy costs and reduce cooling equipment capacity requirements.

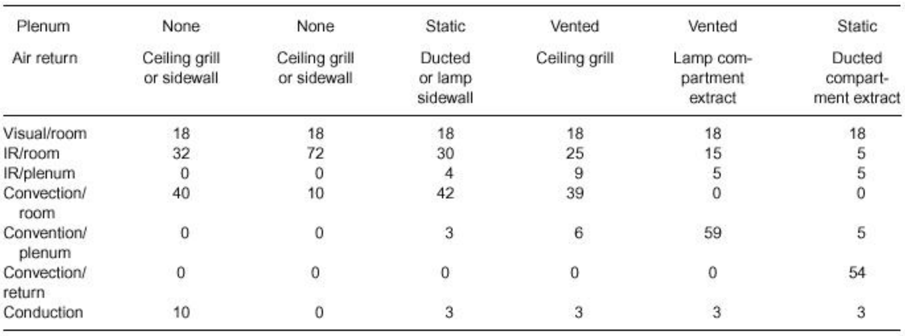
Lighting Energy Distribution Fractions.

In general, the electrical energy input to a luminaire is dissipated via the following mechanisms:

- Downward visible light
- Upward visible light
- Downward infrared radiation
- Upward infrared radiation
- Downward convection
- Upward convection
- Convection to return air
- Conduction

The magnitude of each of these components depends on the type of lamp and luminaire, the HVAC design, and the design of the building space, particularly the presence or absence of a ceiling plenum. Some of the fractions may be zero for some configurations. The table in Figure 7-51 lists typical values of the lighting energy distribution fractions for various luminaire, HVAC, and room types.[6] In this table, all visible light output, both up and down, is lumped together, since the split can vary greatly depending on the luminaire photometric distribution.

Several test methods have been employed to assess the total energy distribution from a particular luminaire. One involves an adaptation of photometric techniques. Two others involve calorimetry, including the use of continuous-water-flow[7] and continuous-air-flow[8,9] calorimeters. In one study, though procedures and equipment varied widely, the test results were of the same order of magnitude.[10]



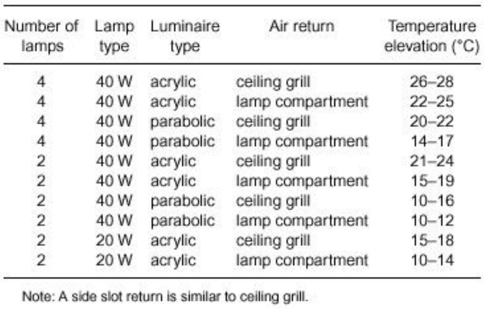
Plenum	None	None	Static	Vented	Vented	Static
Air return	Ceiling grill or sidewall	Ceiling grill or sidewall	Ducted or lamp sidewall	Ceiling grill	Lamp compartment extract	Ducted compartment extract
Visual/room	18	18	18	18	18	18
IR/room	32	72	30	25	15	5
IR/plenum	0	0	4	9	5	5
Convection/ room	40	10	42	39	0	0
Convention/ plenum	0	0	3	6	59	5
Convection/ return	0	0	0	0	0	54
Conduction	10	0	3	3	3	3

Figure 7-51. Lighting Energy Distribution Percentages

Testing guides for determining the thermal performance of luminaires have been published by IESNA, the Air Diffusion Council (ADC), and the National Electrical Manufacturers Association (NEMA). The IESNA issues an approved test method that considers the effect of plenum temperature and air return on the light output. The test also provides data on the manner in which heat distribution and power input depend on the return airflow through the luminaire.[11]

Lamp Temperature as a Function of Lighting System Design. Fluorescent lamps are widely used in commercial and industrial spaces, and their performance is strongly dependent on lamp wall temperature. The type of fixture and its location relative to supply and return air ducts influence the lamp temperature and therefore performance. A convenient way of characterizing lamp thermal performance is in terms of the elevation of lamp temperature above ambient air temperature for each luminaire and HVAC configuration. This allows the determination of the lamp temperature for any ambient air temperature by adding the lamp temperature elevation to the air temperature.

For example, an unvented four-lamp fixture with an acrylic lens usually has hotter lamps than the same fixture if vented, a similar fixture with two lamps, or a fixture with an open-cell diffuser. For each fixture type and airflow configuration, the possible lamp temperatures span a fairly narrow range, approximately 3 to 6°C. Some variation in lamp temperature can be obtained by changing the airflow rate, but this has a limited effect unless lamp compartment extract is used.



Number of lamps	Lamp type	Luminaire type	Air return	Temperature elevation (°C)
4	40 W	acrylic	ceiling grill	26–28
4	40 W	acrylic	lamp compartment	22–25
4	40 W	parabolic	ceiling grill	20–22
4	40 W	parabolic	lamp compartment	14–17
2	40 W	acrylic	ceiling grill	21–24
2	40 W	acrylic	lamp compartment	15–19
2	40 W	parabolic	ceiling grill	10–16
2	40 W	parabolic	lamp compartment	10–12
2	20 W	acrylic	ceiling grill	15–18
2	20 W	acrylic	lamp compartment	10–14

Note: A side slot return is similar to ceiling grill.

Figure 7-52. Lamp Temperature Elevations

Most fluorescent lamps are designed to operate most efficiently with a minimum lamp wall temperature of about 40°C. For further information on the thermal performance of fluorescent lamps, see Chapter 6, Light Sources. A fixture with an acrylic lens operates about 6 to 8°C warmer than a similar open-cell parabolic fixture. Lamp compartment air return reduces the lamp temperature by about 4 to 6°C. A two-lamp fixture operates about 4 to 7°C cooler than a similar four-lamp fixture. Lamp temperatures are very similar with ceiling grill and side slot returns.

Figure 7-52 lists ranges of minimum lamp wall temperature elevations above ambient air temperature for various luminaire and HVAC design configurations. These values were determined from full-scale testing.[6]

Cooling Load Due to Lighting. Luminaire mounting has an important role in the distribution of thermal energy. The ASHRAE Fundamentals Handbook covers the calculation of the space load due to lighting for various luminaires and ventilation arrangements.[12] Figure 7-53 illustrates typical heat flows for various types of ceiling-to-luminaire relationships. The total energy distribution involves all three mechanisms of heat transfer: radiation, conduction, and convection. The illustration shows a fluorescent lamp luminaire, but HID luminaires exhibit similar patterns. The input of the suspended luminaire in Figure 7-53a would be convected and radiated in all directions, to be reflected or absorbed and reradiated. Essentially all of the input energy would remain within the occupied space.

Heat transfers from the surface-mounted semidirect luminaire in Figure 7-53b involve radiation, conduction, and convection. Assuming good contact with the ceiling, upper surfaces of the luminaire transfer energy to or from the ceiling by conduction. Since many acoustical ceiling materials are also good thermal insulators, it may be assumed that temperatures within the luminaire are elevated. Thus, lower luminaire surfaces tend to radiate and convect to the space below at a somewhat higher rate. Unless the ceiling material is a good heat conductor and can reradiate above, essentially all of the input energy remains in the space.

A different situation exists when components of the system are separated from the space. The recessed luminaire in Figure 7-53c distributes some portion of its input wattage above the suspended ceiling. The actual ratio is a function of the luminaire design and plenum and ambient conditions. For most recessed static luminaires, the ratio is very nearly 50% above the ceiling and 50% below.

Heat-transfer recessed luminaires are illustrated in Figure 7-53e. Here, the convected and radiated components to the space have been reduced considerably, while the upward energy has increased correspondingly. Under certain conditions it is possible for the space load to consist almost entirely of light energy. The majority of the power input to the luminaire is directed upward, where it can be captured by the system and be subject to some form of control. Laboratory tests conducted in accordance with IESNA procedures[11] provide energy distribution data for evaluative purposes. However, the total system must be evaluated, because heat removal to the plenum may raise plenum temperatures, causing conductive heat transfer back through the ceiling and floor to the space below and above, thereby adding thermal load back to the space.

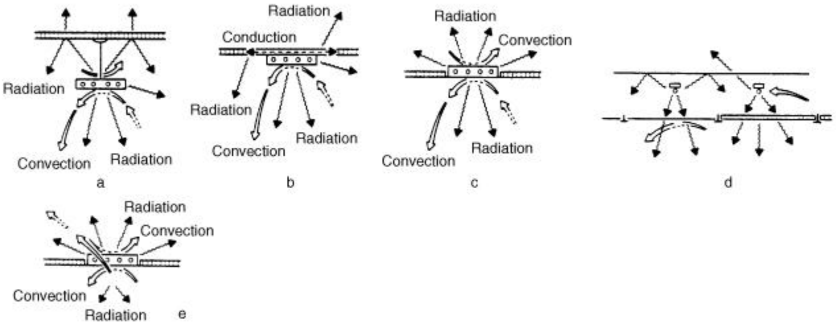


Figure 7-53. Effect of the ceiling-to-luminaire relationship on the lighting system heat transfer. The fluorescent luminaire has a direct-indirect total energy distribution classification. (a) Suspension-mounting, (b) surface mounting, (c) recessed, (d) luminous and louvered ceiling, and (e) heat transfer luminaire.

Task-ambient lighting systems have a different lighting energy distribution. Care must be exercised in the selection of the cooling load factor (CLF) used in calculations of space load. Depending on the installation, it may be necessary to calculate task and ambient heat loads separately. It is possible to have both systems completely within the space. This is the case if suspended or surface-mounted luminaires are used for ambient lighting, with task lighting being incorporated into the furniture or with suspended or surface-mounted luminaires being used for both. In this case, the entire input power is an instantaneous space load.

With recessed luminaires used for ambient lighting and either suspended or furniture-mounted luminaires for task lighting, the heat loads must be figured separately, as only the task lighting load is entirely instantaneous space load. The recessed luminaire heat contribution may be considerably less, depending on the CLF.

Systems can also use recessed luminaires for both task and ambient lighting. Here, both impose a heat load that is reduced by the CLF.

Mechanical

Typically the application and environment determine the important mechanical aspects of luminaires. Ceiling-mounted luminaires must be compatible with the ceiling system, including appropriate sizes, weights, and mounting mechanisms. Luminaires intended for outdoor use should incorporate mounting and design features suitable to withstand high winds and rain and snow accumulation. Luminaires recessed in poured concrete should have an enclosure of suitable strength, water tightness, and rigidity for the application. Surface-mounted luminaires should be strong enough so that they do not excessively distort when mounted on uneven ceilings. Suspended luminaires should have adequate strength to limit vertical sag between supports as well as lateral distortion and twist. Provision must be made for attachment of supports at suitable locations. Certain locations may require vandal-proof luminaires of heavy construction, which may in turn require additional or heavier mounting equipment. Some applications require waterproof luminaires or luminaires with housing and gasketing designed for hazardous locations. In locations that experience seismic disturbances, attention must be paid to luminaire support.[13]

Acoustical

Undesirable sound generation is sometimes a problem with fluorescent or other discharge lamps ballasted with electromagnetic or solid-state devices. Luminaires can transmit this sound to the rest of the space and, in some cases, add luminaire vibration to it. Large, flat surfaces and loose parts amplify the sound. Steps taken to minimize transmission of sound from the ballast to the luminaire may affect heat transfer characteristics.

Where luminaires are used as air supply or air return devices, the air-controlling surfaces should be designed with full consideration for air noise. In this case, there are well-accepted criteria for permissible sound levels.[14,15]

Some ballast hum is inevitable in view of the electromagnetic principle involved, and each ballast type has a different sound rating. Where low noise levels are necessary, consideration should be given to mounting the ballasting equipment remotely or using light sources having inherently quieter operation. Remote locations of ballasts may involve complications of wiring, voltage, and thermal considerations and code restrictions. Details are available in the National Electrical Code (NEC).[3]

Maintenance

Maintaining luminaire performance requires periodic cleaning and relamping. If luminaires are mounted in places normally out of reach, consideration should be given to how they will be accessed. If special equipment is required or if lamps are used that have a short life, luminaire placement should be reconsidered. Doors and frames should be hinged to permit easy access to the lamps and cleaning of reflectors. If luminaires are aimed, it may be necessary to specify locking hardware to prevent them from moving.

The presence of dirt and insects should be considered when choosing a luminaire. Enclosed luminaires or gasketed doors can reduce dirt and insect penetration and accumulation and reduce required maintenance.

Issues for Fiber-Optic Luminaires

Operating Temperature. The range of operating temperatures varies with the material composition of the optical fibers. The specifier must consider the range of temperatures at which the installed system operates.

Flexibility. The flexibility of an optical fiber is important in some applications. Most manufacturers specify the bend radius of their products. If a fiber is bent too sharply, tiny micro-cracks can form in the bend, which scatter some of the light into the cladding. Light may escape because the sharpness of the bend allows light to strike the core/cladding interface at unacceptable angles. Bending could also break the fiber in the sheathing, causing substantial light loss.

The bend radius is related to the diameter of the fiber. The general rule of thumb is that the minimum radius of a bend should be no less than eight to ten times the diameter of the individual fibers.

Attenuation and Light Loss in Fiber. Light transmission within a fiber is a function of length. Some light within the core is lost, and this loss is expressed in terms of attenuation in dB/m or percent loss per unit length. The attenuation of a fiber is an expression of the ratio of the light into the fiber to the light out of the fiber. Attenuation is extremely sensitive to fiber manufacturing conditions.

Attenuation also varies with the wavelength of transmitted light, an indication that the spectral composition of the light may change with transmission distance.

This occurs because materials absorb the range of wavelengths associated with visible light in varying degrees and, in addition, the refractive index of a material varies slightly for each wavelength of light. As "white" light passes through a material the wavelengths separate. In fibers, these characteristics can result in the output illumination taking on coloring.

The attenuation of optical fiber restricts the maximum lengths that can be used. With minimal bending the attenuation values vary from 7 to 13% per meter (2 to 4% per foot) for glass and plastic optical fiber. The length of fiber tails are limited to less than 15 m (50 ft) in most practical end light and side light applications. If side-emitting fiber is illuminated at both ends, if high luminances are not required, and if fiber attenuation is very low, runs of up to 45 m (150 ft) are possible.

Fiber Life. Theoretically, glass optical fibers last indefinitely and are generally impervious to adverse environments. Plastic fibers can yellow over time and become brittle after a number of years, particularly if subjected to UV radiation. PMMA fiber can last 10 to 15 years.

DESIGN OF LUMINAIRES

General Considerations[16]

Some of the factors to be considered in luminaire design include: codes and standards for their construction and installation, their physical and environmental characteristics, electrical and mechanical considerations, thermal properties, safety, and economic factors.

Reflector Design Considerations. Most lamps do not act like point sources relative to the size of the reflectors into which they are placed. Physically large arcs or coated bulbs require larger reflectors to control light to the degree obtained from small arcs or sources. Generally, the larger the source, the larger the reflector required for equivalent control.

Secondary effects of reflector or housing design can often be detrimental to the performance of a luminaire. As an example, if reflected energy is concentrated on the lamp, lamp parts may fail or lamp life may be reduced; if the beam is concentrated on a lens front, the glass may fail from thermal stress.

When fluorescent lamps are used in confining luminaires, two effects take place. The buildup of heat in the lamp compartment raises the bulb wall temperature, which may reduce the light output (see Chapter 6, Light Sources). As lamps are moved closer together, a mutual heating occurs.

Lamp Position and Replacement. The lamp operating position is important. Many lamps are designed only for base-up or base-down operation or some other specified operating position. Ignoring such limitations normally results in unsatisfactory lamp performance, reduced lamp life, or both. A basic consideration is that of easy lamp insertion and removal. Recognition should be made of possible lamp changing devices that might be used, and space should be allowed for this purpose.

Effects of Radiant Energy. Consideration must be given to the effects of lamp energy in the nonvisible regions of the electromagnetic spectrum on luminaire materials and performance. Some plastics and rubber materials, for example, can be altered by UV radiation. Some reflector materials are excellent for visible light but absorb IR, thus creating thermal problems. If the intended lamp can present a hazard to people or objects under some conditions of operation (for example, some high-intensity discharge lamps operated with broken envelopes), protective devices that switch the lamp off should be designed into the luminaire or lamp.

Luminaire Efficiency. Efficiency is normally a function of physical configuration and the selection of materials used. It should be recognized that many materials change to some extent with use.

Appearance. The luminaire designer must coordinate technical, safety, and economic considerations with the final appearance. Where the lighting is primarily functional, performance has maximum importance. Design efforts generally are concentrated on reflectors, refractors, and shielding elements.

Decorative luminaires are often selected because of their appearance. In this case they may serve to complement, accent, or decorate. It may be desirable to sacrifice optimum performance in order to attain pleasing proportions and shapes. Sometimes both can be coordinated into a single luminaire.

Glare. Light sources and luminaires are potential sources of discomfort and disability glare, both indoors and out. The degree of luminance control to be designed into a luminaire depends on its intended use and the luminous environment within which it is used. Frequently, design compromises are required between visual comfort, use, and aesthetics.

Computational and measurement systems exist to evaluate the potential glare from luminaires (see Chapter 3, Vision and Perception, and Chapter 9, Lighting Calculations). They establish criteria commonly used to guide the luminaire designer in determining acceptable limits of maximum and average luminances. A thorough understanding of the principles involved is essential.

Thermal Distribution. The integration of luminaires into the air handling and architectural aspects of a building greatly influences their basic construction. Some materials used in luminaires can be good reflectors of light and good absorbers of IR radiation. For reflectance data see Figure 7-50.

Ventilation and Circulation. Air movement through the lamp compartment of a luminaire may result in the lowering of light output due to accumulation of dust and dirt, or it may maintain the lumen output by the cleaning action of air moving past the lamps.

In fluorescent lamp heat transfer luminaires a reverse airflow is sometimes used to trap dirt and dust before it enters the lamp compartment. Consideration must also be given to the effect air currents have on bulb wall temperature, since minimum bulb wall temperature affects light output (see Chapter 6, Light Sources). Ambient temperature affects the striking voltage of all discharge lamps.[17]

Vibration. Incandescent lamps are normally made smaller for vibration service (up to 150 W) and for rough service (up to 500 W). Where more severe vibration is present or larger wattages are required, vibration-resisting sockets or shock-absorbing mountings may be used. For high bay mounting on a building's steel structure, a spring steel loop of proper size and tension for the luminaire's weight usually solves even the most difficult vibration problems.

High-intensity discharge lamps are less fragile than most incandescent lamps and consequently withstand more vibration. If vibration is severe, then shock absorbers should be used.

For fluorescent lamp luminaires that may be installed in vibration areas, spring-loaded lampholders should be used, rather than those of the twist type. There are conditions of very high frequencies, such as turbine deck areas, where special lampholders may be required.

Radiation Interference

Electromagnetic radiation from gaseous discharge lamps, especially of the fluorescent type, and from auxiliary components such as starters and phase control devices may be sufficient to cause interference with nearby radios, television receivers, sound equipment, medical devices, radar and tracking equipment, and other sensitive electronic equipment. This interference is transmitted by direct radiation through the luminaire and by conduction through ballast and supply line.

To eliminate direct electromagnetic radiation the luminaire should be enclosed entirely with metal, except for the light-transmitting opening. Normal tolerances on the fit of parts are acceptable, but there should be no large open holes in any of the metal parts, and the electrical service should be brought in through grounded conduit or shielded cable. Proper line filters located at the luminaire can isolate conducted interference. In special cases shielded lenses over the lamps can provide additional electromagnetic radiation suppression.

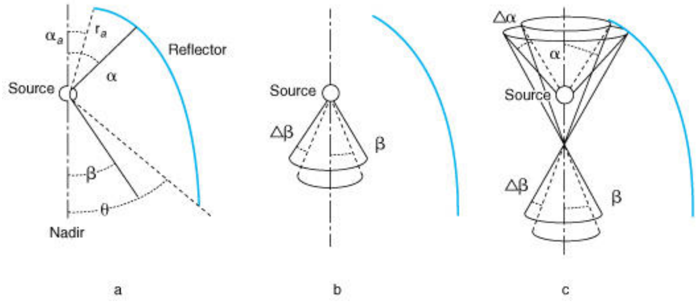


Figure 7-54. (a) Coordinate system and initial conditions for axially symmetric reflector design, (b) direct flux cone at angle β and size $\Delta\beta$, and (c) reflected flux cone from source angle α and size $\Delta\alpha$ into angle β and size $\Delta\beta$.

Life and Maintenance. The life of any luminaire is dependent primarily on its ability to withstand the environmental conditions in which it is installed. To ensure reasonable life, appropriate treatment of all materials should be considered. Where conditions are such that electrolytic action may occur, the use of dissimilar metals and high-copper-content alloys of aluminum should be avoided where possible.

Maintenance may be a problem unless proper consideration is given to minimizing luminaire light loss factors at the time the luminaire is designed. Ventilation, gasketing, and filtering, in addition to the selection of materials to diminish the effect of dust and dirt, should be used. Ease of relamping and access to auxiliary components are important considerations as well.

Environmental Conditions

Ambient Temperature. The most obvious influence of ambient temperature is its effect on the starting and the operating characteristics of fluorescent lamps. The effect of high and low temperatures on other luminaire components should also be considered. Excess heat generated by internal heat sources such as lamps, and in some cases ballasts, must be transferred to the environment. For a discussion on the effects of temperature on lamp performance, see Chapter 6, Light Sources.

Surface-mounted luminaires and recessed equipment, especially when operating in nonventilated plenums, are often exposed to high ambient temperatures. Some industrial areas may be 65°C (150°F), or even higher. Refrigerated storage areas, and in some climates unheated storage areas, attain temperatures of −29°C (−20°F) or lower. Proper design and component selection result in luminaires that operate efficiently through these extremes.

Incandescent filament lamps operate at a very high temperature, near 2620°C (4750°F) for a 200-W lamp. Normal changes in ambient temperature do not appreciably affect its light output or life.

Ambient temperature and convection affect the performance of fluorescent lamps (see Chapter 6, Light Sources). In totally enclosed interior luminaires, fluorescent lamps usually operate at temperatures above those for optimum light output. Ventilation and other means of heat dissipation are helpful and should be considered.

Ambient temperature normally is not a significant factor in the light output of conventional high-intensity discharge lamps. Starting requirements are sometimes affected at low temperatures, and ballasts meeting such requirements must be used. Special auxiliary equipment also may be required at elevated temperatures. The relationships between temperature and service life (wiring and components) must be considered. There are Underwriters Laboratories (UL), NEC, and Canadian Electrical Code (CEC)[4] requirements that apply in some cases.

Radiation. Certain areas of buildings, especially laboratories with specialized equipment, may emit radiation that has a detrimental effect on the luminaire. These are special cases, and the possible effects of fading or color change of paints and degradation of plastics should be studied. In these cases, special consideration should be given to selection of luminaire materials.

Air Movement. Outdoor luminaires should be designed to withstand wind loading. In indoor locations, such as subway stations or small offices, the air pressure on a fluorescent troffer lens or a luminous ceiling component can dislodge a diffuser when doors are suddenly opened.

Miscellaneous Environmental Effects. A complete listing of the possible effects of the environment on luminaire design is impossible. The designer, however, should be alert to the possibilities of many others not specifically covered, such as the effect of UV energy on outdoor components, thermal shock, extremes in humidity, and foreign substances in the atmosphere.

Electrical Considerations. Sockets and lampholders, wire, ballasts, and other controls are parts of electrical circuits of luminaires. All gas discharge lamps require some form of ballast or control equipment to provide adequate starting voltage and to limit the current after the lamp has started.

Lamp Circuits. Each type of lamp requires a specific ballast circuit (see Chapter 6, Light Sources).

Ballast Quality. Rated lamp life and light output for fluorescent and HID lamps are directly dependent on the ballast's ability to meet specified limits set by the American National Standards Institute (ANSI) standards. Ballasts not meeting ANSI standards may reduce lamp life as much as 50% and light output by more than 30%.

The life of ballasts made with 105°C (Class A) insulation is approximately 45,000 h (continuous operation not exceeding 105°C). Ballast coil temperatures do not exceed the 105°C rating in properly designed ballasts when luminaires maintain a maximum ballast case temperature of 90°C. Other factors affecting ballast life are input voltage, luminaire heat dissipation characteristics, luminaire mounting, and the environment. Field data indicate a 12-yr median ballast life for a duty cycle of 16 h per day, 6 days per week, or 5000 h per year. This life rating assumes that because of ballast warmup time, the ballast operates only at peak temperatures for 12 h out of the 16-h duty cycle, or 3750 h per year.

Ballast safety standards are set by UL and CSA. Case temperatures of fluorescent lamp ballasts are limited to 90°C with the ballast mounted in a luminaire and the luminaire operating in an ambient temperature of 25°C. Ballasts for HID lamps have limits that apply to the coil and core temperatures, depending on the insulation system used; that is, whether it is rated for 105°C, 130°C, or 180°C.

Excessive ballast operating temperature causes ballast insulation deterioration, resulting in short life and possible activation of the ballast protective device. A convenient rule of thumb is that every 10°C increment above 90°C results in a 50% reduction in life. Luminaire design should limit heating within the luminaire.

Thermally Protected Ballasts. The NEC requires that thermally protected ballasts be used in some fluorescent and HID luminaires. For fluorescent lamp ballasts, UL requires that the protector open so that maximum ballast case temperature does not exceed 90°C when the luminaire is in service. Protected ballasts for fluorescent lamps are called Class P ballasts and are listed by UL as such. All new fluorescent lamp luminaires must use UL-listed Class P ballasts in order to carry the UL label. The intent is to limit the maximum temperature that a ballast case can reach in a luminaire under any condition. All recessed HID ballasts, both integral and remote, must be thermally protected.

High-Frequency Operation

Most fluorescent lamps can be operated on higher frequencies, resulting in increased luminous efficacy (see Chapter 6, Light Sources). As a rule, high-frequency ballasts are smaller, lighter, and more efficient.

Low-Temperature Operation. Fluorescent and HID lamps require higher open-circuit voltages for low-temperature starting. Low-temperature ballasts should be used where ambient temperatures are below 10°C.

Sockets and Lampholders. The ratings of voltage, current, and wattage should not be exceeded for any socket or lampholder. Limitations also usually exist for operations. Specific consideration should be given to the following:

- UL or Canadian Standards Association (CSA) listing and ratings should be followed for the specific application of any socket or lampholder.
- Materials used for contacts and screw shells, such as aluminum, copper, brass, nickel, stainless steel, silver, or plated metals and their alloys, limit the operating temperature, wattage, and current during use.
- Metallic, porcelain, plastic, or other nonmetallic housings have temperature limits that affect usage.
- Where high voltage or a starting pulse is required in lamp operation, the lampholder or socket, as well as associated wire, should be rated for these voltages or pulses.
- High temperatures occur with some lamps, such as tungsten halogen, and the wire, contacts, and housing should be rated for the temperatures that occur during lamp operation.
- Spring tension at lamp contacts may deteriorate under excessive temperatures or abuse, causing contact loss and deterioration and resulting in socket failure. Improper seating of lamps into a socket, as well as vibrations, can also cause arcing and contact deterioration. Arcing of lamp base pins, screw shells and other lamp or socket contacts can be detected through the burning or pitting of the material. Any lamps or sockets found with such deterioration should be replaced.
- Wet, damp, or hazardous environment applications, as well as usage in outdoors, mining, stage, or photographic locations, may require special consideration for sockets and lampholders.[18,19]

Wire. The ratings of voltage and current should not be exceeded in the use of any wire. The material used for the conductor(s) and insulation may limit wire application, both indoors and outdoors. Specific considerations should be given to the local, state, and national electric codes designations for types of wire and their usage in various applications. Further limits are designated in UL and CSA standards for wire in specific luminaires. Common limitations include:

- Wire smaller than no. 18 American Wire Gauge (AWG) may not be used for line circuits of 120 V or higher.
- Luminaire wires have designations of 300, 600, or 1000 V, and higher-voltage wire may be required for some special applications.
- Wire temperature designations range from 60 to 200°C.
- Some applications require stranded wire, especially where it must flex.
- Nickel-plated conductors are common in high-temperature applications.
- Grounded cord sets are common.
- When luminaires are not wired through metallic conduit, a metallic luminaire should be grounded using acceptable ground wire.
- Users and specifiers should be familiar with electric codes, requirements for which include the use of at least no. 14 AWG wire for the supply leads of a recessed luminaire, despite a low-current requirement.

Starters and Igniters. Fluorescent, HID, and specialty arc lamps may be operated on circuits that include starters and igniters. They provide voltage pulses to start lamps, or a time delay to heat cathodes prior to lamp starting. They can also disconnect lamps from the circuit when the lamp fails. Accessibility is necessary for any that are replaceable or contain an element such as a spark gap that may fail and require replacement. Temperature limits must be observed for starters and igniters, and they must be used only with the lamps and ballasts designated for them. The various circuits and lamp starter and igniter requirements are found in Chapter 6, Light Sources.

Mechanical Considerations

Tolerances. It is necessary to establish suitable dimensional tolerances for both the component parts and the final assembly. This includes allowances for the different rates of thermal expansion of the various parts. An industry standard[20] defines tolerances of recessed fluorescent lamp luminaires. Surface- and pendant-mounted luminaires may have less critical tolerances. When using recessed luminaires, availability of plenum space must be considered.

Strength. All luminaires should have housings of sufficient rigidity to withstand normal handling and installation. Local conditions, such as in earthquake areas, sometimes require conformity with special local codes.

Component Support. Lampholders and sockets should be fixed in place to prevent movement and to maintain good lamp contact in luminaires with double-ended fluorescent, tungsten-halogen, or HID lamps. To hold large, high-wattage incandescent and HID lamps, gripping sockets are often helpful. Large horizontally operated HID mogul base lamps benefit from the use of an end support. Ballasts should be securely fastened to the luminaire housing for good thermal contact. Door glasses, lenses, and refractors should be securely fastened to withstand the effects of wind, rain, and shock.

Mounting. Mounting components should satisfy the requirements of UL, CSA, local codes, and end-use environmental conditions. Tamper-proof fastenings may be required in public areas as well as in correctional institutions and mental hospitals. Wire guards may be required around exposed lamps in accessible locations. Local codes should be considered with regard to power supply, continuous row wiring, and grounding of the luminaire. Instructions and warnings should be marked in a readily discernible and permanent manner. The text and physical dimensions of instructions and warnings may be governed by code requirements.

Maintenance. Ease of maintenance is an important consideration. Instructions for maintenance and correct lamping should be provided to prevent luminaire damage and ensure performance. Electrical components should be replaceable without removing the luminaire from its mounting. Where ceiling plenums are not otherwise accessible, provision must be made for access through the luminaire to splice boxes that connect to the branch circuit.

Size. The size of a luminaire is usually controlled by components such as lamps, ballasts, and reflectors. Mounting limitations and building modules can also limit the size.

Thermal Considerations. The lamp efficacy, wattage, and type affect the temperature of a luminaire. Ballasts and transformers also affect the temperature, as does the luminaire's environment. Finally, the heat-dissipating properties of the luminaire itself affect its temperature.

Very high or low ambient temperatures may cause electrical components to fail. For example, contact of hot glass with cold air or water may result in breakage, and excess heat may cause thermoplastics to distort. Satisfactory performance at the luminaire interior temperature is a major consideration in selecting components and finishes.

Higher-than-nominal line voltages usually cause higher temperatures within electrical components. Lower voltages do not necessarily produce lower temperatures.

Metal components and their finishes may be affected by temperature within a luminaire. Thought must also be given to metals as conductors of heat either to or from component parts.

Glass and plastic components should be chosen very carefully to prevent cracking, shattering, deformation, or other deterioration. This consideration may be long term, short term, or both.

Expansion or contraction of components due to thermal changes should be considered. Different coefficients of expansion between materials in close contact can lead to serious problems.

Safety Considerations.

The need for attention to safety considerations, particularly in the design stage, cannot be overemphasized. Usually, if the design meets applicable code requirements, it conforms to the following criteria.

Electrical Safety. The safe conversion of electrical energy to light is of utmost importance. In this context important wiring considerations are:

- Current-carrying capacity of the conductors.
- Insulation rating of the conductors.
- Grounding. In most cases portable lighting equipment is required to have a polarized plug cap such that the screwshell of the socket is neutral or electrically dead. All permanently installed lighting equipment must be provided with grounding to eliminate shock hazard.
- Temperature rating of the conductors.
- Connections to the junction boxes. Where supplied, connections must be in conformance with local codes.
- Wire termination color coding in conformance with code requirements for safe field installation.
- Mechanical strength and flexing requirements.
- Safety interlocks. These are advisable in equipment where high open-circuit voltages are present for protection during servicing and are often advisable in damp areas and basements.
- Fuses and thermal protectors. Where required, these must be included in the design of the equipment.
- Applicable UL, CSA, and ANSI requirements for splices, clearances, and sockets.
- Low-voltage units. These should be considered for outdoor applications and may be required around pools and hot tubs.

Thermal Safety. Luminaires should be designed to meet the requirements of the thermal environment and use. If the unit is to be firmly mounted and not handled during operation, it can operate at a higher temperature than a unit that must be held or moved by hand.

The NEC,[3] the CEC,[4] and their respective testing laboratories set specific temperature limits for electrical components and critical areas immediately surrounding a luminaire. Much of their testing is performed at an ambient temperature of 25°C (77°F). Code requirements usually do not relate to performance characteristics, and thermal considerations are regarded solely from a safety standpoint.

Ballasts and other auxiliary equipment, sockets, and wires have definite safe operating temperature limits defined by UL, CSA, ANSI, and the manufacturer. Special electrical components may have to be specified for extreme temperatures.

Ultraviolet Radiation. An enclosure and cover glass that absorb UV radiation may be required for some types of luminaires. Safety interlock switches are required to disconnect the lamps on opening the luminaire or on breakage of the glass cover. Labels should be provided with such luminaires to warn users of this hazard.

Many lamps produce some UV, but of insufficient quantities to require total enclosure and interlock switches. In applications such as museums, the long-term exposure to such UV radiation is considered a hazard (see Chapter 14, Lighting for Public Places and Institutions). Only UV-stabilized plastics do not transmit significant quantities of UV. Some food processing applications and UV-sensitive manufacturing processes require nearly complete elimination of UV. Common glasses transmit some UV and might not be appropriate in these applications.

Optical Design Methods

Luminaire optical design attempts to control and redirect the output of lamps to produce luminous output appropriate for an intended application. Optical design for luminaires is usually considered a type of nonimaging optics design, that is, the optics are intended to control the amount and distribution of emitted light for a desired photometric performance. This is different from imaging optics, where geometric rays of light are managed to preserve, manipulate, or modify images.

Overview of Reflector Design.

The reflector design process produces a shape that reflects light from a lamp and generates a desired luminous intensity distribution. Reflector design almost always assumes the use of specular reflecting materials, though reflector analysis can account for real (nonspecular) reflectance of materials. The process is as follows.

1. Choose the lamp appropriate for the application. Consider the luminaire mounting and size and other requirements such as thermal conditions, need for sealing, and lamp access.

2. Evaluate the nominal luminaire output and determine the luminous intensity distribution or the illuminance distribution on the target plane. In many applications, flux is contributed to the luminous intensity distribution or arrives at the target plane direct from the lamp. The difference between the nominal distribution and that provided by the lamp is what the reflector must provide.

3. Determine other factors that affect distribution, such as cutoff, shielding, and the behavior of lamp images in the reflector.

4. Optionally, scale the nominal lumen output of the luminaire so that it is consistent with the lumens available from the lamp, the reflectance of the material being used, and the number of interreflections the light undergoes before it leaves the luminaire.

5. Generate a reflector shape using either of two general procedures: flux mapping and flashed area. For flux mapping, reflector shape is determined either from a closed mathematical solution to the problem or iteratively by successively closer approximations. The simplest of these procedures assumes a point source.[21] More elaborate techniques have been devised to account for lamp size.[22-24] The flashed area procedure usually results in a facetted reflector. Individual facets are designed to send flux into particular directions, taking into account the size and luminance of the lamp.

6. Construct and prototype and test for photometric performance.

Theoretical shapes offer some guidance regarding lamp and reflector behavior. In the simplest case, the lamp is a point source and the reflector is perfectly specular. A few of the conic sections are useful.

Parabolic Reflectors. An inherent property of the parabola is its ability to redirect a ray of light originating at its focal point along a direction parallel to the axis of the parabola. If the parabola is rotated about its axis, a paraboloid is swept out. Assume a perfectly specular mirror is made to this shape, and that a point source is at the focus. Then all light from the source striking the mirror is redirected as a circular beam parallel to the parabolic axis. Similarly, the parabola can be extruded and placed around a line source, producing a rectangular beam.

The larger the lamp is, the greater the deviation of the light from a parallel beam. Formulas have been derived expressing the light divergence from shallow mirrors when sources of various shapes are used.

Ellipsoidal Reflectors. If an ellipse is rotated about its major axis, a surface is swept out which is an ellipsoid. This surface, having two foci, takes light from one focus and reflect it through the other focus. Ellipsoidal reflectors are an efficient means for producing beams of controlled divergence and for collecting light to be controlled by a lens or lens system. This shape can also be extruded.

Spherical Reflectors. A spherical reflector can be considered as a special form of the ellipsoidal reflector where the two foci are coincident. Any light leaving the source located at the focus returns and passes through the same point. This can cause problems when using some HID sources, since the concentration of energy can damage the source or the bulb wall surrounding it. However, the principle is often used in projecting devices to increase the amount of light collected by a lens, and in the design of reflectors for fluorescent lamps.

Implementation of Reflector Design. The simplest case of flux mapping reflector design involves the following assumptions:

- The source is axially symmetric and sufficiently smaller than the reflector so that it can be considered a point source.
- The nominal luminous intensity distribution is axially symmetric.
- The material used for the reflector exhibits very specular reflectance.

The procedure begins by determining the difference between the flux provided directly by the source (see Figure 7-54b) and the flux required to give the nominal luminous intensity distribution. The reflector is generated incrementally by determining the shape necessary to reflect light from the source and make up this difference. The steps are as follows:

1. The point source is located at the origin of a spherical coordinate system shown in Figure 7-54a. Angles describing intensities or flux from the source are measured from zenith. Angles describing intensities or flux into the luminaire distribution are measured from nadir.

2. Determine the angular size of the opening at the back of the reflector, α_o, and the initial distance, r_o, from the source to the reflector at this angle. These are usually fixed by lamp size, desired reflector size, the need for mounting, and lamp socket placement.

3. Determine the available luminous intensity distribution, $I_s(\alpha)$ of the source. This is available from lamp manufacturers and often is provided as axially averaged values if the lamp is nominally axially symmetric.

4. Determine the nominal luminous intensity distribution, $I'(\beta)$, of the luminaire, including the cut-off angle, Θ. Usually the relative shape of $I'(\beta)$ (the indicatrix) is constrained by some requirement, whereas the magnitude is not. A specific illuminance distribution requirement, such as a limit on the ratio of maximum to minimum illuminance, is an example of such a shape constraint. Requirements of cut-off angle for computer area lighting applications is another.

5. Calculate the available (source) flux distribution of the source, $\varphi_s(\alpha)$, using the source luminous intensities and the solid angle of annular cones in α.

6. Calculate the nominal flux distribution, $\varphi'(\alpha)$, using the nominal luminous intensities and the solid angles of annular cones in β.

7. Calculate the flux in the nominal intensity distribution, the total flux emitted by the source, the flux provided by the source directly into the distribution, and the flux provided by the source after redirection by the reflector. Note that the cut-off angle, Θ, may not fall on a cone boundary. If the angular increment that defines the cones is small, the error introduced is small.

8. Calculate the scale factor K for achieving flux balance by accounting for the flux available from the lamp and the reflectance ρ. If $K < 1.0$ then the source and reflector cannot meet the flux requirements of the nominal distribution and either the reflector must be scaled down or the source output increased. If $K > 1.0$ then source and reflector should produce more flux than required and the nominal distribution is scaled up or the source output decreased.

9. Calculate the actual luminaire intensity distribution, $I(\beta)$, and the flux distribution, $\varphi(\beta)$, by scaling with K. In other words, $I(\beta) = I'(\beta)\,K$ and $\varphi(\beta) = \Phi'(\beta)\,K$.

10. Determine the required (reflected) flux distribution, $\varphi_r(\beta)$, by subtracting the direct (source) flux from the luminaire flux, or $\varphi_r(\beta) = \Phi(\beta) - \Phi s(\pi - \beta)$. $\varphi_r(\beta)$ is the flux that the reflector must provide to produce the final distribution of the luminaire. It is assumed that this flux comes from the source by only one reflection of the reflector. Note that source angles are specified from zenith, so $\pi - \beta$ is used.

11. Calculate the cumulative available flux function $\Sigma\Phi_s(\alpha)$ and cumulative required flux function $\Sigma\Phi_r(\beta)$. Figure 7-55 shows examples of these cumulative functions. The use of K guarantees that the final (maximum) value of $\Sigma\Phi_s(\alpha)$ equals that of $\Sigma\Phi_r(\beta)$. The appropriate reflector shape distributes the available flux according to the required flux distribution. That is, any fraction of available flux must be matched by the same fraction of required flux. Thus, a relationship is established between β and α by matching flux fractions.

12. Using $\Sigma\Phi_s(\alpha)$ and $\Sigma\Phi_r(\beta)$, determine pairs of (α,β). Figure 7-55 shows this procedure graphically. For each α, use the $\Sigma\Phi_s(\alpha)$ function to determine a fraction of available flux. At this same fraction, use the $\Sigma\Phi_r(\beta)$ function to determine the matching β.

13. For each pair of angles (α,β), calculate the angle ε that the reflector must have at that α to send flux in the direction β (see Figure 7-56a.)

14. Beginning with α_o, r_o, and ε_o, use the sequence of values α_i and ε_i, to calculate the radial distances r_i from the source to the reflector and thus the coordinates (x_i, y_i) of the reflector (see Figure 7-56b). The step size in α determines the size of the reflector facets. A smooth interpolating curve can be passed through the point (x_i, y_i).

In the procedure outline above, the (α,β) pairs are generated so that a small value of β (perhaps zero) is matched with α_o. There are simple modifications to this procedure that generate other reflector shapes using the same source and nominal luminous intensity. The cumulative available flux distribution can be reversed so that it begins with $\alpha = \pi - \Theta$, and this is matched with a small value of β. Additionally, for each of these two cases, the reflector slope ε can be changed so that flux does not cross the axis of the luminaire. Thus, there are four possibilities, as shown in Figure 7-57. The procedure given here generates the smallest reflector. Similar procedures can be used to generate a shape for an extruded reflector using a source that is assumed to be a line.

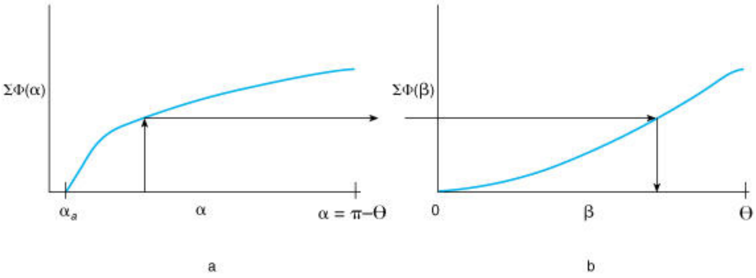


Figure 7-55. (a) Cumulative available flux distribution of the source, and (b) cumulative required flux distribution of the reflector.

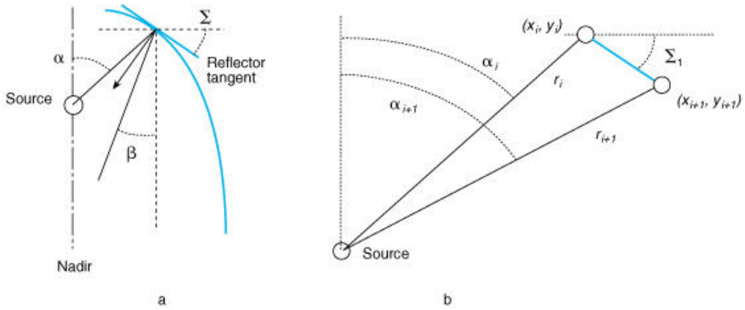


Figure 7-56. (a) Local tangent of reflector for angle pair (α,β), and (b) determination of reflector coordinates.

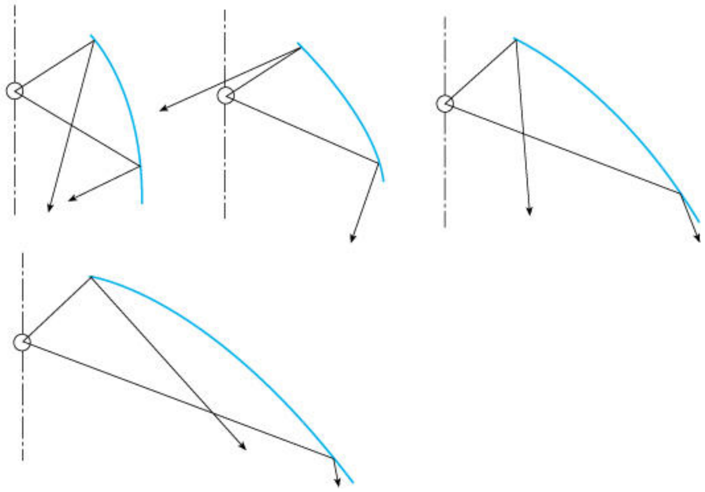


Figure 7-57. Four basic reflector shapes for point sources.

Overview of Refractor Design.[25,26] Luminaire refractor design is typically used to produce prismatic lenses. With the exception of some special applications such as automotive headlights, refractors are designed using a procedure similar to that for reflectors. In addition to luminous intensity distribution requirements, refractors can be designed to hide lamps or otherwise to spread emitted flux over the full extent of the prismatic lens. This produces a luminaire luminance that can be significantly less than that of the lamp. The basics of refraction are addressed in Chapter 1, Light and Optics.

Individual prisms are designed to refract light into appropriate directions, or in some cases to provide for total internal reflection. Prism size and angles are affected by the index of refraction of the material. Geometric ray tracing is almost always used to determine the size and angle of the optic surfaces.

Prototyping refractors is more difficult than for reflectors. Machining is used to produce temporary molds for plastic refractors. In other cases, optical material is machined directly and suitably finished to produce a prototype refractor.

Computer Modeling[27,28]

Analysis. Modern computer technology has produced powerful photometric analysis tools to evaluate proposed luminaire optical designs. In most cases, photometric ray tracing is used to model the interaction of light and the reflector surface. Reflectance models are available to describe the directional reflectance characteristics of real reflector surface finishes. These computer simulation tools can also model the effects of refractors. The reflector and/or refractor shapes are described in one of the standard forms for CAD drawings. Lamp and material characteristics are specified from a library of available data.

Synthesis. Reflector shapes can be synthesized in certain situations. These procedures involve elaborate iterative procedures, such as "genetic algorithms"[29] that systematically modify and evaluate a reflector shape. Closed procedures have also been developed to account for lamp size and produce a reflector shape that generates the nominal luminous intensity distribution. These procedures are currently limited to axially symmetric or extruded reflectors.

Prototypes. Prototypes of luminaires are made to test optical designs, that is, to identify problems in the photometric performance of the luminaire and help determine manufacturing issues for the luminaire. Simple handmade prototypes of metal, plastic, cardboard, and other temporary framework are constructed to hold reflective film. Parts can be machined in metal or plastic according to design specifications and then polished or coated to give an adequate approximation of the final shape and specular finish.

Computer-driven laser and resin tomography can produce prototype shapes of cured resin, which are then polished and coated to make a reflector. In this process, the reflector design is expressed in instructions for a machine that guides intersecting laser beams passing through a vat of liquid resin. Where the beams overlap the resin solidifies. Complex three-dimensional shapes can be generated quickly and inexpensively.

CONSTRUCTION OF LUMINAIRES

Materials Used in Luminaires

The materials most commonly used in luminaires are glass, plastics, metals, and applied finishes and coatings. Each of these materials is briefly described below. For more specific applications the material manufacturer's data should always be consulted.

Glass. Glass is an inorganic product of fusion that has been cooled to a rigid condition without crystallizing. Chemically, glasses are mixtures of oxides such as silicon, boron, aluminum, lead, sodium, magnesium, calcium, and potassium. The chemical and physical properties of glasses, such as color, refractive index, thermal expansion, hardness, corrosion resistance, dielectric strength, and elasticity, are obtained by varying the composition, heat treatment, and surface finish. Glasses used in luminaires can be classified into several groups with characteristic properties.

Soda-Lime. Soda-lime glasses (or lime glasses) used for windows, incandescent lamp bulbs, lens covers, and cover glasses (tempered) are easily formed when heated and are usually specified for service where high heat resistance and chemical stability are not required.

Lead-Alkali. Lead-alkali glasses (or lead glasses) are used for fluorescent and HID lamp bulbs, neon sign tubing, and certain optical components. They are useful because they are easy to form and have high electrical resistivity and high refractive indices. When formed, however, they do not withstand high temperatures or sudden temperature changes. UV radiation is absorbed by this type of glass.

Borosilicate. Borosilicate glasses are used for refractors, reflectors, and sealed beam lamp parts because of their high chemical stability, high heat shock resistance, and excellent electrical resistivity. They may be used at higher temperatures (about 230°C) than soda-lime or lead-alkali glasses, but they are not as convenient to fabricate. Near UV radiation is transmitted by this glass.

Aluminosilicate. Aluminosilicate glasses are used where high thermal shock resistance is required. They have good chemical stability, high electrical resistivity, and a high softening temperature, enabling use at moderately high temperatures (about 400°C).

Ninety-Six-Percent Silica. Ninety-six-percent silica glasses are used where high operating temperatures are required. They may be regularly used at 800°C. They are also useful because of their extremely high chemical stability, good transmittance to UV and IR radiation, and resistance to severe thermal shock. They are considerably more expensive than soda-lime and borosilicates and are more difficult to fabricate. Because of their low coefficient of thermal expansion, these glasses cannot be tempered to increase mechanical strength.

Vitreous Silica. Vitreous silica is a glass composed essentially of SiO_2. It is used for lamp bulbs and arc tubes where high-temperature operation and excellent chemical stability are required. It has high resistance to severe thermal shock; high transmission to UV, visible, and IR radiation; and excellent electrical properties. However, due to its low coefficient of thermal expansion, it cannot be tempered to increase mechanical strength. Depending on the method of manufacture, this glass may be known as fused silica, synthetic fused silica, or fused quartz.

Functions. The functions of glass in lighting may be divided into the following general categories: (1) control of light and other radiant energy, (2) protection of the light source, (3) safety, and (4) decoration. These functions may be combined for a particular application. Typical properties of glasses are shown in Figure 7-58.

Plastics.[30] Plastics generally are high-molecular-weight organic compounds that can be, or have been, changed by application of heat and pressure, or by pressure alone. Once formed, they retain their shape under normal conditions.

Plastics can be broadly classified as thermoplastic or thermosetting. Thermoplastic resins may be repeatedly softened and hardened by heating and cooling. No chemical change takes place during such actions. Thermosetting resins cannot be softened and reshaped once they have been heated and set, since their chemical structure has changed. Some of the commercially important thermoplastics are acrylonitrile butadiene styrenes (ABS), acrylics, cellulosics, acetals, fluorocarbons, nylons, polyethylenes, polycarbonates, polypropylenes, polystyrenes, and vinyls. In the thermosetting group, resins of importance are epoxies, melamines, phenolics, polyesters, ureas, and silicones.

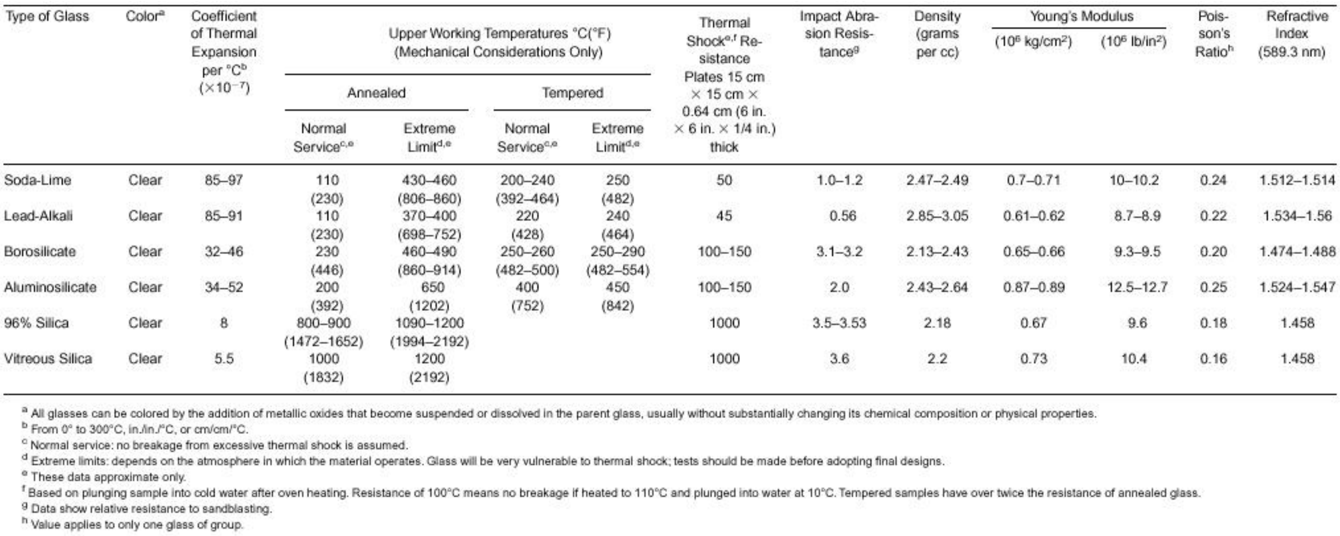
Most resins, whether thermoplastic or thermosetting, can be processed into structural or low-ratio expanded foams. Among the important properties of many foams are stress-free parts, improved insulation characteristics and lighter weight, and sometimes greater strength and toughness than the unfoamed form of the material. Important resins and properties of plastics used in lighting are shown in Figures 7-59 and 7-60, respectively.

Fillers and reinforcing agents frequently are added to plastics to obtain improved heat resistance, strength, toughness, electrical properties, and chemical resistance, and to alter formability characteristics. Some of the fillers and reinforcements in general use are aluminum powder, asbestos, calcium carbonate, clay, cotton fibers, fibrous glass, graphite, nylon, powdered metals, and wood flour.

The basic compounds from which today's plastics are produced are obtained from such sources as air, water, natural gas, petroleum, coal and salt, biomass, and wood fiber. The required chemicals are reacted in large closed vessels under controlled heat and pressure with the aid of catalysts. The resultant solid product is then subjected to such further operations as reduction of particle size; addition of fillers, softeners, and modifiers; and conversion of form to granules, pellets, and film.

If the plastic surfaces need protection from UV radiation, an UV-resistant film can be laminated onto the surface facing the energy source. UV-resistant clear coatings can also be applied on the interior and exterior surfaces of transparent plastic materials to retard discoloration. Optically transparent plastics may have UV stabilizer introduced into the base resin of the material for maximum UV resistance.

Steel. In the fabrication of lighting equipment, steel serves primarily in a structural capacity. Sheet steel, while having the great strength and low cost needed for a large-volume material, must be processed additionally with platings or applied coatings before it can serve as a light-controlling medium. Many grades and types of sheet steel are available in a variety of forms.



Type of Glass	Color[a]	Coefficient of Thermal Expansion per °C[b] $(\times 10^{-7})$	Upper Working Temperatures °C(°F) (Mechanical Considerations Only)				Thermal Shock[e,f] Resistance Plates 15 cm × 15 cm × 0.64 cm (6 in. × 6 in. × 1/4 in.) thick	Impact Abrasion Resistance[g]	Density (grams per cc)	Young's Modulus		Poisson's Ratio[h]	Refractive Index (589.3 nm)
			Annealed		Tempered					$(10^6$ kg/cm$^2)$	$(10^6$ lb/in$^2)$		
			Normal Service[c,e]	Extreme Limit[d,e]	Normal Service[c,e]	Extreme Limit[d,e]							
Soda-Lime	Clear	85–97	110 (230)	430–460 (806–860)	200–240 (392–464)	250 (482)	50	1.0–1.2	2.47–2.49	0.7–0.71	10–10.2	0.24	1.512–1.514
Lead-Alkali	Clear	85–91	110 (230)	370–400 (698–752)	220 (428)	240 (464)	45	0.56	2.85–3.05	0.61–0.62	8.7–8.9	0.22	1.534–1.56
Borosilicate	Clear	32–46	230 (446)	460–490 (860–914)	250–260 (482–500)	250–290 (482–554)	100–150	3.1–3.2	2.13–2.43	0.65–0.66	9.3–9.5	0.20	1.474–1.488
Aluminosilicate	Clear	34–52	200 (392)	650 (1202)	400 (752)	450 (842)	100–150	2.0	2.43–2.64	0.87–0.89	12.5–12.7	0.25	1.524–1.547
96% Silica	Clear	8	800–900 (1472–1652)	1090–1200 (1994–2192)			1000	3.5–3.53	2.18	0.67	9.6	0.18	1.458
Vitreous Silica	Clear	5.5	1000 (1832)	1200 (2192)			1000	3.6	2.2	0.73	10.4	0.16	1.458

[a] All glasses can be colored by the addition of metallic oxides that become suspended or dissolved in the parent glass, usually without substantially changing its chemical composition or physical properties.
[b] From 0° to 300°C, in./in./°C, or cm/cm/°C.
[c] Normal service: no breakage from excessive thermal shock is assumed.
[d] Extreme limits: depends on the atmosphere in which the material operates. Glass will be very vulnerable to thermal shock; tests should be made before adopting final designs.
[e] These data approximate only.
[f] Based on plunging sample into cold water after oven heating. Resistance of 100°C means no breakage if heated to 110°C and plunged into water at 10°C. Tempered samples have over twice the resistance of annealed glass.
[g] Data show relative resistance to sandblasting.
[h] Value applies to only one glass of group.

Figure 7-58. Properties of Glasses Used in Luminaires

Resin	Uses
Thermoplastics	
Acrylics	louvers, formed light diffusers, prismatic lenses, diffusers, film
Cellulosics	sign faces, vacuum-formed diffusers, globes, light shades, light supports
Flexible vinyls	gaskets, wire coating
Nylons	electro-mechanical parts, wire insulation, coil forms
Polycarbonates	insulators, globes, diffusers, antivandalism street lighting globes
Polyethylenes	(high density)—wire coatings, housings
Polyethylenes	(low density)—formed light diffusers, blow-molded globes
Polystyrenes	same as acrylic
Rigid vinyls	formed lighting diffusers, corrugated sheet for luminous ceilings
Thermosetting	
Melamines	switches, insulators
Phenolics	wire connectors, switches, sockets, shades
Polyesters	(glass reinforcing)—shades, reflector housings, diffusers
Ureas	louvers, lampholders, shades
Filled reinforced plastics	insulators, reflectors, housings, globes, light shades, switch bases

Figure 7-59. Uses of Resins in Lighting Applications

Sheet steel used in lighting equipment is of three basic types: hot-rolled steel, cold-rolled steel, and porcelain enameling sheets. Hot-rolled steel, because of the rolling process at elevated temperatures, carries an oxide coating (mill scale). It is not normally used where a smooth appearance is desired. The scale can be removed in an acid bath (pickling), but the surface is still somewhat rough. Cold-rolled steel is used primarily because of its smooth surface appearance. It is also available in thinner gauges than hot-rolled steel. It is usually obtained by pickling hot-rolled steel coil and further reducing the thickness without heating. Porcelain enameling sheets have very low carbon content in order to prevent mill scale beneath the porcelain coating. All of these steels are available in several grades and finishes. The types of finishes include galvanized sheet, prepainted sheet, aluminum-clad sheet, and plastic-coated sheet. Preplated sheets are also available, and the platings include chrome, brass, and copper.

Steel sheet used in lighting is often referred to by its thickness, or gauge. The metal gauge most commonly used is the Manufacturer's Standard Gauge for Steel Sheets.

Aluminum.

Aluminum is a nonferrous, corrosion-resistant, lightweight, nonmagnetic metal having good thermal and electrical conductivity. It is high in the electrochemical series but resists attack by either air or water because of the formation of an invisible protective covering of aluminum oxide.

Uses in Lighting. Aluminum is used in lighting for structural parts such as tubes or poles, housings, channels, mechanical parts, and trim, and for light-controlling surfaces such as reflectors, louvers, and decorative surfaces. Aluminum is also used as a reflecting surface when vaporized on glass and plastic, and as a paint when in fine powder form and suspended in a suitable liquid vehicle. An aluminum reflector can have a high-permanence, high-reflectance, diffuse, or semidiffuse surface of graduated reflectance.

Materials	Common Forms										Reasons for Use and General Data													Secondary Methods								
	Castings	Compression Moldings	Extrusions	Fiber	Film	Foam	Injection Moldings	Rotational Molding	Sheet	Reinforced Plastic Moldings	Industrial Laminates	Chemical Resistance	Colorability	Flammability Rating*	Flexibility	High Dielectrics	Low Moisture Absorption	Clarity	Strength and Rigidity	Toughness	Effect of Ultraviolet†	Resistance to Heat °C Continuous	Resistance to Impact	Metalizable	Plating	Dichroic Coating	Hard Coating	Paint	Hot Stamp Inks/Foils	Pad Printing	Sonic Weld	Sonic Staking
THERMOPLASTICS																																
ABS			X				X		X			X	X	HB-VO		X			X	X	NP	60–110		X	X			X	X	X	X	X
Acetals			X				X					X	X	HB		X			X	X	C	80			X					X	X	X
Acrylics	X		X	X			X		X			X	X	HB				X	X		N	60–90		X			X	X	X	X	X	X
Acrylics (High Heat)							X					X	X					X	X	X	SL	95–110		X			X	X	X			
Acrylic-Styrene Copolymers			X				X		X			X	X	HB		X	X	X		X	NP-SL	80–95		X				X	X	X	X	X
Cellulose Acetates			X	X	X		X		X				X	HB-VO		X		X	X	X	SL	65–105		X				X	X	X	X	X
Cellulose Acetate Butyrates			X		X		X		X				X	HB		X		X	X	X	N	60–105		X				X	X	X	X	X
TFE-Fluorocarbons			X		X				X			X		VO		X	X				N	260										
Nylons			X	X	X		X		X			X		HB-VO		X			X	X	CO	80–150		X				X	X	X	X	X
Polycarbonates			X	X	X	X	X	X	X			X	X	HB-VO			X		X	X	SL	120		X			X	X	X	X	X	X
Polyesters	X	X	X	X	X	X	X			X												120–160		X				X	X	X	X	X
Polyetherimides			X	X	X	X	X		X													180–200		X	X	X		X	X	X	X	X
Polyethylenes			X	X	X	X	X		X			X	X	HB-VO	X	X	X		X	X	NP	80–120									X	X
Polyphenylene Oxide				X			X	X														80–110		X				X	X	X	X	X
Polypropylenes			X	X	X		X		X			X	X	HB-VO		X	X		X	X	NP	120–160		X	X				X	X	X	X
Polystyrenes	X		X	X	X		X		X			X	X	HB-VO		X		X	X	X	NP	75–95		X				X	X	X	X	X
Polyphenylene Sulfides				X			X															200–250		X							X	X
Polysulfones			X	X		X	X						X	V1-VO		X			X	X		150–175		X		X		X	X	X	X	X
Styrene Acrylonitrile Copolymers			X	X			X		X			X	X	HB-VO		X		X	X		NP	80–95		X				X	X	X	X	X
Vinyls	X		X	X	X	X	X		X			X	X	HB-VO	X	X	X		X	X	SL	65–95		X					X	X	X	X
THERMOSETTING PLASTICS																																
Expoxies	X					X				X	X	X	X	HB-VO		X	X		X		SL	120–290						X		X		
Melamines		X								X	X	X	X	VO		X	X		X	X	SL	100						X		X		
Phenolics	X	X				X				X	X	X		HB-VO		X			X	X	D	120						X	X	X		
Polyesters	X			X	X					X	X	X	X	HB-VO		X		X		X	SL	150–210						X	X	X		
Polyesters (Molding Compounds)		X								X	X			HB-VO		X	X				SL	150–175						X	X	X		
Silicones	X	X				X				X	X			HB-VO		X	X				SL-N	315								X		X
Ureas		X										X	X	V1-VO							G	75						X	X	X		

* See Reference 31.

†NP-needs protection, C-chalks, N-none, SL-slight, CO-colors, D-darkens, G-grays.

Figure 7-60. Properties of Plastics Used in Luminaires

Aluminum Purity	Designation	Reflectance, specular sheet with 0.2 mil anodic coating	Reflectance, diffuse sheet with 0.2 mil anodic coating
99.99%	Lurium	0.90	0.85
99.90%	3002	0.82	0.78
99.80%	1100 or 5005	0.76 0.73 with 0.4 mil coating	0.72 0.70 with 0.4 mil coating
99.70%	3003	0.68	0.65

Figure 7-61. Typical Reflective Properties of Aluminum

Types of Aluminum. Aluminum is used in its near-pure state or may be alloyed by the addition of other elements to improve its mechanical, physical, and chemical properties. Silicon, iron, copper, manganese, magnesium, chromium, nickel, and zinc are the most common elements used. Aluminum alloys may be cast, extruded, and rolled as shapes or sheets. In sheet form, aluminum is available in a variety of alloys and finishes.

Finishes. The final finish on aluminum parts depends on service requirements. Aluminum may be etched, polished, brushed, plated, anodized, vacuum coated with a dielectric, color anodized, brightened, plastic coated with or without vaporization, coated with clear or dye lacquers, finished with baked or porcelain enamel, or given some combination of these finishes. Reflector finishes may range from diffuse, such as baked enamel or etched surfaces, to highly specular, such as polished, anodized, or coated surfaces. Aluminum paint has found wide use as an attractive and practical finish for many surfaces.

Processing. Anodizing, an electrochemical process, is used to form a protective surface of aluminum oxide of a thickness greater than 100 times that formed naturally in air. The aluminum oxide surface is smooth, continuous, and inseparable, with a particle hardness of Mohs value 9. Anodizing combined with chemical or electrochemical brightening provides surface finishes of uniformly high reflectance and permanence.

High-purity aluminum must be used if a clear, colorless transparent, high-reflectance oxide surface is required. Impurities and alloying materials result in lower reflectance, cloudiness, dullness, or streaking of the oxide surface. Prefinished anodized sheet is available for forming simple reflector elements. Figure 7-61 gives typical reflective properties of various types of aluminum.

In the anodizing process, colored surfaces may be obtained by depositing dyes or pigments within the open pores of the aluminum oxide just before the final sealing of the surface. A wide range of colors and tints are available.

Physical Characteristics. Properties of several alloys of aluminum that may be of interest to the designer are shown in Figure 7-62. The types and values shown are intended as typical illustrations. New alloys are being developed continually, and any contemporary listing rapidly becomes out of date.

Other Metals

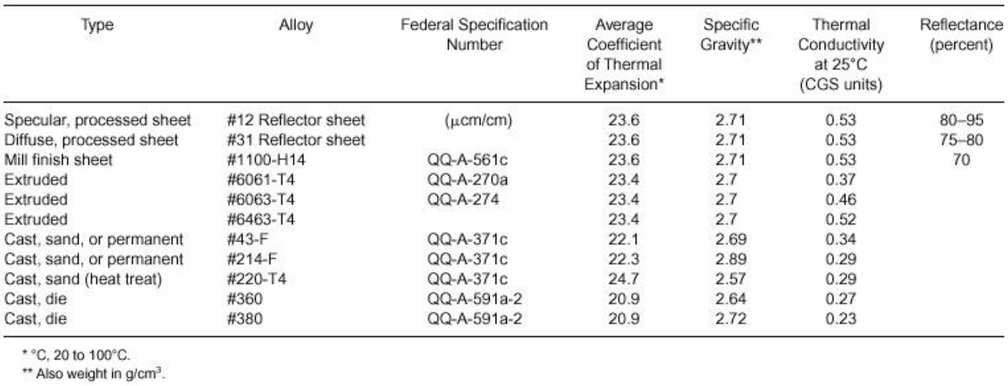
Stainless Steel. Stainless steel includes those iron-base alloys that contain sufficient chromium to render them corrosion resistant. The classification "stainless" is usually reserved for those steels having 12 to 30% chromium; those with more than 30% are classed as heat-resisting alloys and not as stainless. The family of stainless steels may be divided into three main groups: straight chrome, chrome-nickel, and chrome-nickel-manganese. Straight chrome steels are all magnetic.

They may rust on exposure to corrosive atmospheres; however, the rusting is only a superficial film and acts as a barrier to further corrosive action. These are identified by the American Iron and Steel Institute (AISI) as AISI Type 400 Series. Chrome-nickel steels are nonmagnetic. They do not rust, but some alloys may not be satisfactory in certain corrosive atmospheres. These steels are designated as AISI Type 300 Series. Chrome-nickel-manganese steels are nonmagnetic. In this group, manganese substitutes for part of the nickel. These steels do not rust, but some alloys may not be satisfactory in certain corrosive atmospheres. These steels are designated as AISI Type 200 Series.

Stainless steels are widely used in luminaires intended for outdoor installation or in other corrosive atmospheres. Some applications of stainless steel are for housings, springs, latches, mounting straps, hinges, fittings, fasteners, and lampholder screw shells.

Copper. Copper is used extensively for the conductors, bus bars, and associated switchgear necessary for the distribution and control of electrical energy used for lighting. Copper is ductile, malleable, flexible, and fairly strong and may be formed by a variety of standard machines and processes.

Nonferrous Alloys. Bronze, an alloy of copper and tin, and brass, an alloy of copper and zinc, are often used in special luminaires where the attractive color is a prime consideration. A more utilitarian use of bronze and brass is in luminaires for marine use, where strength and resistance to saltwater corrosion are highly important. Chromium copper and beryllium copper are often used for conducting springs, contacts, and similar highly stressed members that have to be formed in manufacture. The parts are shaped soft and then stiffened by heat treatment.



Type	Alloy	Federal Specification Number	Average Coefficient of Thermal Expansion*	Specific Gravity**	Thermal Conductivity at 25°C (CGS units)	Reflectance (percent)
Specular, processed sheet	#12 Reflector sheet	(µcm/cm)	23.6	2.71	0.53	80–95
Diffuse, processed sheet	#31 Reflector sheet		23.6	2.71	0.53	75–80
Mill finish sheet	#1100-H14	QQ-A-561c	23.6	2.71	0.53	70
Extruded	#6061-T4	QQ-A-270a	23.4	2.7	0.37	
Extruded	#6063-T4	QQ-A-274	23.4	2.7	0.46	
Extruded	#6463-T4		23.4	2.7	0.52	
Cast, sand, or permanent	#43-F	QQ-A-371c	22.1	2.69	0.34	
Cast, sand, or permanent	#214-F	QQ-A-371c	22.3	2.89	0.29	
Cast, sand (heat treat)	#220-T4	QQ-A-371c	24.7	2.57	0.29	
Cast, die	#360	QQ-A-591a-2	20.9	2.64	0.27	
Cast, die	#380	QQ-A-591a-2	20.9	2.72	0.23	

* °C, 20 to 100°C.
** Also weight in g/cm^3.

Figure 7-62. Typical Physical Properties of Aluminum

Fiber Optic. Polymethacrylate (PMMA) and various copolymer products are the most widely used plastic materials for the manufacture of plastic optical fiber. PMMA fibers (SPF) are small diameter fibers on the order of 125 to 3000 µm. The copolymer products (LPF) are available with diameters of 3 to 19 mm.

Plastic optical fiber (POF) is sensitive to ultraviolet wavelengths, high temperature, and the radiant power density of light incident on its ends. POF absorbs radiation in the ultraviolet spectrum. Over time, plastic fiber yellows and becomes unusable if subjected to unacceptable amounts of ultraviolet radiation. Like most plastics, POF melts or burns if subjected to high levels of infrared radiation or heat. In addition, if too much light is put into the fiber, the fiber rapidly burns or darkens. For example, some POF is rated at a maximum luminous power capacity of 30 lm/mm^2. Power densities below this value ensure a long operating life.

SPF has an acceptance angle of 66°. The various LPF products have acceptance angles between 75 and 80°.

Glass Fiber. Glass optical fibers are typically 50 to 150 µm in diameter. Glass can be manufactured in larger diameters, but its lack of flexibility quickly precludes its use in practical architectural applications. The small individual glass fibers are grouped together in bundles (GFB) of various diameters. These bundles of extremely small fibers result in light guides that are very flexible. Glass fiber has a greater radiant power handling capacity and longer life and can operate continuously at higher temperatures than POF. These characteristics make GFB useful where harsh environmental requirements prevent the use of POF.

Glass fiber is impervious to the ultraviolet spectrum. Designers need not concern themselves with fiber degradation resulting from UV radiation, but they should be aware that although most GFB available for lighting applications absorbs and thus filters UV radiation, some glass fiber is designed to transmit specific UV wavelengths.

The numerical aperature (NA) of glass fiber can vary with the index of refraction of the component materials. Typically the numerical apertures of glass fibers are 0.64 and 0.55, yielding acceptance angles of 80° and 66°, respectively.

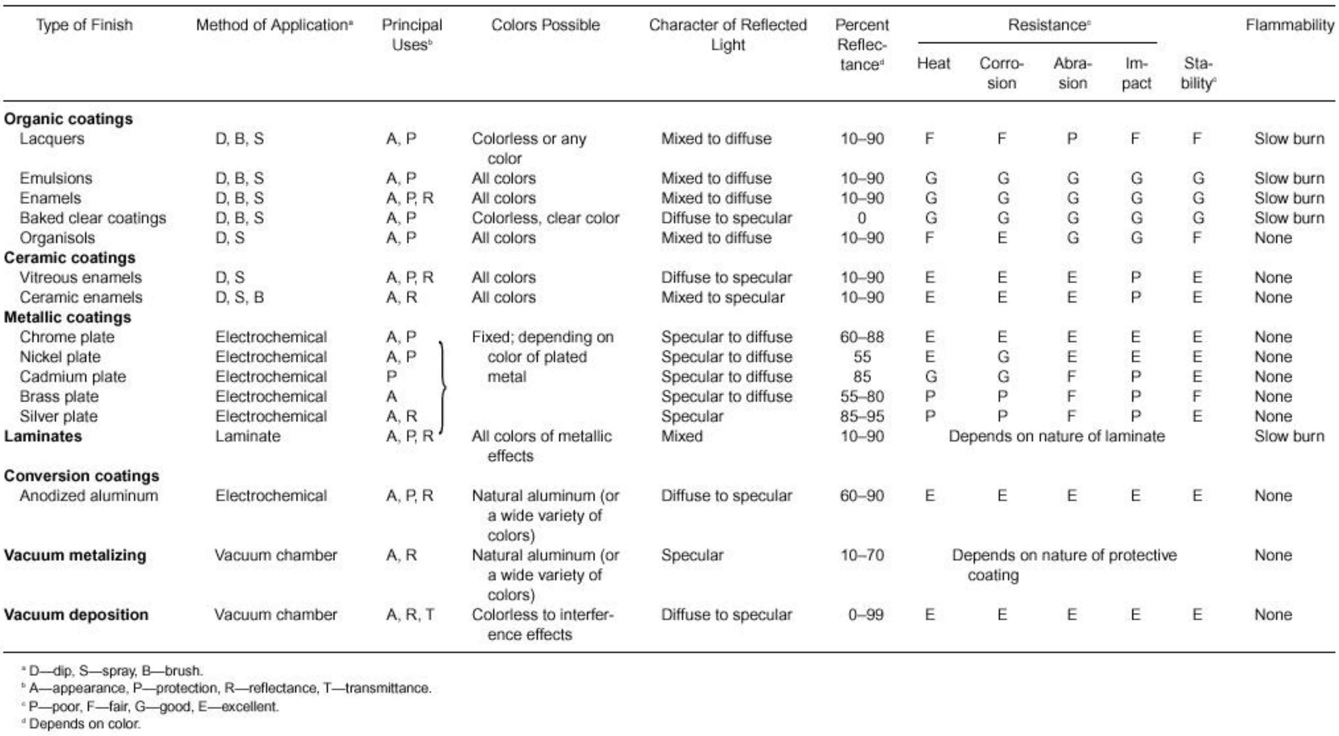
The ends of glass fibers must be terminated and polished by the manufacturer. Users generally must specify the required lengths of an application when placing an order. In contrast, POF can be cut to any desired length in the field at the time of installation.

Finishes Used in Luminaires

A finish is the final treatment given to the surface of a material in the course of manufacturing to render it ready for use. Three major purposes for finishes on lighting equipment are the control of light, the protection of material, and the enhancement of appearance. In addition, there are finished for several special applications, such as flame-retardant and color-stabilizing treatments.

Finishes are classified both by the method of application and by the kind of material applied. The three basic types are coatings, laminates, and chemical conversion finishes. Coatings can be divided into four general classes: organic, ceramic, metallic, and other.

Typical characteristics of finishes are indicated in Figure 7-63. Because of the great number of possible variations in composition and application of all types of finishes, numerical values are not shown and relative gradings only are used. For more details on finishes, technical assistance should be obtained from suppliers and available literature.



Type of Finish	Method of Application[a]	Principal Uses[b]	Colors Possible	Character of Reflected Light	Percent Reflectance[d]	Resistance[c]					Flammability
						Heat	Corrosion	Abrasion	Impact	Stability[c]	
Organic coatings											
Lacquers	D, B, S	A, P	Colorless or any color	Mixed to diffuse	10–90	F	F	P	F	F	Slow burn
Emulsions	D, B, S	A, P	All colors	Mixed to diffuse	10–90	G	G	G	G	G	Slow burn
Enamels	D, B, S	A, P, R	All colors	Mixed to diffuse	10–90	G	G	G	G	G	Slow burn
Baked clear coatings	D, B, S	A, P	Colorless, clear color	Diffuse to specular	0	G	G	G	G	G	Slow burn
Organisols	D, S	A, P	All colors	Mixed to diffuse	10–90	F	E	G	G	F	None
Ceramic coatings											
Vitreous enamels	D, S	A, P, R	All colors	Diffuse to specular	10–90	E	E	E	P	E	None
Ceramic enamels	D, S, B	A, R	All colors	Mixed to specular	10–90	E	E	E	P	E	None
Metallic coatings											
Chrome plate	Electrochemical	A, P	Fixed; depending on color of plated metal	Specular to diffuse	60–88	E	E	E	E	E	None
Nickel plate	Electrochemical	A, P		Specular to diffuse	55	E	G	E	E	E	None
Cadmium plate	Electrochemical	P		Specular to diffuse	85	G	G	F	P	E	None
Brass plate	Electrochemical	A		Specular to diffuse	55–80	P	P	F	P	F	None
Silver plate	Electrochemical	A, R		Specular	85–95	P	P	F	P	E	None
Laminates	Laminate	A, P, R	All colors of metallic effects	Mixed	10–90	Depends on nature of laminate					Slow burn
Conversion coatings											
Anodized aluminum	Electrochemical	A, P, R	Natural aluminum (or a wide variety of colors)	Diffuse to specular	60–90	E	E	E	E	E	None
Vacuum metalizing	Vacuum chamber	A, R	Natural aluminum (or a wide variety of colors)	Specular	10–70	Depends on nature of protective coating					None
Vacuum deposition	Vacuum chamber	A, R, T	Colorless to interference effects	Diffuse to specular	0–99	E	E	E	E	E	None

[a] D—dip, S—spray, B—brush.

[b] A—appearance, P—protection, R—reflectance, T—transmittance.

[c] P—poor, F—fair, G—good, E—excellent.

[d] Depends on color.

Figure 7-63. Properties of Finishes Used in Luminaires

Coatings

Organic Coatings. Lacquers are clear, transparent, or opaque and cure rapidly at room temperature. They may be used for decoration or protection. Enamels are pigmented coatings and are applied for protection, decoration, or reflectance. They cure by oxidation (air or forced drying) or polymerization (baking or catalytic action) and result in tougher finishes than lacquers. Baked clear coatings, sometimes called baking lacquers, are used for decoration and protection. They cure by polymerization (baking or catalytic action).

Organisols and plastisols are usually applied by dipping and spraying. These plastic dispersion coatings offer good exterior corrosion as well as scratch and abrasion resistance and also are able to conceal many surface defects.

Ceramic Coatings. Ceramic coatings, including porcelain enamels, are fired on glass and metals at temperatures above 540°C. Primary features on metals include high resistance to corrosion, good reflectance, and easy maintenance, and on glass, reduction of brightness and increase of diffusion.

Metallic Coatings. Electrochemical deposition, commonly called electroplating, causes a second metal to be deposited over the first by means of an electrolytic action. Zinc, cadmium, or nickel is used to provide protection. Brass and silver finishes are primarily decorative.

Vacuum metallizing consists of vaporizing a metal, usually aluminum, in a vacuum chamber and depositing it on surfaces of plastic, glass, or metal. Finishes of high specular reflectance are obtained and can be used for either light control or decorative purposes. Dip and spray coatings, as in galvanizing, are deposits of a second metal to protect the base metal against corrosion.

Other Coatings. Semiconductors, such as silicon and germanium, and inorganic dielectrics, such as magnesium fluoride and titanium dioxide, are vacuum deposited on such materials as glass, aluminum, and plastics. The coatings of interest for lighting uses are multilayered and less than 1 µm thick.

Laminates. This type of finish is created by bonding a thin layer to a base material, such as a plastic film to sheet metal. The laminate can be a decorative material or it can be a light-controlling material.

Chemical Conversion Finishes. Anodizing converts an aluminum surface by an anodic process to aluminum oxide, which has outstanding protective qualities against corrosion and abrasion. The resultant finish may be clear or can be dyed in a variety of colors.

Overview of Manufacturing Methods

Metal Working

Spinning. In this process a metal blank in the form of a thin disk is mounted against a wood or steel chuck between the headstock and the tailstock of a lathe. While the blank and chuck are rotating, the metal is forced against the chuck by means of a tool held by the operator. The blank assumes the shape of the chuck. Automatic equipment exists that forms the metal against the chuck by means of rollers. This is called autospinning. This process is characterized by low tool investment. Manual spinning usually is performed only for low quantities and for special or prototype pieces.

Stamping. Also known as drawing or deep drawing, this metal-forming process places a metal blank on top of a negative cavity die, usually a cast block of steel. While the perimeter of the blank is held firmly by a ring, a positive die forces the blank into the negative cavity. The blank assumes the shape of the matching positive and negative dies. This process is characterized by high tool and setup costs, but low piece costs in high-volume production.

Hydroforming. In this process a metal blank is placed on a die plate and forced against a diaphragm of synthetic material, behind which is a large container filled with oil. The oil container is called the pressure dome. A positive die is forced against the metal blank. The oil is nearly incompressible and helps form the metal blank to the shape of the die. Water, rather than oil, was originally used in this process; thus its name. This process is characterized by low tool costs and low piece costs in high-volume production.

Die Casting. In this process molten metal is pumped at high pressure into a two-piece die. The die halves open when the part is sufficiently cooled, and ejector pins push the part out of one of the die halves. This process is characterized by very high tool costs but low piece costs in very high volume production.

Plastics. The forming and converting of plastics into end products is a highly specialized field. Some of the more important processes are as follows:

- Injection molding: Fluid plastic is forced under pressure into a controlled-temperature mold.
- Compression molding: Resin is placed in the mold, and the cavity is filled by application of heat and pressure.
- Blow molding: A thin cylinder of plastic is placed in a mold and inflated by air pressure to conformity with the mold cavity.
- Extrusion: Fluid plastic is forced through a die.
- Thermoforming: A sheet, heated to a state of limpness, is draped over a mold and forced into close conformity with it by pressure or vacuum.
- Spray coating: A solution or emulsion is sprayed on a prepared surface.
- Machining: Solid plastic is shaped by usual wood- or metal-working operations.
- Rotational molding: Resin is charged into a mold rotated in an oven, centrifugal forces distribute the resin, and the heat melts and fuses the charge to the shape of the cavity.
- Cold stamping: Cold plastic sheets are stamped and formed.
- Ultrasonic welding: Plastics are bonded by conversion of sonic vibrations to heat.
- Coextrusion: Two compatible plastics are extruded simultaneously to produce a finished profile. This is performed with a twin-head extruding machine.
- Two-color molding: One part is molded and a second material is injected into designated areas of the part. This method uses a twin-head injection molding machine, or two machines and dies.
- Transfer molding: A decorating film or ink is placed on a tape, which is spooled through the mold. The tape indexes to the desired position, and the material is then injected into the mold, against the underside of the tape. When the mold opens for ejection of the part, the tape is stripped away, leaving a completed, decorated part.

Secondary operations for molded plastics include vacuum metallizing for reflectors, painting, silk-screening, hot stamping, decorative or protective pad printing, plating for chemical resistance, sonic welding for bonding, laser cutting for hole piercing or machining, and the use of high-pressure water jets for custom fabrication. Dichroic coating can be applied to some plastic materials to produce cold-mirror reflectors.

Glass. Glass may be formed by several techniques: pressing, blowing, rolling, drawing, centrifugal casting, and sagging. These operations may be performed by hand methods or by automatic machines, depending on volume. After being formed, many glass products must be annealed to relieve excessive stress. Additional finishing operations may be required, such as cutting, grinding, polishing, and drilling. Further treatment, such as tempering or chemical strengthening, may be required to obtain the desired physical properties.

The finishes for glass surfaces are varied in nature, depending on the forming technique. The surfaces may be subsequently altered by chemical etching, sandblasting or shot blasting, polish staining, and coating. These operations are used to obtain reflection, control radiation, or make a surface electrically conductive.

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8

Daylighting

Daylight[1] is distinguished as a light source by its unique, changing spectra and distributions. It can increase occupant satisfaction and conserve energy if considerations such as view design, glare control, human factors, and integration of building systems are properly addressed. It is essential that daylight effects be considered in any space where daylight is admitted, even if it is not exploited as a light source, in order to avoid problems with glare and damage to materials.

To use daylight effectively, the following factors should be taken into account:

- Human factors, including physiology, perception, preferences, and behavior
- Effects of daylight on all materials, including furniture, artwork, and plants
- Controlled admission of direct sunlight
- Controlled admission of diffuse daylight
- Effects of local terrain, landscaping, and nearby buildings on the available light
- Integration of building systems, including the electric lighting, fenestration, interior geometry and finishes, manual and automatic control systems, and active climate control systems

DAYLIGHT SOURCES AND AVAILABILITY

The daily and seasonal movements of the sun with respect to a particular geographic location on the earth produce a predictable pattern of amount and direction of available daylight. Superimposed on this predictable pattern is variation caused by changes in the weather, temperature, and air pollution.

Of the solar energy received at the earth's surface, 40% is visible radiation. The rest is ultraviolet (UV) and infrared (IR) wavelengths. When absorbed, virtually all the radiant energy from the sun is converted to heat. The amount of usable visible energy in the solar spectrum varies with the depth and condition of the atmosphere through which the light traverses. Because the spectral distribution of daylight changes continuously with sun position and sky conditions, the Commission Internationale de l'Éclairage (CIE) has adopted three standard spectral radiant power distributions for daylight (Figure 8-1).

The Sun as a Light Source

The rotation of the earth about its axis, as well as its revolution about the sun, produces an apparent motion of the sun with respect to any point on the earth's surface. The position of the sun with respect to such a point is expressed in terms of two angles: the solar altitude, which is the vertical angle of the sun above the horizon, and the solar azimuth, which is the horizontal angle of the sun from due south in the northern hemisphere (Figure 8-2). See Chapter 1, Light and Optics, for the average luminance of the sun and the illuminance of the earth's surface by the sun.

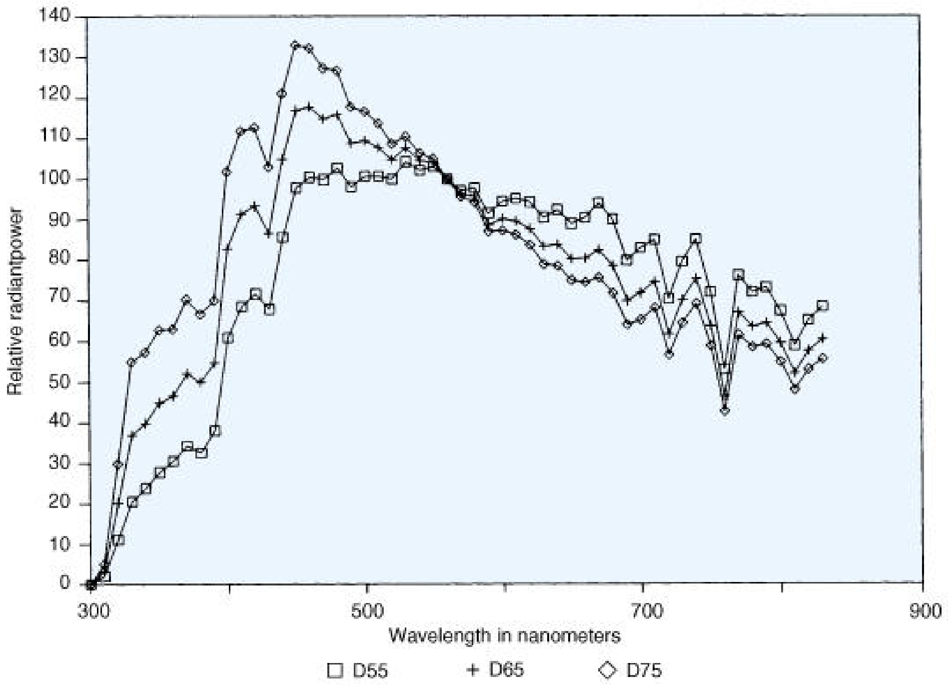


Figure 8-1. Three spectral radiant power distributions of daylight. developed by the CIE, daylight at 5500k (D_{55}), 6500K (D_{65}), and 7500K (D_{75}).

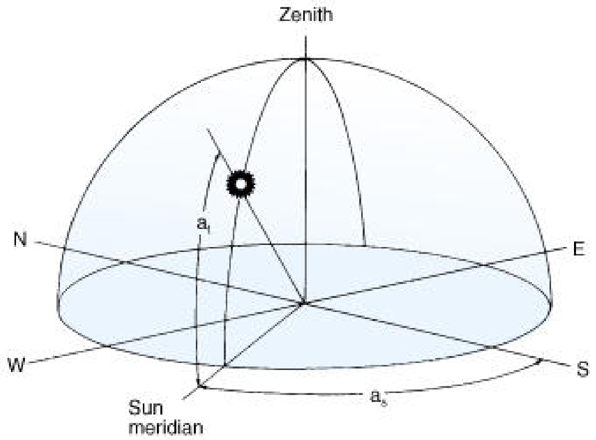


Figure 8-2. The sun's position in terms of solar altitude (a_t) and azimuth (a_s) with respect to the cardinal points of the compass.

The Sky as a Light Source

As sunlight passes through the atmosphere, a portion is scattered by dust, water vapor, and other suspended particles. This scattering, acting in concert with clouds, produces sky luminance. Skies are divided into three categories: (1) clear, (2) partly cloudy, and (3) overcast. When the sky is not completely overcast, the sky luminance distribution may change rapidly and by a large amount as the sun is alternately obscured, partly obscured, or fully revealed.

The Ground as a Light Source

Light reflected from the ground may be important in daylighting design. Such light is, in turn, reflected from the ceiling or walls onto other interior surfaces. On daylighted elevations, the light reflected from the ground typically represents 10 to 15% of the total daylight reaching a window. It frequently exceeds this with light-colored ground surfaces such as sand and snow. On shaded exposures, it may account for even more of the total light reaching a window, depending on the sky condition and building design.

Daylight Availability

Lighting calculations for daylighting can be considerably more complex than for electric lighting. Determination of the illuminance incident on windows and skylights must take into account the time-varying characteristics of the sky and sun, including the changing spatial relationship between the sun and daylighting apertures.

The phrase "daylight availability" refers to the amount of light from the sun and the sky for a specific location, time, date, and sky condition. Over the past 60 years measurements of daylight illuminance by researchers in locations all over the world have resulted in very similar mean values.[2] Equations giving available daylight illuminance are determined from these values.

Daylight availability data, and the equations derived from them, do not express instantaneous values of illuminance and luminance; they give mean values. In other words, the equations provide best fits to data averaged over time and measurement sessions. For this reason, measured instantaneous luminances and illuminances may differ widely from those determined by calculation methods based on daylight availability. It is not unusual for the instantaneous values to be more than twice or less than half the mean design values.

Calculation of daylight availability at a site begins with a determination of the solar position, which is a function of latitude and longitude of the site, day of the year (Julian date), and local time.[3] The local time is converted to solar time. Angles are computed that give the position of the sun in the sky. Finally, for a particular sky condition, the daylight availability equations are used to compute the daylight illuminance. All angles are expressed in radians.

Site Location

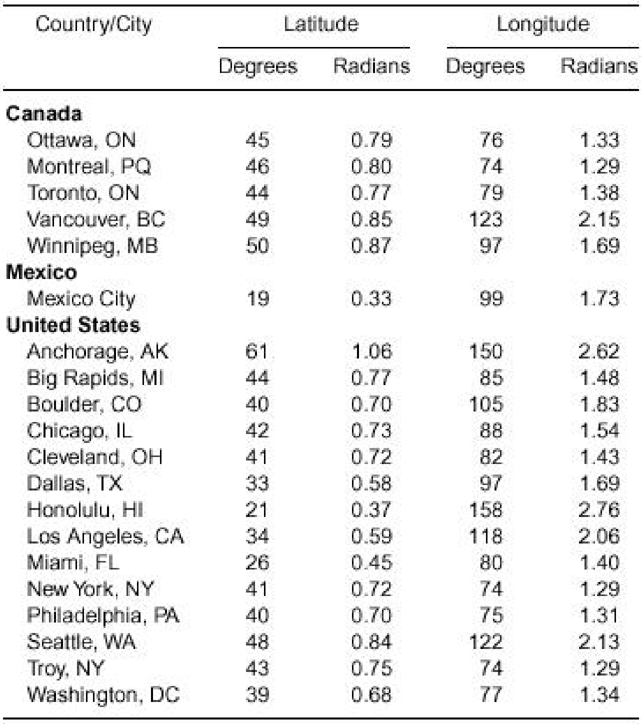
The site location is specified by a latitude *l* and a longitude *L*. Latitudes and longitudes may be found in any standard atlas or almanac. Figure 8-3 shows the latitudes and longitudes of some North American cities.[4]

Conventions used in expressing latitudes are:

Positive = northern hemisphere
Negative = southern hemisphere

Conventions used in expressing longitudes are:

Positive = west of prime meridian (Greenwich, United Kingdom)
Negative = east of prime meridian



Country/City	Latitude		Longitude	
	Degrees	Radians	Degrees	Radians
Canada				
Ottawa, ON	45	0.79	76	1.33
Montreal, PQ	46	0.80	74	1.29
Toronto, ON	44	0.77	79	1.38
Vancouver, BC	49	0.85	123	2.15
Winnipeg, MB	50	0.87	97	1.69
Mexico				
Mexico City	19	0.33	99	1.73
United States				
Anchorage, AK	61	1.06	150	2.62
Big Rapids, MI	44	0.77	85	1.48
Boulder, CO	40	0.70	105	1.83
Chicago, IL	42	0.73	88	1.54
Cleveland, OH	41	0.72	82	1.43
Dallas, TX	33	0.58	97	1.69
Honolulu, HI	21	0.37	158	2.76
Los Angeles, CA	34	0.59	118	2.06
Miami, FL	26	0.45	80	1.40
New York, NY	41	0.72	74	1.29
Philadelphia, PA	40	0.70	75	1.31
Seattle, WA	48	0.84	122	2.13
Troy, NY	43	0.75	74	1.29
Washington, DC	39	0.68	77	1.34

Figure 8-3. Latitude and Longitude of Some North American Cities

Time

A 24h clock is used to express time. Solar time can be determined from standard time (or daylight time) by correcting both for site longitude within a time zone and for the equation of time. The equation of time gives the difference between solar time and clock time due to elliptical orbit of the earth and solar declination of the axis. The value for the equation of time may be determined from:[5]

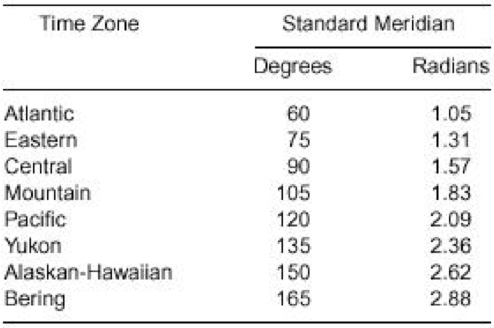
$$\mathrm{ET} = 7.637 \sin\left(\frac{2\pi(\mathrm{J}-2.5)}{365.25}\right) - 9.863 \sin\left(\frac{2\pi(\mathrm{J}-81.6)}{365.25}\right)\Bigg]\frac{1}{60} \qquad (8\text{-}1)$$

where

ET = time expressed in decimal hours (for example, 1:30 p.m.=13.5),
J = Julian date, a number between 1 and 365.

This equation is accurate to within 5 degrees and suitable for most terrestrial daylighting calculations. If an application requires more accuracy, the equation by Meeus[6] may be used.

Each time zone has a reference longitude that is used in calculating solar time. These standard meridians are given in Figure 8-4.



Time Zone	Standard Meridian	
	Degrees	Radians
Atlantic	60	1.05
Eastern	75	1.31
Central	90	1.57
Mountain	105	1.83
Pacific	120	2.09
Yukon	135	2.36
Alaskan-Hawaiian	150	2.62
Bering	165	2.88

Figure 8-4. Time Zone Standard Meridians

The relationship between standard time and daylight time is given by

$$t_s = t_d - 1 \qquad (8\text{-}2)$$

where t_s is standard time in decimal hours and t_d is daylight time in decimal hours.

Solar time is calculated from standard time by the equation

$$t = t_s + ET + \frac{12(SM - L)}{\pi} \qquad (8\text{-}3)$$

where

t = solar time in decimal hours,
t_s = standard time in decimal hours,
ET = time from equation 8-1 in decimal hours,
SM = standard meridian for the time zone in radians,
L = site longitude in radians.

Solar Position

The position of the sun is specified by the solar altitude and solar azimuth and is a function of site latitude, solar time, and solar declination. The solar declination can be closely approximated by

$$\delta = 0.4093 \sin\left(\frac{2\pi(J - 81)}{368}\right) \qquad (8\text{-}4)$$

where

δ= solar declination in radians,
J = Julian date.

The solar altitude is given by

$$a_t = \arcsin\left(\sin l \sin \delta - \cos l \cos \delta \cos \frac{\pi t}{12}\right) \quad (8\text{–}5)$$

where

a_t = solar altitude in radians,
l = site latitude in radians,
δ=solar declination in radians,
t = solar time in decimal hours.

The solar altitude has a range of 0 to $\pi/2$. If the sun is below the horizon, Equation 8-5 gives a negative value. The solar azimuth is given by

$$a_s = \arctan\left(\frac{-\left[\cos\delta \sin\left(\frac{\pi t}{12}\right)\right]}{\qquad}\right) \quad (8\text{-}6)$$

where a_s is the solar azimuth in radians; the other variables are the same as in Equation 8-5. Positive solar azimuthal angles indicate a direction west of south, and negative angles indicate a direction east of south. The arctangent must be placed in the proper quadrant by assessing the signs of the numerator and denominator of its argument.

In many daylighting calculations, it is necessary to calculate the daylight on a vertical surface such as a wall or a window. The elevation azimuth angle is needed for this calculation. It is the angle, measured in the horizontal plane, between the normal to the vertical surface and south (in the northern hemisphere) (Figure 8-5). It is measured clockwise from south.

The solar elevation azimuth gives the azimuthal angle between the sun and the normal to a vertical surface of interest (Figure 8-5). It is given by

$$a_z = a_s - a_e \qquad (8\text{-}7)$$

where

a_z = solar elevation azimuth in radians,
a_s = solar azimuth in radians,
a_e = elevation azimuth in radians.

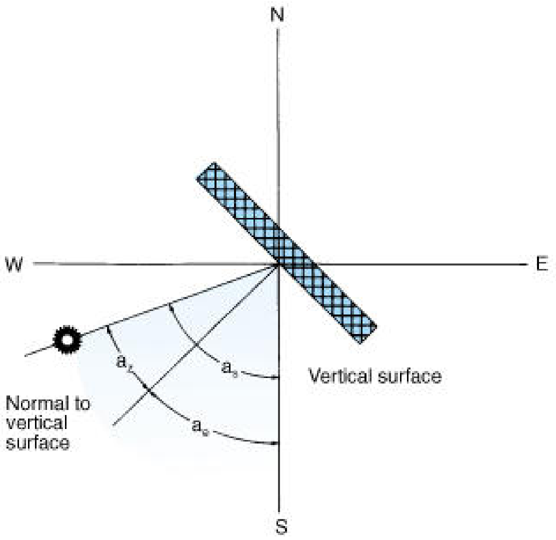


Figure 8-5. Azimuth angles (plan view). See Equation 8-7.

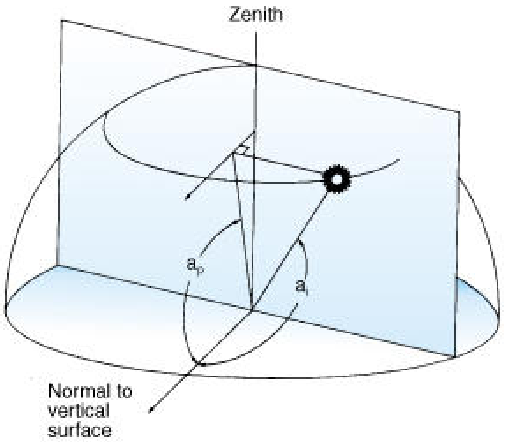


Figure 8-6. Incident and profile angles. See Equations 8-8 and 8-9.

The incident angle is the angle between the normal to a vertical surface of interest and the direction to the sun (Figure 8-6) and can be computed from

$$a_i = \arccos(\cos a_t \cos a_z) \tag{8-8}$$

where

a_i = incident angle in radians,
a_t = solar altitude in radians,
a_z = solar elevation azimuth in radians.

The profile angle is the apparent altitude of the sun relative to a vertical surface of interest (Figure 8-6) and is calculated by Equation 8-9a or 8-9b below. It is used primarily to determine shadows and to plot sunlight penetration on building sections:

$$a_p = \arctan\left(\frac{\sin a_t}{\cos a_i}\right) \tag{8-9a}$$

$$a_p = \arctan\left(\frac{\tan a_t}{\cos a_z}\right) \tag{8-9b}$$

where

a_p = profile angle in radians,
a_t = solar altitude in radians,
a_i = incident angle in radians,
a_z = solar elevation azimuth in radians.

Sunlight

For the purpose of most basic daylighting calculations, the sun is considered to be a point source that provides a constant illuminance at a point on a plane that is normal to the direction of the sun and near the earth's orbit. The solar illumination constant is the total solar illuminance at normal incidence on a surface in free space at the earth's mean distance from the sun. It is obtained from

$$E_{sc} = K_m \int_{380}^{770} G_\lambda V_\lambda \, d\lambda \qquad (8\text{-}10)$$

where

E_{sc} = solar illumination constant in klx,
K_m = spectral luminous efficacy of radiant solar flux in lm/W,
$G(\lambda)$ = solar spectral irradiance at wavelength λ, in W,
$V(\lambda)$ = photopic vision spectral luminous efficiency at wavelength λ,
λ = wavelength in nm (for photopic vision at 380 to 770 nm).

The following are important solar parameters based on current standards:[7,8]

Solar illumination constant: 128 klx

Solar irradiation constant: 1350 W/m^2 (126 W/ft^2)

Solar luminous efficacy: 94.2 lm/W

To calculate the sunlight reaching the ground, two conditions must be considered: the varying distance of the earth to the sun caused by the earth's elliptical orbit and the effect of the earth's atmosphere. The extraterrestrial solar illuminance, corrected for the earth's elliptical orbit, is

$$E_{xt} = E_{sc}\left(1 + 0.034 \cos \frac{2\pi(J-2)}{365}\right) \qquad (8\text{-}11)$$

where

E_{xt} = extraterrestrial solar illuminance in klx,
E_{sc} = solar illumination constant in klx,
J = Julian date.

The direct normal illuminance at sea level, E_{dn}, corrected for the attenuating effects of the atmosphere, is given by[9]

$$E_{dn} = E_{xt} e^{-cm} \qquad (8\text{-}12)$$

where

E_{dn} = direct normal solar illuminance in klx,

E_{xt} = extraterrestrial solar illuminance in klx,
c = atmospheric extinction coefficient (Figure 8-7),
m = optical air mass (dimensionless).

Values for the atmospheric extinction coefficient, discussed below, vary with the sky condition. The equation that is the simplest and the most often used[10] representation for the optical air mass is

$$m = \frac{1}{\sin a_t} \qquad (8\text{-}13)$$

where m is the optical air mass (dimensionless) and a_t is the solar altitude in radians. The direct sunlight on a horizontal plane is expressed by

$$E_{dh} = E_{dn} \sin a_t \qquad (8\text{-}14)$$

where

E_{dh} = direct horizontal solar illuminance in klx,
E_{dn} = direct normal solar illuminance in klx,
a_t = solar altitude in radians.

The direct sunlight on a vertical elevation is expressed by

$$E_{dv} = E_{dn} \cos a_i \qquad (8\text{-}15)$$

where

E_{dv} = direct vertical solar illuminance in klx,
E_{dn} = direct normal solar illuminance in klx,
a_i = incident angle in radians.

Skylight

Either the sky-ratio method or the sky-cover method is used to classify a sky. The sky ratio is determined by dividing the horizontal sky irradiance by the global horizontal irradiance. Since the sky ratio approaches 1.0 when the solar altitude approaches zero (regardless of the sky condition), this method is not accurate for low solar altitudes. The sky conditions are defined as follows:

Clear:	sky ratio ≤ 0.3
Partly cloudy:	0.3 <sky ratio <0.8
Overcast:	0.8 ≤ sky ratio

The sky cover method uses estimates of the amount of cloud cover. Cloud cover is estimated in tenths and is expressed on a scale from 0.0 for no clouds to 1.0 for complete sky cover. The sky conditions are as follows:

Clear	0.0 to 0.3
Partly cloudy	0.4 to 0.7
Overcast	0.8 to 1.0

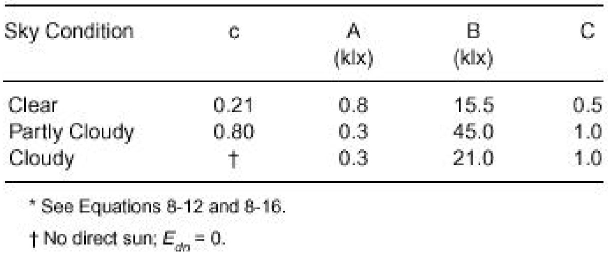
The horizontal illuminance produced by the sky can be expressed as a function of solar altitude:[2]

$$E_{kh} = A + B \sin^C a_t \qquad (8\text{-}16)$$

where

E_{kh} = horizontal illuminance due to unobstructed skylight in klx,
A = sunrise/sunset illuminance in klx,
B = solar altitude illuminance coefficient in klx,
C = solar altitude illuminance exponent,
a_t = solar altitude in radians.

The form of the equation is the same for all three sky conditions, with different constants for different sky conditions (Figure 8-7).



Sky Condition	c	A (klx)	B (klx)	C
Clear	0.21	0.8	15.5	0.5
Partly Cloudy	0.80	0.3	45.0	1.0
Cloudy	†	0.3	21.0	1.0

* See Equations 8-12 and 8-16.

† No direct sun; $E_{dn} = 0$.

Figure 8-7. Daylight Availability Constants*

A different equation is used to represent the mean luminance distribution of each of the three sky conditions. The luminance of the sky is a function of luminance distribution with respect to zenith luminance and absolute value of the zenith luminance. In the method used here, a zenith luminance factor is used to calculate the zenith luminance from the horizontal sky illuminance:

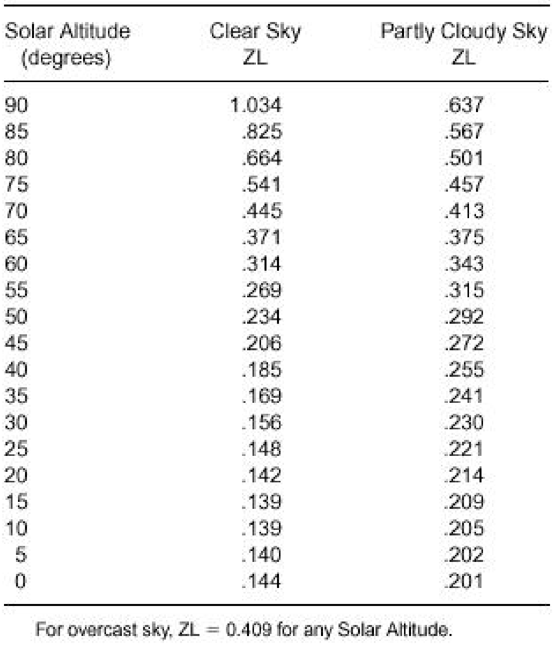
$$L_z = E_{kh}\,\mathrm{ZL} \qquad (8\text{-}17)$$

where

L_z = zenith luminance in kcd/m^2,
E_{kh} = horizontal illuminance due to unobstructed skylight from Equation 8-16, in klx,
ZL = zenith luminance factor at the same solar altitude as E_{kh}, in kcd/(m^{2}klx).

Values for the zenith luminance factor can be found in Figure 8-8. More detailed equations for the zenith luminance have been developed, which include effects such as differences in atmospheric turbidity.[11]

The angles used in sky luminance determinations are shown in Figure 8-9. The position of the sun in Figure 8-9 is given by the solar azimuth a_s and zenithal sun angle Z_0. Note that Z_0 is related to the solar altitude a_t by the simple formula



Solar Altitude (degrees)	Clear Sky ZL	Partly Cloudy Sky ZL
90	1.034	.637
85	.825	.567
80	.664	.501
75	.541	.457
70	.445	.413
65	.371	.375
60	.314	.343
55	.269	.315
50	.234	.292
45	.206	.272
40	.185	.255
35	.169	.241
30	.156	.230
25	.148	.221
20	.142	.214
15	.139	.209
10	.139	.205
5	.140	.202
0	.144	.201

For overcast sky, ZL = 0.409 for any Solar Altitude.

Figure 8-8. Sky Zenith Luminance (ZL) Constants

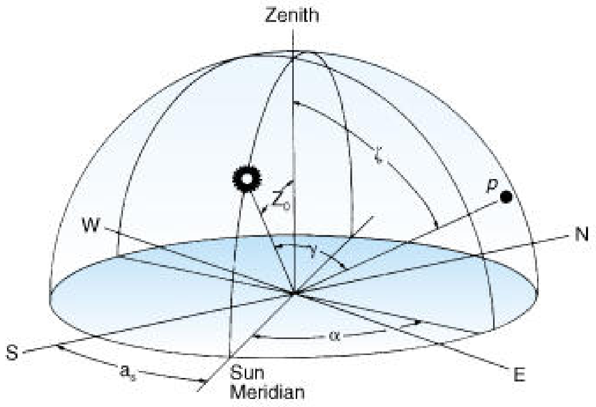


Figure 8-9. Sky angles. See Equation 8-19 and Figure 8-2.

$$Z_o = \frac{\pi}{2} - a_t \tag{8-18}$$

The position of a point *p* in the sky (at which the sky luminance is calculated) is given by angles *z*, the zenithal point angle in radians, and ξ, the azimuth angle from the sun in radians.

A standard clearsky luminance distribution function was developed by Kittler[12] and adopted by the CIE:[13]

$$L(\zeta,\alpha) = L_z \frac{\left(0.91 + 10\,\mathrm{e}^{-3\gamma} + 0.45\cos^2\gamma\right)\left(1 - \mathrm{e}^{-0.32/\cos\zeta}\right)}{\left(0.91 + 10\,\mathrm{e}^{-3Z_0} + 0.45\cos^2 Z_0\right)\left(1 - \mathrm{e}^{-0.32}\right)} \tag{8-19}$$

where

$L(\zeta,\alpha)$ = sky luminance at point *p* with spherical coordinates ξ and α, in kcd/m^2,

L_z = sky zenith luminance in kcd/m^2,
γ = angle between the sun and sky point p in rad (Equation 8-20),
ζ = zenithal point angle in radians,
α= azimuth angle from the sun in radians,
Z_0 = zenithal sun angle in radians.

The angle γ between the sun and sky point p is given by

$$\gamma = \arccos\,(\cos Z_0 \cos\zeta + \sin Z_0 \sin\zeta \cos\alpha) \qquad (8\text{-}20)$$

where

Z_o, γ, ζ, and α are defined as in Equation 8-19. This equation does not take account of changes in the luminance distribution due to changes in atmospheric turbidity, which can substantially alter the luminance distribution of the sky.

The equation for a partly cloudy sky[14] is similar in form to the clear-sky distribution but has different values of the constants based on mean data for partly cloudy skies:

$$L(\zeta,\alpha) = L_z \frac{(0.526 + 5\,e^{-1.5\gamma})\,(1 - e^{-0.80/\cos\zeta})}{(0.526 + 5\,e^{-1.5\,Z_o})\,(1 - e^{-0.80})} \qquad (8\text{-}21)$$

where the symbols have the same meaning as in Equation 8-19. The overcast-sky equation is

$$L(\zeta,\alpha) = L_z \left(0.864\,\frac{e^{-0.52/\cos\zeta}}{e^{-0.52}} + 0.136\,\frac{1 - e^{-0.52/\cos\zeta}}{e^{-0.52}}\right) \quad (8\text{-}22)$$

The form of the overcast-sky equation can be derived from first principles.[13] The first term provides the luminance contribution of the cloud layer, and the second term provides the luminance contribution of the atmosphere between the bottom of the cloud layer and the ground. Constants have been chosen to give a best fit to the original data used by Moon and Spencer[15] in their treatment of the overcast sky.

The empirical Moon-Spencer[15] equation for the luminance distribution of an overcast sky is

$$L(\zeta,\alpha) = \frac{L_z}{3}\,(1 + 2\cos\zeta) \qquad (8\text{-}23)$$

where

$L(\zeta,\alpha)$ = sky luminance in kcd/m^2,
L_z = sky zenith luminance in kcd/m^2,
ζ = zenithal point angle in radians.

This equation has been almost universally used to represent overcast skies for the past 40 years and was adopted by the CIE in 1955.[16] It is historically significant in that a large number of daylight calculation methods are based on it. There is very little numerical difference between Equations 8-22 and 8-23 for the appropriate constants.

The illuminance on a horizontal surface produced by a differential element of the sky is given by

$$dE_{kh} = L(\zeta,\alpha)\cos\zeta\,d\omega = L(\zeta,\alpha)\cos\zeta\sin\zeta\,d\zeta\,d\alpha \quad (8\text{-}24a)$$

where

E_{kh} = illuminance on the horizontal surface in klx,
$L(\zeta,\alpha)$ = sky luminance at point p with spherical coordinates ζ and α, in kcd/m^2,
$d\omega$ = differential element of solid angle in the direction to point p,
ζ = zenithal point angle in radians,
α = azimuth angle from the sun in radians.

This equation assumes spherical coordinates. It can be integrated to give the horizontal illuminance produced by an area of sky:

$$E_{kh} = \iint L(\zeta,\alpha) \sin\zeta \ \cos\zeta \ d\zeta \ d\alpha \qquad (8\text{-}24b)$$

where

E_{kh} = illuminance on the horizontal surface in klx,
$L(\zeta,\alpha)$ = sky luminance at point p with spherical coordinates ζ and α, in kcd/m^2,
$d\omega$ = differential element of solid angle in the direction to point p,
ζ = zenithal point angle in radians,
α = azimuth angle from the sun in radians.

The limits of integration depend on the position and extent of the sky patch. In the limit of the entire sky, the integration is over a hemisphere. This gives

$$E_{kh} = \int_0^{2\pi} \int_0^{\pi/2} L(\zeta, \alpha) \sin\zeta \cos\zeta \, d\zeta \, d\alpha \qquad (8\text{-}25)$$

Similarly, the illuminance on a vertical surface due to the sky only is given by

$$E_{kh} = \int_{a_z - \pi/2}^{a_z + \pi/2} \int_0^{\pi/2} L(\zeta, \alpha) \sin^2\zeta \cos\alpha \, d\zeta \, d\alpha \qquad (8\text{-}26)$$

In numerical methods, Equations 8-25 and 8-26 are usually approximated by finite sums of products of differentials and discrete values.

For those cases where the illuminance is desired at a point on a horizontal or vertical plane that has unobstructed access to the sky and the sun, illuminances for given sky conditions and sun positions can be obtained from graphs based on Equations 8-25 and 8-26 (Figures 8-10 through 8-17).

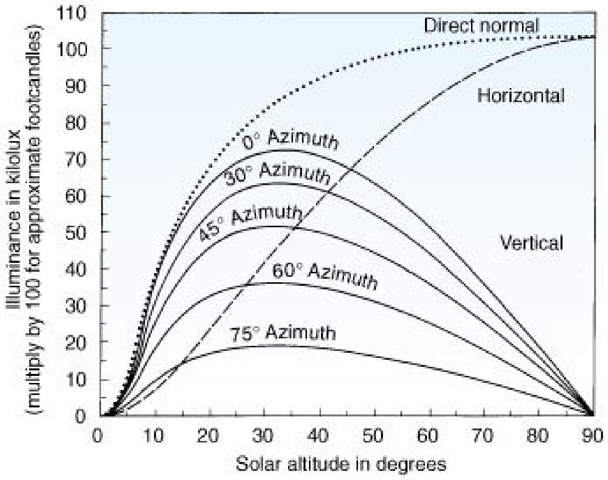


Figure 8-10. Illuminance from the sun under clear sky conditions as a function of solar altitude and azimuth.

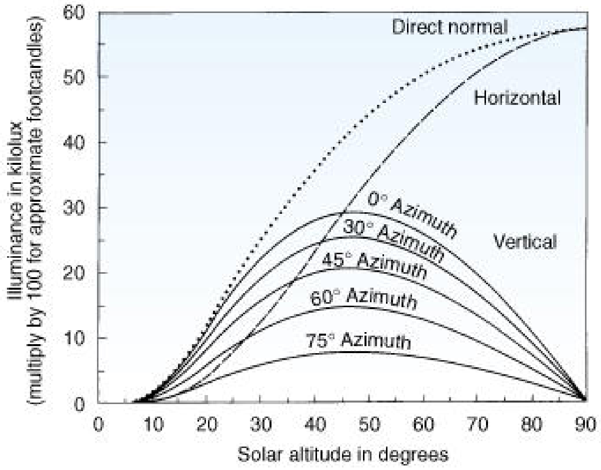


Figure 8-11. Illuminance from the sun under partly cloudy sky conditions as a function of solar altitude and azimuth.

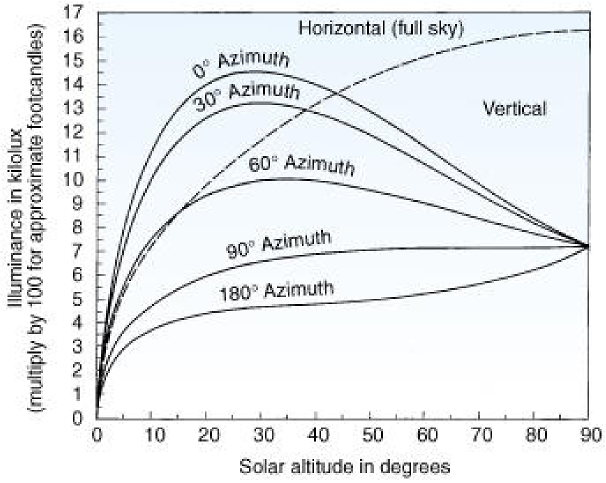


Figure 8-12. Illuminance on vertical surfaces from clear sky conditions as a function of solar altitude and azimuth.

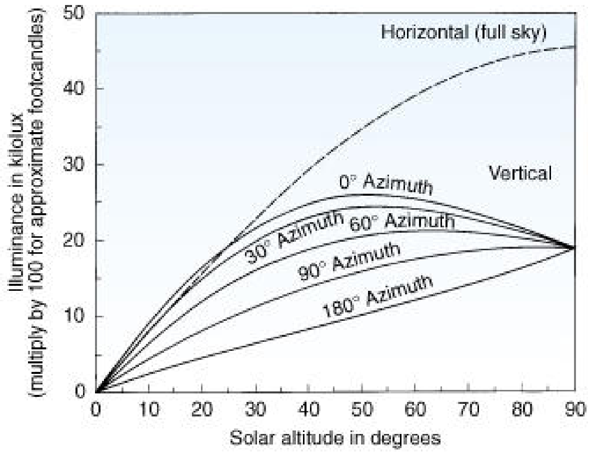


Figure 8-13. Illuminance on vertical surfaces from partly cloudy sky conditions as a function of solar altitude and azimuth.

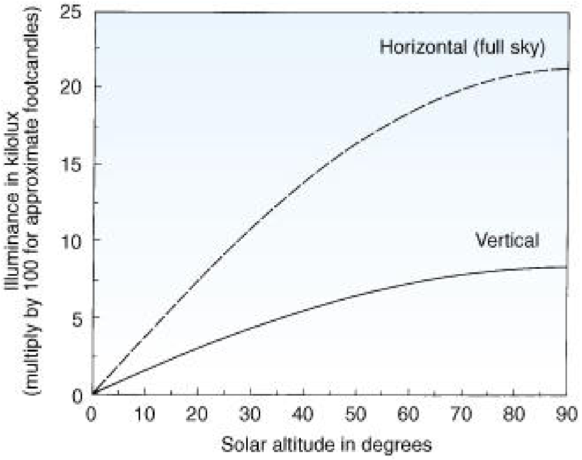


Figure 8-14. Illuminance on vertical surfaces from overcast sky conditions as a function of solar altitude.

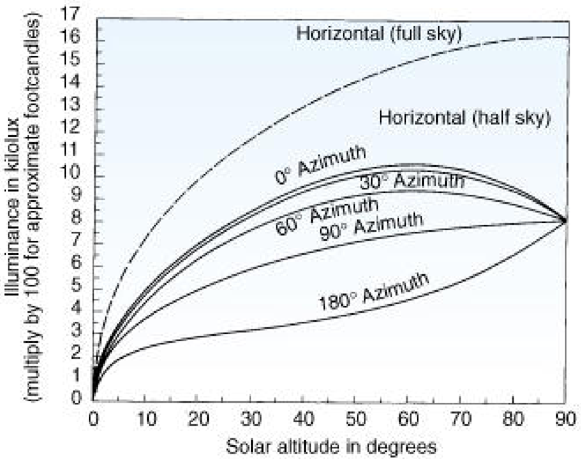


Figure 8-15. Illuminance on horizontal surfaces from clear sky conditions as a function of solar altitude and azimuth.

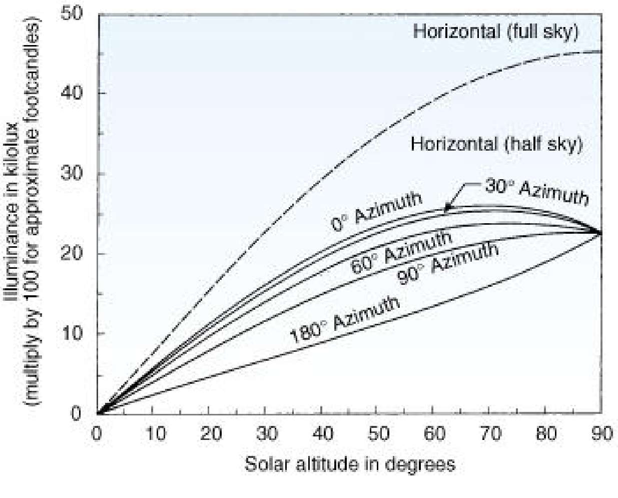


Figure 8-16. Illuminance on horizontal surfaces from partly cloudy sky conditions as a function of solar altitude and azimuth.

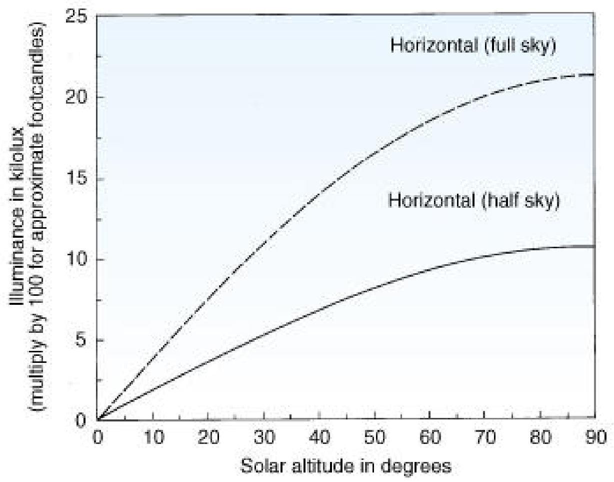


Figure 8-17. Illuminance on horizontal surface from overcast sky conditions as a function of solar altitude.

DAYLIGHTING AND HUMAN FACTORS

View Design and Human Reaction to Windows

It is important that the provision of view and the delivery of daylight be clearly differentiated. Although the terms "view" and "daylighting" are sometimes used interchangeably, the view function of windows is very different from the daylight delivery function. The provision of daylight alone (for example, through skylights) will not satisfy user desires for views including sky, horizon, and ground.[17]

It has been suggested that, to satisfy most workers, windows must cover at least 20% of the window wall area.[18-20] Heavily tinted glass, used to reduce glare and solar heat gain from such windows, gives outdoor areas an overcast and gloomy appearance, even on sunny days.[21]

Glare from Daylight

Daylighting systems can produce discomfort glare.[22] Very high luminance ratios are produced unless care is taken to balance and reduce luminances. Increased interior electric lighting may be required to balance luminances and reduce glare produced by daylight, thus increasing energy use when daylighting is used. Glare is critically dependent on the luminance of the window. Methods for predicting the presence of glare from large area sources have been developed.[23]

Because of its intensity, direct sunlight also must be considered in glare control. While it may be used as an amenity, it should be excluded from critical task areas. The duration of sunlight, rather than its intensity or the size of the illuminated patch, correlates best with the appreciation of interior sunlight.[24-26]

Human Behavior with Respect to Blinds and Shades

Venetian blinds and curtains are commonly used devices for adjusting the amount of daylight entering spaces and reducing window luminance to control glare. These devices can drastically reduce the amount of daylight admitted to a space, so occupant use of blinds is an important consideration in estimating energy savings from daylighting. Occupants adjust venetian blinds infrequently, having preferred blind positions that are dependent on the orientation of the facade and the season of the year.[27-29]

DAYLIGHT EFFECTS ON BUILDING CONTENTS

Daylight Effects on Materials and Artwork

Daylight is of particular concern with respect to light damage to materials and artwork because of its high intensity relative to light from electric sources. Light at all wavelengths, not just in the UV range, contributes to fading, bleaching, and other damage.[30] However, UV is known to be especially active in the fading and bleaching process. Unfiltered daylight has about ten times as much UV radiation per lumen as light from incandescent lamps. The length of time that materials are exposed to daylight is a factor in fading; the longer the exposure time, the greater the damage.

Exposure of items such as sensitive display merchandise to daylight should therefore be minimized. Fading and bleaching are discussed in Chapter 5, Nonvisual Effects of Optical Radiation, and in Chapter 14, Lighting for Public Spaces.

Daylight Effects on Plants

Daylight provides the full spectrum that plants need for all photoresponses in order to maintain health. Lighting for plant health is discussed in Chapter 5, Nonvisual Effects of Optical Radiation.

CALCULATION OF INTERIOR ILLUMINANCES

Calculation methods are useful in comparing alternative daylight delivery systems or considering the limits of daylight utilization for various buildings and systems under a wide variety of lighting conditions. Calculation methods are useful alternatives when weather or sky conditions do not permit appropriate or comparable scale model measurements and evaluation.

Manual Methods

Manual methods for calculating illuminance at a point involve determination of the sky, sun, and interreflected components of daylight. The sky and sun components are computed from flux that reaches a window aperture or point directly. The interreflected component results from sunlight and skylight that have initially reached other surfaces and have then been reflected to the point of interest. Methods for determining the direct and interreflected components of illuminance at a point are described in Chapter 9, Lighting Calculations. Average illuminance on a workplane can be calculated using the lumen methods described below.

Computer Calculations[31-35]

Because of the speed with which design alternatives can be explored and the complexity that can be evaluated, computer-based daylight calculations are important design tools. Capabilities for visualization of interior scenes with combined electric sources and daylighting are included with many software packages.[33,36-38]

Calculations of point illuminance are usually made with computer software because of the capacity to model electric lighting and to calculate lighting energy savings, which may be problematic with scale models and other manual methods. There are two basic approaches to the computer computation of daylight: radiative transfer and ray tracing. These methods are described in detail in Chapter 9, Lighting Calculations.

With radiative transfer-based computer programs, the sky and sun components at the points of interest are determined using a finite-sum approximation for Equations 8-25 and 8-26. The summation is performed using only those (small) sections of the sky that illuminate the points directly. The interreflected component of illuminance is determined using the finite element radiative transfer method. This process is described in detail in Chapter 9, Lighting Calculations. In its application to daylight calculations, the initial exitances of room surfaces are determined from the flux input from windows and skylights. Most radiative transfer methods assume that room surface reflectances are diffuse. Hybrid flux transfer programs that provide for the display of specular highlights often use a second pass of the scene to add gloss to the surfaces.

Because the flux-transfer approach bases its calculation on a finite-element analysis of the surfaces of the scene, calculation of the direct and interreflected components can become very complicated for elaborate fenestration and skylight systems if space contents are to be modeled (for example, partitions and furniture) or if the space geometry is complicated. There is a logarithmic relationship between geometric complexity (number of surfaces) and computer resources necessary to complete the calculations. Ray tracing is inherently slower for geometrically simple spaces but is capable of handling almost unlimited geometric complexity with a sublinear relationship to computer resource requirements (Chapter 9, Lighting Calculations.)

The utility of the computational technique is usually dictated by the nature of the information required. If illuminances at points are the only requirement, a radiative transfer procedure is usually sufficient. If accurate and realistic visualization of a space is required, ray tracing can be the better technique. The advantage of radiative transfer is that one computation allows for all views of the room to be readily redisplayed without additional computations, facilitating a simulation of a walk-though of the space. Several commercially available programs use this technique.[33,36-38] The advantage of ray tracing is that nondiffuse surfaces and greater geometric complexity are inherently more accurately and easily calculated. Programs using this technique are also available.[33] The software packages most successful at solving real-world problems usually employ a hybrid of these methods. Factors affecting the accuracy of computer simulations are discussed in References 39 and 40.

Lumen Method[41]

The lumen method for calculation of interior illuminances is similar to the zonal cavity method for electric lighting and is simple enough to permit manual computation. It provides a simple way to predict interior daylight illumination through skylights and windows. It assumes an empty rectangular room with simple fenestration and shading devices. Since room obstructions can substantially reduce illuminances, especially in sidelit spaces,[42,43] other methods should be considered in this case (see Chapter 9, Lighting Calculations). The lumen method has been extended to include skylights[44,45] and sidelit spaces with lightshelves.[46]

The lumen method consists of four basic steps:

1. The exterior illuminances at the window or skylight are determined. These can be calculated as shown in the above section "Daylight Availability."

2. The net transmittance of the fenestration reduces the amount of light that reaches the interior of the room. It includes the transmittance of the glazing, the light loss factor, and other factors that may be required, depending on the sophistication of the fenestration controls used.

3. Coefficients of utilization are ratios of interior to exterior horizontal illuminances. For the lumen method for toplighting the coefficients provide the average daylight illuminance on the workplane. For the lumen method for sidelighting, coefficients give the illuminance at five predetermined points.

4. The interior illuminance is calculated by taking the product of the factors determined in the first three steps.

The basic equation for the illuminance at a prescribed point using the lumen method is the simple formula

$$E_i = E_x \,\mathrm{NT}\,\mathrm{CU} \qquad (8\text{-}27)$$

where

E_i = interior illuminance in lx,
E_x = exterior illuminance in lx,
NT = net transmittance,
CU = coefficient of utilization.

The procedures for determining the net transmittance and the coefficient of utilization differ for toplighting and sidelighting. If both types of systems are being employed, the illuminance can be computed for each and the illuminances added to give the combined effect.

Lumen Method for Toplighting.

For daylighting systems employing horizontal apertures such as skylights at or slightly above roof level, the lumen method for toplighting is used. It is assumed that the skylights are positioned uniformly across the ceiling. The average horizontal illuminance on the workplane is

$$E_{\mathrm{i}} = E_{\mathrm{xh}}\, \tau\, \mathrm{CU} \frac{A_s}{A_w} \qquad (8\text{-}28)$$

where

E_i = average incident illuminance on the workplane from skylights in lx,
E_{xh} = horizontal exterior illuminance on the skylights in lx,
A_s = gross projected horizontal area of all the skylights in m^2

A_w = area of the workplane in $m^{2,}$

τ = net transmittance of the skylights and light well, including losses because of solar control devices and maintenance factors,
CU = coefficient of utilization.

Equation 8-28 can be used to determine the average workplane illuminance if the total skylight area and the horizontal exterior illuminance are known. Conversely, the required skylight area can be determined if the required average workplane illuminance and the horizontal exterior illuminance are known.

The exterior horizontal illuminance is the sum of the illuminances from the sun and sky. These are determined using the procedures given in the above section "Daylight Availability."

The net transmittance is determined from a direct transmittance T_D and a diffuse transmittance T_d [44] The direct transmittance is used for the sun component and is a function of the angle of incidence. The diffuse transmittance is single valued and is used for the sky component, which is treated as diffuse. Generally, manufacturers provide transmittance data for flat sheets of their glass or plastic in the form of a single value of T_d and a curve showing the variation of T_D with incidence angle.

The net transmittance is also affected by the shape of a skylight, multiple layering, the presence of a skylight well, the presence of louvers or other shades, and light loss factors. Most skylights are domed. This decreases the sheet thickness at the center of the dome, modifying the dome transmittance to

$$T_{DM} = 1.25\,T_{FS}\,(1.18 - 0.416\,T_{FS}) \qquad (8\text{-}29)$$

where

T_{DM} = dome transmittance,
T_{FS} = flatsheet transmittance.

This does not change the transmittance of the transparent sheet ($T_{FS} = 0.92$) but does increase the transmittance of a translucent sheet ($T_{FS} = 0.44$) by about 25%.

Doming causes the angle of incidence of the direct sunlight to vary over the dome's surface, and increases the lightgathering surface area than a flat sheet. Both these factors may be considered together by noting that the effect of doming is to cause T_D to become constant within 10% for all angles of incidence less than 70° (sun angles greater than 20°).[44] Thus, for most dome applications a single number for T_D equal to its value at 0° angle of incidence can be used.

To reduce heat gains and heat losses, most contemporary skylights are double domed, most often a transparent dome over a translucent dome. The overall transmittance of such a unit may be obtained from the following equation, which takes into account the interreflections between the two domes:[47]

$$T = \frac{T_1\,T_2}{1 - \rho_1\,\rho_2} \qquad (8\text{-}30)$$

where

T_1, T_2 =diffuse transmittances of the individual domes,
ρ_1 = reflectance from the bottom side of the upper dome,
ρ_2 = reflectance from the top side of the lower dome.

Reflective losses and interreflections in any light well between the dome and the ceiling plane of the room reduce the net transmittance. This reduction is expressed as a well efficiency N_w, which can be obtained from Figure 8-18 if well wall reflectance and the well cavity ratio (WCR) are known. The well cavity ratio is given by

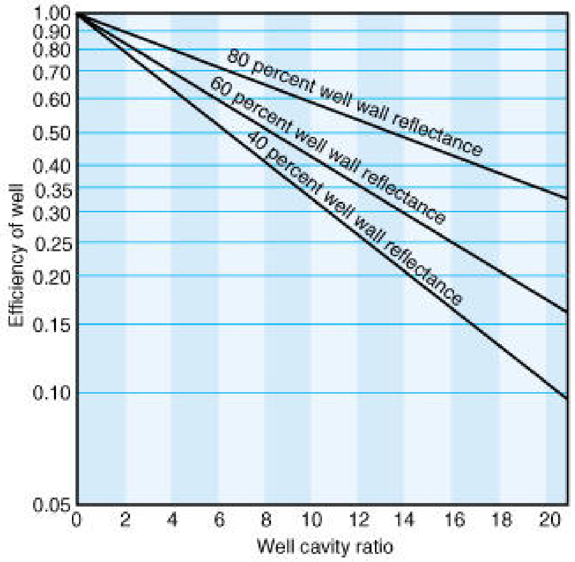


Figure 8-18. Efficiency factors for various depths of light wells, based on well-interreflectance values. See Equation 8-31 for definition of well cavity ratio (WCR).

$$\mathrm{WCR} = \frac{5h(w + l)}{wl} \qquad (8\text{-}31)$$

where h is the well height, w is the well width, and l is the well length. The dimensions h, w, and l must be expressed in the same units.

The net transmittance should also take into account the ratio of net to gross skylight area (R_a). If any diffusers, lenses, louvers, or other controls are present, their transmittances (T_c) must be included. Finally, the light loss factor (LLF) must be included to take account of dirt depreciation of the skylight and well surfaces. Typical values are given in Figure 8-19. The net transmittances of the skylightwell system are found from

$$\tau_d = T_d N_w R_a T_c \,\mathrm{LLF} \qquad (8\text{-}32a)$$

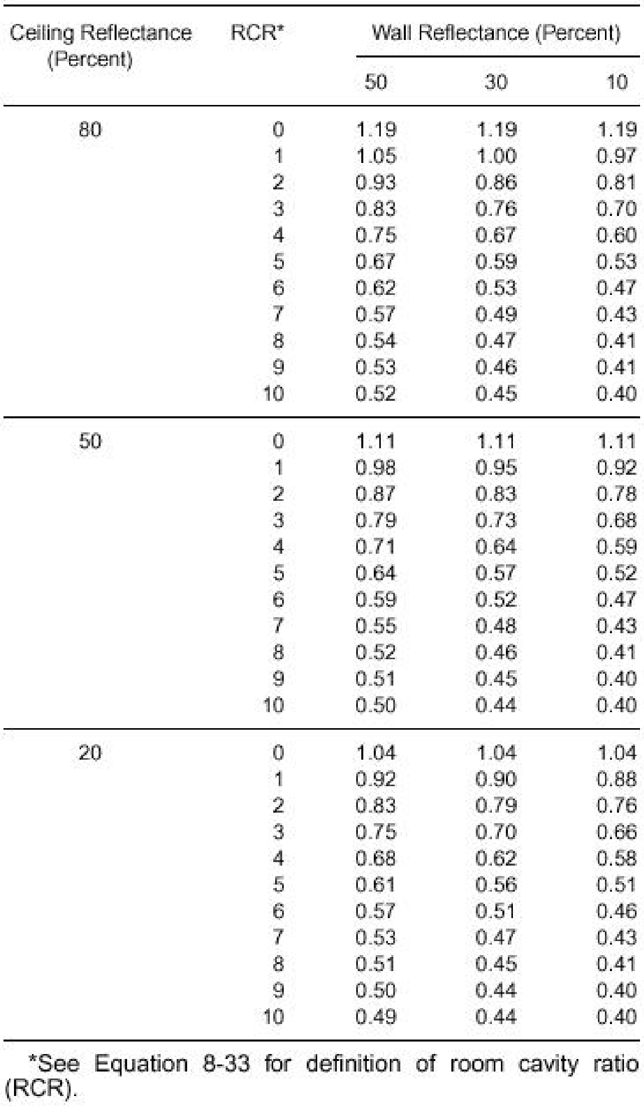
$$\tau_D = T_D N_w R_a T_c \,\mathrm{LLF} \qquad (8\text{-}32b)$$

where T_d is equal to the diffuse transmittance and T_D is equal to the direct transmittance of the dome.

Coefficients of utilization (CU) are given in Figure 8-20. These are based on a spacing-to-mounting-height ratio of 1.5:1, a lambertian distribution from the skylight, and a floor reflectance of 0.2. The wall and ceiling reflectances, as well as room cavity ratios (RCR), are required. Room cavity ratios may be obtained from

Locations	Light Loss Factor Glazing Position		
	Vertical	Sloped	Horizontal
Clean Areas	0.9	0.8	0.7
Industrial Areas	0.8	0.7	0.6
Very Dirty Areas	0.7	0.6	0.5

Figure 8-19. Typical Light Loss Factors for Daylighting Design



Ceiling Reflectance (Percent)	RCR*	Wall Reflectance (Percent)		
		50	30	10
80	0	1.19	1.19	1.19
	1	1.05	1.00	0.97
	2	0.93	0.86	0.81
	3	0.83	0.76	0.70
	4	0.75	0.67	0.60
	5	0.67	0.59	0.53
	6	0.62	0.53	0.47
	7	0.57	0.49	0.43
	8	0.54	0.47	0.41
	9	0.53	0.46	0.41
	10	0.52	0.45	0.40
50	0	1.11	1.11	1.11
	1	0.98	0.95	0.92
	2	0.87	0.83	0.78
	3	0.79	0.73	0.68
	4	0.71	0.64	0.59
	5	0.64	0.57	0.52
	6	0.59	0.52	0.47
	7	0.55	0.48	0.43
	8	0.52	0.46	0.41
	9	0.51	0.45	0.40
	10	0.50	0.44	0.40
20	0	1.04	1.04	1.04
	1	0.92	0.90	0.88
	2	0.83	0.79	0.76
	3	0.75	0.70	0.66
	4	0.68	0.62	0.58
	5	0.61	0.56	0.51
	6	0.57	0.51	0.46
	7	0.53	0.47	0.43
	8	0.51	0.45	0.41
	9	0.50	0.44	0.40
	10	0.49	0.44	0.40

*See Equation 8-33 for definition of room cavity ratio (RCR).

Figure 8-20. Room Coefficients of Utilization for Skylighting (based on a 20% floor reflectance)

$$\mathrm{RCR} = \frac{5\,h_c\,(l + w)}{lw} \qquad (8\text{-}33)$$

where h_c is the height from the workplane to the bottom of the skylight well, l is the length of the room, and w is the width of the room. All three parameters must have the same units.

The general lumen method for toplighting (Equation 8-28) can now be applied. For overcast skies, this is

$$E_i = E_{\mathrm{xh\ sky}}\,\tau_{\mathrm{d}}\,\mathrm{CU}\,N\frac{A}{A_w} \qquad (8\text{-}34)$$

For a clear or partly cloudy sky, the equation is

$$E_i = (E_{\mathrm{xh\,sky}}\,\tau_{\mathrm{d}} + \mathrm{E}_{\mathrm{xh\,sun}}\,\tau_{\mathrm{D}})\,\mathrm{CU}\,N\frac{A}{A_w} \qquad (8\text{-}35)$$

where

$E_{xh\ \mathrm{sky}}$ = exterior horizontal illuminance due to the sky only, in lx,

$E_{xh\ \mathrm{sun}}$ = exterior horizontal illuminance due to the sun only, in lx,
τ_d = net diffuse transmittance,
τ_D = net direct transmittance,
CU = coefficient of utilization,
N = number of skylights,
A = area of each skylight in m^2,
A_w = area of the workplane in m^2.

Note that because the net transmittance depends in part on the well efficiency and the ratio of net to gross skylight area, these factors must be recalculated if the skylight size changes.

Lumen Method for Sidelighting. The prediction of interior daylight illuminance from sidelighting has been simplified by using the standard conditions shown in Figure 8-21. The floor cavity extends from the window sill to the floor and has a reflectance of 30%. The ceiling cavity extends from the top of the windows to the ceiling and has a reflectance of 70%. The room cavity extends in height (*H*) from the top of the floor cavity to the bottom of the ceiling cavity, in width (*W*) along the window wall, and in depth (*D*) from the window wall to the rear wall; it has a wall reflectance of 50%. The interior daylight illuminance is calculated at five reference points located on a line perpendicular to the window wall across the center of the room at the same height as the window sill. The five points are located along a line at 0.1*D*, 0.3*D*, 0.5*D*, 0.7*D*, and 0.9*D*.

The procedure described here provides for shades, drapes, solar film, or other simple daylight controls on or at the fenestration. It does not provide for horizontal or vertical window blinds, nor for exterior elements such as sidewalks, streets, other buildings, and overhangs. A more elaborate procedure is available to take account of such elements.

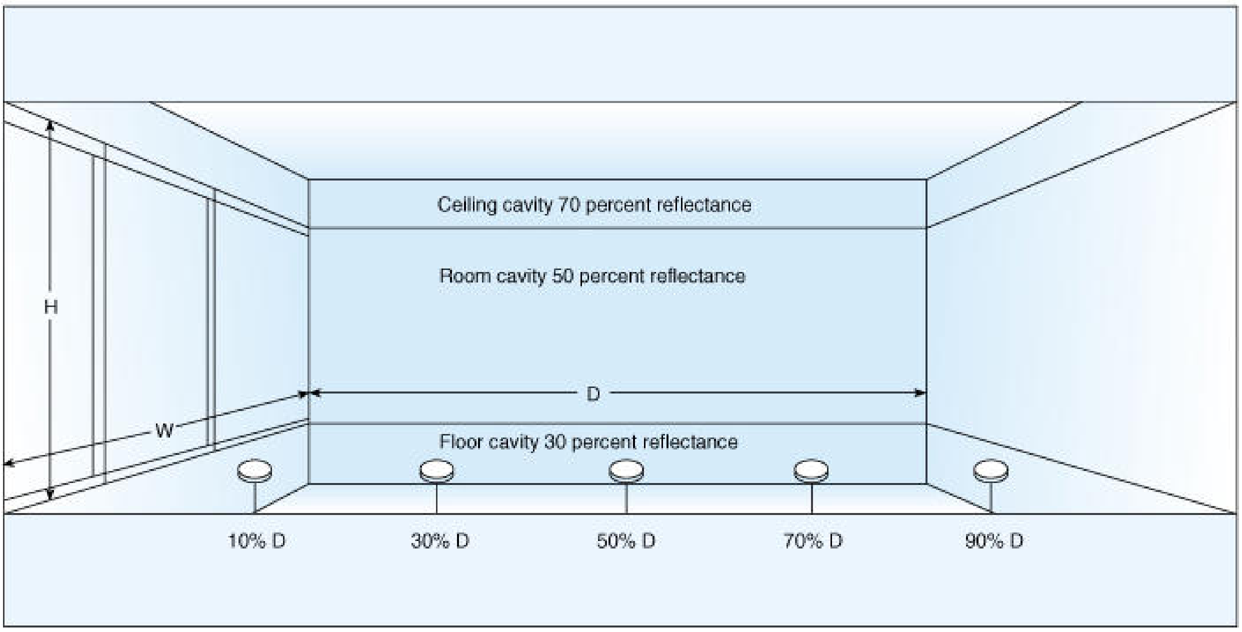


Figure 8-21. Standard conditions in a room for calculating sidelighting. H, W, and D represent room height, width, and depth, respectively.

The basic formula used to calculate the horizontal interior daylight illuminance at one of the five reference points is

$$E_i = E_{xv}\,\tau\,\mathrm{CU} \qquad (8\text{-}36)$$

where

E_i = interior horizontal illuminance on a reference point from sidelighting, in lx,
E_{xv} = exterior vertical illuminance on the window wall in lx,
τ = net transmittance of the window wall,
CU = coefficient of utilization.

Superposition is used to obtain the final interior illuminance at a reference point due to multiple sets of daylighting apertures. For instance, the illuminance from the sky and ground are calculated separately and added together to determine the combined effect. The lumen method does account for direct sunlight entering into the room cavity.

The exterior vertical illuminance E_{xv} is the illuminance on the vertical aperture, excluding direct sunlight. For simple exterior situations, that is, with no obstructions, this illuminance is from the sky and ground. That portion due to the sky can be determined using the procedures in the above section "Daylight Availability." The illuminance on the vertical aperture due to the ground can be determined using the method of configuration factors (see Chapter 9, Lighting Calculations), in which exitances and configuration factors are used to calculate the illuminance produced at a point by a large diffuse source. The ground is assumed to be such a source and to exhibit a diffuse exitance, which is given by

$$M_g = \rho_g (E_{xh\,\mathrm{sky}} + E_{xh\,\mathrm{sun}}) \qquad (8\text{-}37)$$

where

M_g = exitance from the ground in lm/m^2,
ρ_g = reflectance of the ground,
$E_{xh\,\mathrm{sky}}$ = horizontal illuminance from the sky in lx,
$E_{xh\,\mathrm{sun}}$ = horizontal illuminance from the sun in lx.

The net transmittance is the product of the transmittance (T) of the glazing; a light loss factor (LLF) representing dirt accumulation; the net-to-gross window area ratio (R_a), representing such elements as mullions and glazing bars; and a factor T_c representing other elements such as shades and drapes which reduce the transmittance of the window. The net transmittance of the window wall is found from

$$\tau = T\,R_a\,T_c\,\mathrm{LLF} \qquad (8\text{-}38)$$

The coefficients of utilization (CU) for each of the five reference points in the room are given in Figure 8-22.[48] If the fenestration is transparent (view-preserving), then the horizontal and vertical exterior illuminances from the half-sky are calculated for the center of the window. Based on a ratio of vertical to horizontal illuminance at the window of 0.75, 1.00, 1.25, 1.50, or 1.75, the coefficients of utilization from Figures 8-22a through 8-22e are used. The ground component coefficient of utilization is given in Figure 8-22f.

If the fenestration is not image preserving, as would be expected from frosted glass, shades, or drapes, then the vertical illuminances from the sky and ground are added. Half of this value is used for both of the sky illuminance and the ground illuminance. Figure 8-22b, based on a uniform sky distribution is used, for the coefficient of utilization of the sky component, and Figure 8-22f is used for the coefficient of utilization of the ground component.

Equations 8-39 and 8-40 below are used to calculate the illuminance at each of the five reference points in the room. If the window is image preserving, then the illuminances are given by

$$E_i = \tau\,(E_{xv\,\mathrm{sky}}\,\mathrm{CU}_{\mathrm{sky}} + E_{xv\,g}\,\mathrm{CU}_g) \qquad (8\text{-}39)$$

and for a diffuse window by

$$E_i = 0.5\,\tau\,(E_{xv\,\mathrm{sky}} + E_{xv\,g})\,(\mathrm{CU}_{\mathrm{sky}} + \mathrm{CU}_g) \qquad (8\text{-}40)$$

where

E_i = interior illuminance at a reference point in lx,
τ = net transmittance of the window wall,
$E_{xv\,\mathrm{sky}}$ = exterior vertical illuminance from the sky on the window in lx,

$\mathrm{CU}_{\mathrm{sky}}$ = coefficient of utilization from the sky,
$E_{xv\,g}$ = exterior vertical illuminance from the ground on the window in lx,
CU_g = coefficient of utilization from the ground.

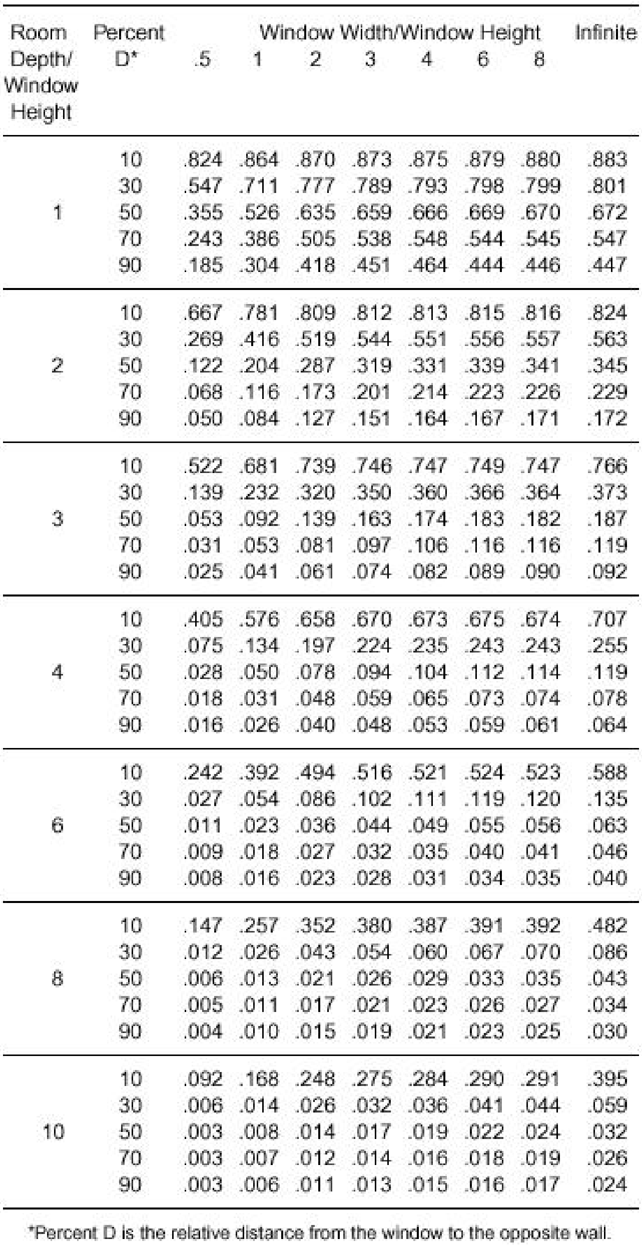
The Daylight Factor Method

The daylight factor method is a low-precision procedure for determining the illuminance at any point in an interior space produced by a sky with a known luminance distribution. Direct sunlight is excluded. The method is generally used with uniform or CIE overcast skies.[3,49] It is used in northern Europe, where overcast skies predominate, and has some application in North America as well. Daylight factor (DF) is the ratio of the illuminance at a point on a plane, generally the horizontal work plane, produced by the luminous flux received directly or indirectly at that point from a sky whose luminance distribution is known, to the illuminance on a horizontal plane produced by an unobstructed hemisphere of this same sky.

There are three ways in which daylight may reach a point on a horizontal plane within an interior space (Figure 8-23). The sky component (SC) is due to daylight received directly at the point from the sky. The externally reflected component (ERC) is due to daylight received directly at the point from external reflecting surfaces. The internally reflected component (IRC) is due to daylight reaching the point after one or more interreflections from interior surfaces. The daylight factor is the sum of the three components:

$$\mathrm{DF} = \mathrm{SC} + \mathrm{ERC} + \mathrm{IRC} \qquad (8\text{-}41)$$

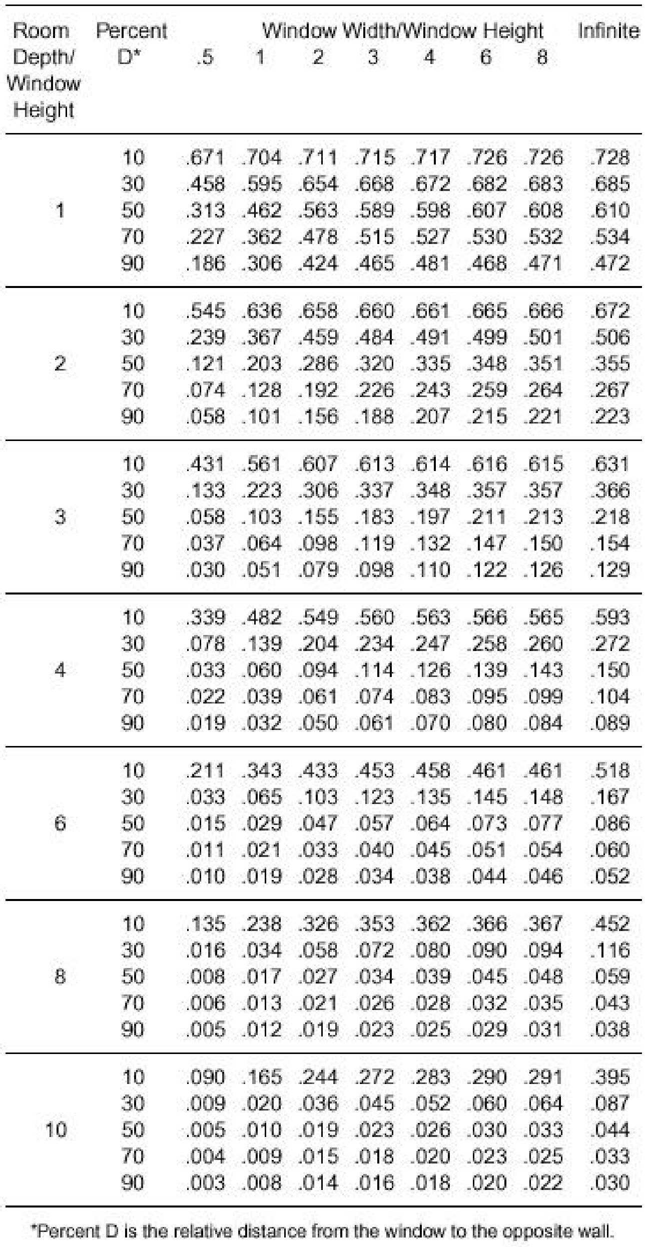
In simple interior environments, daylight factor can be determined by hand calculation methods using tables of precalculated components for typical geometries. These environments are usually rectangular rooms with a wall of windows. Daylight factors from individual windows can be added to produce the daylight factor due to all the windows. The procedure for determining a daylight factor in such a space is as follows.



Room Depth/ Window Height	Percent D*	.5	1	2	3	4	6	8	Infinite
		Window Width/Window Height							
1	10	.824	.864	.870	.873	.875	.879	.880	.883
	30	.547	.711	.777	.789	.793	.798	.799	.801
	50	.355	.526	.635	.659	.666	.669	.670	.672
	70	.243	.386	.505	.538	.548	.544	.545	.547
	90	.185	.304	.418	.451	.464	.444	.446	.447
2	10	.667	.781	.809	.812	.813	.815	.816	.824
	30	.269	.416	.519	.544	.551	.556	.557	.563
	50	.122	.204	.287	.319	.331	.339	.341	.345
	70	.068	.116	.173	.201	.214	.223	.226	.229
	90	.050	.084	.127	.151	.164	.167	.171	.172
3	10	.522	.681	.739	.746	.747	.749	.747	.766
	30	.139	.232	.320	.350	.360	.366	.364	.373
	50	.053	.092	.139	.163	.174	.183	.182	.187
	70	.031	.053	.081	.097	.106	.116	.116	.119
	90	.025	.041	.061	.074	.082	.089	.090	.092
4	10	.405	.576	.658	.670	.673	.675	.674	.707
	30	.075	.134	.197	.224	.235	.243	.243	.255
	50	.028	.050	.078	.094	.104	.112	.114	.119
	70	.018	.031	.048	.059	.065	.073	.074	.078
	90	.016	.026	.040	.048	.053	.059	.061	.064
6	10	.242	.392	.494	.516	.521	.524	.523	.588
	30	.027	.054	.086	.102	.111	.119	.120	.135
	50	.011	.023	.036	.044	.049	.055	.056	.063
	70	.009	.018	.027	.032	.035	.040	.041	.046
	90	.008	.016	.023	.028	.031	.034	.035	.040
8	10	.147	.257	.352	.380	.387	.391	.392	.482
	30	.012	.026	.043	.054	.060	.067	.070	.086
	50	.006	.013	.021	.026	.029	.033	.035	.043
	70	.005	.011	.017	.021	.023	.026	.027	.034
	90	.004	.010	.015	.019	.021	.023	.025	.030
10	10	.092	.168	.248	.275	.284	.290	.291	.395
	30	.006	.014	.026	.032	.036	.041	.044	.059
	50	.003	.008	.014	.017	.019	.022	.024	.032
	70	.003	.007	.012	.014	.016	.018	.019	.026
	90	.003	.006	.011	.013	.015	.016	.017	.024

*Percent D is the relative distance from the window to the opposite wall.

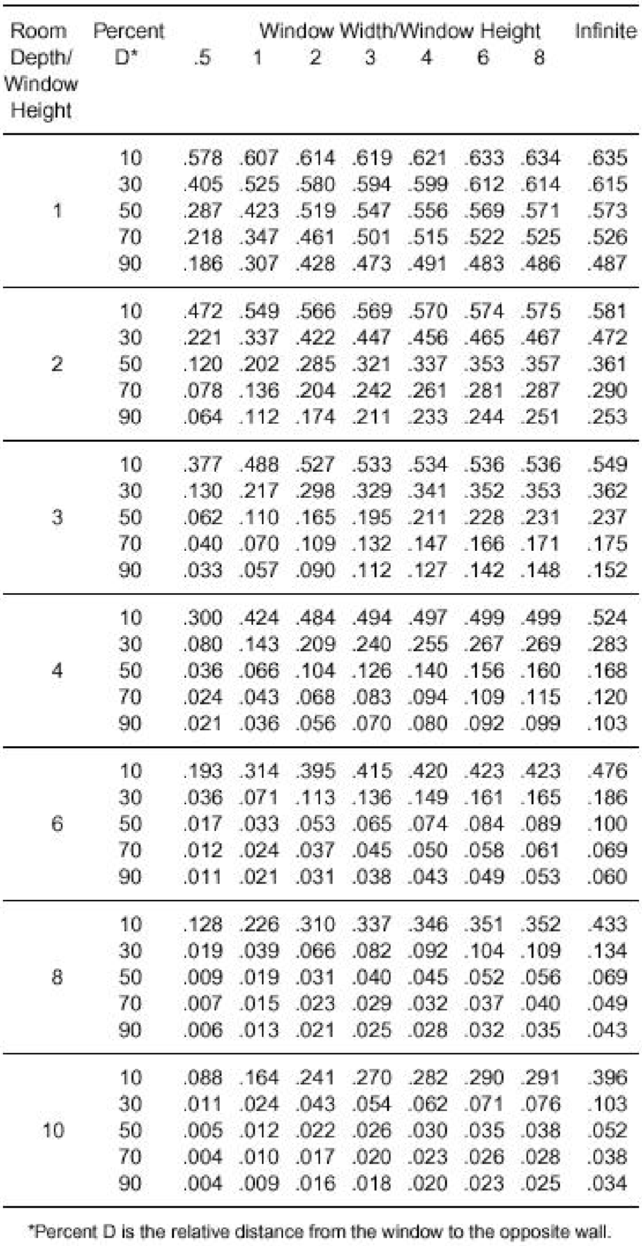
Figure 8-22a. Coefficients of Utilization (CU) from Window Without Blinds, Sky Component E_{xvsky}/E_{xhsky} = 0.75



Room Depth/ Window Height	Percent D*	Window Width/Window Height .5	1	2	3	4	6	8	Infinite
1	10	.671	.704	.711	.715	.717	.726	.726	.728
	30	.458	.595	.654	.668	.672	.682	.683	.685
	50	.313	.462	.563	.589	.598	.607	.608	.610
	70	.227	.362	.478	.515	.527	.530	.532	.534
	90	.186	.306	.424	.465	.481	.468	.471	.472
2	10	.545	.636	.658	.660	.661	.665	.666	.672
	30	.239	.367	.459	.484	.491	.499	.501	.506
	50	.121	.203	.286	.320	.335	.348	.351	.355
	70	.074	.128	.192	.226	.243	.259	.264	.267
	90	.058	.101	.156	.188	.207	.215	.221	.223
3	10	.431	.561	.607	.613	.614	.616	.615	.631
	30	.133	.223	.306	.337	.348	.357	.357	.366
	50	.058	.103	.155	.183	.197	.211	.213	.218
	70	.037	.064	.098	.119	.132	.147	.150	.154
	90	.030	.051	.079	.098	.110	.122	.126	.129
4	10	.339	.482	.549	.560	.563	.566	.565	.593
	30	.078	.139	.204	.234	.247	.258	.260	.272
	50	.033	.060	.094	.114	.126	.139	.143	.150
	70	.022	.039	.061	.074	.083	.095	.099	.104
	90	.019	.032	.050	.061	.070	.080	.084	.089
6	10	.211	.343	.433	.453	.458	.461	.461	.518
	30	.033	.065	.103	.123	.135	.145	.148	.167
	50	.015	.029	.047	.057	.064	.073	.077	.086
	70	.011	.021	.033	.040	.045	.051	.054	.060
	90	.010	.019	.028	.034	.038	.044	.046	.052
8	10	.135	.238	.326	.353	.362	.366	.367	.452
	30	.016	.034	.058	.072	.080	.090	.094	.116
	50	.008	.017	.027	.034	.039	.045	.048	.059
	70	.006	.013	.021	.026	.028	.032	.035	.043
	90	.005	.012	.019	.023	.025	.029	.031	.038
10	10	.090	.165	.244	.272	.283	.290	.291	.395
	30	.009	.020	.036	.045	.052	.060	.064	.087
	50	.005	.010	.019	.023	.026	.030	.033	.044
	70	.004	.009	.015	.018	.020	.023	.025	.033
	90	.003	.008	.014	.016	.018	.020	.022	.030

*Percent D is the relative distance from the window to the opposite wall.

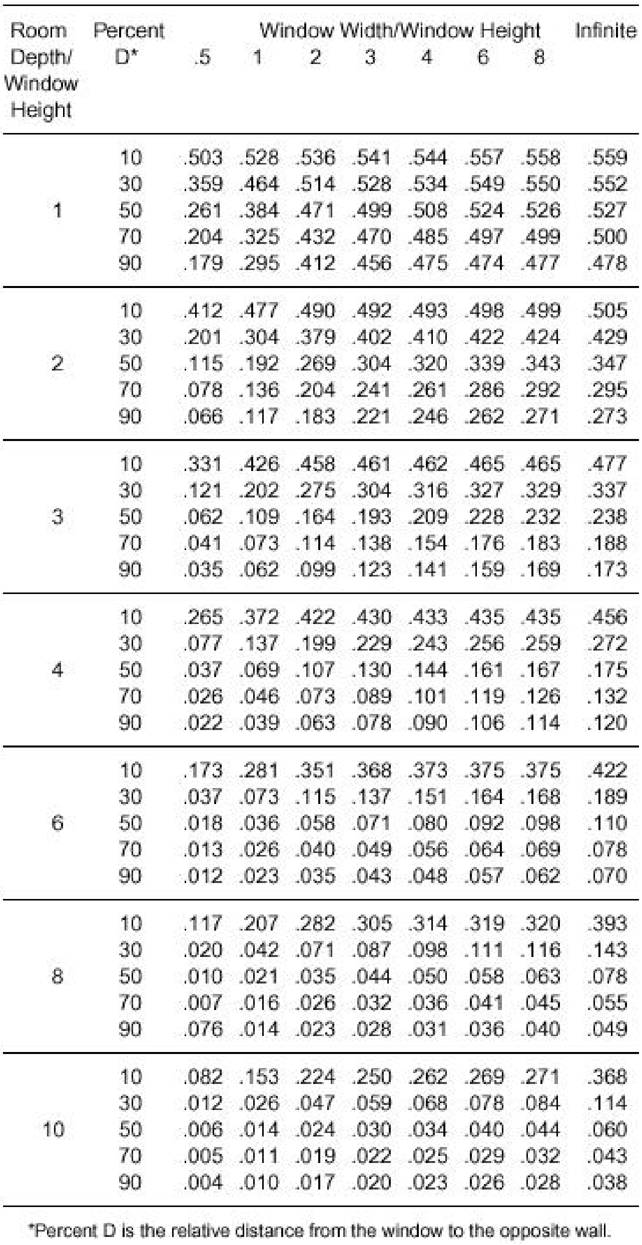
Figure 8-22b. Coefficients of Utilization (CU) from Window Without Blinds. Sky Component $E_{xvsky}/E_{xhsky} = 1.00$



Room Depth/ Window Height	Percent D*	Window Width/Window Height							Infinite
		.5	1	2	3	4	6	8	
1	10	.578	.607	.614	.619	.621	.633	.634	.635
	30	.405	.525	.580	.594	.599	.612	.614	.615
	50	.287	.423	.519	.547	.556	.569	.571	.573
	70	.218	.347	.461	.501	.515	.522	.525	.526
	90	.186	.307	.428	.473	.491	.483	.486	.487
2	10	.472	.549	.566	.569	.570	.574	.575	.581
	30	.221	.337	.422	.447	.456	.465	.467	.472
	50	.120	.202	.285	.321	.337	.353	.357	.361
	70	.078	.136	.204	.242	.261	.281	.287	.290
	90	.064	.112	.174	.211	.233	.244	.251	.253
3	10	.377	.488	.527	.533	.534	.536	.536	.549
	30	.130	.217	.298	.329	.341	.352	.353	.362
	50	.062	.110	.165	.195	.211	.228	.231	.237
	70	.040	.070	.109	.132	.147	.166	.171	.175
	90	.033	.057	.090	.112	.127	.142	.148	.152
4	10	.300	.424	.484	.494	.497	.499	.499	.524
	30	.080	.143	.209	.240	.255	.267	.269	.283
	50	.036	.066	.104	.126	.140	.156	.160	.168
	70	.024	.043	.068	.083	.094	.109	.115	.120
	90	.021	.036	.056	.070	.080	.092	.099	.103
6	10	.193	.314	.395	.415	.420	.423	.423	.476
	30	.036	.071	.113	.136	.149	.161	.165	.186
	50	.017	.033	.053	.065	.074	.084	.089	.100
	70	.012	.024	.037	.045	.050	.058	.061	.069
	90	.011	.021	.031	.038	.043	.049	.053	.060
8	10	.128	.226	.310	.337	.346	.351	.352	.433
	30	.019	.039	.066	.082	.092	.104	.109	.134
	50	.009	.019	.031	.040	.045	.052	.056	.069
	70	.007	.015	.023	.029	.032	.037	.040	.049
	90	.006	.013	.021	.025	.028	.032	.035	.043
10	10	.088	.164	.241	.270	.282	.290	.291	.396
	30	.011	.024	.043	.054	.062	.071	.076	.103
	50	.005	.012	.022	.026	.030	.035	.038	.052
	70	.004	.010	.017	.020	.023	.026	.028	.038
	90	.004	.009	.016	.018	.020	.023	.025	.034

*Percent D is the relative distance from the window to the opposite wall.

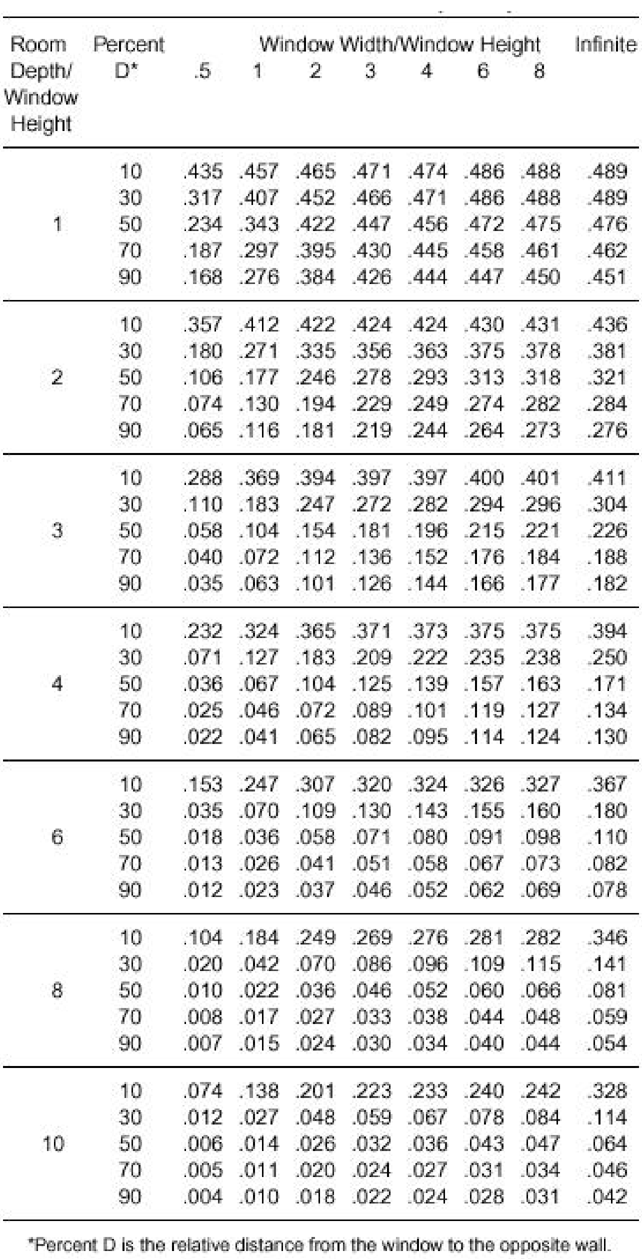
Figure 8-22c. Coefficients of Utilization (CU) from Window Without Blinds. Sky Component E_{xvsky}/E_{xhsky} = 1.25



Room Depth/ Window Height	Percent D*	Window Width/Window Height							Infinite
		.5	1	2	3	4	6	8	
1	10	.503	.528	.536	.541	.544	.557	.558	.559
	30	.359	.464	.514	.528	.534	.549	.550	.552
	50	.261	.384	.471	.499	.508	.524	.526	.527
	70	.204	.325	.432	.470	.485	.497	.499	.500
	90	.179	.295	.412	.456	.475	.474	.477	.478
2	10	.412	.477	.490	.492	.493	.498	.499	.505
	30	.201	.304	.379	.402	.410	.422	.424	.429
	50	.115	.192	.269	.304	.320	.339	.343	.347
	70	.078	.136	.204	.241	.261	.286	.292	.295
	90	.066	.117	.183	.221	.246	.262	.271	.273
3	10	.331	.426	.458	.461	.462	.465	.465	.477
	30	.121	.202	.275	.304	.316	.327	.329	.337
	50	.062	.109	.164	.193	.209	.228	.232	.238
	70	.041	.073	.114	.138	.154	.176	.183	.188
	90	.035	.062	.099	.123	.141	.159	.169	.173
4	10	.265	.372	.422	.430	.433	.435	.435	.456
	30	.077	.137	.199	.229	.243	.256	.259	.272
	50	.037	.069	.107	.130	.144	.161	.167	.175
	70	.026	.046	.073	.089	.101	.119	.126	.132
	90	.022	.039	.063	.078	.090	.106	.114	.120
6	10	.173	.281	.351	.368	.373	.375	.375	.422
	30	.037	.073	.115	.137	.151	.164	.168	.189
	50	.018	.036	.058	.071	.080	.092	.098	.110
	70	.013	.026	.040	.049	.056	.064	.069	.078
	90	.012	.023	.035	.043	.048	.057	.062	.070
8	10	.117	.207	.282	.305	.314	.319	.320	.393
	30	.020	.042	.071	.087	.098	.111	.116	.143
	50	.010	.021	.035	.044	.050	.058	.063	.078
	70	.007	.016	.026	.032	.036	.041	.045	.055
	90	.076	.014	.023	.028	.031	.036	.040	.049
10	10	.082	.153	.224	.250	.262	.269	.271	.368
	30	.012	.026	.047	.059	.068	.078	.084	.114
	50	.006	.014	.024	.030	.034	.040	.044	.060
	70	.005	.011	.019	.022	.025	.029	.032	.043
	90	.004	.010	.017	.020	.023	.026	.028	.038

*Percent D is the relative distance from the window to the opposite wall.

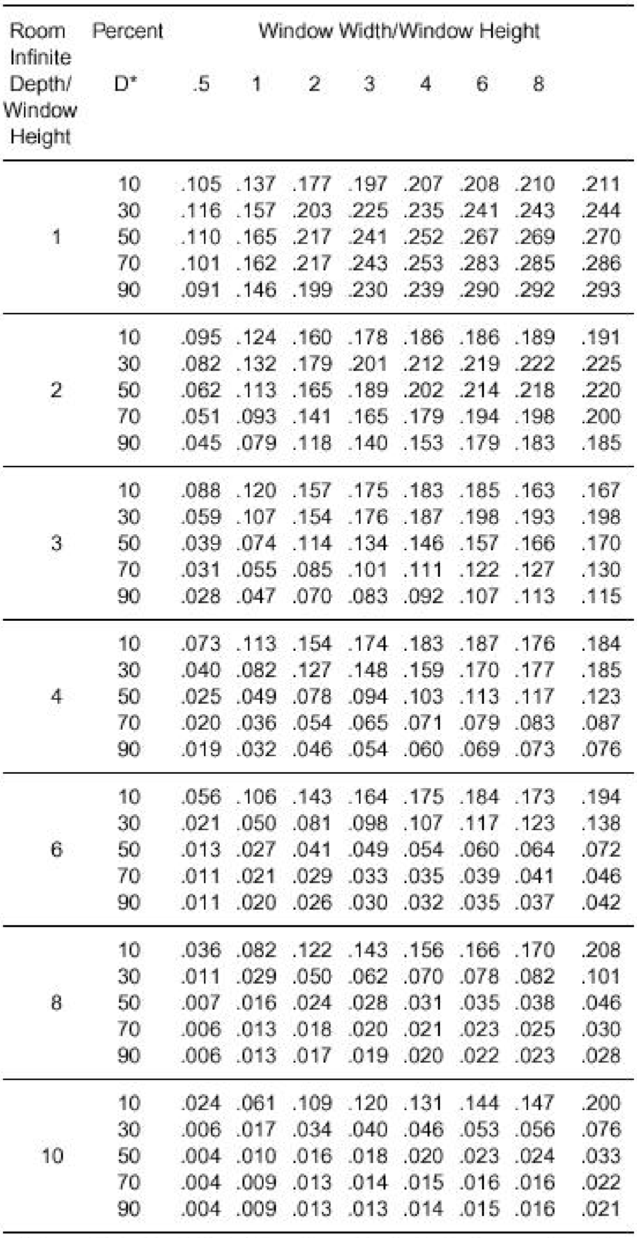
Figure 8-22d. Coefficients of Utilization (CU) from Window Without Blinds. Sky Component E_{xvsky}/E_{xhsky} = 1.50



Room Depth/ Window Height	Percent D*	Window Width/Window Height .5	1	2	3	4	6	8	Infinite
1	10	.435	.457	.465	.471	.474	.486	.488	.489
	30	.317	.407	.452	.466	.471	.486	.488	.489
	50	.234	.343	.422	.447	.456	.472	.475	.476
	70	.187	.297	.395	.430	.445	.458	.461	.462
	90	.168	.276	.384	.426	.444	.447	.450	.451
2	10	.357	.412	.422	.424	.424	.430	.431	.436
	30	.180	.271	.335	.356	.363	.375	.378	.381
	50	.106	.177	.246	.278	.293	.313	.318	.321
	70	.074	.130	.194	.229	.249	.274	.282	.284
	90	.065	.116	.181	.219	.244	.264	.273	.276
3	10	.288	.369	.394	.397	.397	.400	.401	.411
	30	.110	.183	.247	.272	.282	.294	.296	.304
	50	.058	.104	.154	.181	.196	.215	.221	.226
	70	.040	.072	.112	.136	.152	.176	.184	.188
	90	.035	.063	.101	.126	.144	.166	.177	.182
4	10	.232	.324	.365	.371	.373	.375	.375	.394
	30	.071	.127	.183	.209	.222	.235	.238	.250
	50	.036	.067	.104	.125	.139	.157	.163	.171
	70	.025	.046	.072	.089	.101	.119	.127	.134
	90	.022	.041	.065	.082	.095	.114	.124	.130
6	10	.153	.247	.307	.320	.324	.326	.327	.367
	30	.035	.070	.109	.130	.143	.155	.160	.180
	50	.018	.036	.058	.071	.080	.091	.098	.110
	70	.013	.026	.041	.051	.058	.067	.073	.082
	90	.012	.023	.037	.046	.052	.062	.069	.078
8	10	.104	.184	.249	.269	.276	.281	.282	.346
	30	.020	.042	.070	.086	.096	.109	.115	.141
	50	.010	.022	.036	.046	.052	.060	.066	.081
	70	.008	.017	.027	.033	.038	.044	.048	.059
	90	.007	.015	.024	.030	.034	.040	.044	.054
10	10	.074	.138	.201	.223	.233	.240	.242	.328
	30	.012	.027	.048	.059	.067	.078	.084	.114
	50	.006	.014	.026	.032	.036	.043	.047	.064
	70	.005	.011	.020	.024	.027	.031	.034	.046
	90	.004	.010	.018	.022	.024	.028	.031	.042

*Percent D is the relative distance from the window to the opposite wall.

Figure 8-22e. Coefficients of Utilization (CU) from Window Without Blinds. Sky Component $E_{xvsky}/E_{xhsky} = 1.75$



Room Infinite Depth/ Window Height	Percent	Window Width/Window Height							
	D*	.5	1	2	3	4	6	8	
1	10	.105	.137	.177	.197	.207	.208	.210	.211
	30	.116	.157	.203	.225	.235	.241	.243	.244
	50	.110	.165	.217	.241	.252	.267	.269	.270
	70	.101	.162	.217	.243	.253	.283	.285	.286
	90	.091	.146	.199	.230	.239	.290	.292	.293
2	10	.095	.124	.160	.178	.186	.186	.189	.191
	30	.082	.132	.179	.201	.212	.219	.222	.225
	50	.062	.113	.165	.189	.202	.214	.218	.220
	70	.051	.093	.141	.165	.179	.194	.198	.200
	90	.045	.079	.118	.140	.153	.179	.183	.185
3	10	.088	.120	.157	.175	.183	.185	.163	.167
	30	.059	.107	.154	.176	.187	.198	.193	.198
	50	.039	.074	.114	.134	.146	.157	.166	.170
	70	.031	.055	.085	.101	.111	.122	.127	.130
	90	.028	.047	.070	.083	.092	.107	.113	.115
4	10	.073	.113	.154	.174	.183	.187	.176	.184
	30	.040	.082	.127	.148	.159	.170	.177	.185
	50	.025	.049	.078	.094	.103	.113	.117	.123
	70	.020	.036	.054	.065	.071	.079	.083	.087
	90	.019	.032	.046	.054	.060	.069	.073	.076
6	10	.056	.106	.143	.164	.175	.184	.173	.194
	30	.021	.050	.081	.098	.107	.117	.123	.138
	50	.013	.027	.041	.049	.054	.060	.064	.072
	70	.011	.021	.029	.033	.035	.039	.041	.046
	90	.011	.020	.026	.030	.032	.035	.037	.042
8	10	.036	.082	.122	.143	.156	.166	.170	.208
	30	.011	.029	.050	.062	.070	.078	.082	.101
	50	.007	.016	.024	.028	.031	.035	.038	.046
	70	.006	.013	.018	.020	.021	.023	.025	.030
	90	.006	.013	.017	.019	.020	.022	.023	.028
10	10	.024	.061	.109	.120	.131	.144	.147	.200
	30	.006	.017	.034	.040	.046	.053	.056	.076
	50	.004	.010	.016	.018	.020	.023	.024	.033
	70	.004	.009	.013	.014	.015	.016	.016	.022
	90	.004	.009	.013	.013	.014	.015	.016	.021

*Percent D is the relative distance from the window to the opposite wall.

Figure 8-22f. Coefficients of Utilization (CU) from Window Without Blinds (Ground Component)

Necessary dimensions are shown in Figure 8-24. A room has a widow of width *w* and height *h* above the workplane. The point of interest, *P*, is in the workplane. Portions of the window that lie below the workplane should be neglected. An exterior building has height above the workplane *H* and is a distance *D* from the plane of the window.

Sky Component of Daylight Factor. The sky component is due to flux reaching the point directly from the sky through the window. It is the illuminance at the point due to the window, divided by the horizontal illuminance produced by the entire sky. Values have been calculated and tabulated for various sky luminance distributions. Figure 8-25[3] is such a tabulation for the CIE overcast sky, a window transmittance of 0.85, and point located a distance *q* perpendicularly away from a lower corner of the window.

The procedure for determining sky component from a window is

1. Determine ratios w_1/q, w_2/q, and h/q, as illustrated in Figure 8-24.

2. For each piece of window, use Figure 8-25 to determine a value of the sky component of the daylight factor.

3. If point *p* splits the windows as in Figure 8-24b, then add these two components.

4. If point *p* is away from the window as in Figure 8-24c, then subtract these two components.

5. If window transmittance is not 0.85, scale the values by the ratio of the actual window transmittance to 0.85.

If an external building obstructs the view of the sky from point *p* through the window then

6. Determine the ratios $w_1/(q + D)$, $w_2/(q + D)$, and $H/(q + D)$.

7. For each piece of building, use Figure 8-25 to determine a value of obstructed sky component of the daylight factor.

8. If point *p* splits the building, then add these two components.

9. If point *p* is away from the building, then subtract these two components.

10. If window transmittance is not 0.85, scale the values by the ratio of the actual window transmittance to 0.85.

11. Subtract the result obtained from the unobstructed window.

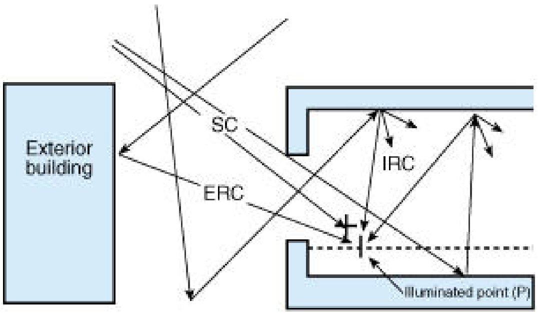
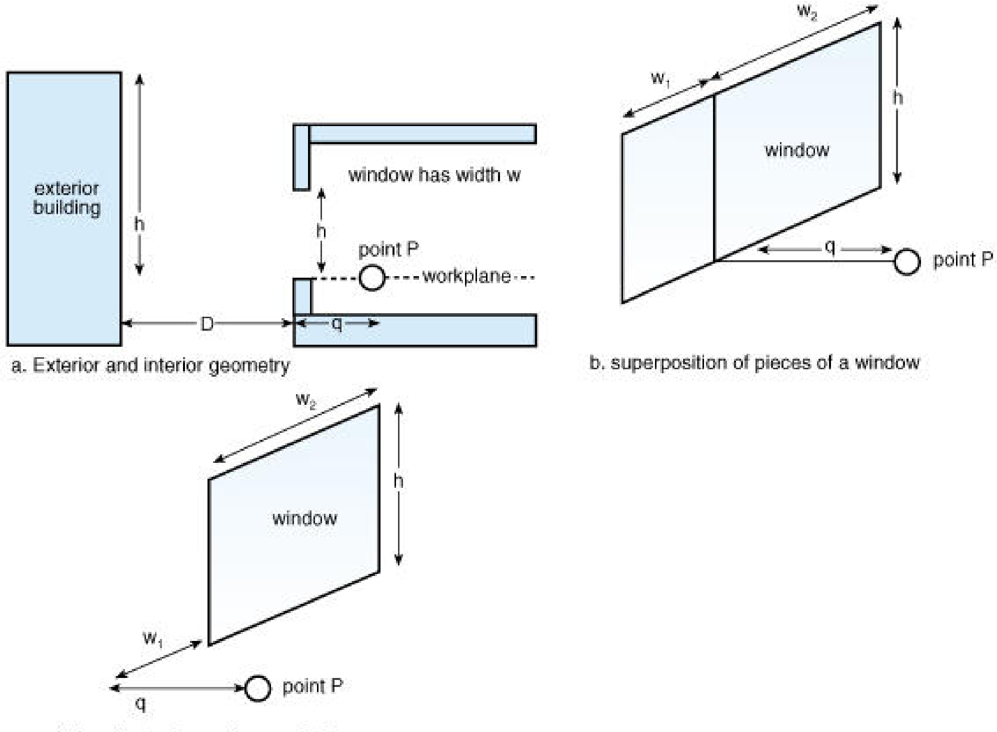


Figure 8-23. Daylight factor components. See Equation



a. Exterior and interior geometry

b. superposition of pieces of a window

c. window located away from point P

Figure 8-24. Geometry for determining daylight factor in a simple environment. See text.

Externally Reflected Component of Daylight Factor. The externally reflected component is generally small and is usually roughly approximated. To obtain its value for the CIE overcast sky, the obstructed sky component (obtained in steps 6 to 10 above) is multiplied by 0.2 if it is less than 20, or by 0.1 if it is greater than 20.

Internally Reflected Component of Daylight Factor. The procedure for obtaining the internally reflected component is based on the theory of the integrating sphere and the concept of split flux, namely that the internally reflected flux reaching the point in question is composed of two parts, a component reflected first from the room cavity above the workplane and a second component reflected first from the floor cavity.

Values of minimum internally reflected component of daylight factor can be tabulated for various room sizes, surface reflectances, and amount of window area. Values for a room of 36 m^2 (390 ft^2) floor area, 3 m (10 ft) ceiling height, and 70% ceiling reflectance are shown in Figure 8-26. With a precision appropriate for the daylight factor method, these values of minimum internally reflected component can be modified for different floor areas and wall reflectances, different ceiling reflectances, and average internally reflected component.

Figure 8-27a shows the multipliers to convert values of minimum internally reflected daylight factor from Figure 8-26 for other floor areas and wall reflectances. Figure 8-27b shows the multipliers to convert for different ceiling reflectances. Figure 8-27c gives the multipliers to convert minimum internally reflected daylight factors to average internally reflected daylight factors.

Approximate Average Daylight Factor. Very often the average daylight factor on a horizontal reference plane, usually the work plane, is desired. This can be obtained from the following empirical expression:

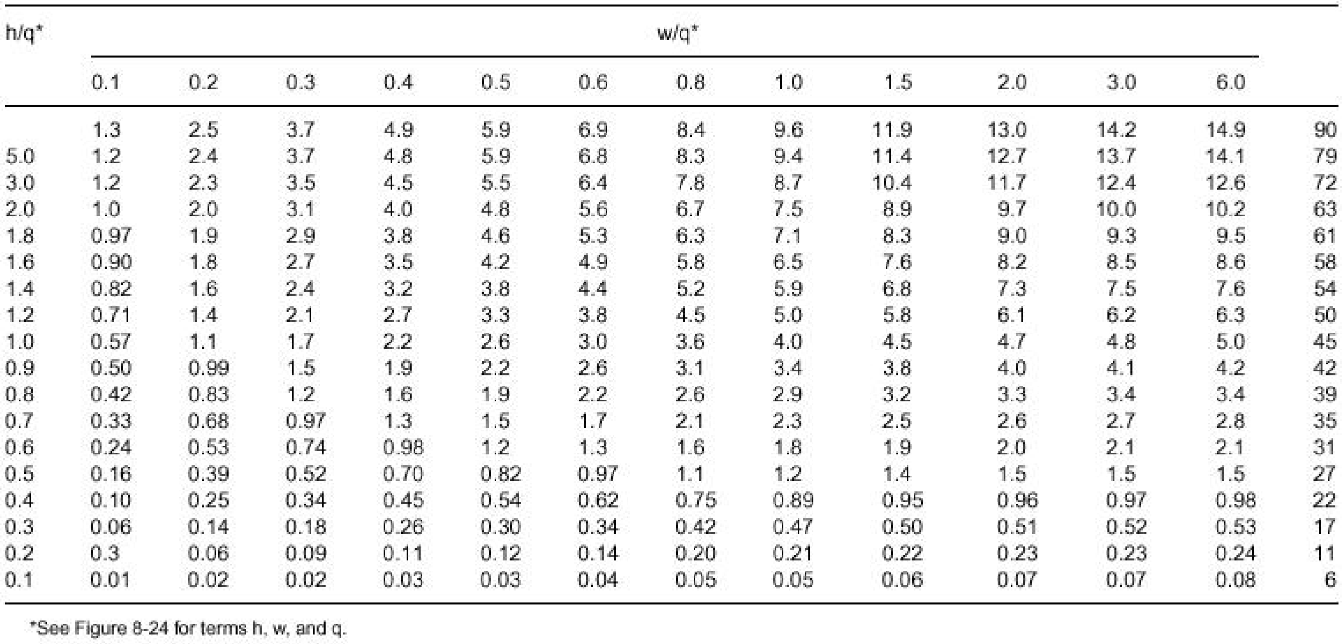
$$\mathrm{ADF} \cong \frac{\tau A_g \theta}{A_s (1 - \rho^2)} \qquad (8\text{-}42)$$

where

ADF = average daylight factor, in percent,
τ = the decimal transmittance of the glazing,
A_g = the net glazing area,
A_s = the total interior surface area, including windows, in the same units as A_g,
ρ = is the area-weighted average reflectance of all interior room surfaces, including windows,
θ = the angle in degrees in the vertical plane subtended by the portion of the sky that is visible from the center of the window.

Experience has shown that when ADF is 5% or greater, an interior space will appear to be well lighted. When the ADF is less than 2%, the interior space will seem dimly lighted.

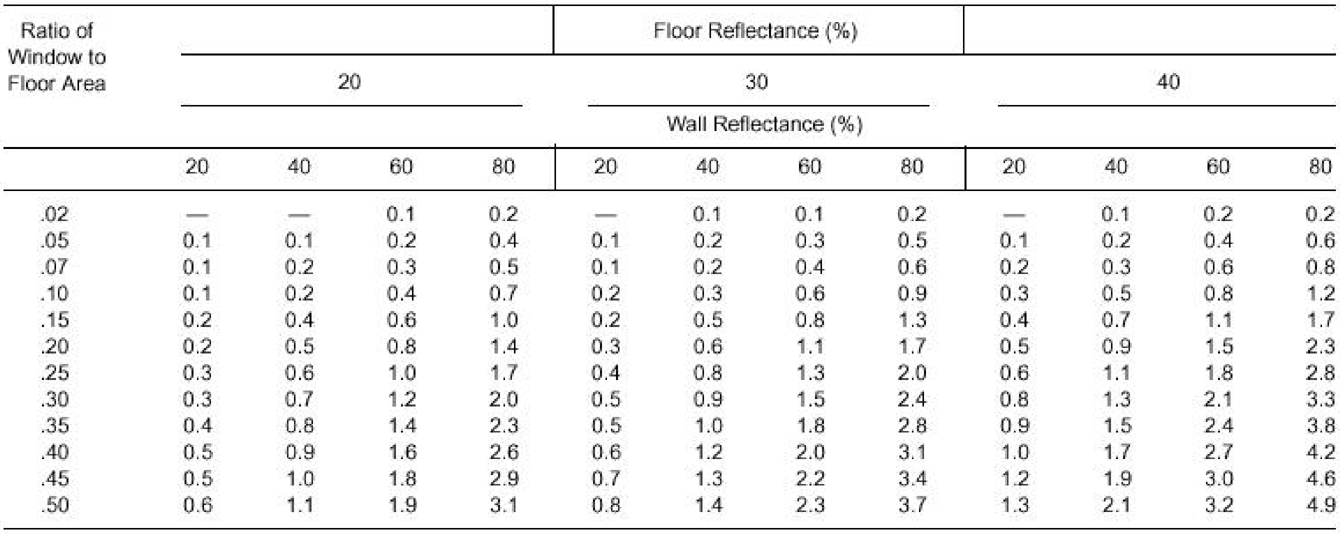
The ADF is a suitable metric for shallow side-lighted rooms and for rooms lighted by skylights. It is not a valid metric for deep side-lighted rooms because of the effect of the exponential decay of daylighting as distance from the window increases. Limiting room is 3 to 4 window heights above the work plane.



h/q*	w/q*												
	0.1	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.5	2.0	3.0	6.0	
	1.3	2.5	3.7	4.9	5.9	6.9	8.4	9.6	11.9	13.0	14.2	14.9	90
5.0	1.2	2.4	3.7	4.8	5.9	6.8	8.3	9.4	11.4	12.7	13.7	14.1	79
3.0	1.2	2.3	3.5	4.5	5.5	6.4	7.8	8.7	10.4	11.7	12.4	12.6	72
2.0	1.0	2.0	3.1	4.0	4.8	5.6	6.7	7.5	8.9	9.7	10.0	10.2	63
1.8	0.97	1.9	2.9	3.8	4.6	5.3	6.3	7.1	8.3	9.0	9.3	9.5	61
1.6	0.90	1.8	2.7	3.5	4.2	4.9	5.8	6.5	7.6	8.2	8.5	8.6	58
1.4	0.82	1.6	2.4	3.2	3.8	4.4	5.2	5.9	6.8	7.3	7.5	7.6	54
1.2	0.71	1.4	2.1	2.7	3.3	3.8	4.5	5.0	5.8	6.1	6.2	6.3	50
1.0	0.57	1.1	1.7	2.2	2.6	3.0	3.6	4.0	4.5	4.7	4.8	5.0	45
0.9	0.50	0.99	1.5	1.9	2.2	2.6	3.1	3.4	3.8	4.0	4.1	4.2	42
0.8	0.42	0.83	1.2	1.6	1.9	2.2	2.6	2.9	3.2	3.3	3.4	3.4	39
0.7	0.33	0.68	0.97	1.3	1.5	1.7	2.1	2.3	2.5	2.6	2.7	2.8	35
0.6	0.24	0.53	0.74	0.98	1.2	1.3	1.6	1.8	1.9	2.0	2.1	2.1	31
0.5	0.16	0.39	0.52	0.70	0.82	0.97	1.1	1.2	1.4	1.5	1.5	1.5	27
0.4	0.10	0.25	0.34	0.45	0.54	0.62	0.75	0.89	0.95	0.96	0.97	0.98	22
0.3	0.06	0.14	0.18	0.26	0.30	0.34	0.42	0.47	0.50	0.51	0.52	0.53	17
0.2	0.3	0.06	0.09	0.11	0.12	0.14	0.20	0.21	0.22	0.23	0.23	0.24	11
0.1	0.01	0.02	0.02	0.03	0.03	0.04	0.05	0.05	0.06	0.07	0.07	0.08	6

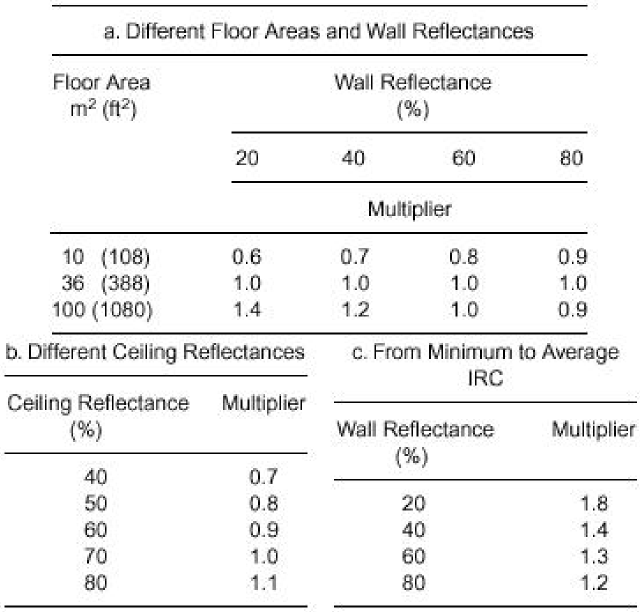
*See Figure 8-24 for terms h, w, and q.

Figure 8-25. Sky Components of Daylight Factor, in Percent, for CIE Overcast Sky *See Figure 8-24 for terms h, w, and q.



Ratio of Window to Floor Area	Floor Reflectance (%)											
	20				30				40			
	Wall Reflectance (%)											
	20	40	60	80	20	40	60	80	20	40	60	80
.02	—	—	0.1	0.2	—	0.1	0.1	0.2	—	0.1	0.2	0.2
.05	0.1	0.1	0.2	0.4	0.1	0.2	0.3	0.5	0.1	0.2	0.4	0.6
.07	0.1	0.2	0.3	0.5	0.1	0.2	0.4	0.6	0.2	0.3	0.6	0.8
.10	0.1	0.2	0.4	0.7	0.2	0.3	0.6	0.9	0.3	0.5	0.8	1.2
.15	0.2	0.4	0.6	1.0	0.2	0.5	0.8	1.3	0.4	0.7	1.1	1.7
.20	0.2	0.5	0.8	1.4	0.3	0.6	1.1	1.7	0.5	0.9	1.5	2.3
.25	0.3	0.6	1.0	1.7	0.4	0.8	1.3	2.0	0.6	1.1	1.8	2.8
.30	0.3	0.7	1.2	2.0	0.5	0.9	1.5	2.4	0.8	1.3	2.1	3.3
.35	0.4	0.8	1.4	2.3	0.5	1.0	1.8	2.8	0.9	1.5	2.4	3.8
.40	0.5	0.9	1.6	2.6	0.6	1.2	2.0	3.1	1.0	1.7	2.7	4.2
.45	0.5	1.0	1.8	2.9	0.7	1.3	2.2	3.4	1.2	1.9	3.0	4.6
.50	0.6	1.1	1.9	3.1	0.8	1.4	2.3	3.7	1.3	2.1	3.2	4.9

Figure 8-26. Minimum Internally Reflected Components of Daylight Factor, in Percent



a. Different Floor Areas and Wall Reflectances

Floor Area m² (ft²)	Wall Reflectance (%)			
	20	40	60	80
	Multiplier			
10 (108)	0.6	0.7	0.8	0.9
36 (388)	1.0	1.0	1.0	1.0
100 (1080)	1.4	1.2	1.0	0.9

b. Different Ceiling Reflectances

Ceiling Reflectance (%)	Multiplier
40	0.7
50	0.8
60	0.9
70	1.0
80	1.1

c. From Minimum to Average IRC

Wall Reflectance (%)	Multiplier
20	1.8
40	1.4
60	1.3
80	1.2

Figure 8-27. Multipliers for Minimum Internally Reflected Daylight Factor

Comparison and Accuracy of Methods

The utility of computational methods for daylighting depends on the information required, the complexity of the daylighting system, and the stage in the design process at which computations are being performed. Methods that give average illuminance for typical sky conditions can be useful early in the design process when alternative strategies are being evaluated. The relative simplicity of these methods can not only help make clear what the lighting will be like in the space but also reveal changes to the design that yield improvement.

Later in the design process, detailed calculations are often necessary to verify illuminances at points and luminance ratios. In this case, insight into how the design functions is not revealed by the computational method itself but by the results it gives, that is, illuminances and luminances. The most complex methods are required to produce computer visualizations of daylighted spaces.

The accuracy of these computational methods depends on the nature and extent of the assumptions they make, and on the accuracy of the data used. Predicting absolute levels of illuminance in daylighted interiors is difficult and often unnecessary, since the amount of light getting into a building will depend on the availability of daylight; often the ratios are what is important. Reasonable accuracy in the ratio between interior levels and exterior availability can be expected from most physical models and computational models. Ten percent is achievable in a carefully made physical model or an accurate computer model based on physical principles and an accurate description of the geometry of the space.

DESIGN METHODS AND EVALUATION TECHNIQUES[50-52]

Daylighting designs may be evaluated throughout the design stages by manual methods, scale model photometry, and computer simulation.

Shading Mask and Sun Path Diagram

A shading mask, when combined with a sun path diagram, can be used to determine several important metrics of daylighting efficacy, including hourly and annual solar exposure of fenestration; degree of shading provided by trees; effects of overhangs, fins, or other architectural features; and solar penetration. Successful construction of a shading mask depends on an accurate determination of the relevant profile angle. The Libby-Owens-Ford Sun Angle Calculator[53] is a convenient manual tool for determining profile angles for a wide range of northern latitudes.

Instructions for constructing and using shading masks can be found in Moore[54] and Olgyay and Olgyay.[55] Computer software simulation and architectural rendering programs that offer daylighting computations[56] also can be used to show the amount of shading and direct sun penetration for particular dates and times.

Scale Model Photometry[57,58]

Scale-model and full-scale photometry allow the investigation of spaces and fenestration systems that are more complex than can be evaluated using lumen methods or currently available computer programs. Scale models provide a simple means of changing one variable at a time (e.g., window geometry, shading system, surface reflectance), allowing the designer to select optimum conditions to integrate the natural and electric lighting systems. Smaller models (1/4 in. = 1 ft and smaller) are used to evaluate exterior shading, building massing, and siting issues. Larger scales (3/8 in. = 1 ft and larger) are required for interior evaluations and quantitative measurements.

The performance of most models is evaluated under both clear and overcast sky conditions. Artificial sunlight is created with a nearly parallel beam electric light source. The variation in solar angles can be reproduced either by moving the "sun" in an arc around the model or by inclining the model on a tilting heliodon table. For quantitative sun studies, the CIE standard clear-sky component also must be simulated. If the clear-sky component is not represented, the sun study is limited to qualitative evaluations of shading angles, sunlight penetration, and glare, which are usually documented visually, photographically, or on video.

The overcast sky condition is simulated by reproducing the luminance distribution of the CIE standard overcast sky inside a model testing room. The daylighting model is placed inside the room and illuminance measurements are taken with a series of photocells at selected locations inside the model. The photocells are usually connected to a lighting logger or computer. The measurements are used to generate interior daylight illuminance contours and to estimate potential electric lighting energy savings from daylighting control systems.

However, photometry requires the use of special-purpose equipment, and illuminances can be determined only for the sky conditions under which measurements are made. They may not be representative of average conditions, because instantaneous sky conditions can vary considerably from longterm averages. The measured sky conditions can be compared with daylight availability measurements, as discussed below. In making this comparison, it is desirable to obtain measurements for a range of sky conditions (that is, overcast and clear) and, in the case of clear skies, for a range of sun positions (for example, at 4-min intervals from 8 a.m. to 8 p.m., 4 min being the interval in which the sun changes position by 1°). Measurements under overcast skies are discussed in Reference 49.

Considerations in Using Photometric Instruments

Because of the short-term variability of daylight, it is usually necessary to use sensors connected to a data logger with recording capability. An alternative is the use of artificial skies and suns, although only a few such facilities exist, mostly at universities or research institutions. Artificial skies and suns also have limitations.[50]

Some factors contributing to error in scale model photometry[50,58] are substantially under the control of the user, including relative calibration of sensors, surface reflectances, and the fidelity with which the model replicates the space and fenestration of interest (although this can become quite difficult with complex fenestration systems). Other factors to consider are listed below.

Photocell Leveling. At the rear of deep sidelighted spaces, where much of the light striking a photocell does so at an oblique angle, small errors in leveling a photocell may produce large errors in illuminance measurements; for an incidence angle of 85°, a sensor misalignment of 2° will result in an error of 40% for the sky component.[59]

Photocell Size. A given sensor has a different view of the sky in a model than in a fullscale space. Where illuminances are changing rapidly and by large amounts (for example, close to a window without shading controls), significant error may result.

Sensor Placement. While it is not difficult to place photocell faces with sufficient accuracy for most conditions, small placement errors in models result in large errors where flux gradients are steep.

Effects of Space Contents. Space contents, such as sensor holders in scale models, may increase internal reflections and lead to significant overestimates. Such holders should be painted matte black unless their luminous characteristics correspond to features that would exist in the proposed design.

Luminance-based measurements using calibrated video cameras can record thousands of luminance measurements in a physical model,[40] allowing evaluation of lighting attributes such as luminance distribution, color, and visual performance. These videobased systems can also assist the designer in recording subjective evaluations of the model.

Measurement of Sky Conditions

It is generally necessary to make measurements of the total illuminance on an unobstructed horizontal surface (the global illuminance) simultaneously with interior measurements as a record of daylight availability. Other important measures are the diffuse illuminance on an unobstructed horizontal surface and the zenith luminance. The most basic means of determining the diffuse illuminance is screening a sensor with a shadow band and using a correction factor to compensate for the diffuse daylight obstructed by the shadow band.[60] It may also be useful to record daylight on vertical planes of interest, usually facing one or more of the cardinal directions, which necessitates the use of screening devices to cut off ground-reflected light.[61]

Computer Simulation

Computer-based simulation methods for daylighting evaluation offer flexibility that scale-model photometry and manual methods sometimes cannot. They are especially valuable when the complexity of the building would make a scale model too costly to construct or when there is the need to evaluate a variety of glazing options. Computer-based simulations provide a convenient means of parametrically evaluating designs in comparison to other design alternatives. Computer programs are readily available for common computer hardware. They can calculate workplane illuminance, daylight factors, surface luminance, a variety of glare and illumination quality, and performance metrics, and often can produce realistic color renderings.[36-38] The procedures used in these programs are described in the section "Computer Calculations."

Analysis of sunlight penetration and fixed shading can be carried out with many CAD programs that provide shadow-casting as part of their rendering features. For calculation of illuminances, dedicated lighting software with daylighting capability is available.[36-38]

DAYLIGHTING DESIGN CONSIDERATIONS[62]

Developing Goals

The earlier in the design process that daylighting is considered as a fundamental, form-giving component of building design,[63] the greater the building benefits from the use of daylighting features.[64,65]

The most successfully implemented daylighting design involves broad agreement among all design disciplines as the goals and features of the building are developed. The provisions for daylighting are affected by decisions pertaining to many other building parameters. For example, the installation of dimmable lighting control systems may provide only minimal savings if heavily tinted glazing, specified to control heat gain and glare, excessively reduces the admission of all daylight, even if there is no direct sun.

Daylight apertures serve two distinct purposes: allowing views to the exterior and providing functional ambient light for the interior. Frequently the design considerations for these functions conflict. For example, view windows occur low in the wall at eye height, while functional daylight apertures distribute light most evenly when they are placed high in the wall. It is important to identify the role and function each aperture is intended to perform, which may require providing separate apertures for view and daylighting.

Daylight Penetration and Glare Control

Glare control is a major consideration in daylighting because of the intensity of the source (especially in the case of direct sunlight) and because, in many situations, achieving spatially balanced illumination is difficult with a source that is unevenly distributed through the space (for example, sidelighting of deep-plan buildings). A rule of thumb is that the distance of useful daylight penetration with sidelighting is usually not more than twice the window head height. Room furnishings in particular may drastically reduce daylight penetration in sidelighted spaces.[42,43]

Advanced daylighting designs manipulate the daylight entering the space to carefully control the distribution of light and the balance of surface luminances under a variety of sun angles and sky conditions. The effects of daylight on the luminance and illuminance ratios in a space can be studied with daylight models, computer simulations, and full-scale mockups.

Control of Glare from Direct Sunlight. Designs should be developed such that direct sunlight is, or can be, excluded from critical task areas. Sources of direct specular reflection should also be identified and eliminated, or their reflectances reduced as much as possible. An exception is if the reflecting surface is used as part of a daylight harvesting feature such as a lightshelf. In this case, care should be taken to ensure that the reflected sunlight is sufficiently diffused and strikes surfaces that are not in the direct line of sight of building occupants.

Control of Glare from Diffuse Skylight. Glare increases substantially with larger views of the upper portions of the sky. This can be avoided by limiting the height of the view window head in critical task areas, by screening upper window areas from view, or by placing daylighting apertures high enough to be out of the normal field of vision. The task also may be arranged so that the user does not face the window, although this may conflict with user view preferences. Glare can also be reduced by using light colors on interior surfaces, especially near windows, to reduce luminance ratios.

Evaluation of Designs[66]

A logical sequence in evaluating a proposed design is the following:

1. Evaluate the balance of luminances and illuminance levels through the space. Surface luminance balances (or imbalances) and illuminance levels are major factors in lighting quality and mood, task performance, and associated comfort.

2. Determine whether sunlight will fall on any areas where it should be excluded, and address any resulting problems by changing the daylighting apertures or providing fixed or movable controls.

3. Determine whether sky glare will be a problem, and either make adjustments to the design to control glare or provide fixed or movable controls.

4. Evaluate the performance of the daylighting system acting in concert with the electric lighting, using illuminance, luminance, and energy use as metrics. Assess the pattern of sunlight in spaces where it is being provided as an amenity.

For a minimum investigation at the conceptual stage, daylighting should be evaluated with solar altitudes corresponding to the solstices, around December 21 and June 21, and one equinox, around March 21 or September 22. A range of sky conditions should be tested, including, at least, the extremes for a particular orientation, such as solar noon and the earliest and darkest hours when daylighting occurs for a south-facing facade.

It is important that designs be checked for critical conditions when sunlight may enter spaces. For instance, at northern latitudes, direct sunlight may strike the north-facing facades of buildings on summer evenings. In the winter, the sun will be low in the sky, resulting in deep penetration of shading systems and sidelighted spaces. Nearer the equator, the high midday summer sun can more readily enter spaces through skylights.

Assessment of Daylighting Effects on Energy Use

Daylighting apertures can have either a positive or negative impact on the overall building energy performance. Direct solar gains into the building interior can require additional cooling, whereas electric lighting load reductions can have a direct electricity cost savings as well as an indirect reduction in cooling loads. A well-designed daylighted building can provide significant improvement in overall building energy performance when these impacts are balanced for the building type, use, and location.

Use of daylight in buildings can reduce the need for electric lighting during the day while maintaining sufficient illuminance levels. Because the IR heat component of daylight can be excluded from the building with spectrally selective, low-emissivity glazing and low U-value glazing assemblies, the result is a building that places a lower demand upon the cooling system. In heating-dominated climates daylighting permits the maximum benefit from passive solar heating and can shift heating costs from electrical sources to more economical gas sources. The Illuminating Engineering Society of North America (IESNA) and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) have produced an energy-efficient design guide,[67] which provides procedures for estimating the contribution of daylighting to energy conservation.

Integration of Daylight and Electric Lighting

The integration of daylight and electric light begins with an understanding of the overall intention of the lighting design. The designer must decide what roles daylight and electric lighting will play in meeting the lighting objectives. Daylight's contribution across the space at different times of the day and year must be determined. This may include evaluating daylight surface luminance ratios, illuminance levels and contours, daylight zones, temporal variations in daylight availability (direction and intensity), and how daylight distribution changes with adjustable shading and fenestration elements.

The electric lighting may be designed to contrast with the daylight, as in an atrium that dramatically changes moods as it goes from a predominantly daylighted, daytime ambiance to a predominantly electrically lighted nighttime scene. In many daylighted buildings, however, the two components are designed to work together in a task/ambient approach, where daylight provides the ambient lighting (supplemented by electric light as necessary) and electric light provides the task and accent lighting. In this case, the ambient electric lighting system is designed to reduce daylight gradients and to balance luminances in the space. The ambient electric lighting must be circuited and zoned to follow the daylight zones. This is accomplished by aligning the electric lighting circuits parallel to the daylight contours. Ideally, the ambient electric light is delivered to the same surfaces as the daylight so that the transition between daylight and electric light is smooth.

Electric Lighting Control

If ambient electric lighting has been designed to correspond with daylight zones, an automatic control system can be implemented to turn off or dim the electric lights in response to daylight availability. Automatic control is accomplished by a photocell that evaluates the light level and sends a signal to a control unit to dim or switch the electric lights to maintain a preset target level. Automatic control provides more predictable performance than manual control, but control zones must be sufficiently small and matched well with daylight availability to achieve light level consistency.

For sidelighting, the photocell usually is placed on the ceiling looking down at a representative task area; for skylighting, it is frequently placed in a skylight looking up at the available daylight. Switching of electric lighting in response to daylight produces abrupt changes in the light level when the switching occurs. This can be reduced by using multiple switching steps. Dimming is more expensive, but it is also more gradual and acceptable to building occupants.

Commissioning

In order for a well-designed daylighting system to provide the benefits expected by owners and occupants over time, the system should be commissioned after installation. Commissioning can be defined as a systematic process that ensures that all elements of the daylighting system perform interactively and continuously according to documented design intent and the needs of the building owner. Most daylighting systems consist of a fenestration element, typically with some operational elements to modulate daylight and glare, and an electric lighting control system, which may consist of a sensor, a controller, and a dimming ballast. At a minimum, commissioning implies verification that the proper equipment was installed in a manner that meets documented installation requirements. In this context, commissioning could be completed by the general contractor. However, commissioning more typically includes calibration of any electrical or mechanical sensors such that they produce the desired control signal to the system under the specific conditions of the room design and over a wide range of incident daylighting conditions. This often requires special skills and equipment, such as a photometer to set proper light levels.

Experience to date[68] suggests that commissioning of daylighting systems is commonly ignored and, when it is done, is often fraught with technical and procedural difficulties. Commissioning criteria should be specified by the designer and/or provided by the manufacturer. In most cases, commissioning activities should be carried out in spaces that are furnished and ready for occupancy. Commissioning must be completed for each unique physical zone or control system zone and for each building orientation.

Operationally it is useful to think about the daylighting system in two elements: fenestration controls and lighting controls. Commissioning of fenestration controls can be divided into three cases, each with its own specific requirements and procedures: 1) systems with fixed elements that may need adjustment after installation, such as some lightshelves; 2) systems with manually operated controls, such as interior venetian blinds, and 3) systems with automated controls, such as exterior motorized louvers. Once the performance of the fenestration systems is verified, the lighting control system can be commissioned. The placement and orientation of the photosensor must be verified for optimum operation. The light sensor and controller must be adjusted to provide the desired light level at the task location. The specifics of this procedure vary with control system type (open versus closed loop control) and hardware selection.[69]

DAYLIGHTING SYSTEMS

Fenestration and Building Sections[3,63,70-75]

Unilateral Sidelighting. This design (Figure 8-28a) lends itself to continuous fenestration and curtain wall construction. To avoid large ranges in daylight illuminances (greater than 25:1), the distance from the window wall to the inner wall should normally be limited to twice the window head height with clear glazing. For this reason, window heads are often placed close to the ceiling, although the resulting increase in the view of the sky also increases glare. Deeper spaces may be created if additional lighting opposite the window wall is used to balance illuminances.

Window with Overhang. Overhangs (Figures 8-28a and b) may be used to reduce sunlight penetration in latitudes where the sun is high in the sky during the times that spaces are occupied. This reduces the view of the upper portion of the sky and provides a less drastic range of illuminances across a space. However, overhangs also reduce daylight penetration, although this may be offset to some degree by the redirection of ground-reflected light into the space.

Window with Blinds. Venetian blinds can be effective in controlling the entry of sunlight, reducing sky glare, and redirecting light to the ceiling. They can provide a shading effect equivalent to a very substantial overhang. Building occupants claim to enjoy the control offered by blinds, but they tend to adjust blinds infrequently.

Split Window with Upper and Lower Blinds. This allows for different adjustments for the upper and lower portions of the glazing. For instance, daylight can still be admitted deep into the space when the lower blinds are closed to exclude sunlight from a task area.

Split Window with Low-Transmittance Upper Panel. This reduces glare from the upper portion of the sky while not distorting the view of the ground plane.

Window with Vertical Shading Elements. Devices such as fins are effective sun controls on east and well walls. Combinations of vertical and horizontal elements (for example, egg crate shades) as sun controls are common in southern latitudes.

Window with Light Shelf. Light shelves are fixed exterior and interior shading systems used in combination with glazing placed above the lower glazing used for viewing in sidelighting systems. By screening the upper portion of the sky, they allow the use of higher window heads, providing deeper and more uniform daylighting while eliminating the glare that would normally accompany the use of tall windows.

Bilateral. Bilateral daylighting (Figure 8-28b) balances the admission of light. This system permits doubling of the room width receiving light that is possible with unilateral daylighting. The second set of windows often occupies only the upper part of the wall. At least one set of windows is exposed to the sun, necessitating glare control. Sloped ceilings, sometimes employed with this design, have little effect on the quantity or quality of illumination except where they can allow a higher window head.

Roof Monitor. This daylighting system is most frequently used in industrial buildings where a central high bay is set between two lower flanking areas (Figure 8-28c). High-reflectance roof surfaces below the monitors increase interior illuminances.

Clerestory. Additional windows on the roof, facing the same direction as the main side-lighting window, aid in overcoming the daylighting penetration limitations of the unilateral section (Figure 8-28d).

Staggered Building Sections. Staggered building sections can allow for deep penetration of daylight along with greater flexibility in the layout of spaces. They are a variation on combinations of clerestory lighting and other sidelighting systems.

Sawtooth. This fenestration (Figure 8-28e) is used principally in large industrial buildings. Slanting the windows to face the sky increases the potential daylighting contribution, but this may be offset by increased dirt collection on the glazing. Heat gain may also increase.

Skylights. Skylights assume many forms, including domes, panels with integral sun and luminance control, panels of fiber-glass-reinforced plastic, and louvers for heat and glare control. Skylight detailing requires special attention to prevent moisture penetration and dripping due to condensation. Operable skylights may also provide ventilation and cooling (Figure 8-28f).[51,76] The use of skylight wells, splayed at about 60° and matte-white finished, is essential if a uniform, glare-free daylight distribution is to be achieved.

Atria.[77,78] These are large-area daylighting sources that have several forms, such as ridge-type (Figure 8-28g), sheds, pyramids, and domes. Because of the large area, lower-range (10 to 25%) light transmissions are used. Translucent sandwich panels with highly diffusing glass fiber-reinforced polymer faces are especially suitable for diffuse shadow-free daylighting, even under direct sun conditions. These panels provide excellent control of light and heat.

Solar Lighting Systems. Solar lighting systems include systems of reflectors or other optical elements intended for steering or redirecting direct solar flux with relatively minor contributions from diffuse sky light. Tubular skylights are representative of such systems, as are a variety of additional schemes including mirrored louvers in clerestory windows, mirrored louvers in otherwise conventional skylights, and more complex systems using sun-tracking, concentrating, and piping subsystems.[79]

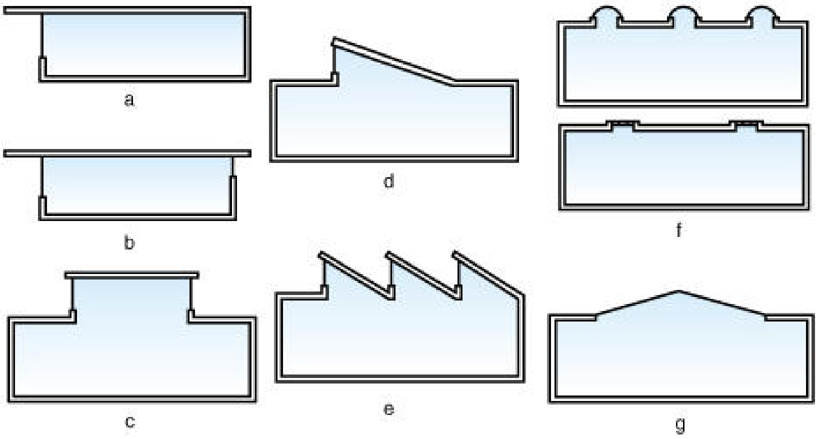
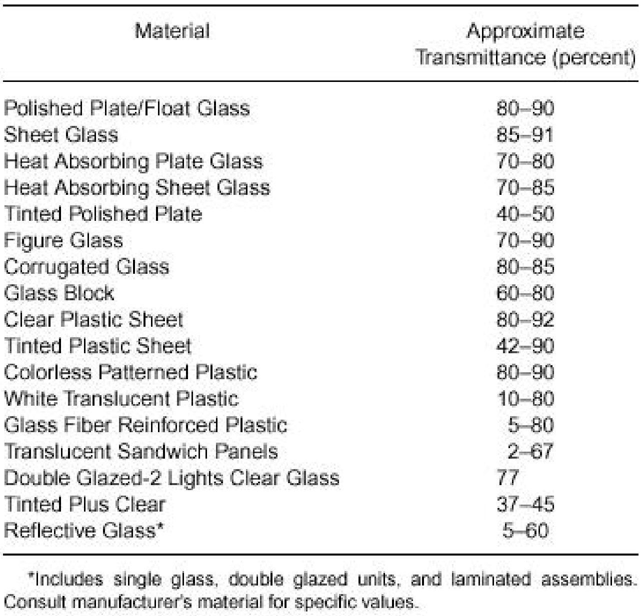


Figure 8-28. a. Unilateral lighting section. b. Bilateral lighting section. c. Roof monitor lighting section. d. Clerestory lighting section. e. Sawtooth lighting section. f. Skylight sections. g. Atrium section.

Material and Control Elements

A variety of materials are used in daylighting systems. Transmittance data for several of these materials are provided in Figure 8-29. It should be noted that the transmittance of materials is a function of the incident angle of the light.



Material	Approximate Transmittance (percent)
Polished Plate/Float Glass	80–90
Sheet Glass	85–91
Heat Absorbing Plate Glass	70–80
Heat Absorbing Sheet Glass	70–85
Tinted Polished Plate	40–50
Figure Glass	70–90
Corrugated Glass	80–85
Glass Block	60–80
Clear Plastic Sheet	80–92
Tinted Plastic Sheet	42–90
Colorless Patterned Plastic	80–90
White Translucent Plastic	10–80
Glass Fiber Reinforced Plastic	5–80
Translucent Sandwich Panels	2–67
Double Glazed-2 Lights Clear Glass	77
Tinted Plus Clear	37–45
Reflective Glass*	5–60

*Includes single glass, double glazed units, and laminated assemblies. Consult manufacturer's material for specific values.

Figure 8-29. Transmittances for of Glass and Plastic Materials

Transparent (High-Transmittance) Materials. These transmit light without appreciably changing its direction or color; they are image preserving. Common types are sheet, polished plate, and float and molded glass, as well as some rigid plastic materials and formed panels.

Transparent (Low-Transmittance) Materials. Low-transmittance (gray) glasses and plastics offer luminance reduction that increases as their transmittance decreases. During daylight hours, the ability to view into a room is reduced. At night, the view into a room is apparent while the view from a room to the outdoors is reduced. Lower transmittances, below 0.5, can give a gloomy appearance to daytime outdoor views.

Angular Dependence of Transmittance. The transmittance of glazing materials is a function of the incident angle. Designers can reduce or increase solar gains by orienting the glass of toplighting systems. For instance, glazing tilted at a steep angle to the south admits more direct solar radiation in winter than horizontal glass because of the lower incident angle of sunlight.

Electrically Controlled Glazings. These have transmittance properties that are a function of applied voltage. Currently available products require the application of a low voltage to render them colored. They become clear when the voltage is switched off.[80] Recent advancements in the development of electrochromic technologies have resulted in glazing assemblies that can switch between 7 and 68% transmittance in two to three minutes.

Translucent Diffusing Materials. The amount of diffusion in materials varies over a wide range, depending on the material and its surface treatment. Generally, transmittance and luminance decrease as diffusion increases. The luminance of highly diffusing materials is nearly constant from all viewing angles (Lambertian). Diffusing materials include translucent and surface-coated or patterned glasses, plastics, translucent sandwich panels,[81] and diffusing glass blocks.

High-Reflectance, Low-Transmittance Materials. Reflective glasses and plastics provide luminance control by having high exterior reflectances. These materials act as one-way mirrors, depending on the ratio of indoor to outdoor illuminance. Their low transmittance often gives outdoor areas an overcast or dark appearance, even on sunny days.[21] Some selectively admit visible light while reflecting IR wavelengths that would otherwise add to the cooling load.

Directional Transmitting Materials. These include glasses and plastics with prismatic surfaces that are used to obtain directional control of light and luminance. Most of these use the exterior or interior structure of the material to totally internally reflect direct radiation from the sun. In skylights and hollow light pipes, they can reduce throughput in summer and enhance it in winter. In windows under clear sky conditions, they can redirect radiation onto the ceiling and hence deeper into the room while reducing glare close to windows. Recent examples include laser-cut panels and polymer sheets with internal cavities and smooth external surfaces.

Many of these systems interfere with the view through a window and thus are often used above the line of sight. Laser-cut panels used in a flat configuration (e.g., as louver panels) allow preservation of view. Thin films for windows can attenuate direct radiation from high angles while preserving view and admitting most sky radiation from lower angles. These are good for glare control. All of these systems are often referred to as angular-selective, since their effect on radiation strongly depends on the direction of incidence.

Superglazings. High-performance glazings use multiple cavities, often separated by films and usually filled with special gases. They have low-emissivity coatings on one or more glass surfaces to reduce heat transfer.

Specularly Selective Transmitting Materials. These include the various heat-absorbing and reflecting materials that are designed to pass most visible radiation but absorb or reflect a portion of the IR radiation, which would otherwise contribute to cooling loads. Absorbed heat is reradiated indoors and outdoors in approximately equal proportions. Low-emissivity glass comes under this general classification because it selectively admits the visible portion of the spectrum while rejecting the far IR. However, the term "specularly selective glazing" is usually reserved for glass that transmits the visible while rejecting near (and far) IR radiation. The appropriateness of these types of glazing strongly depends on building use and site climate.

Louvers. Louvers may be fixed or adjustable, horizontal or vertical. They are capable of excluding direct sunlight and reducing radiant heat while reflecting sun, sky, and ground light into the interior. In the case of fixed louvers, the spacing and height of the slats should be designed to exclude direct sunlight at common sun angles. Overhangs for sun control are often made with louver elements so that light from the rest of the sky can reach the windows. Louvers are also employed in top-lighting arrangements, sometimes with two sets of slats set at right angles to form an egg crate. Matte textures and high reflectances should be used where possible.

Shade and Draperies. These include opaque and diffusing shades and draperies for excluding or moderating daylight and sunlight, to darken a room, as for projection.

Landscaping. Trees can be effective shading devices for buildings of low elevation if placed in an appropriate position with respect to windows. Deciduous trees provide protection against glare due to direct sun during the warm months but transmit sunlight during the winter. Deciduous vines on louvered overhangs or arbors provide similar seasonal shade.

Exterior Reflecting Elements. Reflective pavements and similar surfaces increase the amount of ground light entering the building. Reflecting materials or finished roofs below windows have the same effect.

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9

Lighting Calculations

Lighting calculations are performed during the design process to obtain information about lighting system performance. A designer can use the results of calculations to choose between design alternatives or to refine a particular design. Lighting calculations are mathematical models of the complex physical processes that occur within a lighted space. Since these models can never be accurate in every detail, the computations are approximations of real situations.[1]

This chapter contains many of the fundamental calculation methods that are used in lighting system analysis, including both simple and complex methods. For methods that apply to specific applications, such as luminaire design, daylighting, floodlighting, roadway lighting, sports lighting, or merchandise lighting, see the special chapters for procedures particular to those areas.

The simplest lighting calculation methods can be performed by hand, whereas the more advanced methods can be performed only by using a computer. More advanced models generally provide more accurate information. Accuracy, for the purpose of this discussion, is defined as the degree to which the calculations agree with reality. In actuality, it is very difficult to achieve perfect agreement, as discussed later in this chapter.

Lighting calculation methods are application driven. The type of information that is desired about a lighting system and the complexity of the lighting condition being analyzed determine which calculation method is best applied to the problem. The aspects that must be evaluated in determining the lighting analysis model to use are the following:

- Information desired
- Equipment choice
- Equipment number and placement
- Space characteristics

It is the responsibility of the designer to determine and use the most appropriate calculation methods for an application. The material presented in this chapter provides the lighting practitioner with information that can be used in making these decisions.

This chapter provides general calculation procedures that are used in the analysis of direct and reflected light. In general, these are fundamental procedures that can be applied to all lighting analysis situations. Also included are specialized calculations commonly used in the evaluation of lighting systems. Finally, a set of example calculations is provided to illustrate the general algorithm for lighting calculations discussed in this chapter.

BASIC PRINCIPLES

Predicting the radiative transport of luminous flux (or flux transfer) from a source to a receiving surface is fundamental to all lighting calculations. This transport is through air, which is assumed to be nonabsorbing and nonscattering.

Flux transfer is categorized into six types by geometry and emitter type:

1. Point source to a point or differential receiving area
2. Point source to a finite receiving area
3. Diffuse area source to a point or differential receiving area
4. Diffuse area source to a receiving area
5. Nondiffuse area source to a point or differential receiving area
6. Nondiffuse area source to a receiving area

Transfer type 1 is conceptually the simplest and is the easiest to formulate. Transfer types 2, 3, and 4 are obtained from the formulation of type 1 by integrating over the source, the receiving area, or both. Transfer types 5 and 6 are the most complicated, but they are also the most commonly encountered in practice. Light reaching a point or an area is described by *illuminance*, the measure of flux density or the incident flux per unit area.

It is often necessary to know how light reflects from a point or an area. Exitance is the simplest case and is measured as flux density leaving the surface. More complicated is *luminance*, which describes the flux leaving a surface in a particular direction. For exitance and luminance calculations the reflecting properties of the surface must be known. In these cases, methods for predicting illuminance are combined with reflectance information to predict exitances and luminances.

Photometric measurement of a luminaire provides a luminous intensity distribution from which the spatial distribution of flux from the luminaire is obtained. For calculations, the simplest cases are those in which the luminaire is small and can be considered a point. Flux transfer types 1 and 2 can be used. In many cases, the luminaires are large and flux transfer types 3 and 4 are required to provide adequate accuracy. Methods for assessing luminaire size are given below.

Interreflection is the multiple reflection of light among surfaces. It is an important aspect of most interior lighting systems, since it is by interreflection that many interior architectural surfaces acquire a luminance. It is by these luminances that architecture is also revealed and given perceptual form. For some interior lighting systems, interreflection is the only process by which the illuminance on the visual task is produced. Such is the case for indirect electric lighting and many daylighting systems.

Direct Flux Transfer

Flux Transfer Type 1, Point Source to a Point. The illuminance *E* produced on an area *A* centered at a point *P* is related to the luminous intensity of a light source, $I(\theta,\psi)$, as follows. Given the intensity distribution of the light source in spherical coordinates (θ,ψ), the geometric arrangement is shown in Figure 9-1.

The illuminance E is defined in terms of the flux Φ incident on an area A:

$$E = \frac{\Phi}{A} \qquad (9\text{-}1)$$

That flux can also be analyzed directionally in terms of the solid angle ω. If the origin of a spherical coordinate system is located at the source, and the area *A* is small with respect to the distance *D*, then

$$\omega = \frac{A}{D}\cos\xi \qquad (9\text{-}2)$$

where

D = distance between the source and point P,
ξ = angle between the normal $(\hat{n})$ to the surface A and direction of the distance D.

The definition of the luminous intensity from the source is used to related Equations 9-2 and 9-1:

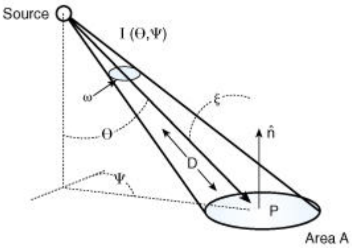


Figure 9-1. Geometric arrangement for the inverse square cosine law.

$$I(\theta,\psi) = \frac{\Phi}{\omega}$$

or

$$\Phi = I(\theta,\psi)\omega \qquad (9\text{-}3)$$

Substituting this into Equation 9-1 gives

$$E = \frac{I(\theta,\psi)\omega}{A}$$

Substituting Equation 9-2 into this gives

$$E = \frac{I(\theta,\psi)\cos\xi}{D^2} \qquad (9\text{-}4)$$

Equation 9-4 is the fundamental equation of flux transfer, the so-called inverse square cosine law.[2] Its validity assumes that of Equation 9-2 and that the luminous intensity is (nearly) constant in the neighborhood of the direction (θ,ψ).

As the area A (the neighborhood around point P) is made smaller, the solid angle ω becomes smaller and Equation 9-2 becomes more accurate. In the limit of a differential area, dA, the solid angle becomes differential, $d\omega$, and Equation 9-2 is exactly correct. The transfer of flux is conceptually equivalent to an infinitesimally narrow ray of light. The computational consequence of this consideration is that Equation 9-4 describes the illuminance at a differentially small neighborhood around point P or, more briefly, gives the illuminance at P.

Equation 9-2 expresses the solid angle subtended by the area A at a point; the light source is assumed to be coincident with this point. The computational consequence is that Equation 9-4 describes the illuminance from a point source.

The intensity value used in Equation 9-4 is most often obtained by interpolation from values in a table. Intensity distributions are almost always expressed using the two angles of spherical coordinates; thus the required interpolation is over these two angles. Bilinear splines, bicubic splines, and double Fourier series are among the methods used.[3,4]

Flux Transfer Type 2, Point Source to a Receiving Area.

The flux transferred from a point source to a differential area can be expressed using Equation 9-4. This is integrated over the receiving area to give the flux received by the entire area:

$$d\Phi = E\,dA$$

$$\Phi = \int E\,dA$$

$$\Phi = \int \frac{I(\theta,\psi)\cos\xi}{D^2}\,dA \qquad (9\text{-}5)$$

The integration is over the receiving area A.

Equation 9-5 can alternatively be solved using Monte Carlo integration.[5-7] Conceptually, light rays are traced from the point source P to randomly selected points on the receiving area, A, with Equation 9-4 being evaluated for each ray. Assuming a random distribution of n points on A, the flux received by A is approximately:

$$\Phi = \sum_{i=1}^{n} \frac{E_i A}{n}$$

where E_i is the illuminance of A at the receiving point due to ray i. The accuracy of the solution improves with increasing n.

Analytic integration of Equation 9-5 is possible only if the intensity distribution is a simple function and the geometric arrangement is simple.[3] Otherwise it is necessary to approximate the area integral of Equation 9-5 with a finite sum. In this case the receiving surface is broken up into small areas, or discretized, and Equation 9-4 is applied to each. The smaller and more numerous the n discrete areas, the more accurate the result:

$$\Phi = \sum_{i=1}^{n} I(\theta_i, \psi_i) \cos \xi_i \frac{a_i}{D_i^2} \qquad (9\text{-}6)$$

where

$I(\theta_i,\psi_i)$ = intensity of the point source in the direction of the *i*th piece of area *A*,
ξ_i = incident angle at the *i*th piece of area *A*,
a_i = area of the *i*th piece of area *A*,
D_i = distance between the source and the *i*th piece of area *A*.

The average illuminance, $\overline{E}$, can be obtained from either Equation 9-5 or 9-6:

$$\overline{\mathrm{E}} = \frac{\Phi}{A}$$

Flux Transfer Type 3, Diffuse Area Source to a Point. In many applications the light source is too large, or the point at which the illuminance is to be calculated is too close, for the conditions of validity for direct use of Equation 9-4 to be met. However, if the source is a diffuse emitter, Equation 9-4 can be used indirectly.

The intensity distribution of a diffuse emitter, in spherical coordinates, is given by

$$I(\theta, \psi) = I_n \cos \theta$$

The distribution is axially symmetric about the direction (0,0), which is also the surface normal (perpendicular). I_n is the luminous intensity in the direction of the surface normal.

Because each differential element *dA* of the source is a diffuse emitter, the intensity distribution of such an element is

$$dI(\theta, \psi) = \frac{M_{dA} \cos \theta}{\pi} dA$$

where M_{dA} is the exitance of the source at the differential element *dA*. The illuminance produced at the point *P* is

$$dE = \frac{M_{dA} \cos \theta \cos \xi}{\pi D^2} dA$$

and the illuminance produced by the entire source is

$$E = \frac{1}{\pi} \int \frac{M_{dA} \cos \theta \cos \xi}{D^2} dA \qquad (9\text{-}7)$$

If the source exhibits a constant exitance *M* over its extent, then

$$E = \frac{M}{\pi} \int \frac{\cos \theta \cos \xi}{D^2} dA \qquad (9\text{-}8)$$

The integration is over the extent of the source.

The quantity that multiplies the exitance *M* is purely geometric and is called the configuration factor, *c*.[8] More simply,

$$E = Mc \qquad (9\text{-}9)$$

where

$$c = \frac{1}{\pi} \int \frac{\cos \theta \cos \xi}{\mathrm{D}^2} dA \qquad (9\text{-}10)$$

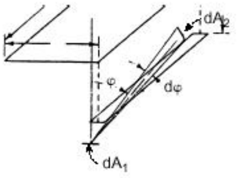
The configuration factor relates the exitance of a diffuse area emitter to the illuminance it produces at a point. It has the limiting values

$$0 \leq c \leq 1$$

Alternative definitions of the configuration factor are possible. It can be defined as that fraction of the total flux emitted by a differential diffuse emitter that is received directly by an area. The analytic result of this definition is Equation 9-10. This configuration factor has been evaluated for a large number of geometric conditions.[9] A selection of these equations is given in Figures 9-2 and 9-3.

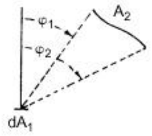
Equation 9-10 assumes that there are no intervening objects between the diffuse area source *A* and the point receiver *P*. If there are, then Equation 9-10 becomes:

$$c = \frac{1}{\pi} \int \frac{V(\theta, \xi) \cos\theta \cos\xi}{D^2} \, dA$$



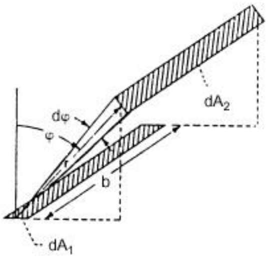
Area dA_1 of differential width and any length, to infinitely long strip dA_2 of differential width and with parallel generating line to dA_1.

$$C = \frac{\cos\varphi}{2} d\varphi$$



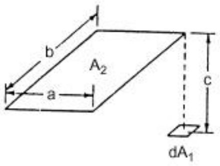
Area dA_1 of differential width and any length to any cylindrical surface A_2 generated by a line of infinite length moving parallel to itself and parallel to the plane of dA_1.

$$C = \frac{1}{2}(\sin\varphi_2 - \sin\varphi_1)$$



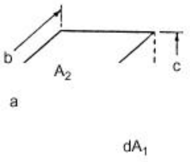
Strip A_1 of length b and differential width, to differential strip dA_2 of same length on parallel generating line.

$$C = \frac{\cos\varphi}{\pi} d\varphi \arctan\frac{b}{r}$$



Plane element dA_1 to plane parallel rectangle A_2; normal to element passes through corner of rectangle. $X = a/c$; $Y = b/c$.

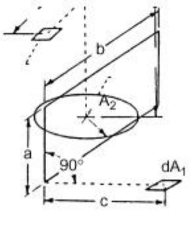
$$C = \frac{1}{2\pi}\left(\frac{X}{\sqrt{1+X^2}}\arctan\frac{Y}{\sqrt{1+X^2}} + \frac{Y}{\sqrt{1+Y^2}}\arctan\frac{X}{\sqrt{1+Y^2}}\right)$$



Strip element dA_1 to rectangle A_2 in plane parallel to strip; strip is opposite one edge of rectangle. $X = a/c$; $Y = b/c$.

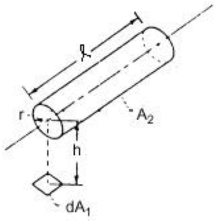
$$C = \frac{1}{\pi Y}\left[\sqrt{1+Y^2}\arctan\frac{X}{\sqrt{1+Y^2}} - \arctan X + \frac{XY}{\sqrt{1+X^2}}\arctan\frac{Y}{\sqrt{1+X^2}}\right]$$

Figure 9-2. *Continued*



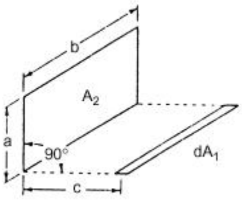
Plane element dA_1 to rectangle A_2 in plane 90° to plane of element. $X = a/b$; $Y = c/b$.

$$C = \frac{1}{2\pi}\left[\arctan\frac{1}{Y} - \frac{Y}{\sqrt{X^2+Y^2}}\arctan\frac{1}{\sqrt{X^2+Y^2}}\right]$$



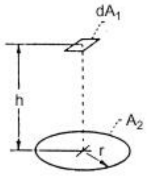
Plane element dA_1 to right circular cylinder A_2 of finite length ℓ and radius r; normal to element passes through one end of cylinder and is perpendicular to cylinder axis. $L = \ell/r$; $H = h/r$; $X = (1 + H^2) + L^2$; $Y = (1 - H^2) + L^2$.

$$C = \frac{1}{\pi H}\arctan\frac{L}{\sqrt{H^2-1}} + \frac{L}{\pi}\left[\frac{(X-2H)}{H\sqrt{XY}}\arctan\sqrt{\frac{X(H-1)}{Y(H-1)}} - \frac{1}{H}\arctan\sqrt{\frac{H-1}{H+1}}\right]$$



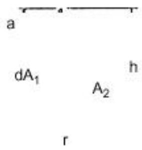
Strip element dA_1 to rectangle A_2 in plane 90° to plane of strip. $X = a/b$; $Y = c/b$.

$$C = \frac{1}{\pi}\left\{\arctan\frac{1}{Y} + \frac{Y}{2}\ln\left[\frac{Y^2(X^2+Y^2+1)}{(Y^2+1)(X^2+Y^2)}\right] - \frac{Y}{\sqrt{X^2+Y^2}}\arctan\frac{1}{\sqrt{X^2+Y^2}}\right\}$$



Plane element dA_1 to circular disk A_2 in plane parallel to element; normal to element passes through center of disk.

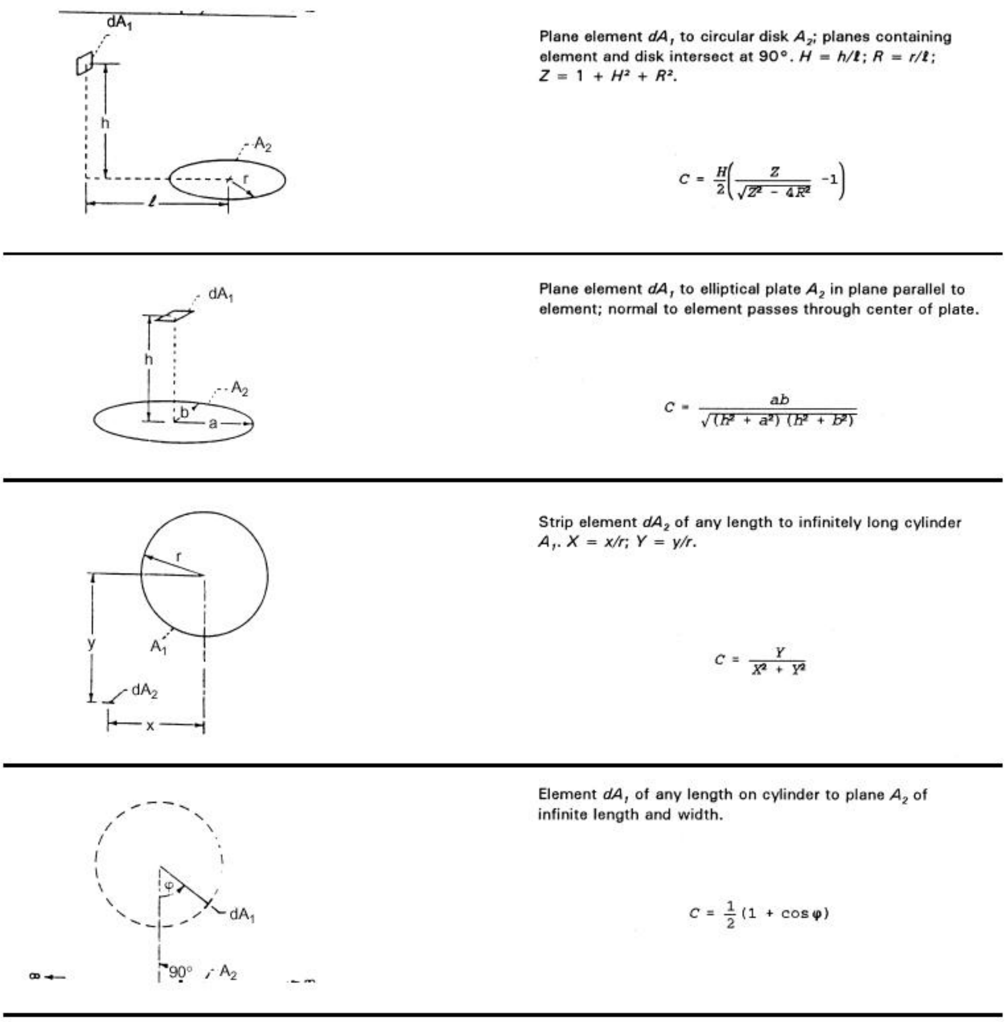
$$C = \frac{r^2}{h^2 + r^2}$$



Plane element dA_1 to circular disk A_2 in plane parallel to element. $H = h/a$; $R = r/a$; $Z = 1 + H^2 + R^2$.

$$C = \frac{1}{2}\left(1 - \frac{1 + H^2 - R^2}{\sqrt{Z^2 - 4R^2}}\right)$$

Figure 9-2. *Continued*



Plane element dA_1 to circular disk A_2; planes containing element and disk intersect at 90°. $H = h/\ell$; $R = r/\ell$; $Z = 1 + H^2 + R^2$.

$$C = \frac{H}{2}\left(\frac{Z}{\sqrt{Z^2 - 4R^2}} - 1\right)$$

Plane element dA_1 to elliptical plate A_2 in plane parallel to element; normal to element passes through center of plate.

$$C = \frac{ab}{\sqrt{(h^2 + a^2)(h^2 + b^2)}}$$

Strip element dA_2 of any length to infinitely long cylinder A_1. $X = x/r$; $Y = y/r$.

$$C = \frac{Y}{X^2 + Y^2}$$

Element dA_1 of any length on cylinder to plane A_2 of infinite length and width.

$$C = \frac{1}{2}(1 + \cos\varphi)$$

Figure 9-2. Configuration factors (*C*) for diffuse line and area sources.

where the visibility term $V(\theta,\xi)$ is 1 if P is visible from dA and 0 if it is hidden by an intervening object. In complex environments such as rooms with partitions and furniture, it is often necessary to solve this equation using numerical integration methods such as the hemicube method[5-7] or quasi-Monte Carlo ray casting.[7] Both approaches are based on Nusselt's analogy (Figure 9-4), where the configuration factor c is equal to the area of the double projection of A onto the base of the hemisphere, divided by the area of the base.

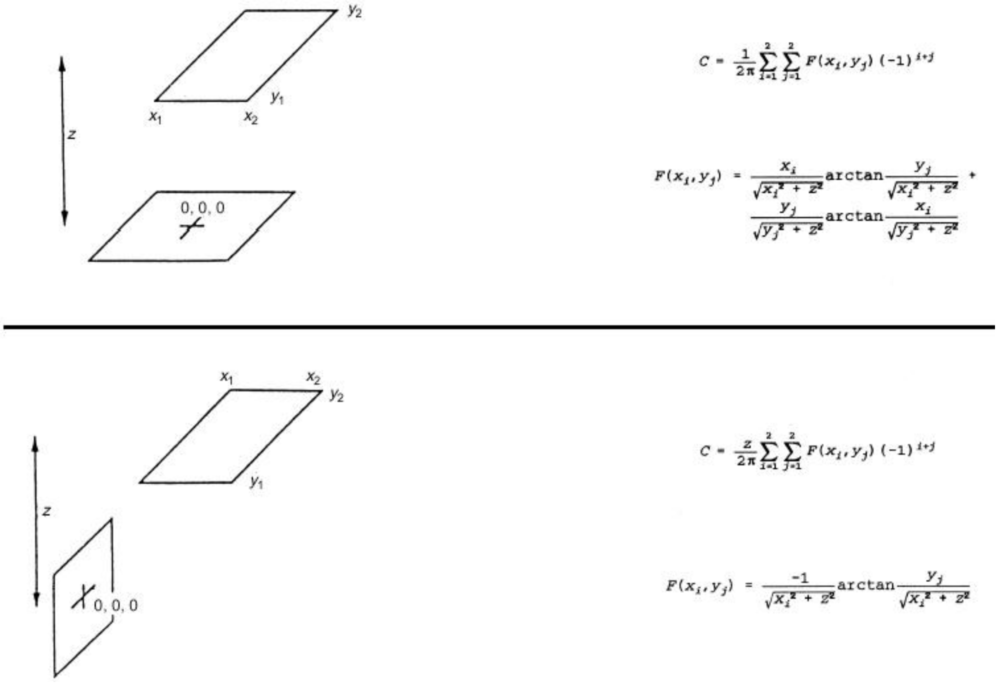
Equation 9-9 can be used to calculate the illuminance at a point produced by any diffuse emitter having a shape for which the configuration factor is known or can be calculated. Note that the emitter is assumed to have a uniform diffuse exitance.

Flux Transfer Type 4, Diffuse Area Source to a Receiving Area. If the emitting surface is specified as A_1 and the receiving surface as A_2, then the flux sent from A_1 to A_2, or Φ_2, is

$$\Phi_2 = \int E_{dA_2}\, dA_2$$

where E_{dA2} is the illuminance at element dA_2 from all of source A_1. Substituting for E_{dA2} using Equation 9-7 gives

$$\Phi_2 = \int \frac{1}{\pi} \int \frac{M_{1dA_1} \cos\theta \cos\xi}{D^2}\, dA_1 dA_2$$



$$C = \frac{1}{2\pi}\sum_{i=1}^{2}\sum_{j=1}^{2} F(x_i, y_j)\,(-1)^{i+j}$$

$$F(x_i, y_j) = \frac{x_i}{\sqrt{x_i^2 + z^2}}\arctan\frac{y_j}{\sqrt{x_i^2 + z^2}} + \frac{y_j}{\sqrt{y_j^2 + z^2}}\arctan\frac{x_i}{\sqrt{y_j^2 + z^2}}$$

$$C = \frac{z}{2\pi}\sum_{i=1}^{2}\sum_{j=1}^{2} F(x_i, y_j)\,(-1)^{i+j}$$

$$F(x_i, y_j) = \frac{-1}{\sqrt{x_i^2 + z^2}}\arctan\frac{y_j}{\sqrt{x_i^2 + z^2}}$$

Figure 9-3. General configuration factors (*C*) for parallel and perpendicular rectangles.

If the source exhibits a constant exitance M_1 over its extent, then

$$\Phi_2 = \frac{M_1}{\pi}\iint \frac{\cos\theta\cos\xi}{D^2}\,dA_1 dA_2 \qquad (9\text{-}11)$$

The integration is over the extent of the source and the extent of the illuminated area. The quantity that multiplies the exitance M_1 is purely geometric. It is customary to divide it by the area A_1 so that it is the fraction of flux leaving surface A_1 that reaches A_2. This is called the form factor $f_{1\to2}$.[8] Subscripts for form factors are necessary to indicate the direction in which flux is transferred. We have

$$f_{1\to2} = \frac{1}{\pi A_1}\iint \frac{\cos\theta\cos\xi}{D^2}\,dA_1 dA_2 \qquad (9\text{-}12)$$

With this definition, Equation 9-11 becomes

$$\Phi_2 = M_1 A_1 f_{1\to2}$$

The average illuminance, $\bar{E}_2$, produced on surface A_2 is then

$$\bar{E}_2 = \frac{\text{flux emitted by } A_1 \text{ reaching } A_2}{A_2}$$

$$\bar{E}_2 = \frac{M_1 A_1 f_{1\to2}}{A_2}$$

Form factors and areas relate the exitance of a diffuse area emitter to the average illuminance produced on a receiving surface. The form factors have the limiting values

$$0 \le f \le 1$$

and exhibit reciprocity:

$$A_1 f_{1\to2} = A_2 f_{2\to1}$$

Application of reciprocity gives

$$\bar{E}_2 = M_1 f_{2\to1} \qquad (9\text{-}13)$$

The equation for the form factor has been evaluated for a large number of geometric conditions. A selection of these equations is given in Figures 9-5 and 9-6.

Equations 9-9 and 9-13 have wide application for the calculation of illuminance and average illuminance produced by any form of diffuse emitter. Most large architectural surfaces exhibit a diffuse reflectance and therefore are diffuse emitters by reflection. The illuminance produced by such surfaces can be calculated using Equations 9-9 and 9-13. This includes surfaces made luminous by interreflection of light and indirectly lighted surfaces.

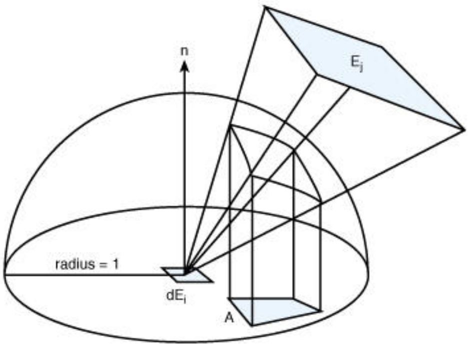


Figure 9-4. Construction of Nusselt's analogy for diffuse radiative transfer from a point to an area.

It is difficult to analytically evaluate the form factor between two areas with arbitrary geometry, and even more difficult in the presence of occluding objects.[10,11] Approximate evaluations can be obtained using Monte Carlo ray casting.[6,7]

Skylights and windows are commonly approximated as diffuse emitters by reason of the type of transmittance they exhibit. Equations 9-9 and 9-13 can be used in these cases also.

If an area diffuse emitter does not have a uniform exitance, it can be discretized into smaller elements, each of which has a nearly uniform exitance. The illuminance produced by each element is then calculated by repeated application of Equation 9-9 or 9-13. The total effect is obtained by adding the individual illuminances.

Flux Transfer Type 5, Nondiffuse Area Source to a Point. Nondiffuse area emitters are significantly more difficult to treat than diffuse emitters. If a far-field intensity distribution is available for the luminaire, Equation 9-4 can be used in certain cases. If the distance from the luminaire to the calculation point is greater than five times the largest dimension of the luminaire, then treating the luminaire as a point source using Equation 9-4 gives a computational accuracy of approximately 5% or better.

For points closer to the luminaire, an assumption can be made about homogeneity (surface uniformity) that permits a useful approximation to be made.[3] Under this assumption, the intensity distribution of any differential element of the emitter, $dI(\theta,\psi)$, is proportional to the intensity distribution, $I(\theta,\psi)$, of the entire luminaire. The constant of proportionality is the ratio of the area dA of the differential element to the area A of the entire luminaire. That is,

$$dI(\theta, \psi) = I(\theta, \psi)\,\frac{dA}{A}$$

The differential element is then treated as a point source, and Equation 9-4 is used to express the differential illuminance it produces:

$$dE = \frac{dI(\theta, \psi)\cos\xi}{D^2} = \frac{1}{A}\,\frac{I(\theta, \psi)\cos\xi}{D^2}\,dA$$

Integration over the surface of the luminaire gives

$$E = \frac{1}{A}\int \frac{I(\theta, \psi)\cos\xi}{D^2}\,dA \qquad (9\text{-}14)$$

Analytic integration of Equation 9-14 is possible only if the intensity distribution is a simple function and the geometric arrangement is simple. Otherwise it is necessary to approximate the area integral of Equation 9-14 with a finite sum. In this case, the luminaire is discretized into small areas. The smaller and more numerous the discrete areas, the more accurate the result:

$$E = \frac{1}{A}\sum_i I(\theta_i, \psi_i)\cos\xi_i\,\frac{a_i}{D_i^2} \qquad (9\text{-}15)$$

where the summation is over all the discrete pieces of the luminaire, and

$I(\theta_i,\psi_i)$ = intensity of the ith piece of the luminaire surface to point P,
ξ_i = incident angle for flux from the ith piece of the luminaire surface,
a_i = area of the ith piece of the luminaire surface,
D_i = distance between the ith piece of the luminaire surface and point P,
A = area of the luminaire surface.

Equation 9-15 has wide application for the calculation of illuminance produced by luminaires with nondiffuse distributions.

Flux Transfer Type 6, Nondiffuse Area Source to a Receiving Area. If the nondiffuse emitting surface is specified as A_1 and the receiving surface as A_2, then the flux Φ_2 sent from A_1 to A_2 is

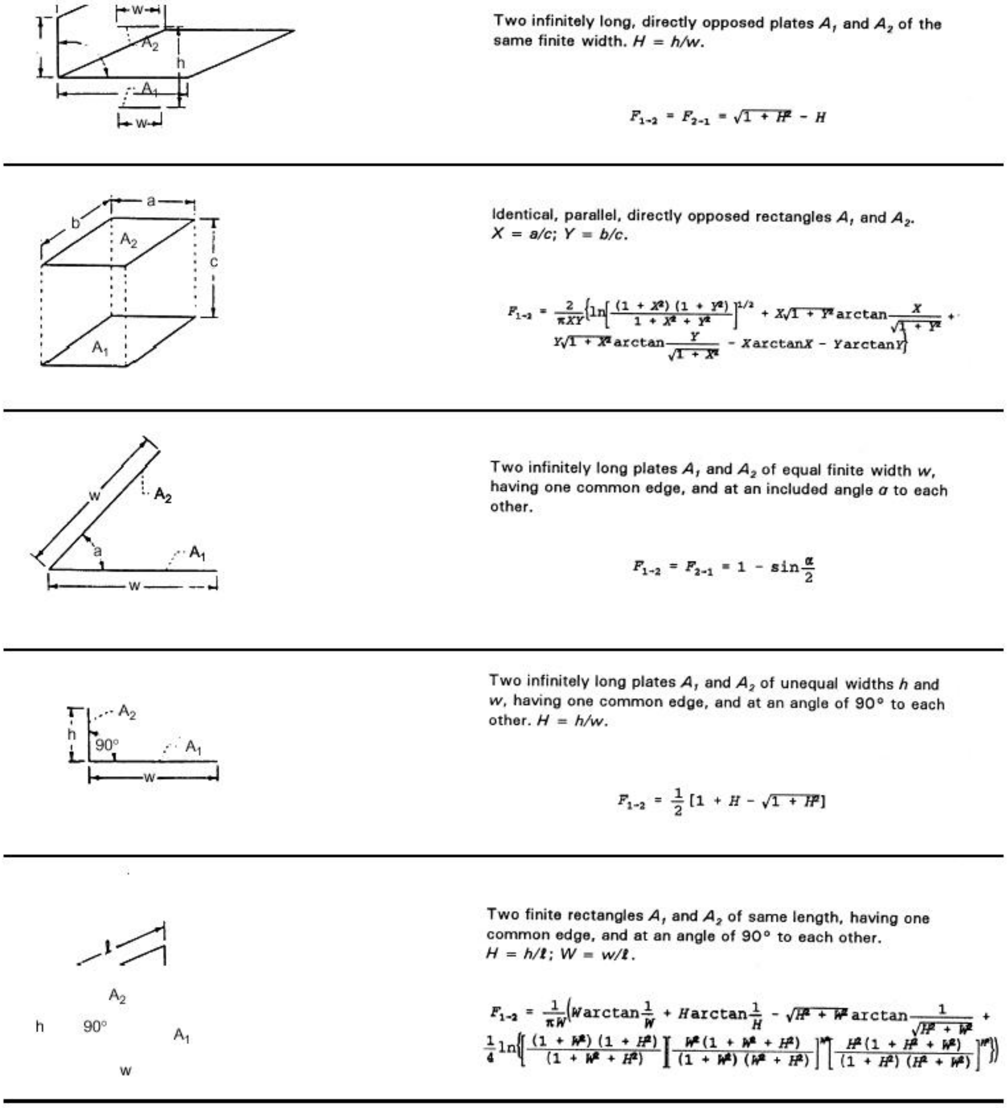
$$\Phi_2 = \int E_{dA_2}\,dA_2$$

where E_{dA2} is the illuminance at element dA_2 from all of source A_1.

Under the same assumption of luminaire homogeneity described above, Equation 9-14 can be used to express E_2:

$$E_2 = \int \frac{1}{A_2} \int \frac{I(\theta, \psi) \cos \xi}{D^2} \, dA_1 dA_2 \qquad (9\text{-}16)$$

The double area integrals usually cannot be evaluated analytically, and a double area summation is used as an approximation. In this case the luminaire and the receiving surface are discretized into small areas. The smaller and more numerous the discrete areas, the more accurate the result:



Two infinitely long, directly opposed plates A_1 and A_2 of the same finite width. $H = h/w$.

$$F_{1-2} = F_{2-1} = \sqrt{1 + H^2} - H$$

Identical, parallel, directly opposed rectangles A_1 and A_2. $X = a/c$; $Y = b/c$.

$$F_{1-2} = \frac{2}{\pi XY}\left\{\ln\left[\frac{(1 + X^2)(1 + Y^2)}{1 + X^2 + Y^2}\right]^{1/2} + X\sqrt{1 + Y^2}\arctan\frac{X}{\sqrt{1 + Y^2}} + Y\sqrt{1 + X^2}\arctan\frac{Y}{\sqrt{1 + X^2}} - X\arctan X - Y\arctan Y\right\}$$

Two infinitely long plates A_1 and A_2 of equal finite width w, having one common edge, and at an included angle α to each other.

$$F_{1-2} = F_{2-1} = 1 - \sin\frac{\alpha}{2}$$

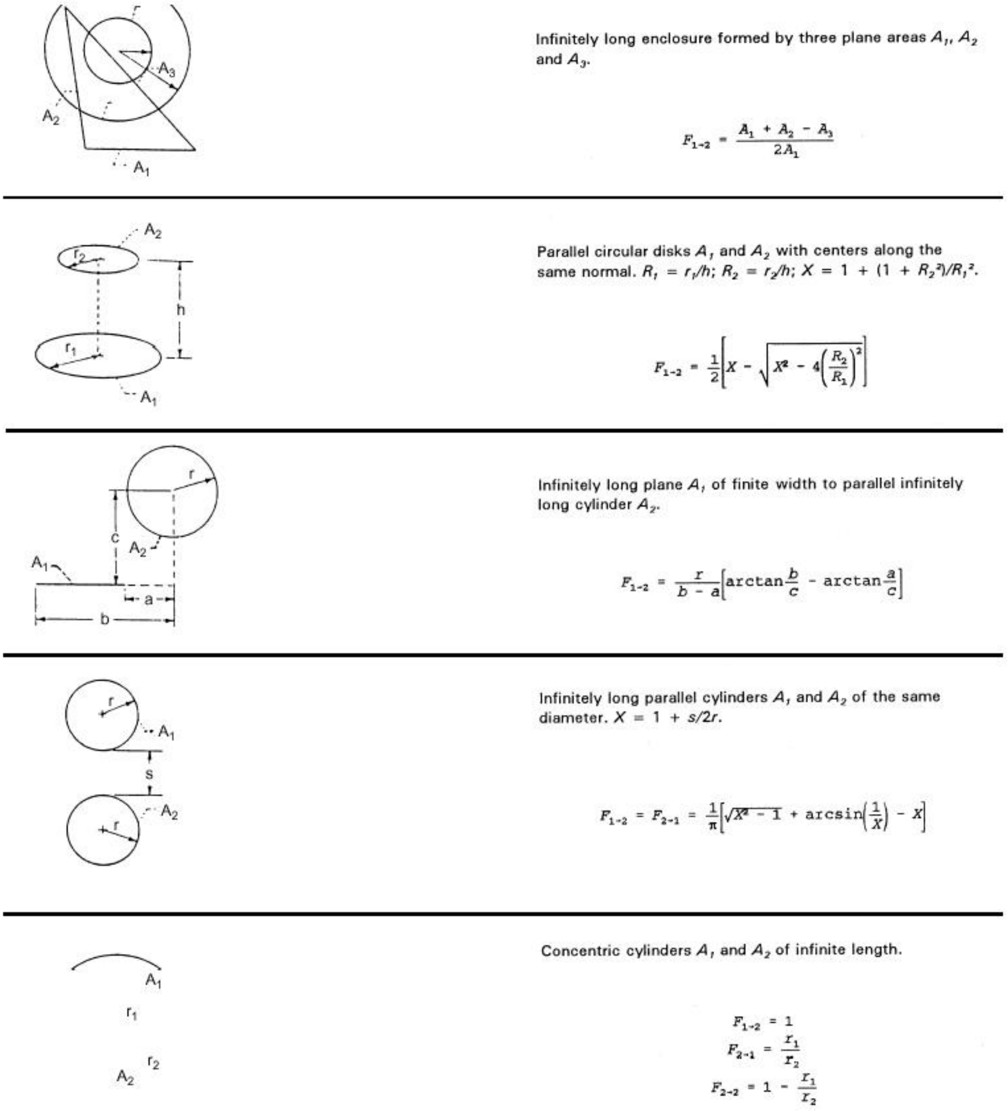
Two infinitely long plates A_1 and A_2 of unequal widths h and w, having one common edge, and at an angle of 90° to each other. $H = h/w$.

$$F_{1-2} = \frac{1}{2}\left[1 + H - \sqrt{1 + H^2}\right]$$

Two finite rectangles A_1 and A_2 of same length, having one common edge, and at an angle of 90° to each other. $H = h/\ell$; $W = w/\ell$.

$$F_{1-2} = \frac{1}{\pi W}\left(W\arctan\frac{1}{W} + H\arctan\frac{1}{H} - \sqrt{H^2 + W^2}\arctan\frac{1}{\sqrt{H^2 + W^2}} + \frac{1}{4}\ln\left\{\left[\frac{(1 + W^2)(1 + H^2)}{(1 + W^2 + H^2)}\right]\left[\frac{W^2(1 + W^2 + H^2)}{(1 + W^2)(W^2 + H^2)}\right]^{W^2}\left[\frac{H^2(1 + H^2 + W^2)}{(1 + H^2)(H^2 + W^2)}\right]^{H^2}\right\}\right)$$

Figure 9-5. *Continued*



Infinitely long enclosure formed by three plane areas A_1, A_2 and A_3.

$$F_{1-2} = \frac{A_1 + A_2 - A_3}{2A_1}$$

Parallel circular disks A_1 and A_2 with centers along the same normal. $R_1 = r_1/h$; $R_2 = r_2/h$; $X = 1 + (1 + R_2^2)/R_1^2$.

$$F_{1-2} = \frac{1}{2}\left[X - \sqrt{X^2 - 4\left(\frac{R_2}{R_1}\right)^2}\right]$$

Infinitely long plane A_1 of finite width to parallel infinitely long cylinder A_2.

$$F_{1-2} = \frac{r}{b-a}\left[\arctan\frac{b}{c} - \arctan\frac{a}{c}\right]$$

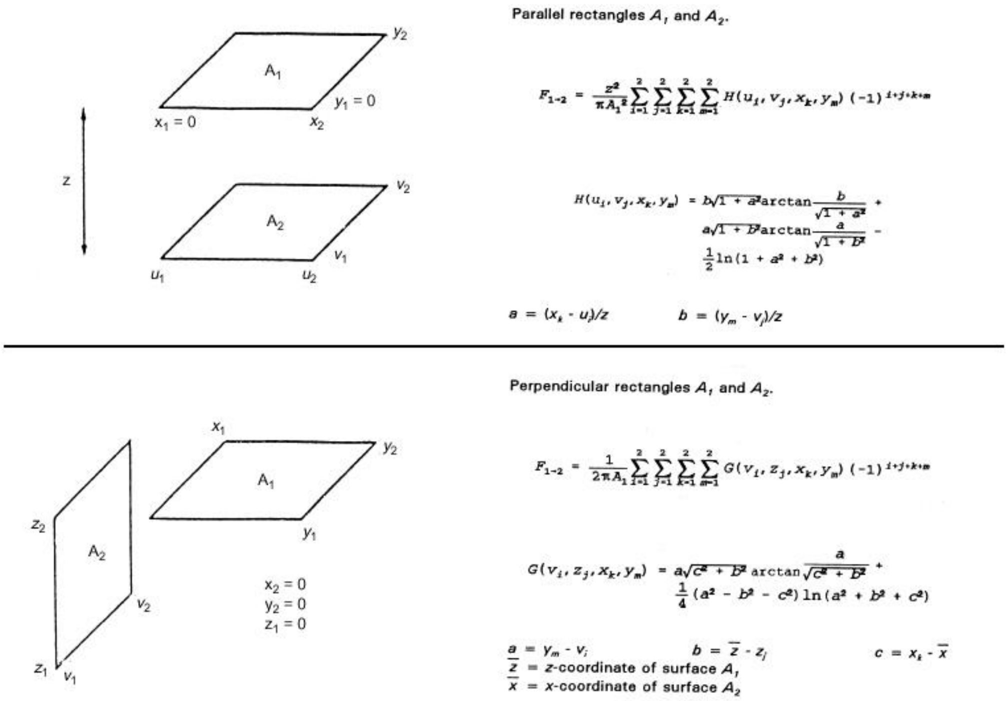
Infinitely long parallel cylinders A_1 and A_2 of the same diameter. $X = 1 + s/2r$.

$$F_{1-2} = F_{2-1} = \frac{1}{\pi}\left[\sqrt{X^2 - 1} + \arcsin\left(\frac{1}{X}\right) - X\right]$$

Concentric cylinders A_1 and A_2 of infinite length.

$$F_{1-2} = 1$$
$$F_{2-1} = \frac{r_1}{r_2}$$
$$F_{2-2} = 1 - \frac{r_1}{r_2}$$

Figure 9-5. Radiative transfer theory form factors (*F*) for diffuse area sources.



Parallel rectangles A_1 and A_2.

$$F_{1-2} = \frac{z^2}{\pi A_1^2}\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2}\sum_{m=1}^{2} H(u_i, v_j, x_k, y_m)\,(-1)^{i+j+k+m}$$

$$\begin{aligned} H(u_i, v_j, x_k, y_m) = {} & b\sqrt{1+a^2}\arctan\frac{b}{\sqrt{1+a^2}} + \\ & a\sqrt{1+b^2}\arctan\frac{a}{\sqrt{1+b^2}} - \\ & \frac{1}{2}\ln(1 + a^2 + b^2) \end{aligned}$$

$a = (x_k - u_i)/z$ $\qquad$ $b = (y_m - v_j)/z$

Perpendicular rectangles A_1 and A_2.

$$F_{1-2} = \frac{1}{2\pi A_1}\sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2}\sum_{m=1}^{2} G(v_i, z_j, x_k, y_m)\,(-1)^{i+j+k+m}$$

$$\begin{aligned} G(v_i, z_j, x_k, y_m) = {} & a\sqrt{c^2+b^2}\arctan\frac{a}{\sqrt{c^2+b^2}} + \\ & \frac{1}{4}(a^2 - b^2 - c^2)\ln(a^2 + b^2 + c^2) \end{aligned}$$

$a = y_m - v_i$ $\qquad$ $b = \overline{z} - z_j$ $\qquad$ $c = x_k - \overline{x}$

$\overline{z}$ = z-coordinate of surface A_1

$\overline{x}$ = x-coordinate of surface A_2

Figure 9-6. General expressions for form factors (*F*) between parallel and perpendicular rectangles.

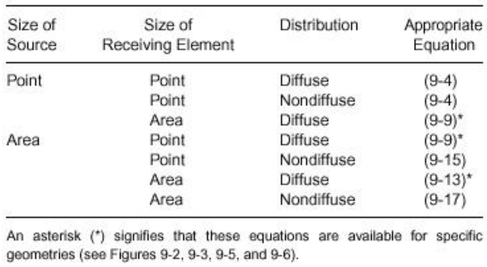
$$E_2 = \frac{1}{A_2} \sum_i \sum_j I(\theta_{ij}, \psi_{ij}) \cos \xi_{ij} \frac{a_{1i} a_{2j}}{D_{ij}^2} \qquad (9\text{-}17)$$

where the summation is over all the discrete pieces of luminaire and the discrete pieces of the receiving surface, and

$I(\theta_{ij}, \psi_{ij})$ = intensity of the *i*th piece of the luminaire in the direction of the *j*th piece of the receiving surface,
ξ_{ij} = incident angle of flux from the *i*th piece of the luminaire,
a_{1i} = area of the *i*th piece of luminaire,
a_{2j} = area of the *j*th piece of the receiving surface,
D_{ij} = distance between the *i*th piece of the luminaire and the *j*th piece of the receiving surface,
A_1 = area of the luminaire surface,
A_2 = area of the receiving surface.

Equation 9-16 can alternatively be evaluated using quasi-Monte Carlo ray casting,[5-7] where the distribution of points that rays are sent from the emitting surface A_1 to the receiving surface A_2 is weighted according to the photometric distribution of the nondiffuse emitting surface.

All of the previous types of analyses are summarized in Figure 9-7. The equation to be used for illuminance calculations is determined by the size of the source, the size of the receiving element, and the nature of the intensity distribution of the source. If the distance between the source and the analysis point is less than five times the largest dimension of the source, the source is considered an area source for the purposes of calculation. This five times rule is discussed in the next section.



Size of Source	Size of Receiving Element	Distribution	Appropriate Equation
Point	Point	Diffuse	(9-4)
	Point	Nondiffuse	(9-4)
	Area	Diffuse	(9-9)*
Area	Point	Diffuse	(9-9)*
	Point	Nondiffuse	(9-15)
	Area	Diffuse	(9-13)*
	Area	Nondiffuse	(9-17)

An asterisk (*) signifies that these equations are available for specific geometries (see Figures 9-2, 9-3, 9-5, and 9-6).

Figure 9-7. Flux Transfer Equations

Photometry as the Basis for Calculations

Intensity distributions are used to specify the spatial distribution characteristics of a light source. This description treats the source as a point and gives the luminous intensity. The set is sufficiently large to provide a complete description of the spatial distribution of flux.

The luminous intensity of a light source or luminaire is calculated from measurements of illuminance. Illuminances are obtained at a convenient measurement distance that defines an imaginary sphere with a radius equal to the measurement distance. The sphere center coincides with a fiducial point inside the luminaire. This so-called photometric center is often the origin of the coordinate system used for calculations.[12]

If the source is assumed to be a point, then the intensity and the illuminance are related by Equation 9-4. If the illuminance measurements are made with the surface normal of the illuminance probe oriented to the photometric center, then the cosine of the viewing angle equals 1 and Equation 9-4 becomes

$$E_t = \frac{I}{D_t^2}$$

or

$$I = E_t D_t^2 \qquad (9\text{-}18)$$

where

I = luminous intensity,
E_t = illuminance measurement,
D_t = measurement (test) distance.

The luminous intensity is distance invariant, since the product $E_t D_t^2$ is distance invariant. Thus, the illuminance at any distance is given by Equation 9-4.

In the photometry of luminaires, Equation 9-18 is generally applied to obtain a relative value of the luminaire's intensity in a particular direction. The magnitude is then determined through photometry of the bare lamps in a procedure known as relative photometry.

Far-Field Photometry

Assuming the luminaire to be a point source permits the illuminance produced under any geometric circumstance to be calculated. The computational value of intensity distributions rests on the assumption that illuminance varies proportionally to the reciprocal of the distance squared and to the cosine of the incident angle.

Only a point light source produces illuminances that always vary as the inverse squared distance. However, regardless of the luminaire size, it is always possible to choose a distance, D_t, sufficiently large so that illuminances produced at distances greater than D_t do vary (nearly) as the inverse squared distance. Yamauti[13] and Fock[14] first showed this for diffuse emitters. For these emitters D_t is five times the maximum dimension of the emitter. This five times rule permits a computational accuracy of at worst 2% for diffuse emitters. In far-field photometry, a distance of at least D_t is used to make the illuminance measurements from which the luminous intensities are calculated. These intensities can then be used to calculate illuminances at distances greater than D_t, treating the luminaire as a point source. Most commercial photometry uses far-field photometry.

Illuminance calculations that assume the luminaire to be a point source at distances less than D_t are likely to be inaccurate. As a guide to the inaccuracies that can be expected, Figure 9-8 shows an illuminance error curve for a square diffuse emitter. The error, in percent of the correct value, is given as a function of the ratio of the calculation distance D to the luminaire dimension. The five times rule requires this ratio to be 5 or larger. Comparison between measurements and predictions using real luminaires gives similar results.[15]

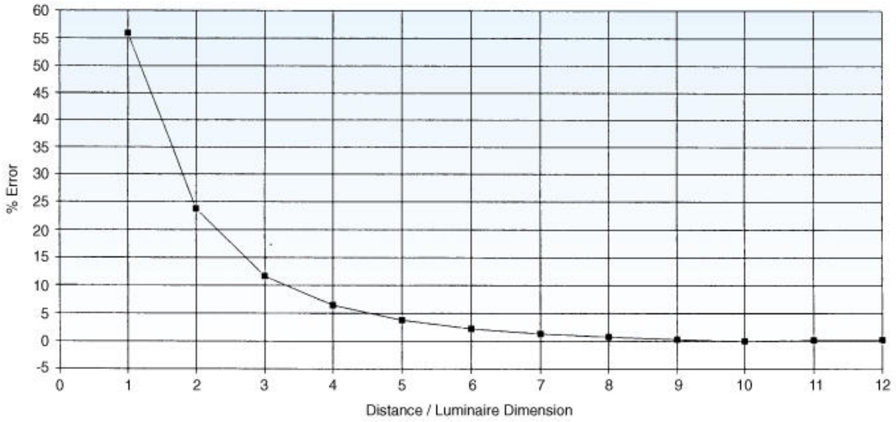


Figure 9-8. Demonstration of the five-times rule for photometric measurements.

It should be noted that intensity distributions other than that of a diffuse emitter have different values of D_t.[16] However, it is customary to apply the five times rule to most indoor luminaire photometry.

Near-Field Photometry

Near-field photometry describes the spatial flux distribution of a luminaire in a manner permitting accurate illuminance calculations at distances less than D_t. Near-field photometry is particularly important for analyzing indirect lighting systems. Two types of near-field photometry have been developed expressly for improving computational accuracy.

Application-distance photometry uses test distances that are equal to the distances at which illuminance calculations are made.[17-19] No assumptions about distance invariance are made. In this case the luminaire must be treated as a point source for calculations. Since illuminance calculations are likely to be made at many distances, application-distance photometry provides intensity distributions for several test distances.

Luminance-field photometry[16,20,21] measures and reports the luminance distribution of the luminaire as viewed from a set of points completely surrounding the luminaire. All points are the same distance from the luminaire photometric center. Precisely stated, the data describe a four-dimensional scalar field of luminance. From these luminance data, illuminance can be calculated at any distance and orientation from the luminaire. Luminance-field photometric measurements can be made using a CCD video camera;[22] however, the quantity of data can be difficult to manage.[23]

Reflection Properties of Surfaces

Useful special cases of reflectance are perfectly diffuse and perfectly specular reflectances. These cases of the spatial distribution permit great simplification of calculations involving the reflection of light from surfaces.

Perfectly diffuse reflection is that for which the luminous intensity in a given direction is proportional to the cosine of the declination angle from the perpendicular to the surface. The flux reflected from a diffuse surface is not a function of the incident direction or the azimuthal angle. Thus, the reflecting surface exhibits a luminance independent of viewing angle.

Perfectly specular reflection is that in which flux is reflected at the mirror angle to the incident direction. That is, the angle of the reflected flux is equal to that of the incident direction with respect to the direction perpendicular to the surface, and the azimuthal separation of the exitant and incident flux is exactly 180°.

Many surfaces and finishes used in architecture exhibit a reflectance that is sufficiently diffuse to be considered perfectly diffuse. This is important for computational purposes, since they can be considered diffuse emitters regardless of the incident direction of the light.

In some cases, assumptions about diffuseness lead to very inaccurate results. An example of this is the calculation of the luminance of visual tasks, such as pencil marks on paper, etched marks on a rule, and roadway surfaces. The bidirectional reflectance distribution function (BRDF) of a surface must be used in these cases.[24]

In addition to simplifying the spatial distribution characteristics of reflectance, it is often permissible (and necessary) to simplify its spectral characteristics. All surfaces exhibit a reflectance that varies with the wavelength of the incident light. The reflectance reported for a particular surface is usually obtained by integrating the proportion of light reflected from the surface at all visible wavelengths. Although the reflectance so defined changes if the spectrum of the illuminant changes, it is a useful approximation to assume that the reflectance is spectrally flat. The surface is assigned a "gray reflectance" equal to the integrated value. Thus, it is assumed that the surface exhibits the same reflectance regardless of the spectral power distribution of incident light used in calculations. This is referred to as the "gray assumption."

Although this simplifies calculations and usually introduces only small errors, difficulties can arise. The reflectance of a surface with a deeply saturated color usually has a significant spectral reflectance only in a narrow band of wavelengths. Use of a light source spectrally different from that used in making a reflectance standard can then lead to large errors.

Interreflection of Light

Some of the light incident on an architectural surface is absorbed, and some is reflected. The reflected portion radiates to other surfaces, where it is absorbed and reflected again. This can be thought of as happening an infinite number of times. The phenomena of repeated exchange of light by multiple reflection is called interreflection.[25-28] Architectural surfaces are made luminous by interreflection, as well as by light that reaches them directly from sources such as luminaires and windows. The exitances that these surfaces exhibit under these circumstances are said to be those at luminous equilibrium. That is, they are the exitances present when the rate at which light is being provided by luminaires and daylighting is balanced by the rate at which it is being absorbed by surfaces. These exitances are called final exitances, in contrast with initial exitances, which are those produced directly by light from luminaires or daylighting, before the process of interreflection.

Surfaces made luminous by interreflections become additional sources of light that should be considered when determining illuminance. The illuminance produced by reflected light is termed the interreflected component. In most architectural settings it is usually assumed that the surfaces involved exhibit a diffuse reflectance and therefore are diffuse emitters. They can then be treated as diffuse area sources, and the illuminance is calculated using the equations for a diffuse area source, involving configuration factors and surface exitance. The total interreflected component at an analysis point is

$$E_{\text{inter}} = \sum_{i=1}^{n} c_{i \to p} M_i \qquad (9\text{-}19)$$

where

$c_{i \to p}$ = configuration factor from surface *i* to point *p*,
M_i = diffuse exitance of surface *i*.

Thus, calculating the interreflected component of illuminance requires the determination of the final exitance of surfaces that are luminous by interreflection.

The most useful calculation procedure for determining the final exitances is the finite-element method.[29-31] The surfaces in the space are discretized, and each element is assumed to have a different but uniform exitance. In most cases it also can be assumed that the reflectances are perfectly diffuse. The accuracy of the calculated luminance pattern depends on the size of the zones and on the degree to which the reflectances are diffuse.

Modeling room surfaces as discrete elements not only allows an approximation to the actual exitance pattern in the room, but such modeling can also represent the effect of doors, windows, bulletin boards, and chalkboards.[29] Since these surfaces generally differ from the walls in reflectance, their exitance is also different, as is their effect on the illuminance within the space.

The degree to which the pattern of exitance in the enclosure is represented by the assemblage of discrete zone exitances depends on the zone size. A highly variable directional component, such as one that can be produced by an indirect lighting or wall-washing system, may require a small discretization of surfaces. This permits an accurate model of the large luminance gradient.

In advanced models, interior obstructions such as partitions, shelves, and furniture can also be considered.[32,33] Other methods have been developed to reduce the amount of work required to solve such systems,[34-36] and approximations for calculations in spaces with interior obstructions have also been developed.[37]

Numerous techniques based on radiative flux transfer theory[5,6] (also known as radiosity methods) and ray tracing[38] have been developed by the computer graphics community. While these techniques have been developed primarily for architectural rendering, they are based on physical principles[5,23] and so can be applied to illumination engineering problems as well.

Radiosity methods model perfectly diffuse reflections, whereas ray tracing techniques are best suited to modeling specular reflections. However, hybrid techniques have been developed to accurately model both diffuse and specular reflections.[23,39,40]

The Radiative Transfer Equation[5-7,10,11,22,23,38-43]

To obtain the equations for calculating interreflection, a flux balance equation is written for each element. It equates the total flux leaving an element to the total incident flux multiplied by the element's reflectance. The total incident flux has both a direct component due to electric and daylight sources and an interreflected component due to the flux from all the other elements. The equality expressing the flux balance exists when all interreflections are taken into account. For the *i*th element of a radiative transfer system, the equation is

$$M_i = M_{0i} + \rho_i(f_{i \to 1} M_1 + f_{i \to 2} M_2 + \ldots + f_{i \to m-1} M_{m-1} + f_{i \to m} M_m) \qquad (9\text{-}20)$$

This can be written for each surface element in the system, and a set of linear, independent, simultaneous equations results. Expressed in matrix form, this gives

$$\begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_m \end{bmatrix} = \begin{bmatrix} M_{01} \\ M_{02} \\ \vdots \\ M_{0m} \end{bmatrix} + \begin{bmatrix} \rho_1 f_{1\to 1} & \rho_1 f_{1\to 2} & \cdots & \rho_1 f_{1\to m-1} & \rho_1 f_{1\to m} \\ \rho_2 f_{2\to 1} & \rho_2 f_{2\to 2} & \cdots & \rho_2 f_{2\to m-1} & \rho_2 f_{2\to m} \\ \vdots & \vdots & & \vdots & \vdots \\ \rho_m f_{m\to 1} & \rho_m f_{m\to 2} & \cdots & \rho_m f_{m\to -1} & \rho_m f_{m\to m} \end{bmatrix} \times \begin{bmatrix} M_1 \\ M_2 \\ \vdots \\ M_m \end{bmatrix} \qquad (9\text{-}21)$$

where

m = number of zones in the system,
M_i = exitance of the *i*th zone, due to direct and interreflected flux (the equation is solved for these values),
ρ_i = diffuse reflectance of the *i*th zone,

M_{0i} = exitance due to the direct component on the *i*th zone (due to luminaires and daylight sources),
$f_{i\rightarrow j}$ = form factor from zone *i* to zone *j* (note that for planar zones, $f_{i\rightarrow i} = 0$).

For simple geometries, the form factors can be computed using the equations found for parallel and orthogonal rectangles in Figures 9-5 and 9-6. For complex geometries, and especially for environments with occluding objects, it is necessary to use numerical integration methods such as hemicubes and Monte Carlo ray casting.

The above matrix equation can be rewritten in terms of the illuminance on each surface. This form is particularly valuable when one or more of the reflectances is assigned a value of zero, since then the illuminance striking each element is independent of the element's reflectance:

$$\begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_m \end{bmatrix} = \begin{bmatrix} E_{01} \\ E_{02} \\ \vdots \\ E_{0m} \end{bmatrix} + \begin{bmatrix} \rho_1 f_{1\rightarrow 1} & \rho_1 f_{1\rightarrow 2} & \cdots & \rho_1 f_{1\rightarrow m-1} & \rho_1 f_{1\rightarrow m} \\ \rho_2 f_{2\rightarrow 1} & \rho_2 f_{2\rightarrow 2} & \cdots & \rho_2 f_{2\rightarrow m-1} & \rho_2 f_{2\rightarrow m} \\ \vdots & \vdots & & \vdots & \vdots \\ \rho_m f_{m\rightarrow 1} & \rho_m f_{m\rightarrow 2} & \cdots & \rho_m f_{m\rightarrow -1} & \rho_m f_{m\rightarrow m} \end{bmatrix} \times \begin{bmatrix} E_1 \\ E_2 \\ \vdots \\ E_m \end{bmatrix} \qquad (9\text{-}22)$$

The simplest way to solve these large matrix finite-element systems is to use the method of iteration.[5,40] The iteration begins by setting the vector *M* equal to the exitance vector M_0 in Equation 9-21, using this as an initial estimate of the system. This initial estimate is then used on the right-hand side of the equation to generate another estimate of the solution vector on the left.

Various iteration methods may be employed. Jacobi iteration exactly simulates physical reflections and absorption of light within an environment.[23] Faster convergence is usually obtained with Gauss-Seidel iteration,[43] typically within five to ten iterations for simple environments with relatively few elements.

Gauss-Seidel iteration has the disadvantage that the entire form factor matrix is required for each iteration. This limits the number of elements that can modeled using computer simulations. A variation of Southwell iteration called progressive refinement[6] is preferred in that only one column of the form factor matrix is required for each iteration. This permits the modeling of complex environments with hundreds of thousands of elements, with convergence attained in a few minutes using desktop computers.[40]

It should be noted that maintained values of the exitance might differ from initial values. Should computation of maintained values be required, the surface reflectances used in the computation of the reflected component should be the reflectances expected under maintained conditions in the environment. Additionally, a light loss factor should be used in the calculation of the initial exitances.

Implementation of the Flux Balance Model

The simplest example of a radiative transfer problem solved by this method is a system with two surfaces. In this case, two equations in two unknowns result. The solution is

$$M_1 = \frac{M_{01} + M_{02}\,\rho_1 f_{1\rightarrow 2}}{1 - \rho_1\,\rho_2 f_{1\rightarrow 2}\, f_{2\rightarrow 1}} \qquad (9\text{-}23a)$$

$$M_2 = \frac{M_{02} + M_{01}\,\rho_2 f_{2\rightarrow 1}}{1 - \rho_1\,\rho_2 f_{1\rightarrow 2}\, f_{2\rightarrow 1}} \qquad (9\text{-}23b)$$

where

M_1 = final exitance of surface 1, taking account of interreflection,
M_2 = final exitance of surface 2, taking account of interreflection,
M_{01} = initial exitance of surface 1,
M_{02} = initial exitance of surface 2,
ρ_1 = diffuse reflectance of surface 1,
ρ_2 = diffuse reflectance of surface 2,
$f_{2\rightarrow 1}$ = form factor from surface 2 to surface 1,
$f_{1\rightarrow 2}$ = form factor from surface 1 to surface 2.

These equations provide a way to estimate the effects of interreflection in situations involving only two surfaces, or where only two elements of a large system participate in interreflection.

Another example of how a simple flux balance model can be applied to the analysis of a lighting system is the three-surface model used in the lumen method (Figure 9-9).[44-46] The geometric arrangement is an empty rectangular room with recessed lighting equipment. The lighting system provides a general uniform illuminance on the workplane. Perfectly diffuse reflectances on all surfaces are assumed, and the same reflectance is assumed for the four wall surfaces. This allows the four walls to be treated as one surface. The average illuminance on the floor is to be calculated.

For the purposes of the finite-element procedure, then, there are three elements or zones in this room: ceiling, walls, and floor. The surfaces have initial exitances M_{0c}, M_{0w}, and M_{0f} respectively. These initial exitances are due to the flux falling on the surfaces from the luminaires within the room.

Since there are interreflections, the final exitances M_c, M_w, and M_f can be expressed as follows:

$$M_c = M_{0c} + \rho c\,(M_w f_{c\to w} + M_f f_{c\to f}) \qquad (9\text{-}24)$$

$$M_w = M_{0w} + \rho_w\,(M_c f_{w\to c} + M_w f_{w\to w} + M_f f_{w\to f}) \qquad (9\text{-}25)$$

$$M_f = M_{0f} + \rho_f (M_c f_{f\to c} + M_w f_{f\to w}) \qquad (9\text{-}26)$$

where

M_c = final ceiling exitance,
M_w = final wall exitance,
M_f = final floor exitance,
M_{0c} = initial ceiling exitance,
M_{0w} = initial wall exitance,
M_{0f} = initial floor exitance,
ρ_f = floor reflectance,
ρ_w = wall reflectance,
ρ_c = ceiling reflectance,
$f_{f\to c}$ = form factor from floor to ceiling,
$f_{f\to w}$ = form factor from floor to walls,
$f_{w\to c}$ = form factor from walls to ceiling,
$f_{w\to w}$ = form factor from walls to walls,
$f_{w\to f}$ = form factor from walls to floor,
$f_{c\to w}$ = form factor from ceiling to walls,
$f_{c\to f}$ = form factor from ceiling to floor.

With these three equations and the form factors, any interior illuminance or exitance can be determined. The above set of simultaneous equations is the basis for generating the tables of the coefficients of utilization, the wall exitance coefficients, and the ceiling cavity exitance coefficients.

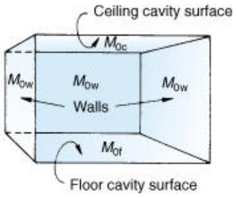


Figure 9-9. Radiative transfer theory diagram.

This simple geometry permits the remaining six form factors to be determined from the form factor, $f_{c\to f}$, between floor and ceiling, using reciprocity and the flux balance requirement (the sum of all form factors leaving a single surface must sum to 1.0 for a closed system).

$$f_{f\to c} = f_{c\to f} \qquad (9\text{-}27)$$

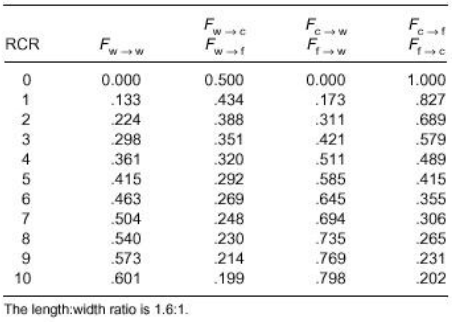
$$f_{c\to w} = f_{f\to w} = 1 - f_{c\to f} \qquad (9\text{-}28)$$

$$f_{w\to c} = f_{w\to f} = \frac{A_c}{A_w}(1 - f_{c\to f}) \qquad (9\text{-}29)$$

$$f_{w\to w} = 1 - 2\,f_{w\to c} \qquad (9\text{-}30)$$

In these equations, A_c and A_w are the surface areas of the ceiling and walls, respectively. This three-surface model is the simplest of all flux transfer models for interior lighting calculations. It assumes that flux strikes each surface in a uniform manner and does not include variations in illuminance across any surface. In accordance with the Commission Internationale de l'Éclairage (CIE) practice and for the lumen method described below, the standard lighting coefficient tables are based upon a length-to-width ratio of 1.6 and given as a function of the room cavity ratio (RCR) only. Figure 9-10 gives numerical values for the various form factors.

The lumen method extends the utility of this three-surface model by letting the ceiling and floor surfaces be virtual surfaces that are actually openings into rectangular cavities. These virtual surfaces are assigned effective reflectances. The top virtual surface is a plane containing the luminaires, and the cavity that this virtual surface represents extends from the luminaires up to the ceiling. The bottom virtual surface is the workplane, and the cavity that this virtual surface represents extends from the workplane down to the floor. Note that the average illuminance onto the workplane is its final exitance divided by its effective reflectance.



RCR	$F_{w \rightarrow w}$	$F_{w \rightarrow c}$ $F_{w \rightarrow f}$	$F_{c \rightarrow w}$ $F_{f \rightarrow w}$	$F_{c \rightarrow f}$ $F_{f \rightarrow c}$
0	0.000	0.500	0.000	1.000
1	.133	.434	.173	.827
2	.224	.388	.311	.689
3	.298	.351	.421	.579
4	.361	.320	.511	.489
5	.415	.292	.585	.415
6	.463	.269	.645	.355
7	.504	.248	.694	.306
8	.540	.230	.735	.265
9	.573	.214	.769	.231
10	.601	.199	.798	.202

The length:width ratio is 1.6:1.

Figure 9-10. Form Factors for a Zonal-Cavity System

Although more complicated, exactly the same procedure can be used for models of radiative transfer in a room that uses more than three surfaces (the finite-element method). Complex models can have thousands of discrete elements as each surface in the room is divided into a collection of smaller zones.[34-36] The result is a more detailed knowledge of the room surface exitance distributions.

Monte Carlo Ray Tracing[7]

One disadvantage of the simple flux balance models is that they can model reflections only from perfectly diffuse surfaces. Although this is adequate for most lighting calculations and architectural renderings, it does not provide sufficient information for estimating veiling reflections from specular surfaces and glare calculations.

Ray tracing techniques provide a more realistic model for the behavior of light, including reflection from specular surfaces and refraction by transparent objects. Reflections from diffuse surfaces can be approximated by reflecting hundreds of rays in random directions from each incident ray.[6] By providing appropriate weights to different directions of ray incidence and reflection, arbitrary bidirectional reflectance distribution functions can also be modeled.

Ray tracing is mathematically equivalent to radiative flux transfer between point emitters and receivers. Whereas evaluation of Equation 9-22 provides estimates for the illuminance of each surface element, Monte Carlo ray tracing provides similar estimates for random points on each surface. Illuminances for surface elements can then be obtained through Monte Carlo integration.

Rays can be traced either from the light sources into the environment (photosimulation)[6,39] or from the observer into the environment (path tracing).[23,38,39] Photosimulation methods are useful in that they provide accurate exitances for all surface elements in the environment. Path tracing methods are useful in that they provide accurate luminances for all surfaces within the observer's field of view, including veiling and specular reflections.

The disadvantage of ray tracing techniques is that millions to hundreds of millions of rays must be evaluated in order to reduce the variance of the solutions to acceptable levels. While various statistical techniques can be used to ensure that randomly chosen ray directions transport on average the maximum amount of flux between surfaces,[6] convergence of the radiative transfer equation using ray tracing techniques is typically slow in comparison to finite element methods.

Lighting Simulation Programs

The radiative transfer equation can be solved using finite element (radiosity) methods, ray tracing techniques, and hybrid approaches. These approaches are collectively referred to as global illumination algorithms by the computer graphics community.[23] Unlike simpler computer graphics techniques, global illumination algorithms are based on physical principles. Because they model the physical behavior of light, they can be used in lighting simulation software programs to create photorealistic architectural renderings and perform sophisticated illumination engineering calculations.

APPLICATION ISSUES

Characterizing Light for Calculation Purposes

Lighting calculations are generally divided into two components for the purpose of determining the amount of light reaching a point in space. The direct component comprises light reaching the point directly from the luminaires or windows. The interreflected component is comprised of light reaching the same point from surfaces due to interreflections.

Direct Component. The direct component must be determined for points of interest on the workplane and for any reflecting surfaces considered in the analysis. The contribution to the reflecting surfaces is used to provide the starting condition for interreflections. On the workplane, the direct component may have special importance because it is the principal component responsible for veiling reflections. Under a typical direct lighting system, the direct component provides the majority of the total illuminance on the workplane. In outdoor lighting situations, the direct component may be the only light that a point receives. The direct component can be determined using the inverse square law or one of the area source methods if the luminaires are large compared to the distances involved. Methods have been developed that take advantage of either special geometries or intensity distributions.[47-51]

Interreflected Component. In most lighting calculations, the interreflected component requires the most time-consuming calculation. The amount of work involved in solving the large matrix problem is proportional to the square of the number of elements involved. To determine the interreflected component, the initial illuminance or direct component must first be determined at each of the discrete elements. In most cases, the value at the center of each element is used as an approximation of the average illuminance across an element. If the elements are sufficiently small, the error involved in this assumption is minimal. Large elements require more careful determinations of the average initial exitance, such as integration methods or calculation of several points to get an average.

Determination of the interreflected component is critical in situations where it is likely to be large relative to the direct component. Situations where this may be true include coves, valences, and indirect lighting applications. It is important that the discretization scheme and calculation model being used for the direct component be capable of providing a light distribution that accurately models that provided by the lighting system.[3,32] Near-field photometry may be required for such calculations.[22,42]

In some cases, a much less rigorous interreflection model may be applied. If the direct component is certain to dominate at the analysis points of interest, it may be possible to use a rather simple interreflected component calculation method involving larger and fewer room surface elements. When using large elements, it is important to remember that the value at the center of a large surface does not necessarily approximate the average across it. The total luminous flux striking the surface should be determined and then divided by the area to determine the average illuminance on the surface.

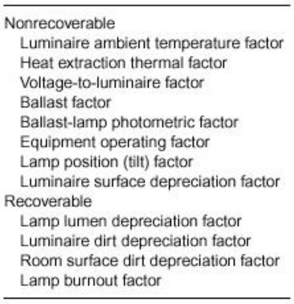
In the simplest approximation, the room is approximated with three surfaces, as used in the lumen method described below, and the interreflected component is calculated using the three surface exitances that result from the lumen method approximation.

Light Loss Factors[52-55]

Light loss factors adjust lighting calculations from a controlled laboratory environment to actual field conditions. They represent differences in lamp lumen output, luminaire output, and surface reflectances between the two sets of conditions. Calculations based on laboratory data alone are likely to provide unrealistically high values if not modified by light loss factors.

Light loss factors are divided into two groups: recoverable and nonrecoverable (Figure 9-11). Recoverable factors are those that can be changed by regular maintenance, such as cleaning and relamping luminaires and cleaning or painting room surfaces. Nonrecoverable factors are those attributed to equipment and site conditions and cannot be changed with normal maintenance.

Light loss factors are assumed to represent independent effects and are therefore multiplicative. The total light loss factor (LLF) is the product of all the applicable factors listed in Figure 9-11. No factor should be ignored (set equal to 1) until investigations justify doing so. Lighting calculations should not be attempted until all light loss factors are considered.


Nonrecoverable
- Luminaire ambient temperature factor
- Heat extraction thermal factor
- Voltage-to-luminaire factor
- Ballast factor
- Ballast-lamp photometric factor
- Equipment operating factor
- Lamp position (tilt) factor
- Luminaire surface depreciation factor

Recoverable
- Lamp lumen depreciation factor
- Luminaire dirt depreciation factor
- Room surface dirt depreciation factor
- Lamp burnout factor

Figure 9-11. Light Loss Factors

Nonrecoverable Factors. The nonrecoverable factors usually are not controlled by lighting maintenance procedures. Some exist initially and continue through the life of the installation, either being of such little effect as to make correction needless, or being too costly to correct. However, all should be studied because they can diminish the planned luminous output of the lighting system.

Luminaire Ambient Temperature Factor. The effect of ambient temperature on the output of some fluorescent lamp luminaires is considerable. Variations in temperature, within the range of those normally encountered in interiors, have little effect on the light output of incandescent and high-intensity discharge lamp luminaires but appreciably affect the light output of fluorescent luminaires. The luminaire ambient temperature factor is the fractional lumen loss of a fluorescent luminaire due to internal luminaire temperatures differing from the temperatures at which photometry was performed. This factor should take into consideration any variation in the temperature around the luminaire, the means and conditions of mounting the luminaire, and the use of any insulation in conjunction with the application of the luminaire.

Generally, firm data on this factor are not available but can be estimated on the following basis. Luminaire photometry is performed in 25° C (77° F) ambient still air. For each degree of rise in ambient temperature above this value, the cold-spot temperature on a fluorescent lamp rises by about 0.6° C (1° F). The effect of lamp temperature rise can be estimated from the manufacturer's literature, recognizing that lamps in luminaires generally operate at temperatures greater than the optimum. Judgment must be applied to factors such as the effect of open versus enclosed luminaires, possible air movement, and the fact that the plenum temperature has a greater effect than the room temperature on recessed luminaires.

Heat Extraction Thermal Factor. Air-handling fluorescent luminaires are integrated with the HVAC system as a means of introducing or removing air. This has an effect on lamp temperature and consequently on lamp lumens. The heat extraction thermal factor is the fractional lumen loss or gain due to the air flow. Generally, manufacturers provide specific luminaire test data for this factor at various air flows. Typically, the factor approaches a constant value for air flows in excess of 10 to 20 ft^3/min through the lamp compartment of a luminaire.

Voltage-To-Luminaire Factor. In-service voltage is difficult to predict, but high or low voltage at the luminaire affects the luminous output of most luminaires. For incandescent units, a 1% voltage deviation causes approximately a 3% change in lumen output. For mercury lamp luminaires with high-reactance ballasts there is a change in lumen output of approximately 3% for each 1% change in primary voltage deviation from rated ballast voltage. When regulated-output ballasts are used, the lamp lumen output is relatively independent of primary voltage within the design range. The luminous output of fluorescent luminaires using conventional magnetic ballasts changes approximately 1% for each 2.5% change in primary voltage. Figure 9-12 shows these variations in graphic form. Different characteristics apply to electronic or energy-saving magnetic ballasts and depend on specific design parameters (see Chapter 6, Light Sources).

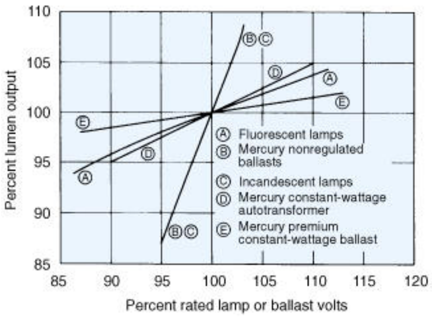


Figure 9-12. Light output change due to voltage change.

Ballast Factor. The lumen output of fluorescent lamps depends on the ballast used to drive the lamps. The lumen output from lamps on commercial ballasts generally differs from that of lamps on the standard reference ballast used for determining rated lumens. For this reason, a multiplicative ballast factor is required to correct nominal rated lamp lumens to actual luminaire performance. The ballast factor is the fractional flux of a fluorescent lamp or lamps operated on the actual ballast divided by the flux when operated on the standard (reference) ballast specified for rating lamp lumens. Ballast factors are determined in accordance with the American National Standard Methods of Measurement of Fluorescent Lamp Ballasts.[56] Manufacturers should be consulted for necessary factors. Data on ballast factors for electronic ballasts are available.[57] Some representative values are shown in Chapter 6, Light Sources. Note that when uncertified ballasts are used, there may be no reliable data available.

The ballast factor depends on the lamp as well as on the ballast, so that a ballast factor developed for a standard lamp does not apply when, for example, an energy-conserving lamp is used, even though the ballast is the same. Magnetic ballasts bearing the label of Certified Ballast Manufacturers (CBM) have a ballast factor that is not less than 0.925 for standard 30- and 40-W rapid start lamps; the ballast factor for such ballasts is frequently estimated at between 0.94 and 0.95. The ballast factor for highly loaded rapid start lamps is 0.95, and for various low-wattage lamps is 0.90.

However, the American National Standards Institute (ANSI)[56] test method for the ballast factor specifies that the test be performed on a cold ballast (for convenience in testing). Significant temperature rise occurs for operating ballasts in luminaires. This causes additional lumen loss, usually on the order of 1.5%, but values as high as 2.5 to 3.5% have been reported. Consequently, a conservative estimate of the operational ballast for a CBM certified ballast would be 0.93.

Ballast-Lamp Photometric Factor. Fluorescent lamp luminaire photometry is performed at a standard ambient temperature of 25° C (77° F). The lamp temperature differs from this value when rated lamp lumens are determined. The consequent lamp lumen change from rated lumens is incorporated into the photometric data. The lamp temperature within the luminaire depends on the particular combination of ballast (standard magnetic, energy-efficient magnetic, or electronic) and lamps (standard loading, reduced-power, and energy-efficient). For this reason the photometric data apply only to the specific lamp and ballast types used in the tests. This also applies to the derived data such as coefficients of utilization and exitance coefficients.

Lamp lumen variations cause a change in the magnitude but not in the spatial distribution of fluorescent luminaire intensity. Consequently, all photometric data can be corrected by a multiplicative factor for ballast and lamp types that differ from those used in the photometric tests. This factor is the ballast-lamp photometric factor, and it is measured for a specific ballast-lamp combination in relation to those used in the luminaire photometry. Values for it are available as part of the luminaire photometric report or from the manufacturer. Note that this factor includes adjustment for lamp and ballast changes at the photometric test temperature of 25° C (77° F). The luminaire ambient temperature factor is a separate correction for differences between the laboratory and the expected luminaire installation temperature.

Equipment Operating Factor. The lumen output of high-intensity discharge (HID) lamps depends on the ballast, the lamp operating position, and the effect of power reflected from the luminaire back onto the lamp. These effects are collectively incorporated in the equipment operating factor (EOF), which is defined as the ratio of the flux of an HID lamp-ballast-luminaire combination, in a given operating position, to the flux of the lamp-luminaire combination operating in the position for rating the lamp lumens and using the standard (reference) ballasting specified for rating lamp lumens. Equipment operating factors are determined in accordance with the IES Approved Method for Determining Luminaire-Lamp-Ballast Combination Operating Factors for High-Intensity Discharge Luminaires.[58]

Lamp Position or Tilt Factor (Part of EOF). For HID lamps, the lamp position factor (sometimes known as the tilt factor) is the ratio of the flux of a HID lamp in a given operating position to the flux when the lamp is operated in the position at which the lamp lumens are rated. This factor is determined at constant lamp wattage and constitutes part of the equipment-operating factor. The lamp position factor is reasonably consistent for mercury lamp types. However, for metal halide lamps it is variable from lamp to lamp and depends on the operating history; thus, it is not actually a constant even for a given lamp.[59,60] Figure 9-13 presents typical average data for the lamp position factor; manufacturers should be consulted regarding specific lamp types.

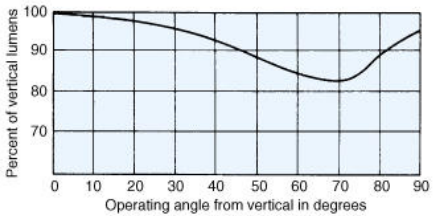


Figure 9-13. Lumen output for HID lamps as a function of operating position.

Luminaire Surface Depreciation Factor. Luminaire surface depreciation results from adverse changes in metal, paint, and plastic components that result in reduced light output. Surfaces of glass, porcelain, or processed aluminum have negligible depreciation and can be restored to original reflectance. Baked enamel and other painted surfaces have a permanent depreciation because all paints are porous to some degree. Among plastics, acrylic is least susceptible to change, but its transmittance may be reduced by use over a period of 15 to 20 years in certain atmospheres. For the same usage, polystyrene has lower transmittance than acrylic and depreciates faster.

Because of the complex relationship between the light-controlling elements of luminaires using more than one type of material (such as a lensed troffer), it is difficult to predict losses due to deterioration of materials. Also, for luminaires with one type of surface, the type of atmosphere in the installation affects the losses. No factors for this effect are available at present.

Recoverable Factors. Recoverable factors always need to be considered in determining the total light loss factor. The magnitude of each depends on the maintenance procedures to be used in addition to the physical environment and the lamps and luminaires to be installed.

Lamp Lumen Depreciation Factor. The lumen outputs of lamps change gradually and continuously over their operating lives, even with constant operating conditions. In almost all cases, the lumens decrease. The lamp lumen depreciation (LLD) factor is the fraction of the initial lumens produced at a specific time during the life of the lamp. Information about LLD as a function of the hours of lamp operation is available from manufacturers' tables and graphs for lumen depreciation and mortality of the chosen lamp. The rated average life should be determined for the expected number of hours per start; it should be known when burnouts begin in the lamp life cycle. From these facts, a practical group relamping cycle can be established, and then, based on the hours elapsed to lamp removal, the LLD factor can be determined. Consult Chapter 6, Light Sources, or manufacturers' data for LLD factors. 70% of average rated life is the recommended criterion for lamp replacement for both group and spot relamping programs. It should be noted that some electronic ballasting systems compensate to varying degrees for change in lamp lumen output through life, either by an average correction or by feedback control.

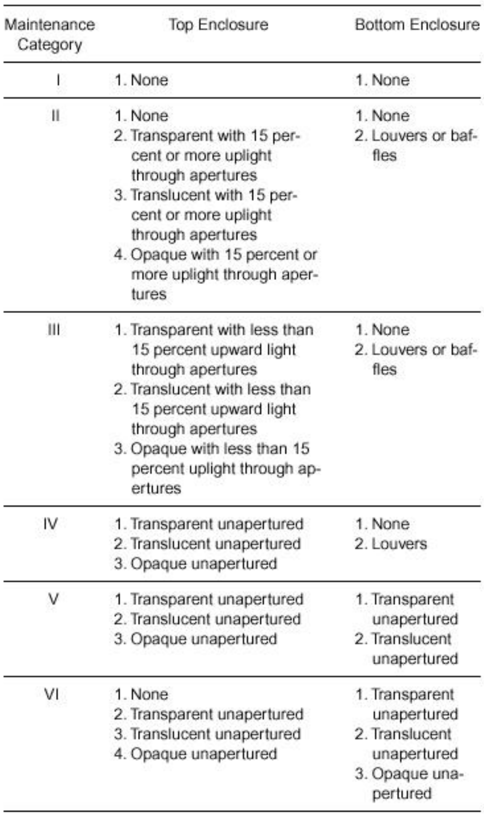
Luminaire Dirt Depreciation Factor. The accumulation of dirt on luminaires results in a loss in light output, and therefore a loss on the workplane. This loss is known as the luminaire dirt depreciation (LDD) factor and is determined as follows:

1. The luminaire maintenance category is selected from manufacturers' data or by using Figure 9-14.

2. The atmosphere (one of five degrees of dirt conditions) in which the luminaire operates is found as follows. Dirt in the atmosphere comes from two sources: that passed from adjacent air, and that generated by work done in the vicinity. Dirt may be classified as adhesive, attracted, or inert, and it may come from intermittent or constant sources. Adhesive dirt clings to luminaire surfaces by its stickiness, whereas attracted dirt is held by electrostatic force. Inert dirt varies in accumulation, from practically nothing on vertical surfaces to as much as a horizontal surface holds before the dirt is dislodged by gravity or air circulation. Examples of adhesive dirt are grease from cooking, particles from machine operation borne by oil vapor, particles borne by water vapor as in a laundry, and fumes from metal-pouring operations or plating tanks. Examples of attracted dirt are hair, lint, fibers, and dry particles that are electrostatically charged from machine operations. Examples of inert dirt are nonsticky, uncharged particles

such as dry flour, sawdust, and fine cinders. Figures 9-15 and 9-16 may be useful for evaluating the atmosphere. Figure 9-16 is intended to evaluate the atmosphere-dirt category. Factors 1 to 5 should be assessed and inserted into the spaces in the table, since they are required to describe the conditions of the space. The "Area Adjacent to Task Area" column represents the area separated from but adjacent to the area in which the luminaire operates (which is the "Area Surrounding Task"). The "Filter Factor" column contains the percentages of dirt allowed to pass from the adjacent atmosphere to the surrounding atmosphere. The "From Adjacent" column indicates the net amount of such dirt that can pass through. This category might include, for example, an open window with a filter factor of 1.0 (no filtering at all), or an air-conditioning system with a filter factor of 0.1 (90% of dirt is filtered out). The total of all the numbers in the "Subtotal" column is a number up to 60 and can be translated into the applicable atmosphere-dirt category listed at the bottom of the table.

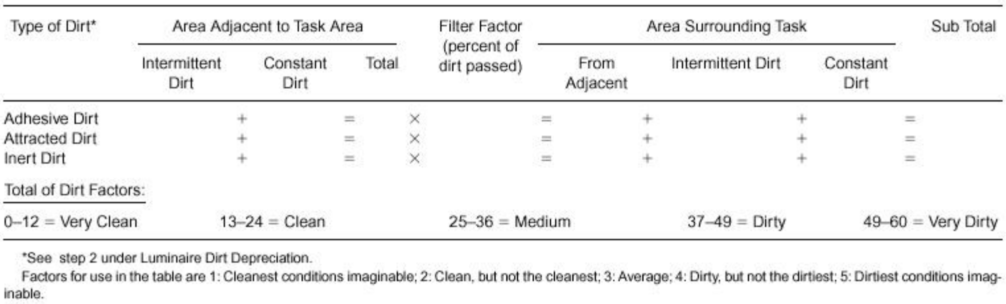
3. From the appropriate luminaire maintenance category curve of Figure 9-17, the applicable dirt condition curve and the proper elapsed time in months of the planned cleaning cycle, the LDD factor is found. For example, if the category is I, the atmosphere is dirty, and cleaning occurs every 20 months, the LDD is approximately 0.80. An alternative procedure to Figure 9-17 is to use the fitted equation



Maintenance Category	Top Enclosure	Bottom Enclosure
I	1. None	1. None
II	1. None 2. Transparent with 15 percent or more uplight through apertures 3. Translucent with 15 percent or more uplight through apertures 4. Opaque with 15 percent or more uplight through apertures	1. None 2. Louvers or baffles
III	1. Transparent with less than 15 percent upward light through apertures 2. Translucent with less than 15 percent upward light through apertures 3. Opaque with less than 15 percent uplight through apertures	1. None 2. Louvers or baffles
IV	1. Transparent unapertured 2. Translucent unapertured 3. Opaque unapertured	1. None 2. Louvers
V	1. Transparent unapertured 2. Translucent unapertured 3. Opaque unapertured	1. Transparent unapertured 2. Translucent unapertured
VI	1. None 2. Transparent unapertured 3. Translucent unapertured 4. Opaque unapertured	1. Transparent unapertured 2. Translucent unapertured 3. Opaque unapertured

To assist in determining Luminaire Dirt Depreciation (LDD) factors, luminaires are separated into six categories (I through VI). To arrive at categories, luminaires are arbitrarily divided into sections, a Top Enclosure and a Bottom Enclosure, by drawing a horizontal line through the light center of the lamp or lamps. The characteristics listed for the enclosures are then selected as best describing the luminaire. Only one characteristic for the top enclosure and one for the bottom enclosure should be used in determining the category of a luminaire. Percentage of uplight is based on 100% for the luminaire. The maintenance category is determined when there are characteristics in both enclosure columns. If a luminaire falls into more than one category, the lower numbered category is used.

Figure 9-14. Procedure for Determining Luminaire Maintenance Categories



Type of Dirt*	Area Adjacent to Task Area			Filter Factor (percent of dirt passed)	Area Surrounding Task			Sub Total
	Intermittent Dirt	Constant Dirt	Total		From Adjacent	Intermittent Dirt	Constant Dirt	
Adhesive Dirt		+	=	×	=	+	+	=
Attracted Dirt		+	=	×	=	+	+	=
Inert Dirt		+	=	×	=	+	+	=

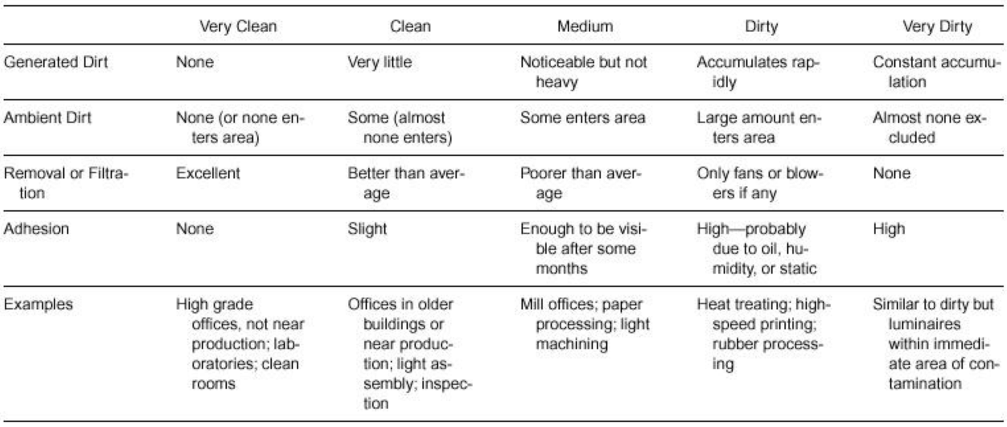
Total of Dirt Factors:

0–12 = Very Clean 13–24 = Clean 25–36 = Medium 37–49 = Dirty 49–60 = Very Dirty

*See step 2 under Luminaire Dirt Depreciation.

Factors for use in the table are 1: Cleanest conditions imaginable; 2: Clean, but not the cleanest; 3: Average; 4: Dirty, but not the dirtiest; 5: Dirtiest conditions imaginable.

Figure 9-15. Evaluation of Operating Atmosphere



	Very Clean	Clean	Medium	Dirty	Very Dirty
Generated Dirt	None	Very little	Noticeable but not heavy	Accumulates rapidly	Constant accumulation
Ambient Dirt	None (or none enters area)	Some (almost none enters)	Some enters area	Large amount enters area	Almost none excluded
Removal or Filtration	Excellent	Better than average	Poorer than average	Only fans or blowers if any	None
Adhesion	None	Slight	Enough to be visible after some months	High—probably due to oil, humidity, or static	High
Examples	High grade offices, not near production; laboratories; clean rooms	Offices in older buildings or near production; light assembly; inspection	Mill offices; paper processing; light machining	Heat treating; high-speed printing; rubber processing	Similar to dirty but luminaires within immediate area of contamination

Figure 9-16. Five Degrees of Dirt Conditions

$$LDD = e^{-At^B} \qquad (9\text{-}31)$$

where the constants *A* and *B* are found from Figure 9-18, based on the luminaire maintenance category and the atmosphere condition involved, and *t* is time in decimal years (e.g., 1 yr 6 mo is entered as 1.5 yr).

Room Surface Dirt Depreciation Factor. The accumulation of dirt on room surfaces reduces the amount of luminous flux reflected and interreflected to the workplane. To take this into account, Figure 9-19 has been developed to provide room surface dirt depreciation (RSDD) factors for use in calculating maintained average illuminance levels. These factors are determined as follows:

1. From one of the five curves in Figure 9-19, find the expected dirt depreciation using Figure 9-15 or 9-16 as a guide to atmospheric dirt conditions, together with an estimate of the time between cleanings. For example, if the atmosphere is dirty and room surfaces are cleaned every 24 months, the expected dirt depreciation is approximately 30%.

2. Knowing the expected dirt depreciation (step 1), the type of luminaire distribution (see Chapter 7, Luminaires) and the room cavity ratio, determine the RSDD factor from Figure 9-19. For example, for a dirt depreciation of 30%, a direct luminaire, and a room cavity ratio (RCR) of 4, the RSDD would be 0.92.

Lamp Burnout Factor. Lamp burnouts contribute to light loss. If lamps are not replaced promptly after burnout, the average illuminance is decreased proportionally. In some instances, more than just the faulty lamp may be lost. For example, when series sequence fluorescent ballasts are used and one lamp fails, both lamps go out. The lamp burnout (LBO) factor is the ratio of the number of lamps remaining lighted to the total, for the maximum number of burnouts permitted.

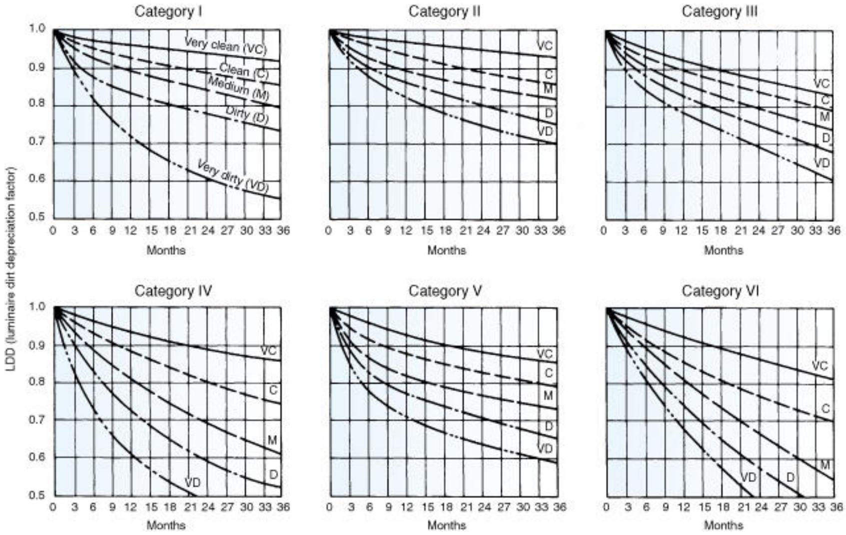
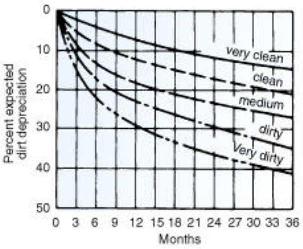


Figure 9-17. Luminaire Dirt Depreciation (LDD) factors for six luminaire categories (I through VI) and for five degrees of dirtiness as determined from Figures 9-14 or 9-15.

Luminaire Maintenance Category	B	A				
		Very Clean	Clean	Medium	Dirty	Very Dirty
I	.69	.038	.071	.111	.162	.301
II	.62	.033	.068	.102	.147	.188
III	.70	.079	.106	.143	.184	.236
IV	.72	.070	.131	.216	.314	.452
V	.53	.078	.128	.190	.249	.321
VI	.88	.076	.145	.218	.284	.396

Figure 9-18. Luminaire Dirt Depreciation Constants Used for Calculating the LDD for Six Luminaire Categories and Five Degrees of Dirtiness



	Luminaire Distribution Type																			
	Direct				Semi-Direct				Direct-Indirect				Semi-Indirect				Indirect			
Percent Expected Dirt Depreciation	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40
Room Cavity Ratio																				
1	.98	.96	.94	.92	.97	.92	.89	.84	.94	.87	.80	.76	.94	.87	.80	.73	.90	.80	.70	.60
2	.98	.96	.94	.92	.96	.92	.88	.83	.94	.87	.80	.75	.94	.87	.79	.72	.90	.80	.69	.59
3	.98	.95	.93	.90	.96	.91	.87	.82	.94	.86	.79	.74	.94	.86	.78	.71	.90	.79	.68	.58
4	.97	.95	.92	.90	.95	.90	.85	.80	.94	.86	.79	.73	.94	.86	.78	.70	.89	.78	.67	.56
5	.97	.94	.91	.89	.94	.90	.84	.79	.93	.86	.78	.72	.93	.86	.77	.69	.89	.78	.66	.55
6	.97	.94	.91	.88	.94	.89	.83	.78	.93	.85	.78	.71	.93	.85	.76	.68	.89	.77	.66	.54
7	.97	.94	.90	.87	.93	.88	.82	.77	.93	.84	.77	.70	.93	.84	.76	.68	.89	.76	.65	.53
8	.96	.93	.89	.86	.93	.87	.81	.75	.93	.84	.76	.69	.93	.84	.76	.68	.88	.76	.64	.52
9	.96	.92	.88	.85	.93	.87	.80	.74	.93	.84	.76	.68	.93	.84	.75	.67	.88	.75	.63	.51
10	.96	.92	.87	.83	.93	.86	.79	.72	.93	.84	.75	.67	.92	.83	.75	.67	.88	.75	.62	.50

Figure 9-19. Room Surface Dirt Depreciation (RSDD) Factors

Manufacturers' mortality statistics should be consulted for the performance of each lamp type to determine the number expected to burn out before the time of planned replacement is reached. In practice, the number of lamp burnouts is a reflection of the quality of the lighting services program.

Total Light Loss Factor. The total light loss factor (LLF) is simply the product of all the contributing factors described above. Where factors are not known, or not applicable, they are assumed to be unity. If the total LLF is excessive, it may be desirable to reselect the luminaire.

STATISTICAL QUANTITIES

When lighting calculations and system modeling are required, it is important that an appropriate method be applied to predict system performance. If an inappropriate model is used, the results can be inaccurate. A designer should therefore have knowledge of the capabilities and limitations of the different modeling options and their applications.

Averages

An average value is the simplest way of specifying the performance of a lighting system. "Average" usually refers to the mean of several calculated or measured values. The greater the number of values, the more accurate the mean. Grids of calculation or measurement points are usually used, often formed by a rectangular array of rows and columns. Point spacing is determined by the accuracy requirements for the average. The accuracy of an average obtained from a calculation or measurement grid can be estimated by doubling the number of points in the grid and determining the size of the change in the average. A large change may indicate the need for more points. This process can be repeated until the change in the average is small enough to indicate that sufficient accuracy has been attained.

An average can be accurate but not indicative of variation in values. For this reason, the average illuminance (or an average of any other quantity) should be used only when the distribution is expected to be relatively uniform across an area. When a localized lighting system is desired, such as for a reception desk in a lobby, bimodal, or multimodal distributions result, and an average-illuminance calculation method should not be used. An average value can be used to design the system for the general circulation space, but for the task area, individual point source calculations should be used to characterize the task lighting.

In general, an average value alone is not sufficient to fully describe or evaluate lighting system performance. Information on the uniformity of the lighting is also important. The following two subsections consider methods for describing the uniformity of lighting across an area.

Minima and Maxima

If a large number of analysis points are used for calculation, then the variability of the lighting can be evaluated and the minimum and maximum values can be determined and located. The minima and maxima can be important indicators of the quality of the design, particularly if they deviate significantly from the desired average. In some design situations, maximum and minimum design values may be specified. In evaluating whether or not a particular design is acceptable, it is important to focus on the critical task areas within a space. Minima often occur around the perimeter of a room or lighted area, where tasks may not be located. Levels below the target level may be acceptable if they are not at actual task locations. In other design situations, the maximum value may be critical. For example, it may not be desirable to have room surface luminances that exceed a particular value. This is the case in the lighting recommendations for spaces with visual display terminals (VDTs).

Uniformity is often expressed in terms of a ratio of two quantities. Examples are maximum to minimum, maximum to average, and average to minimum. Different design situations warrant different uses of these measures.

Criterion Ratings

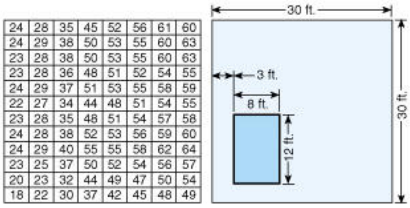
The maximum and minimum values provide little information about the overall distribution of a particular photometric or derived quantity across a space. The criterion rating is a convenient way to obtain greater detail regarding the distribution of a quantity across a space. The criterion rating is the probability that a specific criterion is met or exceeded anywhere within a defined area. It can be used in addition to (or instead of) concepts such as averages and minimum and maximum levels. Lighting criteria to which this technique may be applied include luminance, illuminance, visual comfort probability (VCP), contrast, visibility metrics, and visual performance metrics.

The criterion rating assumes the name of the criterion being rated. For example, the criterion rating for illuminance is called the illuminance rating; for VCP, the VCP rating. Assume, for example, that an illuminance of 500 lx has been established as the design criterion for a space. The illuminance rating defines the likelihood that the illuminance is equal to or greater than 500 lx at any point on the workplane. This criterion rating is determined by evaluating the appropriate quantity (by calculation or measurement) at a grid of points covering the area in question. The distance between evaluation points must not exceed one-fifth the distance from any luminaire to the evaluation plane. The percentage of points that comply with the criterion is the criterion rating:

$$\text{criterion rating} = \frac{(\text{number of points satisfying criterion}) \times 100\%}{\text{number of points computed or measured}} \qquad (9\text{-}32)$$

Criterion ratings may be expressed using a notation that lists the rating, in percent, followed by the criterion, separated by the symbol @, which stands for "at." For example, a lighting system producing a luminance of 20 cd/m^2 over 60% of the specified area may have its luminance rating expressed as 60%@20 cd/m^2. For dimensionless criteria, such as contrast and VCP, the shorthand form for the criterion rating must include the name and value of the criteria; for example, 92%@70 VCP means 92% of the area has a VCP of 70 or better. The designer determines the desired coverage area for a particular criterion value.

As an example of the use of the criterion rating technique (using the foot as the unit of length), consider a square room 30 ft on a side, as shown in Figure 9-20, with an 8-ft ceiling height, a 3-ft-high workplane, and recessed luminaires. The tabulated values in Figure 9-20 are calculated illuminances in the 8×12-ft shaded area. The required illuminance is 50 fc in the shaded area. The distance from the workplane to the luminaires is 5 ft (8 ft-3 ft). Thus, the distance between rows and columns of analysis points must be no greater than 1 ft (5 ft/5). To determine the criterion rating, the calculated illuminance values are examined for criterion compliance. It is found that 47 of the 96 locations receive an illuminance of 50 fc or more. The illuminance rating of this lighting system for the shaded area is then 48.9% [(47/96)×100%]. This can be expressed as 48.9%@50 fc.



24	28	35	45	52	56	61	60
24	29	38	50	53	55	60	63
23	28	38	50	53	55	60	63
23	28	36	48	51	52	54	55
24	29	37	51	53	55	58	59
22	27	34	44	48	51	54	55
23	28	35	48	51	54	57	58
24	28	38	52	53	56	59	60
24	29	40	55	55	58	62	64
23	25	37	50	52	54	56	57
20	23	32	44	49	47	50	54
18	22	30	37	42	45	48	49

Figure 9-20. Example of criterion rating technique. The numbers in the grid represent the calculated illuminances, in fc, in the center of each ft^2 of the shaded portion of the work plane.

CALCULATION OF BASIC QUANTITIES

Illuminance

Illuminance is one of the fundamental quantities used in designing and evaluating lighting systems. To determine the direct illuminance at a point on an area, one must determine that either a point or an area source method is applicable to the situation. To obtain the total illuminance at any point or on any surface, the interreflected component must be appropriately determined and added to the direct component (see Examples 2, 3, and 4 in the section "Examples of Basic Lighting Calculations," in this chapter).

Luminance

As a primary visual stimulus, luminance is the most important and useful calculated quantity. One of the most common situations in which luminance must be calculated is for the evaluation of visual tasks, such as for print on paper. Methods for evaluating the visual performance or visibility of a task require a value for the task contrast, size and adaptation luminance. The luminances of both the task (L_t) and the background (L_b) are needed to determine the task contrast. The quantities L_t and L_b are specific to a particular task location, lighting condition, and viewer orientation (see Examples 6 and 7 in the section Examples of Basic Lighting Calculations, in this chapter).

Luminance calculations are performed whenever it is necessary to calculate the luminance of a surface that exhibits a directionally sensitive reflectance. A calculation model that computes luminance should be able to predict the luminance at any point. Although it is not required that any given method be able to take all possible ranges of the following nine parameters into account, any restrictions that the method imposes should be adequately noted. Because of the complexity involved in calculating luminance, this calculation is generally performed on a computer.

- Room size and shape
- Room surface reflectances
- Luminaire characteristics
- Number and location of luminaires
- Nature of the given surface
- Observer location, line of sight, and viewing angle
- Nature and luminance of all other surfaces in the environment
- Body shadow effects
- Polarization effects

The luminance at a particular location in a luminous environment is given by

$$L = \int dE(\theta, \psi) f_r(\theta, \psi) \qquad (9\text{-}33)$$

where

L = luminance at a point on a surface in a particular viewing direction,
θ,ψ = spherical coordinates, declination, and azimuth, respectively,
$dE(\theta,\psi)$ = differential amount of illuminance at the point in the plane of the surface from a direction indicated by (θ,ψ),
$f_r(\theta,\psi)$ = bidirectional reflectance distribution function (BRDF) of the surface material for a particular viewing direction.

Figure 9-21 indicates the necessary coordinates. This expression represents the total effect of all components of illuminance multiplied by the appropriate BRDF to give the luminance of the surface. The BRDF is dependent on the surface reflectance characteristics, the viewing angle, and the size of the light source used to measure it.

It should be noted that unlike perfectly diffuse reflectances, the BRDF is sensitive to both incident light and viewing directions. This can be expressed as

$$f_r(\theta_v,\psi_v,\theta_i,\psi_i)$$

where the subscript i represents the incident direction and subscript v the viewing direction. In many cases only the difference in azimuthal angle between the incident and exitant directions is required. Then the specification of the BRDF becomes

$$f_r(\theta_v;\theta_i,\psi_i)$$

where ψ_i is the difference in azimuthal angle between the incident and exitant directions. This simplification is not possible for non-axially-isotropic materials such as brushed metal surfaces. In such cases, the azimuthal incident and viewing angles cannot be made relative but must have a fixed orientation with respect to the surface. For many surfaces, however, the simplification can be made and the equation for luminance becomes

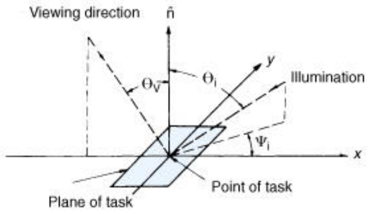


Figure 9-21. Task and illumination coordinates.

$$L(\theta_v) = \int dE(\theta_i, \psi_i) f_r(\theta_v; \theta_i, \psi_i) \qquad (9\text{-}34)$$

The viewing angle θ_v is normally held constant.

Some surfaces exhibit sensitivity to polarization. It is then possible to separate the BRDF into two orthogonal components associated with orthogonal planes of polarization (p_1 and p_2). The BRDFs are

$$f_{rp_1}(\theta_v;\theta_i,\psi_i)$$
$$f_{rp_2}(\theta_v;\theta_i,\psi_i)$$

In a complementary fashion, two orthogonal components of the illuminance can be considered separately, and are indicated by dE_{p1} and dE_{p2}. This gives

$$\begin{aligned} L(\theta_v) = \int [&dE_{p_1}(\theta_i, \psi_i) f_{rp_1}(\theta_v; \theta_i, \psi_i) \\ &+ dE_{p_2}(\theta_i, \psi_i) f_{rp_2}(\theta_v; \theta_i, \psi_i)] \qquad (9\text{-}35)\end{aligned}$$

The expression for L is general and applicable to all situations. Since the illuminance values and luminance factors must be expressed as analytic functions in order to attempt integration of these expressions, there can be, in general, no closed-form analytic expression for L. Approximation by the method of finite elements allows an evaluation of the equation. The BRDFs now take the form of a set of discrete values that sample the continuous BRDF. The resulting approximation is

$$\begin{aligned} L(\theta_v) \approx \sum [&\Delta E_{p_1}(\theta_i, \psi_i) f_{rp_1}(\theta_v;\theta_i,\psi_i) \\ &+ \Delta E_{p_2}(\theta_i, \psi_i) f_{rp_2}(\theta_v; \theta_i, \psi_i)] \qquad (9\text{-}36)\end{aligned}$$

The sum is taken over all the discrete values of illuminance. The number of discrete steps determines the accuracy of the approximation. The step size in these approximations is determined by the need to model high gradients of either the illuminance or the BRDFs. In the case of calculations of luminance for visual tasks, a modification can be applied to the BRDF to take account of a body shadow.

Exitance

If room surfaces are considered to be lambertian, then the exitances of discrete elements can be found using a flux transfer model described above. Exitance distributions across a room surface can be determined at an array of points that cover it, using lighting analysis software. For rooms with a uniform lighting system, average room surface exitances can be determined using the lumen method (see Example 5 in "Examples of Basic Lighting Calculations," in this chapter).

CALCULATION OF DERIVED QUANTITIES

From the photometric quantities--illuminance, luminance, and exitance--it is possible to calculate other quantities that characterize how the human visual system interprets or is affected by a visual scene. This section discusses a number of different quantities of this type and provides equations or references for use in their computation.

Contrast

Contrast represents the difference in luminance between the task detail and its background relative to the luminance of the background or the luminances in the visual scene. There are three different formulas for computing contrast, each of which providing a slightly different answer. See Chapter 3, Vision and Perception, for definitions. See also Example 7 in "Examples of Basic Lighting Calculations," in this chapter.

Visual Performance and Visibility Metrics

Relative visual performance (RVP) and equivalent sphere illumination (ESI) are metrics for the evaluation of visual performance and visibility, respectively. The calculation of these quantities requires the determination of the task and background luminances (to obtain the task contrast). The task size and adaptation luminance are also needed. The equations needed to compute these quantities are provided in the references for Chapter 3, Vision and Perception, where they are discussed in more detail.

Visual Comfort Probability (VCP)

Discomfort glare is the sensation of discomfort caused by luminances that are high relative to the average luminance in the field of view. The visual comfort probability (VCP) is the probability that a normal observer does not experience discomfort when viewing a lighting system under defined conditions.

Equations for the calculation of the VCP are derived from correlating photometric and geometric characteristics of simple lighting patterns with discomfort glare assessments of observers.[61-68] Experiments in simulated rooms have been used to confirm the extension from the laboratory to actual lighting installations.[69,70] This system was tested and validated using lensed direct fluorescent systems only. VCP should not be applied to very small sources such as incandescent and high-intensity discharge luminaires, to very large sources such as ceiling and indirect systems, or to nonuniform sources such as parabolic reflectors.

To calculate the VCP[71-81] several intermediate calculations must first be performed. The position index of a source, *P*, is an inverse measure of the relative sensitivity to a glare source at different positions throughout the field of view. Selected values or families of curves were published in early references. *P* is given by the formula[79]

$$P = \exp[(35.2 - 0.31889\alpha - 1.22e^{-2\alpha/9})10^{-3}\,\beta + (21 + 0.26667\alpha - 0.002963\alpha^2)10^{-5}\,\beta^2] \qquad (9\text{-}40)$$

where

α = angle from vertical of the plane containing the source and the line of sight (Figure 9-22), in degrees,
β = angle between the line of sight and the line from the observer to the source.

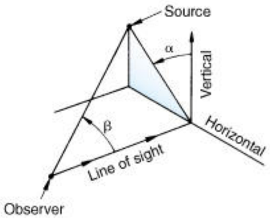


Figure 9-22. Geometry defining position index as used in VCP calculations.

The average luminance for the entire field of view, F_v, is approximated by the following equation:

$$F_v = L_w\omega_w + L_f\omega_f + L_c\omega_c + \sum L_s\omega_s \qquad (9\text{-}41)$$

where

L_w = average luminance of the walls in cd/m^2,
L_f = average luminance of the floor in cd/m^2,
L_c = average luminance of the ceiling in cd/m^2,
L_s = average luminance of the source in cd/m^2,
ω_w = solid angle subtended at the observer by the walls in sr,
ω_f = solid angle subtended at the observer by the floor in sr,
ω_c = solid angle subtended at the observer by the ceiling in sr,
ω_s = solid angle subtended at the observer by the source in sr.

The 5 in the denominator arises from the assumption that the total field of view is 5 sr.[79]

A function Q has been developed for use in the calculation of the VCP. This function is given by

$$Q = 20.4\omega_s + 1.52\omega_s^{0.2} - 0.075 \qquad (9\text{-}42)$$

where ω_s is the solid angle subtended at the observer by the source, in steradians. The values of P, F_v, and Q are used to determine the index of sensation, M:

$$M = \frac{0.50 L_s Q}{P F_v^{0.44}} \qquad (9\text{-}43)$$

The luminance in the above equation is expressed in cd/m^2. The factor 0.50 in the numerator allows for the use of these units.

From the index of sensation of each source, a discomfort glare rating (DGR) can be calculated for the full field of view. The DGR is a metric of discomfort that increases as discomfort increases; it is also used in calculating the VCP. It is given by

$$\mathrm{DGR} = \left(\sum_{i=1}^{n} M_i \right)^{n^{-0.0914}} \qquad (9\text{-}44)$$

where

n = number of sources in the field of view,
M_i = index of sensation for the ith source.

The relation between DGR and VCP may be found from a graph such as Figure 9-23 or may be calculated by[80]

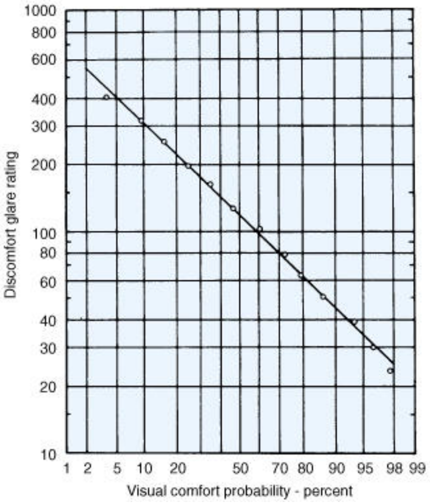


Figure 9-23. A chart for converting discomfort glare ratings (DGR) to VCP (the percentage of observers expected to judge a given lighting condition to be either comfortable or at the borderline between comfort and discomfort).

$$\mathrm{VCP} = \frac{100}{\sqrt{2\pi}} \int_{-\infty}^{6.374 - 1.3227 \ln \mathrm{DGR}} e^{-t^2/2} dt \qquad (9\text{-}45)$$

These basic relations may be applied through a variety of techniques. Generally, the room cavity concept is used, in which the actual ceiling and floor luminances and solid angles are replaced by their equivalent cavity values. The computation can be performed by summing throughout the enclosure.[81]

VCP values are frequently associated with luminaires under standardized conditions of use. In this method, the luminaires are fractionally apportioned over the ceiling according to a standard scheme. VCP values are determined for:[71,74,76]

1. An initial average horizontal illuminance of 1000 lx (100 fc)
2. Room reflectances of $\rho_{CC} = 0.80$, $\rho_W = 0.50$, and $\rho_{FC} = 0.20$
3. Luminaire mounting heights above the floor of 2.6, 3, 4, and 4.9 m (8.5, 10, 13, and 16 ft)
4. A (given) range of room dimensions including square, long narrow, and short wide rooms
5. An observation point 1.2 m (4 ft) in front of the center of the rear wall and 1.2 m (4 ft) above the floor
6. A horizontal line of sight, directly forward
7. An upward limit to the field of view corresponding to an angle of 53° above and directly forward from the observer

There are two objectives in applying the standardized procedure. First, it simplifies calculations by permitting organization of various procedural steps. Second, it allows comparisons between those luminaires for which the standardized values have been tabulated even before a specific lighting layout has been made. Figure 9-24 illustrates a typical tabulation of visual comfort probabilities as developed by the standardized procedure.

Unified Glare Rating (UGR)

The CIE has recently developed a unified glare rating (UGR) system. This system is intended for discomfort glare prediction and is likely to be adopted by many nations. The IESNA is currently considering UGR for future recommendations. UGR is calculated from

$$\mathrm{UGR} = 8 \log_{10} \left(\frac{0.25}{L_b} \right) \sum_i \frac{L_i^2 \omega_i}{P_i^2}$$

where

L_b = luminance of the field of view, in cd/m^2, not including luminaire luminance,
L = luminance of a luminaire in the direction of the observer,
ω = solid angle of a luminaire subtended to the observer,
P = position index of luminaire.

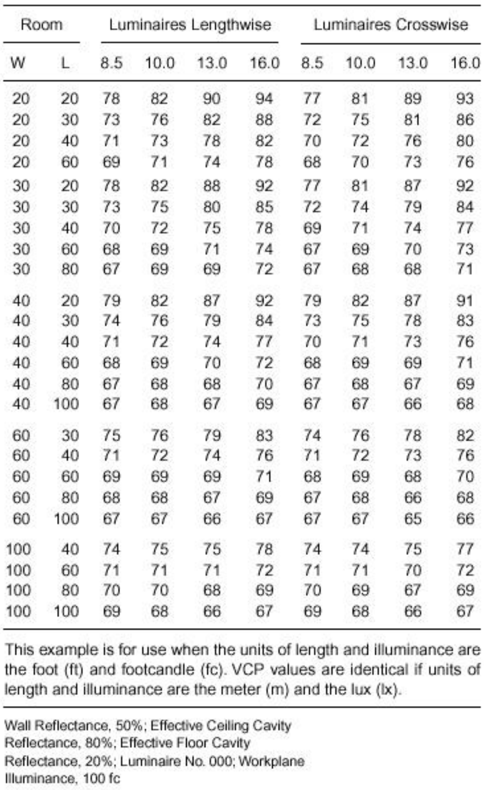
This formula is limited to those situations where $0.0003 \leq \omega \leq 0.1$. Values of UGR range from 5 to 30, with higher numbers indicating greater discomfort glare.

Average Illuminance Calculation: The Lumen Method

The lumen method is used in calculating the average illuminance $\bar{E}$ on the workplane in an interior. This is defined as

$$\bar{E} = \frac{\text{total flux onto workplane}}{\text{workplane area}} \qquad (9\text{-}46)$$

A coefficient of utilization (CU) gives the fraction of lamp lumens that reach the workplane, directly from sources and from interreflections. The CU takes into account the efficiency of the luminaire and the impact of the luminaire distribution and the room surfaces in its derivation. Thus the number of lumens produced by the lamps, multiplied by this CU, determines the number that reaches the workplane:



Room		Luminaires Lengthwise				Luminaires Crosswise			
W	L	8.5	10.0	13.0	16.0	8.5	10.0	13.0	16.0
20	20	78	82	90	94	77	81	89	93
20	30	73	76	82	88	72	75	81	86
20	40	71	73	78	82	70	72	76	80
20	60	69	71	74	78	68	70	73	76
30	20	78	82	88	92	77	81	87	92
30	30	73	75	80	85	72	74	79	84
30	40	70	72	75	78	69	71	74	77
30	60	68	69	71	74	67	69	70	73
30	80	67	69	69	72	67	68	68	71
40	20	79	82	87	92	79	82	87	91
40	30	74	76	79	84	73	75	78	83
40	40	71	72	74	77	70	71	73	76
40	60	68	69	70	72	68	69	69	71
40	80	67	68	68	70	67	68	67	69
40	100	67	68	67	69	67	67	66	68
60	30	75	76	79	83	74	76	78	82
60	40	71	72	74	76	71	72	73	76
60	60	69	69	69	71	68	69	68	70
60	80	68	68	67	69	67	68	66	68
60	100	67	67	66	67	67	67	65	66
100	40	74	75	75	78	74	74	75	77
100	60	71	71	71	72	71	71	70	72
100	80	70	70	68	69	70	69	67	69
100	100	69	68	66	67	69	68	66	67

This example is for use when the units of length and illuminance are the foot (ft) and footcandle (fc). VCP values are identical if units of length and illuminance are the meter (m) and the lux (lx).

Wall Reflectance, 50%; Effective Ceiling Cavity Reflectance, 80%; Effective Floor Cavity Reflectance, 20%; Luminaire No. 000; Workplane Illuminance, 100 fc

Figure 9-24. Example of a Tabulation of VCP Values

$$\bar{E}_{\text{initial}} = \frac{(\text{total lamp lumens}) \times \text{CU}}{\text{workplane area}} \qquad (9\text{-}47)$$

Since the design objective usually is maintained illuminance, a light loss factor must be applied to allow for the estimated depreciation in lamp lumens over time, the estimated losses from dirt collection on the luminaire surfaces (including lamps), and other factors that affect luminaire lumen output over time. The formula thus becomes

$$\bar{E}_{\text{maintained}} = \frac{(\text{total lamp lumens}) \times \text{CU} \times \text{LLF}}{\text{workplane area}} \qquad (9\text{-}48)$$

where

CU = coefficient of utilization,
LLF = light loss factor.

Although design calculations are based on the LLF using both nonrecoverable and recoverable factors, it is sometimes necessary to calculate illuminance in a new lighting installation. In such cases, repeat the calculation using the nonrecoverable losses, since the recoverable losses do not occur at 100 hours, the time at which lamps are nominally at rated lumens.

The lamp lumens in the formula are most conveniently taken as the total rated lamp lumens in the luminaires:

$$\bar{E}_{\text{maintained}} = \frac{(\text{number of luminaires}) \times (\text{lamps per luminaire}) \times (\text{lamp lumens}) \times \text{CU} \times \text{LLF}}{\text{workplane area}} \qquad (9\text{-}49)$$

If the desired maintained illuminance is known, this equation can be solved for the total number of luminaires needed:

$$\text{number of luminaires} = \frac{\bar{E}_{\text{maintained}} \times (\text{workplane area})}{(\text{lamps per luminaire}) \times (\text{lamp lumens}) \times \text{CU} \times \text{LLF}} \qquad (9\text{-}50)$$

For a typical form for calculating illuminance, see Figure 9-25.

Limitations. The illuminance computed by the lumen method is an average value that is representative only if the luminaires are spaced to obtain reasonably uniform illuminance. The calculation of the coefficients of utilization is based on empty interiors having surfaces that exhibit perfectly diffuse reflectance. The average illuminance determined by the lumen method is defined to be the total lumens reaching the workplane divided by the area of the workplane. The average value determined this way might vary considerably from that obtained by averaging discrete values of illuminance at several points.

Calculation Procedure. Figure 9-25 provides a procedure for calculating average maintained illuminance using the zonal-cavity method.[44-46]

Cavity Ratios. The radiative exchange between the top and the base of a rectangular space is a function of the proportions of its length, width, and height. Cavity ratio values approximate this effect by combining these proportions into a single quantity.

In the zonal-cavity method, the effects of room proportions, luminaire suspension length, and workplane height upon the coefficient of utilization are respectively represented by the room cavity ratio, ceiling cavity ratio, and floor cavity ratio. These ratios are determined by dividing the room into three cavities, as shown by Figure 9-26, and substituting dimensions (in m or ft) into the following formula:

$$\text{cavity ratio} = \frac{5h(\text{cavity length} + \text{cavity width})}{\text{cavity length} \times \text{cavity width}} \qquad (9\text{-}51)$$

where

$$h = \begin{cases} h_{\text{RC}} \text{ for the room cavity ratio (RCR)} \\ h_{\text{CC}} \text{ for the ceiling cavity ratio (CCR)} \\ h_{\text{FC}} \text{ for the floor cavity ratio (FCR)} \end{cases}$$

The illuminance in rooms of irregular shape can be determined by calculating the room cavity ratio using the following formula and solving the problem in the usual manner:

$$\text{cavity ratio} = \frac{2.5 \times (\text{cavity height}) \times (\text{cavity perimeter})}{\text{area of cavity base}} \qquad (9\text{-}52)$$

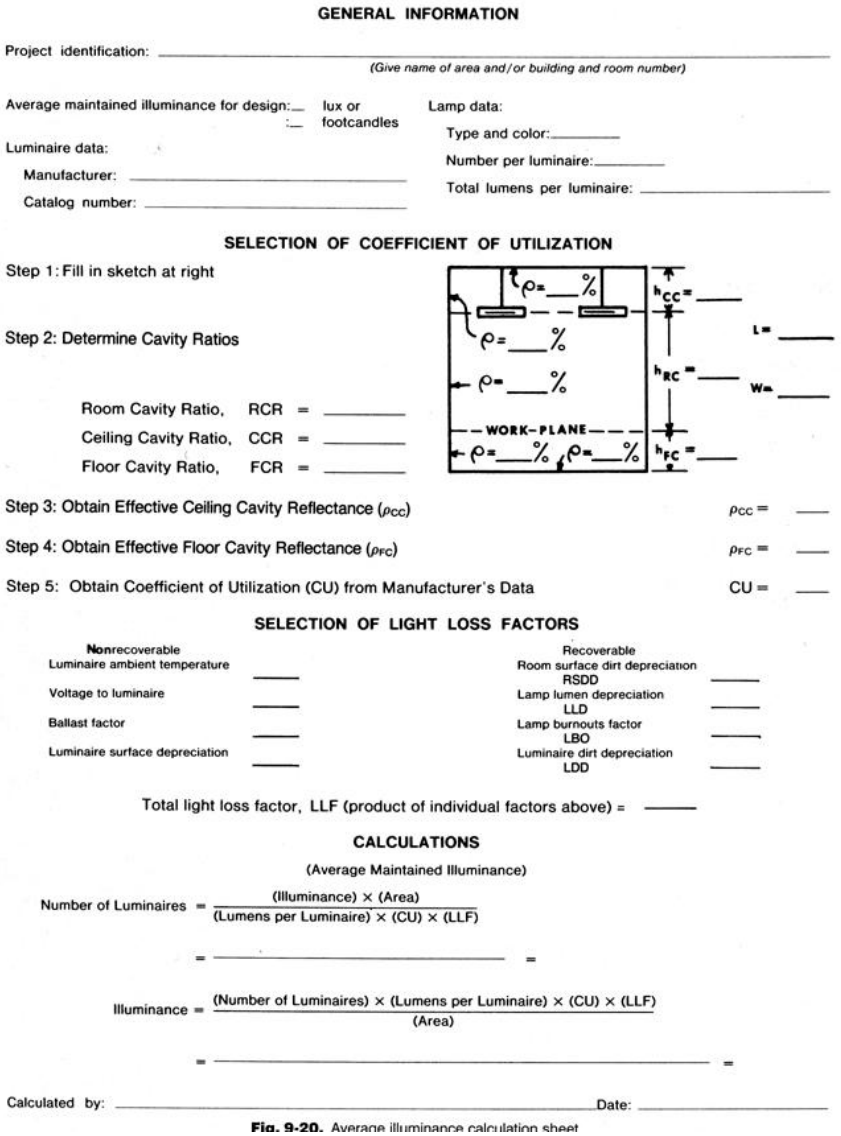
Effective Cavity Reflectances. Figure 9-27 provides a means of converting the combination of wall and ceiling or wall and floor reflectances into a single effective ceiling cavity reflectance, ρ_{CC}, and a single effective floor cavity reflectance, ρ_{FC}. In lumen method calculations, the ceiling, wall, and floor reflectances should be initial values. The RSDD factor compensates for the decrease of reflectance with time. Note that for surface-mounted and recessed luminaires, the CCR equals 0 and the actual ceiling reflectance may be used for ρ_{CC}.

A rectangular cavity consists of four walls, each having a reflectance of ρ_W, and a base of reflectance ρ_B (ceiling or floor reflectance). The effective reflectance, ρ_{eff}, of this cavity is the ratio of the flux reflected out to the flux entering the cavity through its opening. If the reflectances are assumed to be perfectly diffuse and the flux is assumed to enter the cavity in a perfectly diffuse way, it is possible to calculate the effective cavity reflectance using flux transfer theory. The result is

$$\rho_{\text{eff}} = \frac{\rho_B \rho_W f \left(2 \frac{A_B}{A_W}(1-f) - f \right) + \rho_B f^2 + \rho_W \frac{A_B}{A_W}(1-f)^2}{1 - \rho_B \rho_W \frac{A_B}{A_W}(1-f)^2 - \rho_W \left(1 - 2 \frac{A_B}{A_W}(1-f) \right)} \tag{9-53}$$

where

A_B, A_W = areas of the cavity base and walls, respectively,
ρ_B, ρ_W = reflectances of the cavity base and walls, respectively,
f = form factor between the cavity opening and the cavity base.



GENERAL INFORMATION

Project identification: ______________________
(Give name of area and/or building and room number)

Average maintained illuminance for design: __ lux or
: __ footcandles

Lamp data:
Type and color: ________
Number per luminaire: ________
Total lumens per luminaire: ________

Luminaire data:
Manufacturer: ________
Catalog number: ________

SELECTION OF COEFFICIENT OF UTILIZATION

Step 1: Fill in sketch at right

Step 2: Determine Cavity Ratios

Room Cavity Ratio, RCR = ________
Ceiling Cavity Ratio, CCR = ________
Floor Cavity Ratio, FCR = ________

Step 3: Obtain Effective Ceiling Cavity Reflectance (ρ_{CC}) ρ_{CC} = ____

Step 4: Obtain Effective Floor Cavity Reflectance (ρ_{FC}) ρ_{FC} = ____

Step 5: Obtain Coefficient of Utilization (CU) from Manufacturer's Data CU = ____

SELECTION OF LIGHT LOSS FACTORS

Nonrecoverable		Recoverable	
Luminaire ambient temperature	____	Room surface dirt depreciation RSDD	____
Voltage to luminaire	____	Lamp lumen depreciation LLD	____
Ballast factor	____	Lamp burnouts factor LBO	____
Luminaire surface depreciation	____	Luminaire dirt depreciation LDD	____

Total light loss factor, LLF (product of individual factors above) = ____

CALCULATIONS

(Average Maintained Illuminance)

$$\text{Number of Luminaires} = \frac{(\text{Illuminance}) \times (\text{Area})}{(\text{Lumens per Luminaire}) \times (\text{CU}) \times (\text{LLF})}$$

= ______________ =

$$\text{Illuminance} = \frac{(\text{Number of Luminaires}) \times (\text{Lumens per Luminaire}) \times (\text{CU}) \times (\text{LLF})}{(\text{Area})}$$

= ______________ =

Calculated by: ______________ Date: ________

Fig. 9-20. Average illuminance calculation sheet

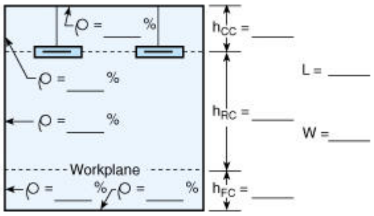


Figure 9-25. Average illuminance calculation sheet.

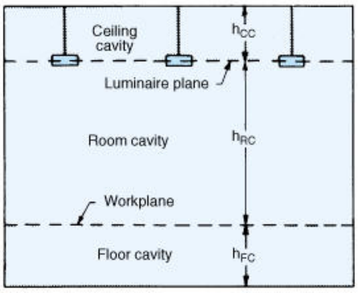


Figure 9-26. The three cavities used in the zonal-cavity method.

The form factor *f* in the above equation is given by

$$\begin{aligned} f = {} & \frac{2}{\pi xy} \ln \left(\frac{(1+x^2)(1+y^2)}{1+x^2+y^2} \right)^{1/2} \\ & + \frac{2}{\pi x}(1+x^2)^{1/2} \arctan \left(\frac{y}{(1+x^2)^{1/2}} \right) \\ & + \frac{2}{\pi y}(1+y^2)^{1/2} \arctan \left(\frac{x}{(1+y^2)^{1/2}} \right) \\ & - \frac{2}{\pi x} \arctan y - \frac{2}{\pi y} \arctan x \end{aligned} \tag{9-54}$$

where *x* and *y* have the following values:

$$x = \frac{\text{cavity length}}{\text{cavity depth}} \tag{9-55a}$$

$$y = \frac{\text{cavity length}}{\text{cavity depth}} \tag{9-55b}$$

The arctangents are expressed in radians. If it is assumed that the cavity is square, then

$$x = y = \frac{10}{\text{cavity ratio}} \tag{9-56}$$

The effective ceiling cavity reflectance of nonhorizontal ceilings can be determined by the following formula. The illuminance problem is then solved in the usual manner:

$$\rho_{CC} = \frac{\rho}{\dfrac{A_s}{A_o} - \rho\left(\dfrac{A_s}{A_o} - 1\right)} \tag{9-57}$$

where

A_o = area of the ceiling opening,
A_s = area of the ceiling surface,
ρ = reflectance of the ceiling surface.

The formula for ρ_{CC} applies to concave ceilings such as a hemispherical dome where all parts of the ceiling are exposed to all other parts. If the ceiling surface reflectance is not the same for all parts of the ceiling, an area-weighted average should be used. Thus, if the ceiling has *n* sections, then

$$\rho = \frac{\sum_{i=1}^{n} \rho_i A_i}{\sum_{i=1}^{n} A_i} \tag{9-58}$$

where

ρ_i = reflectance of the *i*th section of the ceiling,
A_i = area of the *i*th section of the ceiling.

Percent Base† Reflectance	90									
Percent Wall Reflectance	90	80	70	60	50	40	30	20	10	0
Cavity Ratio										
0.2	89	88	88	87	86	85	85	84	84	82
0.4	88	87	86	85	84	83	81	80	79	76
0.6	87	86	84	82	80	79	77	76	74	73
0.8	87	85	82	80	77	75	73	71	69	67
1.0	86	83	80	77	75	72	69	66	64	62
1.2	85	82	78	75	72	69	66	63	60	57
1.4	85	80	77	73	69	65	62	59	57	52
1.6	84	79	75	71	67	63	59	56	53	50
1.8	83	78	73	69	64	60	56	53	50	48
2.0	83	77	72	67	62	56	53	50	47	43
2.2	82	76	70	65	59	54	50	47	44	40
2.4	82	75	69	64	58	53	48	45	41	37
2.6	81	74	67	62	56	51	46	42	38	35
2.8	81	73	66	60	54	49	44	40	36	34
3.0	80	72	64	58	52	47	42	38	34	30
3.2	79	71	63	56	50	45	40	36	32	28
3.4	79	70	62	54	48	43	38	34	30	27
3.6	78	69	61	53	47	42	36	32	28	25
3.8	78	69	60	51	45	40	35	31	27	23
4.0	77	69	58	51	44	39	33	29	25	22
4.2	77	62	57	50	43	37	32	28	24	21
4.4	76	61	56	49	42	36	31	27	23	20
4.6	76	60	55	47	40	35	30	26	22	19
4.8	75	59	54	46	39	34	28	25	21	18
5.0	75	59	53	45	38	33	28	24	20	16
6.0	73	61	49	41	34	29	24	20	16	11
7.0	70	58	45	38	30	27	21	18	14	08
8.0	68	55	42	35	27	23	18	15	12	06
9.0	66	52	38	31	25	21	16	14	11	05
10.0	65	51	36	29	22	19	15	11	09	04

Percent Base† Reflectance	80									
Percent Wall Reflectance	90	80	70	60	50	40	30	20	10	0
Cavity Ratio										
0.2	79	78	78	77	77	76	76	75	74	72
0.4	79	77	76	75	74	73	72	71	70	68
0.6	78	76	75	73	71	70	68	66	65	63
0.8	78	75	73	71	69	67	65	63	61	57
1.0	77	74	72	69	67	65	62	60	57	55
1.2	76	73	70	67	64	61	58	55	53	51
1.4	76	72	68	65	62	59	55	53	50	48
1.6	75	71	67	63	60	57	53	50	47	44
1.8	75	70	66	62	58	54	50	47	44	41
2.0	74	69	64	60	56	52	48	45	41	38
2.2	74	68	63	58	54	49	45	42	38	35
2.4	73	67	61	56	52	47	43	40	36	33
2.6	73	66	60	55	50	45	41	38	34	31
2.8	73	65	59	53	48	43	39	36	32	29
3.0	72	65	58	52	47	42	37	34	30	27
3.2	72	65	57	51	45	40	35	33	28	25
3.4	71	64	56	49	44	39	34	32	27	24
3.6	71	63	54	48	43	38	32	30	25	23
3.8	70	62	53	47	41	36	31	28	24	22
4.0	70	61	53	46	40	35	30	26	22	20
4.2	69	60	52	45	39	34	29	25	21	18
4.4	69	60	51	44	38	33	28	24	20	17
4.6	69	59	50	43	37	32	27	23	19	15
4.8	68	58	49	42	36	31	26	22	18	14
5.0	68	58	48	41	35	30	25	21	18	14
6.0	66	55	44	38	31	27	22	19	15	10
7.0	64	53	41	35	28	24	19	16	12	07
8.0	62	50	38	32	25	21	17	14	11	05
9.0	61	49	36	30	23	19	15	13	10	04
10.0	59	46	33	27	21	18	14	11	08	03

Percent Base† Reflectance	70									
Percent Wall Reflectance	90	80	70	60	50	40	30	20	10	0
Cavity Ratio										
0.2	70	69	68	68	67	67	66	66	65	64
0.4	69	68	67	66	65	64	63	62	61	58
0.6	69	67	65	64	63	61	59	58	57	54
0.8	68	66	64	62	60	58	56	55	53	50
1.0	68	65	62	60	58	55	53	52	50	47
1.2	67	64	61	59	57	54	50	48	46	44
1.4	67	63	60	58	55	51	47	45	44	41
1.6	67	62	59	56	53	47	45	43	41	38
1.8	66	61	58	54	51	46	42	40	38	35
2.0	66	60	56	52	49	45	40	38	36	33
2.2	66	60	55	51	48	43	38	36	34	32
2.4	65	60	54	50	46	41	37	35	32	30
2.6	65	59	54	49	45	40	35	33	30	28
2.8	65	59	53	48	43	38	33	30	28	26
3.0	64	58	52	47	42	37	32	29	27	24
3.2	64	58	51	46	40	36	31	28	25	23
3.4	64	57	50	45	39	35	29	27	24	22
3.6	63	56	49	44	38	33	28	25	22	20
3.8	63	56	49	43	37	32	27	24	21	19
4.0	63	55	48	42	36	31	26	23	20	17
4.2	62	55	47	41	35	30	25	22	19	16
4.4	62	54	46	40	34	29	24	21	18	15
4.6	62	53	45	39	33	28	24	21	17	14
4.8	62	53	45	38	32	27	23	20	16	13
5.0	61	52	44	36	31	26	22	19	16	12
6.0	60	51	41	35	28	24	19	16	13	09
7.0	58	43	38	32	26	22	17	14	11	06
8.0	57	46	35	29	23	19	15	13	10	05
9.0	56	45	33	27	21	18	14	12	09	04
10.0	55	43	31	25	19	16	12	10	08	03

Percent Base† Reflectance	60									
Percent Wall Reflectance	90	80	70	60	50	40	30	20	10	0
Cavity Ratio										
0.2	60	59	59	59	58	57	56	56	55	53
0.4	60	59	59	58	57	55	54	53	52	50
0.6	60	58	57	56	55	53	51	51	50	46
0.8	59	57	56	55	54	51	48	47	46	43
1.0	59	57	55	53	51	48	45	44	43	41
1.2	59	56	54	51	49	46	44	42	40	38
1.4	59	56	53	49	47	44	41	39	38	36
1.6	59	55	52	48	45	42	39	37	35	33
1.8	58	55	51	47	44	40	37	35	33	31
2.0	58	54	50	46	43	39	35	33	31	29
2.2	58	53	49	45	42	37	34	31	29	28
2.4	58	53	48	44	41	36	32	30	27	26
2.6	58	53	48	43	39	35	31	28	26	24
2.8	58	53	47	43	38	34	29	27	24	22
3.0	57	52	46	42	37	32	28	25	23	20
3.2	57	51	45	41	36	31	27	23	22	18
3.4	57	51	45	40	35	30	26	23	20	17
3.6	57	50	44	39	34	29	25	22	19	16
3.8	57	50	43	38	33	29	24	21	19	15
4.0	57	49	42	37	32	28	23	20	18	14
4.2	56	49	42	37	32	27	22	19	17	14
4.4	56	49	42	36	31	27	22	19	16	13
4.6	56	49	41	35	30	26	21	18	16	13
4.8	56	48	41	34	29	25	21	18	15	12
5.0	56	48	40	34	28	24	20	17	14	11
6.0	55	45	37	31	25	21	17	14	11	07
7.0	54	43	35	30	24	20	15	12	09	05
8.0	53	42	33	28	22	18	14	11	08	04
9.0	52	40	31	26	20	16	12	10	07	03
10.0	51	39	29	24	18	15	11	09	07	02

Percent Base† Reflectance	50									
Percent Wall Reflectance	90	80	70	60	50	40	30	20	10	0
Cavity Ratio										
0.2	50	50	49	49	48	48	47	46	46	44
0.4	50	49	48	48	47	46	45	45	44	42
0.6	50	48	47	46	45	44	43	42	41	38
0.8	50	48	47	45	44	42	40	39	38	36
1.0	50	48	46	44	43	41	38	37	36	34
1.2	50	47	45	43	41	39	36	35	34	29
1.4	50	47	45	42	40	38	35	34	35	27
1.6	50	47	44	41	39	36	33	32	30	26
1.8	50	46	43	40	38	35	31	30	28	25
2.0	50	46	43	40	37	34	30	28	26	24
2.2	50	46	42	38	36	33	29	27	24	22
2.4	50	46	42	37	35	31	27	25	23	21
2.6	50	46	41	37	34	30	26	23	21	20
2.8	50	46	41	36	33	29	25	22	20	19
3.0	50	45	40	36	32	28	24	21	19	17
3.2	50	44	39	35	31	27	23	20	18	16
3.4	50	44	39	35	30	26	22	19	17	15
3.6	50	44	39	34	29	25	21	18	16	14
3.8	50	44	38	34	29	25	21	17	15	13
4.0	50	44	38	33	28	24	20	17	15	12
4.2	50	43	37	32	28	24	20	17	14	12
4.4	50	43	37	32	27	23	19	16	13	11
4.6	50	43	36	31	26	22	18	15	13	10
4.8	50	43	36	31	26	22	18	15	12	09
5.0	50	42	35	30	25	21	17	14	12	09
6.0	50	42	34	29	23	19	15	13	10	06
7.0	49	41	32	27	21	18	14	11	08	05
8.0	49	40	30	25	19	16	12	10	07	03
9.0	48	39	29	24	18	15	11	09	07	03
10.0	47	37	27	22	17	14	10	08	06	02

* Values in this table are based on a length to width ratio of 1.6.

†Ceiling, floor, or floor of cavity.

Figure 9-27. *Continued**

Percent Base† Reflectance	40									
Percent Wall Reflectance	90	80	70	60	50	40	30	20	10	0
Cavity Ratio										
0.2	40	40	39	39	39	38	38	37	36	36
0.4	41	40	39	39	38	37	36	35	34	34
0.6	41	40	39	38	37	36	34	33	32	31
0.8	41	40	38	37	36	35	33	32	31	29
1.0	42	40	38	37	35	33	32	31	29	27
1.2	42	40	38	36	34	32	30	29	27	25
1.4	42	39	37	35	33	31	29	27	25	23
1.6	42	39	37	35	32	30	27	25	23	22
1.8	42	39	36	34	31	29	26	24	22	21
2.0	42	39	36	34	31	28	25	23	21	19
2.2	42	39	36	33	30	27	24	22	19	18
2.4	43	39	35	33	29	27	24	21	18	17
2.6	43	39	35	32	29	26	23	20	17	15
2.8	43	39	35	32	28	25	22	19	16	14
3.0	43	39	35	31	27	24	21	18	16	13
3.2	43	39	35	31	27	23	20	71	15	13
3.4	43	39	34	30	26	23	20	17	14	12
3.6	44	39	34	30	26	22	19	16	14	11
3.8	44	38	33	29	25	22	18	16	13	10
4.0	44	38	33	29	25	21	18	15	12	10
4.2	44	38	33	29	24	21	17	15	12	10
4.4	44	38	33	28	24	20	17	14	11	09
4.6	44	38	32	28	23	19	16	14	11	08
4.8	44	38	32	27	22	19	16	13	10	08
5.0	45	38	31	27	22	19	15	13	10	07
6.0	44	37	30	25	20	17	13	11	08	05
7.0	44	36	29	24	19	16	12	10	07	04
8.0	44	35	28	23	18	15	11	09	06	03
9.0	44	35	26	21	16	13	10	08	05	02
10.0	43	34	25	20	15	12	08	07	05	02

Percent Base† Reflectance	30									
Percent Wall Reflectance	90	80	70	60	50	40	30	20	10	0
Cavity Ratio										
0.2	31	31	30	30	29	29	29	28	28	27
0.4	31	31	30	30	29	28	28	27	26	25
0.6	32	31	30	29	28	27	26	26	25	23
0.8	32	31	30	29	28	26	25	25	23	22
1.0	33	32	30	29	27	25	24	23	22	20
1.2	33	32	30	28	27	25	23	22	21	19
1.4	34	32	30	28	26	24	22	21	19	18
1.6	34	33	29	27	25	23	22	20	18	17
1.8	35	33	29	27	25	23	21	19	17	16
2.0	35	33	29	26	24	22	20	18	16	14
2.2	36	32	29	26	24	22	19	17	15	13
2.4	36	32	29	26	24	22	19	16	14	12
2.6	36	32	29	25	23	21	18	16	14	12
2.8	37	33	29	25	23	21	17	15	13	11
3.0	37	33	29	25	22	20	17	15	12	10
3.2	37	33	29	25	22	19	16	14	12	10
3.4	37	33	29	25	22	19	16	14	11	09
3.6	38	33	29	24	21	18	15	13	10	09
3.8	38	33	28	24	21	18	15	13	10	08
4.0	38	33	28	24	21	18	14	12	09	07
4.2	38	33	28	24	20	17	14	12	09	07
4.4	39	33	28	24	20	17	14	11	09	06
4.6	39	33	28	24	20	17	13	10	08	06
4.8	39	33	28	24	20	17	13	10	08	05
5.0	39	33	28	24	19	16	13	10	08	05
6.0	39	33	27	23	18	15	11	09	06	04
7.0	40	33	26	22	17	14	10	08	05	03
8.0	40	33	26	21	16	13	09	07	04	02
9.0	40	33	25	20	15	12	09	07	04	02
10.0	40	32	24	19	14	11	08	06	03	01

Percent Base† Reflectance	20									
Percent Wall Reflectance	90	80	70	60	50	40	30	20	10	0
Cavity Ratio										
0.2	21	20	20	20	20	20	19	19	19	17
0.4	22	21	20	20	20	19	19	18	18	16
0.6	23	21	21	20	19	19	18	18	17	15
0.8	24	22	21	20	19	19	18	17	16	14
1.0	25	23	22	20	19	18	17	16	15	13
1.2	25	23	22	20	19	17	17	16	14	12
1.4	26	24	22	20	18	17	16	15	13	12
1.6	26	24	22	20	18	17	16	15	13	11
1.8	27	25	23	20	18	17	15	14	12	10
2.0	28	25	23	20	18	16	15	13	11	09
2.2	28	25	23	20	18	16	14	12	10	09
2.4	29	26	23	20	18	16	14	12	10	08
2.6	29	26	23	20	18	16	14	11	09	08
2.8	30	27	23	20	18	15	13	11	09	07
3.0	30	27	23	20	17	15	13	11	09	07
3.2	31	27	23	20	17	15	12	11	09	06
3.4	31	27	23	20	17	15	12	10	08	06
3.6	32	27	23	20	17	15	12	10	08	05
3.8	32	28	23	20	17	15	12	10	07	05
4.0	33	28	23	20	17	14	11	09	07	05
4.2	33	28	23	20	17	14	11	09	07	04
4.4	34	28	24	20	17	14	11	09	07	04
4.6	34	29	24	20	17	14	11	09	07	04
4.8	35	29	24	20	17	13	10	08	06	04
5.0	35	29	24	20	16	13	10	08	06	04
6.0	36	30	24	20	16	13	10	08	05	02
7.0	36	30	24	20	15	12	03	07	04	02
8.0	37	30	23	19	15	12	08	06	03	01
9.0	37	29	23	19	14	11	08	06	03	01
10.0	37	29	22	18	13	10	07	05	03	01

Percent Base† Reflectance	10									
Percent Wall Reflectance	90	80	70	60	50	40	30	20	10	0
Cavity Ratio										
0.2	11	11	11	10	10	10	10	09	09	09
0.4	12	11	11	11	11	10	10	09	09	08
0.6	13	13	12	11	11	10	10	09	08	08
0.8	15	14	13	12	11	10	10	09	08	07
1.0	16	14	13	12	12	11	10	09	08	07
1.2	17	15	14	13	12	11	10	09	07	06
1.4	18	16	14	13	12	11	10	09	07	06
1.6	19	17	15	14	12	11	09	08	07	06
1.8	19	17	15	14	13	11	09	08	06	05
2.0	20	18	16	14	13	11	09	08	06	05
2.2	21	19	16	14	13	11	09	07	06	05
2.4	22	19	17	15	13	11	09	07	06	05
2.6	23	20	17	15	13	11	09	07	06	04
2.8	23	20	18	16	13	11	09	07	05	03
3.0	24	21	18	16	13	11	09	07	05	03
3.2	25	21	18	16	13	11	09	07	05	03
3.4	26	22	18	16	13	11	09	07	05	03
3.6	26	22	19	16	13	11	09	06	04	03
3.8	27	23	19	17	14	11	09	06	04	02
4.0	27	23	20	17	14	11	09	06	04	02
4.2	28	24	20	17	14	11	09	06	04	02
4.4	28	24	20	17	14	11	08	06	04	02
4.6	29	25	20	17	14	11	08	06	04	02
4.8	29	25	20	17	14	11	08	06	04	02
5.0	30	25	20	17	14	11	08	06	04	02
6.0	31	26	21	18	14	11	08	06	03	01
7.0	32	27	21	17	13	11	08	06	03	01
8.0	33	27	21	17	13	10	07	05	03	01
9.0	34	28	21	17	13	10	07	05	02	01
10.0	34	28	21	17	12	10	07	05	02	01

Percent Base† Reflectance	0									
Percent Wall Reflectance	90	80	70	60	50	40	30	20	10	0
Cavity Ratio										
0.2	02	02	02	01	01	01	01	00	00	0
0.4	04	03	03	02	02	02	01	01	00	0
0.6	05	05	04	03	03	02	02	01	01	0
0.8	07	06	05	04	04	03	02	02	01	0
1.0	08	07	06	05	04	03	02	02	01	0
1.2	10	08	07	06	05	04	03	02	01	0
1.4	11	09	08	07	06	04	03	02	01	0
1.6	12	10	09	07	06	05	03	02	01	0
1.8	13	11	09	08	07	05	04	03	01	0
2.0	14	12	10	09	07	05	04	03	01	0
2.2	15	13	11	09	07	06	04	03	01	0
2.4	16	13	11	09	08	06	04	03	01	0
2.6	17	14	12	10	08	06	05	03	02	0
2.8	17	15	13	10	08	07	05	03	02	0
3.0	18	16	13	11	09	07	05	03	02	0
3.2	19	16	14	11	09	07	05	03	02	0
3.4	20	17	14	12	09	07	05	03	02	0
3.6	20	17	15	12	10	08	05	04	02	0
3.8	21	18	15	12	10	08	05	04	02	0
4.0	22	18	15	13	10	08	05	04	02	0
4.2	22	19	16	13	10	08	06	04	02	0
4.4	23	19	16	13	10	08	06	04	02	0
4.6	23	20	17	13	11	08	06	04	02	0
4.8	24	20	17	14	11	08	06	04	02	0
5.0	25	21	17	14	11	08	06	04	02	0
6.0	27	23	18	15	12	09	06	04	02	0
7.0	28	24	19	15	12	09	06	04	02	0
8.0	30	25	20	15	12	09	06	04	02	0
9.0	31	25	20	15	12	09	06	04	02	0
10.0	31	25	20	15	12	09	06	04	02	0

* Values in this table are based on a length to width ratio of 1.6.

†Ceiling, floor, or floor of cavity.

Figure 9-27. Percent Effective Ceiling or Floor Cavity Reflectances for Various Reflectance Combinations*

Luminaire Coefficients of Utilization. Absorption of light in a luminaire is taken into account in the computation of coefficient of utilization (CU) for that luminaire. Figure 9-28 is a tabulation of coefficients of utilization calculated by the zonal-cavity method for representative luminaire types. These coefficients are for an effective floor cavity reflectance of 20%, but any CU obtained from the table may be corrected for a different value of ρ_{FC} by applying the appropriate multiplier from Figure 9-29.

Figure 9-28 is based on generic luminaires that can be readily identified. As an example, there are many variations of the flat-bottom fluorescent troffer using prismatic lenses. The luminaires in Figure 9-28 are not to be considered as recommended luminaires. The entries for some present useful data even though the luminaires concerned are no longer commonly used. For example, luminaire 2 is largely out of use; however, the coefficients apply to any indirect luminaire of similar efficiency and direct component, since they do not depend on the shape of the upward intensity distribution. An important feature of these coefficients is that the performance of luminaires of similar distributions but different efficiencies may also be analyzed with their use by making a simple multiplicative correction (see note 3 of Figure 9-28).

Since the light loss factor includes the effect of dirt deposited on wall surfaces, the selection of the proper column of wall reflectances, ρ_W, should be based on the initial values expected. The wall reflectance should also represent the weighted average of the reflectances of the painted areas, fenestration or daylight controls, chalkboards, shelves, and so forth in the area to be lighted. The weighting should be based on the relative areas of each type of surface within the cavity being considered. In using Figure 9-29, it is often necessary to interpolate between room cavity ratios and effective ceiling cavity reflectances. This is most easily accomplished by interpolating first between RCRs to obtain CUs for effective ceiling cavity reflectances that straddle the actual ρ_{CC}, and then interpolating between these CUs.

Instructions and Notes: Tables of Coefficients of Utilization (Figure 9-28)

1. The luminaires in this table are organized by source type and luminaire form rather than by application, for convenience in locating luminaires. In some cases, the data are based on an actual luminaire; in other cases, they represent a composite of generic luminaire types. Therefore, whenever possible, specific luminaire data should be used in preference to those in this table.

2. The polar intensity sketch (intensity distribution curve) and the corresponding luminaire spacing criterion are representative of many luminaires of each type shown. A specific luminaire may differ in perpendicular-plane (crosswise) and parallel-plane (lengthwise) intensity distributions and in spacing criterion from the values shown. However, the various coefficients depend only on the average intensity at each polar angle from nadir. The average intensity values used to generate the coefficients are given at the end of the table, normalized to 1000 lamp lumens for reference.

3. The various coefficients depend only on the average intensity distribution curve and are linearly related to the total luminaire efficiency. Consequently, the tabulated coefficients can be applied to luminaires with similarly shaped average intensity distributions along with a correcting multiplier equal to the new luminaire total efficiency divided by the tabulated luminaire total efficiency. The use of polarizing lenses on fluorescent luminaires has no effect on the coefficients given in this table except as they affect the total luminaire efficiency.

4. Satisfactory installations depend on many factors, including the environment, space utilization, and luminous criteria, as well as the luminaire itself. Consequently, a definitive spacing recommendation cannot be assigned to the luminaire as such. The spacing criterion (SC) values given are only general guides. SC values are not assigned to semi-indirect and indirect luminaires, since the basis of this technique does not apply to such situations. Also, SC values are not given for those bat-wing luminaires that must be located by criteria other than that of horizontal illuminance.

5. Key:

ρ_{CC} = ceiling cavity reflectance (percent),
ρ_W = wall reflectance (percent),
ρ_{FC} = floor cavity reflectance (percent),
RCR = room cavity ratio,
WDRC = wall direct radiation coefficient,
SC = luminaire spacing criterion,
NA = not applicable.

6. Many of the luminaires in this figure appeared in earlier editions of the IESNA *Lighting Handbook*. The identifying number may be different due to a reordering of the luminaires. In some cases, the data have been modified in view of more recent or more extensive information. The user should specifically refer to this edition of the *Lighting Handbook* when referencing luminaires.

7. Fluorescent lamp luminaire efficiencies, and consequently the coefficients, are a function of the number of lamps in relation to the size of the luminaire. This is due to temperature changes and to changes in the blocking of light. In this figure, fluorescent lamp luminaires have been chosen with typical luminaire sizes and numbers of lamps; these are identified under the typical luminaire drawings. Variations of the coefficients with size and number of lamps depend on the many details of luminaire construction. The following correction factors are average values to apply to a four-lamp luminaire 610 mm (2 ft) wide:

No. of lamps	Width, mm	Width, ft	Multiply by
8	1220	4	1.05
3	610	2	1.05
2	610	2	1.1
2	300	1	0.9

Multiply the entries for two-lamp wraparound luminaires by 0.95 for four lamps.

8. Photometric data for fluorescent lamp luminaires in this table are based on tests using standard-wattage fluorescent lamps. Reduced-wattage fluorescent lamps cause lower lamp operating temperatures with some luminaires. Consequently, the efficiency and coefficients may be slightly increased. It is desirable to obtain specific correction factors from the manufacturers. Typical factors for reduced-wattage fluorescent lamps (approximately 10% below standard lamp wattages) are as follows:

Luminaire	Multiply by
2-lamp strip, surface mounted	1.03
4-lamp troffer, enclosed, non-air-handling	1.07
4-lamp wraparound, surface mounted	1.07
2-lamp industrial, vented	1.00

Electronic ballasts can be designed for any arbitrary operating condition. The manufacturer must be consulted for specific data.

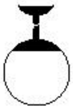
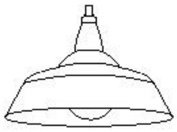
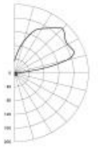
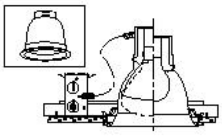
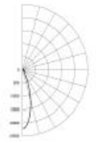
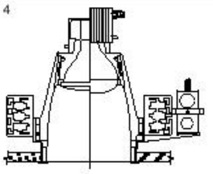
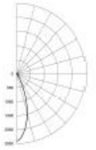
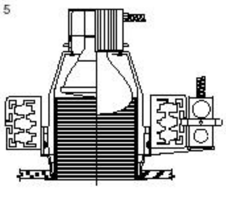
Typical Luminaire	Typical Intensity Distribution	ρcc →	80			70			50			30			10			0
		ρw →	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
1 		RCR ↓	EFF = 80.5%			% DN = 55.9%			% UP = 44.1%			Lamp = 150A21IF SC (along, across, 45°) = 1.5, 1.5, 1.5						
		0	0.87	0.87	0.87	0.81	0.81	0.81	0.70	0.70	0.70	0.59	0.59	0.59	0.49	0.49	0.49	0.45
		1	0.76	0.71	0.66	0.70	0.66	0.61	0.56	0.52	0.50	0.46	0.44	0.42	0.38	0.36	0.34	0.30
		2	0.68	0.60	0.53	0.62	0.55	0.50	0.47	0.42	0.38	0.39	0.35	0.32	0.31	0.29	0.26	0.23
		3	0.61	0.52	0.44	0.56	0.48	0.41	0.40	0.35	0.31	0.33	0.29	0.26	0.27	0.24	0.21	0.18
		4	0.55	0.45	0.37	0.51	0.42	0.35	0.35	0.30	0.25	0.29	0.25	0.21	0.23	0.20	0.17	0.14
		5	0.51	0.40	0.32	0.46	0.37	0.30	0.31	0.25	0.21	0.26	0.21	0.18	0.21	0.17	0.14	0.12
		6	0.46	0.35	0.28	0.42	0.33	0.26	0.28	0.22	0.18	0.23	0.19	0.15	0.19	0.15	0.12	0.10
		7	0.43	0.32	0.25	0.39	0.29	0.23	0.25	0.20	0.16	0.21	0.16	0.13	0.17	0.13	0.11	0.09
		8	0.40	0.29	0.22	0.36	0.27	0.20	0.23	0.17	0.14	0.19	0.15	0.12	0.15	0.12	0.09	0.07
Pendant diffusing sphere with incandescent lamp		9	0.37	0.26	0.19	0.34	0.24	0.18	0.21	0.16	0.12	0.17	0.13	0.10	0.14	0.11	0.08	0.07
		10	0.34	0.24	0.17	0.32	0.22	0.16	0.19	0.14	0.11	0.16	0.12	0.09	0.13	0.10	0.08	0.06
2 			EFF = 86.5%			% DN = 4.0%			% UP = 96.0%			Lamp = 100A21/5B SC (along, across, 45°) = N/A, N/A, N/A						
		0	0.99	0.99	0.99	0.97	0.97	0.97	0.93	0.93	0.93	0.89	0.89	0.89	0.85	0.85	0.85	0.83
		1	0.91	0.87	0.84	0.89	0.85	0.82	0.82	0.79	0.77	0.79	0.76	0.74	0.76	0.74	0.72	0.71
		2	0.83	0.76	0.70	0.80	0.74	0.69	0.71	0.67	0.63	0.69	0.65	0.62	0.66	0.63	0.60	0.59
		3	0.75	0.66	0.59	0.73	0.65	0.59	0.62	0.57	0.53	0.60	0.55	0.52	0.58	0.54	0.51	0.49
		4	0.69	0.58	0.51	0.67	0.57	0.50	0.55	0.49	0.44	0.53	0.48	0.44	0.51	0.47	0.43	0.41
		5	0.63	0.52	0.44	0.61	0.51	0.44	0.49	0.43	0.38	0.47	0.42	0.37	0.46	0.41	0.37	0.35
		6	0.58	0.46	0.39	0.56	0.46	0.38	0.44	0.38	0.33	0.43	0.37	0.33	0.41	0.36	0.32	0.31
		7	0.53	0.42	0.34	0.52	0.41	0.34	0.40	0.33	0.29	0.39	0.33	0.29	0.38	0.32	0.28	0.27
		8	0.50	0.38	0.31	0.48	0.37	0.31	0.36	0.30	0.26	0.35	0.30	0.25	0.34	0.29	0.25	0.24
Porcelain-enameled ventilated standard dome with inc. lamp		9	0.46	0.35	0.28	0.45	0.34	0.28	0.33	0.27	0.23	0.32	0.27	0.23	0.32	0.26	0.23	0.21
		10	0.43	0.32	0.25	0.42	0.32	0.25	0.31	0.25	0.21	0.30	0.24	0.21	0.29	0.24	0.20	0.19
3 			EFF = 100%			% DN = 100%			% UP = 0%			Lamp = 150PAR38FL SC (along, across, 45°) = 0.6, 0.6, 0.6						
		0	1.20	1.20	1.20	1.17	1.17	1.17	1.12	1.12	1.12	1.07	1.07	1.07	1.03	1.03	1.03	1.00
		1	1.14	1.11	1.08	1.11	1.08	1.06	1.04	1.02	1.00	1.01	0.99	0.97	0.97	0.96	0.95	0.93
		2	1.08	1.02	0.98	1.05	1.01	0.97	0.97	0.94	0.91	0.94	0.92	0.89	0.92	0.89	0.87	0.86
		3	1.02	0.95	0 90	1.00	0.94	0.89	0.91	0.87	0.84	0.89	0.85	0.82	0.86	0.84	0.81	0.79
		4	0.97	0.89	0.83	0.95	0.88	0.83	0.86	0.81	0.78	0.84	0.80	0.77	0.82	0.79	0.76	0.74
		5	0.92	0.84	0.78	0.91	0.83	0.77	0.81	0.76	0.72	0.79	0.75	0.72	0.78	0.74	0.71	0.70
		6	0.88	0.79	0.73	0.87	0.78	0.73	0.77	0.72	0.68	0.75	0.71	0.68	0.74	0.70	0.67	0.66
		7	0.84	0.75	0.69	0.83	0.74	0.69	0.73	0.68	0.64	0.72	0.67	0.64	0.71	0.67	0.64	0.62
		8	0.81	0.71	0.66	0.80	0.71	0.65	0.70	0.65	0.61	0.69	0.64	0.61	0.68	0.64	0.61	0.59
		9	0.78	0.68	0.62	0.77	0.68	0.62	0.67	0.62	0.58	0.66	0.61	0.58	0.65	0.61	0.58	0.57
Bare lamp PAR-38 flood		10	0.75	0.65	0.60	0.74	0.65	0.59	0.64	0.59	0.56	0.63	0.59	0.56	0.63	0.58	0.55	0.54
4 			EFF = 66.2%			% DN = 100			% UP = 0			Lamp = 150PAR38FL* SC (along, across, 45°) = 0.6, 0.6, 0.6						
		0	1.10	1.10	1.10	1.07	1.07	1.07	1.02	1.02	1.02	0.98	0.98	0.98	0.94	0.94	0.94	0.92
		1	1.06	1.03	1.02	1.03	1.01	1.00	0.98	0.96	0.95	0.94	0.93	0.92	0.91	0.90	0.90	0.88
		2	1.02	0.08	0.95	1.00	0.96	0.94	0.94	0.91	0.89	0.91	0.89	0.88	0.88	0.87	0.86	0.84
		3	0.98	0.93	0.90	0.96	0.92	0.89	0.90	0.87	0.85	0.88	0.85	0.83	0.86	0.84	0.82	0.81
		4	0.94	0.89	0.85	0.93	0.88	0.84	0.86	0.83	0.80	0.84	0.82	0.79	0.83	0.81	0.79	0.77
		5	0.91	0.85	0.81	0.90	0.84	0.80	0.83	0.79	0.77	0.81	0.78	0.76	0.80	0.77	0.75	0.74
		6	0.88	0.81	0.77	0.87	0.81	0.77	0.80	0.76	0.73	0.78	0.75	0.73	0.77	0.75	0.72	0.71
		7	0.85	0.78	0.74	0.84	0.78	0.74	0.77	0.73	0.70	0.76	0.72	0.70	0.75	0.72	0.70	0.69
		8	0.82	0.75	0.71	0.81	0.75	0.71	0.74	0.70	0.68	0.73	0.70	0.67	0.72	0.69	0.67	0.66
PAR-38 Flood with spec. anodized reflector (45 deg. cutoff)		9	0.79	0.72	0.68	0.78	0.72	0.68	0.71	0.68	0.65	0.70	0.67	0.65	0.70	0.67	0.65	0.64
		10	0.77	0.70	0.66	0.76	0.69	0.65	0.69	0.65	0.63	0.68	0.65	0.62	0.68	0.65	0.62	0.61
5 			EFF = 66.2%			% DN = 100			% UP = 0			Lamp = 150PAR38FL* SC (along, across, 45°) = 0.6, 0.6, 0.6						
		0	0.79	0.79	0.79	0.77	0.77	0.77	0.74	0.74	0.74	0.70	0.70	0.70	0.68	0.68	0.68	0.66
		1	0.76	0.75	0.73	0.75	0.73	0.72	0.71	0.70	0.69	0.68	0.68	0.67	0.66	0.66	0.65	0.64
		2	0.74	0.71	0.69	0.72	0.70	0.68	0.68	0.67	0.65	0.66	0.65	0.64	0.64	0.63	0.63	0.62
		3	0.71	0.68	0.66	0.70	0.67	0.65	0.66	0.64	0.62	0.64	0.63	0.61	0.63	0.61	0.60	0.60
		4	0.69	0.65	0.63	0.68	0.65	0.62	0.63	0.61	0.60	0.62	0.60	0.59	0.61	0.60	0.58	0.58
		5	0.67	0.63	0.60	0.66	0.62	0.60	0.61	0.59	0.57	0.60	0.58	0.57	0.59	0.58	0.56	0.56
		6	0.65	0.61	0.58	0.64	0.60	0.58	0.59	0.57	0.55	0.59	0.57	0.55	0.58	0.56	0.55	0.54
		7	0.63	0.59	0.56	0.62	0.58	0.56	0.57	0.55	0.53	0.57	0.55	0.53	0.56	0.54	0.53	0.52
		8	0.61	0.57	0.54	0.60	0.56	0.54	0.56	0.53	0.52	0.55	0.53	0.52	0.55	0.53	0.51	0.51
		9	0.59	0.55	0.52	0.59	0.55	0.52	0.54	0.52	0.50	0.54	0.51	0.50	0.53	0.51	0.50	0.49
PAR-38 Flood with black baffle		10	0.58	0.53	0.51	0.57	0.53	0.50	0.53	0.50	0.49	0.52	0.50	0.48	0.52	0.50	0.48	0.48

Figure 9-28 *Continued*

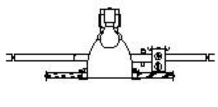
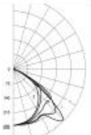
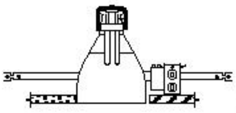
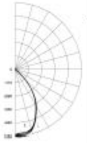
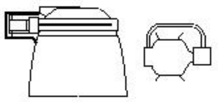
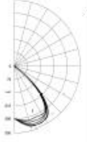
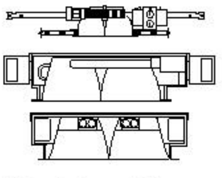
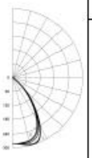
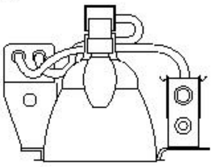
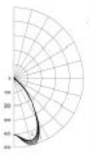
Typical Luminaire	Typical Intensity Distribution	ρcc →	80			70			50			30			10			0
		ρw →	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
		RCR ↓	EFF = 96.2%			% DN = 100%			% UP = 0%			Lamp = 150A21IF SC (along, across, 45°) = 1.2, 1.2, 1.1						
6 		0	0.82	0.82	0.82	0.81	0.81	0.81	0.77	0.77	0.77	0.74	0.74	0.74	0.71	0.71	0.71	0.69
		1	0.78	0.76	0.75	0.77	0.75	0.73	0.72	0.71	0.70	0.70	0.68	0.68	0.67	0.66	0.66	0.64
		2	0.74	0.71	0.68	0.73	0.70	0.67	0.67	0.65	0.63	0.65	0.63	0.62	0.63	0.62	0.61	0.59
		3	0.70	0.66	0.62	0.69	0.65	0.61	0.63	0.60	0.58	0.61	0.59	0.57	0.59	0.57	0.56	0.55
		4	0.66	0.61	0.57	0.65	0.60	0.56	0.58	0.55	0.53	0.57	0.54	0.52	0.56	0.53	0.51	0.50
		5	0.63	0.56	0.52	0.61	0.56	0.52	0.55	0.51	0.48	0.53	0.50	0.48	0.52	0.50	0.48	0.46
		6	0.59	0.53	0.48	0.58	0.52	0.48	0.51	0.47	0.45	0.50	0.47	0.44	0.49	0.46	0.44	0.43
		7	0.56	0.49	0.45	0.55	0.49	0.44	0.48	0.44	0.41	0.47	0.43	0.41	0.46	0.43	0.41	0.40
		8	0.53	0.46	0.41	0.52	0.45	0.41	0.45	0.41	0.38	0.44	0.40	0.38	0.43	0.40	0.38	0.37
A-lamp downlight with spec. anodized reflector		9	0.50	0.43	0.39	0.49	0.43	0.38	0.42	0.38	0.35	0.41	0.38	0.35	0.41	0.37	0.35	0.34
		10	0.47	0.40	0.36	0.47	0.40	0.36	0.39	0.36	0.33	0.39	0.35	0.33	0.38	0.35	0.33	0.32
7			EFF = 64.9%			% DN = 100%			% UP = 0%			Lamp = CF6/32 SC (along, across, 45°) = 1.1, 1.1, 1.1						
		0	0.77	0.77	0.77	0.75	0.75	0.75	0.72	0.72	0.72	0.69	0.69	0.69	0.66	0.66	0.66	0.65
		1	0.73	0.72	0.70	0.72	0.70	0.69	0.67	0.66	0.65	0.65	0.64	0.63	0.63	0.62	0.61	0.60
		2	0.69	0.66	0.63	0.68	0.65	0.62	0.63	0.61	0.59	0.61	0.59	0.58	0.59	0.58	0.57	0.55
		3	0.66	0.61	0.58	0.64	0.60	0.57	0.59	0.56	0.54	0.57	0.55	0.53	0.55	0.54	0.52	0.51
		4	0.62	0.57	0.53	0.61	0.56	0.52	0.55	0.51	0.49	0.53	0.51	0.48	0.52	0.50	0.48	0.47
		5	0.58	0.53	0.49	0.57	0.52	0.48	0.51	0.48	0.45	0.50	0.47	0.45	0.49	0.46	0.44	0.43
		6	0.55	0.49	0.45	0.54	0.48	0.45	0.47	0.44	0.41	0.46	0.43	0.41	0.46	0.43	0.41	0.40
		7	0.52	0.46	0.41	0.51	0.45	0.41	0.44	0.41	0.38	0.44	0.40	0.38	0.43	0.40	0.38	0.37
		8	0.49	0.43	0.38	0.48	0.42	0.38	0.42	0.38	0.35	0.41	0.38	0.35	0.40	0.37	0.35	0.34
8″ Open reflector downlight (32W CFL)		9	0.47	0.40	0.36	0.46	0.40	0.36	0.39	0.35	0.33	0.38	0.35	0.33	0.38	0.35	0.33	0.32
		10	0.44	0.37	0.33	0.44	0.37	0.33	0.37	0.33	0.31	0.36	0.33	0.30	0.36	0.33	0.30	0.29
8			EFF = 61.6%			% DN = 100%			% UP = 0%			Lamp = (2) CFQ26 SC (along, across, 45°) = 1.5, 1.6, 1.5						
		0	0.73	0.73	0.73	0.72	0.72	0.72	0.68	0.68	0.68	0.66	0.66	0.66	0.63	0.63	0.63	0.62
		1	0.69	0.67	0.66	0.68	0.66	0.64	0.63	0.62	0.61	0.61	0.60	0.59	0.59	0.58	0.57	0.56
		2	0.65	0.61	0.59	0.64	0.60	0.58	0.58	0.56	0.54	0.56	0.55	0.53	0.55	0.53	0.52	0.51
		3	0.61	0.56	0.52	0.59	0.55	0.52	0.53	0.51	0.48	0.52	0.49	0.47	0.50	0.48	0.47	0.46
		4	0.57	0.51	0.47	0.56	0.50	0.47	0.49	0.46	0.43	0.48	0.45	0.43	0.47	0.44	0.42	0.41
		5	0.53	0.47	0.42	0.52	0.46	0.42	0.45	0.41	0.39	0.44	0.41	0.38	0.43	0.40	0.38	0.37
		6	0.50	0.43	0.38	0.48	0.42	0.38	0.41	0.38	0.35	0.40	0.37	0.35	0.40	0.37	0.34	0.33
		7	0.46	0.39	0.35	0.45	0.39	0.35	0.38	0.34	0.31	0.37	0.34	0.31	0.36	0.33	0.31	0.30
		8	0.43	0.36	0.32	0.42	0.36	0.32	0.35	0.31	0.29	0.34	0.31	0.28	0.34	0.31	0.28	0.27
8″ Open reflector downlight (2-26W CFL)		9	0.41	0.33	0.29	0.40	0.33	0.29	0.33	0.29	0.26	0.32	0.28	0.26	0.31	0.28	0.26	0.25
		10	0.38	0.31	0.27	0.37	0.31	0.27	0.30	0.26	0.24	0.30	0.26	0.24	0.29	0.26	0.24	0.23
9			EFF = 40.2%			% DN = 100			% UP = 0			Lamp = (2) CFQ26 SC (along, across, 45°) = 1.2, 1.2, 1.1						
		0	0.47	0.47	0.47	0.46	0.46	0.46	0.44	0.44	0.44	0.42	0.42	0.42	0.41	0.41	0.41	0.40
		1	0.45	0.44	0.43	0.44	0.43	0.42	0.41	0.41	0.40	0.40	0.39	0.39	0.39	0.38	0.38	0.37
		2	0.43	0.41	0.39	0.42	0.40	0.38	0.39	0.37	0.36	0.37	0.36	0.35	0.36	0.35	0.35	0.34
		3	0.40	0.37	0.35	0.39	0.37	0.35	0.36	0.34	0.33	0.35	0.33	0.32	0.34	0.33	0.32	0.31
		4	0.38	0.35	0.32	0.37	0.34	0.32	0.33	0.31	0.30	0.32	0.31	0.29	0.32	0.30	0.29	0.28
		5	0.36	0.32	0.29	0.35	0.32	0.29	0.31	0.29	0.27	0.30	0.28	0.27	0.30	0.28	0.27	0.26
		6	0.34	0.30	0.27	0.33	0.29	0.27	0.29	0.27	0.25	0.28	0.26	0.25	0.28	0.26	0.25	0.24
		7	0.32	0.28	0.25	0.31	0.27	0.25	0.27	0.25	0.23	0.26	0.24	0.23	0.26	0.24	0.23	0.22
		8	0.30	0.26	0.23	0.29	0.25	0.23	0.25	0.23	0.21	0.25	0.23	0.21	0.24	0.22	0.21	0.20
		9	0.28	0.24	0.21	0.28	0.24	0.21	0.23	0.21	0.20	0.23	0.21	0.19	0.23	0.21	0.19	0.19
8″ Round with cross baffles		10	0.27	0.22	0.20	0.26	0.22	0.20	0.22	0.20	0.18	0.22	0.20	0.18	0.21	0.19	0.18	0.17
10			EFF = 63.8%			% DN = 78.4			% UP = 21.6			Lamp = M100/C/U SC (along, across, 45°) = 1.2, 1.2, 1.1						
		0	0.76	0.76	0.76	0.74	0.74	0.74	0.71	0.71	0.71	0.68	0.68	0.68	0.65	0.65	0.65	0.64
		1	0.72	0.70	0.68	0.70	0.69	0.67	0.66	0.65	0.64	0.64	0.63	0.62	0.61	0.61	0.60	0.59
		2	0.68	0.64	0.62	0.66	0.63	0.61	0.61	0.59	0.57	0.59	0.57	0.56	0.57	0.56	0.55	0.54
		3	0.64	0.59	0.56	0.63	0.58	0.55	0.57	0.54	0.52	0.55	0.53	0.51	0.54	0.52	0.50	0.49
		4	0.60	0.55	0.51	0.59	0.54	0.50	0.52	0.49	0.47	0.51	0.48	0.46	0.50	0.48	0.46	0.45
		5	0.57	0.51	0.46	0.55	0.50	0.46	0.49	0.45	0.43	0.48	0.45	0.42	0.47	0.44	0.42	0.41
		6	0.53	0.47	0.43	0.52	0.46	0.42	0.45	0.42	0.39	0.44	0.41	0.39	0.43	0.41	0.38	0.37
		7	0.50	0.43	0.39	0.49	0.43	0.39	0.42	0.39	0.36	0.41	0.38	0.36	0.41	0.38	0.35	0.34
		8	0.47	0.41	0.36	0.46	0.40	0.36	0.39	0.36	0.33	0.39	0.35	0.33	0.38	0.35	0.33	0.32
		9	0.45	0.38	0.34	0.44	0.37	0.33	0.37	0.33	0.31	0.36	0.33	0.31	0.36	0.33	0.30	0.29
Metal halide downlight		10	0.42	0.35	0.31	0.42	0.35	0.31	0.35	0.31	0.28	0.34	0.31	0.28	0.34	0.30	0.28	0.27

Figure 9-28 *Continued*

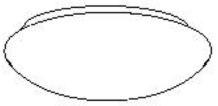
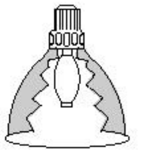
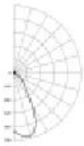
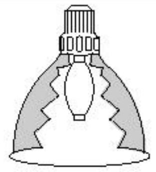
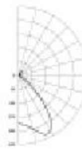
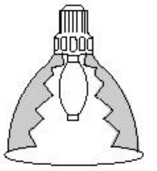
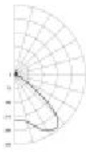
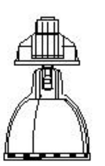
Typical Luminaire	Typical Intensity Distribution	ρcc →	80			70			50			30			10			0
		ρw →	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
		RCR ↓	EFF = 55.9%			% DN = 76.2%			% UP = 23.8%			Lamp = 22 & 32W circ.* SC (along, across, 45°) = 1.3, 1.3, 1.5						
11  CFL surface-mounted disk		0	0.63	0.63	0.63	0.60	0.60	0.60	0.55	0.55	0.55	0.50	0.50	0.50	0.45	0.45	0.45	0.43
		1	0.57	0.54	0.51	0.54	0.51	0.48	0.46	0.44	0.42	0.42	0.40	0.39	0.38	0.36	0.35	0.33
		2	0.51	0.46	0.42	0.48	0.44	0.40	0.40	0.37	0.34	0.36	0.33	0.31	0.32	0.30	0.29	0.27
		3	0.46	0.40	0.35	0.44	0.38	0.34	0.35	0.31	0.28	0.31	0.28	0.26	0.28	0.26	0.24	0.22
		4	0.42	0.35	0.30	0.40	0.34	0.29	0.31	0.27	0.24	0.28	0.24	0.22	0.25	0.22	0.20	0.19
		5	0.39	0.31	0.26	0.37	0.30	0.25	0.27	0.23	0.20	0.25	0.21	0.19	0.22	0.20	0.17	0.16
		6	0.36	0.28	0.23	0.34	0.27	0.22	0.24	0.20	0.18	0.22	0.19	0.16	0.20	0.17	0.15	0.14
		7	0.33	0.25	0.20	0.31	0.24	0.20	0.22	0.18	0.15	0.20	0.17	0.14	0.18	0.16	0.13	0.12
		8	0.31	0.23	0.18	0.29	0.22	0.18	0.20	0.16	0.14	0.18	0.15	0.13	0.17	0.14	0.12	0.11
		9	0.28	0.21	0.16	0.27	0.20	0.16	0.18	0.15	0.12	0.17	0.14	0.11	0.16	0.13	0.11	0.10
		10	0.27	0.19	0.15	0.25	0.19	0.14	0.17	0.13	0.11	0.16	0.13	0.10	0.14	0.12	0.10	0.09
12  High bay, open metal reflector, narrow			EFF = 87.5%			% DN = 85.9%			% UP = 1.6%			Lamp = M400/C/U SC (along, across, 45°) = 1.1, 1.1, 1						
		0	1.04	1.04	1.04	1.01	1.01	1.01	0.96	0.96	0.96	0.92	0.92	0.92	0.88	0.88	0.88	0.86
		1	0.98	0.95	0.93	0.96	0.93	0.91	0.89	0.87	0.86	0.86	0.84	0.83	0.82	0.81	0.80	0.78
		2	0.92	0.87	0.83	0.90	0.85	0.82	0.82	0.79	0.76	0.79	0.77	0.74	0.77	0.75	0.73	0.71
		3	0.86	0.80	0.75	0.84	0.78	0.74	0.76	0.72	0.69	0.73	0.70	0.67	0.71	0.68	0.66	0.64
		4	0.81	0.73	0.68	0.79	0.72	0.67	0.70	0.66	0.62	0.68	0.64	0.61	0.66	0.63	0.60	0.59
		5	0.76	0.68	0.62	0.74	0.67	0.61	0.65	0.60	0.56	0.63	0.59	0.56	0.62	0.58	0.55	0.54
		6	0.72	0.63	0.57	0.70	0.62	0.56	0.60	0.55	0.52	0.59	0.54	0.51	0.57	0.54	0.51	0.49
		7	0.67	0.58	0.52	0.66	0.58	0.52	0.56	0.51	0.47	0.55	0.50	0.47	0.54	0.50	0.47	0.45
		8	0.64	0.54	0.48	0.62	0.54	0.48	0.53	0.47	0.44	0.51	0.47	0.43	0.50	0.46	0.43	0.42
		9	0.60	0.51	0.45	0.59	0.50	0.45	0.49	0.44	0.41	0.48	0.44	0.40	0.47	0.43	0.40	0.39
		10	0.57	0.48	0.42	0.56	0.47	0.42	0.46	0.41	0.38	0.45	0.41	0.38	0.45	0.40	0.37	0.36
13  High bay, open metal reflector, medium			EFF = 83.9%			% DN = 95.2%			% UP = 4.8%			Lamp = M400/C/U SC (along, across, 45°) = 1.6, 1.6, 1.4						
		0	0.99	0.99	0.99	0.96	0.96	0.96	0.91	0.91	0.91	0.86	0.86	0.86	0.82	0.82	0.82	0.80
		1	0.93	0.90	0.87	0.90	0.88	0.85	0.83	0.81	0.80	0.80	0.78	0.77	0.76	0.75	0.74	0.72
		2	0.86	0.81	0.77	0.84	0.79	0.75	0.76	0.73	0.70	0.73	0.70	0.68	0.70	0.68	0.66	0.64
		3	0.80	0.73	0.68	0.78	0.72	0.67	0.65	0.65	0.61	0.66	0.63	0.60	0.64	0.61	0.58	0.57
		4	0.75	0.67	0.61	0.73	0.65	0.60	0.63	0.58	0.54	0.61	0.57	0.53	0.58	0.55	0.52	0.51
		5	0.70	0.61	0.54	0.68	0.59	0.54	0.57	0.52	0.48	0.55	0.51	0.48	0.54	0.50	0.47	0.45
		6	0.65	0.55	0.49	0.63	0.54	0.48	0.53	0.47	0.43	0.51	0.46	0.43	0.49	0.45	0.42	0.41
		7	0.60	0.51	0.44	0.59	0.50	0.44	0.48	0.43	0.39	0.47	0.42	0.39	0.45	0.41	0.38	0.37
		8	0.56	0.47	0.40	0.55	0.46	0.40	0.44	0.39	0.35	0.43	0.38	0.35	0.42	0.38	0.34	0.33
		9	0.53	0.43	0.37	0.52	0.42	0.36	0.41	0.36	0.32	0.40	0.35	0.32	0.39	0.35	0.31	0.30
		10	0.50	0.40	0.34	0.48	0.39	0.33	0.38	0.33	0.29	0.37	0.32	0.29	0.36	0.32	0.29	0.27
14  High bay, open metal reflector, wide			EFF = 83.8%			% DN = 97			% UP = 3			Lamp = M400/C/U SC (along, across, 45°) = 1.9, 1.9, 1.7						
		0	0.99	0.99	0.99	0.97	0.97	0.97	0.92	0.92	0.92	0.87	0.87	0.87	0.83	0.83	0.83	0.81
		1	0.92	0.89	0.86	0.90	0.87	0.84	0.83	0.81	0.79	0.80	0.78	0.76	0.76	0.75	0.74	0.72
		2	0.85	0.80	0.75	0.83	0.78	0.73	0.75	0.71	0.68	0.72	0.69	0.66	0.69	0.66	0.64	0.62
		3	0.79	0.71	0.65	0.76	0.70	0.64	0.67	0.62	0.58	0.64	0.60	0.57	0.62	0.59	0.56	0.54
		4	0.72	0.63	0.57	0.70	0.62	0.56	0.60	0.55	0.51	0.58	0.53	0.50	0.56	0.52	0.49	0.47
		5	0.67	0.57	0.50	0.65	0.56	0.50	0.54	0.48	0.44	0.52	0.47	0.43	0.50	0.46	0.43	0.41
		6	0.62	0.51	0.44	0.60	0.50	0.44	0.49	0.43	0.39	0.47	0.42	0.38	0.46	0.41	0.38	0.36
		7	0.57	0.46	0.40	0.56	0.46	0.39	0.44	0.38	0.34	0.43	0.38	0.34	0.42	0.37	0.33	0.32
		8	0.53	0.42	0.35	0.52	0.42	0.35	0.40	0.34	0.30	0.39	0.34	0.30	0.38	0.33	0.30	0.28
		9	0.49	0.39	0.32	0.48	0.38	0.32	0.37	0.31	0.27	0.36	0.31	0.27	0.35	0.30	0.27	0.25
		10	0.46	0.35	0.29	0.45	0.35	0.29	0.34	0.28	0.24	0.33	0.28	0.24	0.32	0.27	0.24	0.22
15  High bay, open prismatic reflector, narrow			EFF = 61.4%			% DN = 80.6			% UP = 19.4			Lamp = M400/C/U SC (along, across, 45°) = 1.1, 1.1, 1.1						
		0	0.70	0.70	0.70	0.67	0.67	0.67	0.62	0.62	0.62	0.56	0.56	0.56	0.52	0.52	0.52	0.49
		1	0.65	0.62	0.60	0.62	0.59	0.57	0.55	0.53	0.52	0.50	0.49	0.48	0.46	0.45	0.44	0.42
		2	0.60	0.55	0.52	0.57	0.53	0.50	0.49	0.47	0.45	0.46	0.44	0.42	0.42	0.41	0.39	0.37
		3	0.56	0.50	0.46	0.53	0.48	0.44	0.45	0.42	0.39	0.42	0.39	0.37	0.39	0.37	0.35	0.33
		4	0.52	0.45	0.41	0.49	0.44	0.40	0.41	0.38	0.35	0.38	0.35	0.33	0.36	0.33	0.32	0.30
		5	0.48	0.41	0.37	0.46	0.40	0.36	0.38	0.34	0.31	0.35	0.32	0.30	0.33	0.31	0.29	0.27
		6	0.45	0.38	0.33	0.43	0.37	0.33	0.35	0.31	0.28	0.33	0.30	0.27	0.31	0.28	0.26	0.25
		7	0.42	0.35	0.30	0.40	0.34	0.30	0.32	0.28	0.26	0.30	0.27	0.25	0.29	0.26	0.24	0.23
		8	0.40	0.32	0.28	0.38	0.31	0.27	0.30	0.26	0.24	0.28	0.25	0.23	0.27	0.24	0.22	0.21
		9	0.37	0.30	0.26	0.36	0.29	0.25	0.28	0.24	0.22	0.26	0.23	0.21	0.25	0.22	0.20	0.19
		10	0.35	0.28	0.24	0.34	0.27	0.23	0.26	0.22	0.20	0.25	0.22	0.19	0.23	0.21	0.19	0.18

Figure 9-28 *Continued*

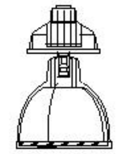
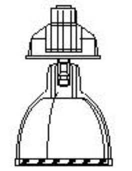
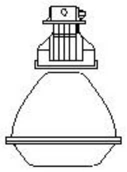
Typical Luminaire	Typical Intensity Distribution	ρcc →	80			70			50			30			10			0
		ρw →	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
		RCR ↓	EFF = 59%			% DN = 77.9%			% UP = 22.1%			Lamp = M400/C/U SC (along, across, 45°) = 1.3, 1.3, 1.2						
16 		0	0.67	0.67	0.67	0.64	0.64	0.64	0.58	0.58	0.58	0.53	0.53	0.53	0.48	0.48	0.48	0.46
		1	0.62	0.59	0.57	0.59	0.57	0.55	0.52	0.50	0.49	0.48	0.46	0.45	0.43	0.43	0.42	0.40
		2	0.57	0.53	0.50	0.55	0.51	0.48	0.47	0.45	0.43	0.43	0.41	0.40	0.40	0.38	0.37	0.35
		3	0.53	0.48	0.44	0.51	0.46	0.43	0.43	0.40	0.37	0.40	0.37	0.35	0.36	0.35	0.33	0.31
		4	0.50	0.44	0.39	0.47	0.42	0.38	0.39	0.36	0.33	0.36	0.34	0.32	0.34	0.32	0.30	0.28
		5	0.46	0.40	0.35	0.44	0.38	0.34	0.36	0.33	0.30	0.33	0.31	0.28	0.31	0.29	0.27	0.26
		6	0.43	0.37	0.32	0.41	0.35	0.31	0.33	0.30	0.27	0.31	0.28	0.26	0.29	0.27	0.25	0.23
		7	0.40	0.34	0.29	0.39	0.33	0.28	0.31	0.27	0.25	0.29	0.26	0.24	0.27	0.24	0.23	0.21
		8	0.38	0.31	0.27	0.36	0.30	0.26	0.28	0.25	0.22	0.27	0.24	0.22	0.25	0.23	0.21	0.20
		9	0.36	0.29	0.24	0.34	0.28	0.24	0.26	0.23	0.21	0.25	0.22	0.20	0.23	0.21	0.19	0.18
High bay, open prismatic reflector, medium		10	0.33	0.27	0.23	0.32	0.26	0.22	0.24	0.21	0.19	0.23	0.20	0.18	0.22	0.19	0.18	0.17
17 			EFF = 61.5%			% DN = 83.7%			% UP = 16.3%			Lamp = M400/C/U SC (along, across, 45°) = 2.2, 2.2, 1.8						
		0	0.71	0.71	0.71	0.68	0.68	0.68	0.63	0.63	0.63	0.58	0.58	0.58	0.54	0.54	0.54	0.51
		1	0.65	0.62	0.59	0.62	0.59	0.57	0.55	0.53	0.52	0.51	0.50	0.48	0.47	0.46	0.45	0.43
		2	0.59	0.55	0.51	0.57	0.53	0.49	0.49	0.46	0.43	0.45	0.43	0.41	0.42	0.40	0.39	0.37
		3	0.54	0.48	0.44	0.52	0.47	0.42	0.43	0.40	0.37	0.40	0.38	0.35	0.38	0.35	0.33	0.32
		4	0.50	0.43	0.38	0.48	0.42	0.37	0.39	0.35	0.32	0.36	0.33	0.30	0.34	0.31	0.29	0.27
		5	0.46	0.38	0.33	0.44	0.37	0.32	0.35	0.31	0.27	0.32	0.29	0.26	0.30	0.27	0.25	0.24
		6	0.42	0.34	0.29	0.40	0.33	0.28	0.31	0.27	0.24	0.29	0.26	0.23	0.27	0.24	0.22	0.21
		7	0.39	0.31	0.26	0.37	0.30	0.25	0.28	0.24	0.21	0.27	0.23	0.20	0.25	0.22	0.19	0.18
		8	0.36	0.28	0.23	0.35	0.27	0.22	0.26	0.21	0.18	0.24	0.20	0.18	0.23	0.19	0.17	0.16
		9	0.34	0.25	0.21	0.32	0.25	0.20	0.23	0.19	0.16	0.22	0.18	0.16	0.21	0.18	0.15	0.14
High bay, open prismatic reflector, wide		10	0.31	0.23	0.19	0.30	0.23	0.18	0.21	0.17	0.15	0.20	0.17	0.14	0.19	0.16	0.14	0.12
18 			EFF = 72.5%			% DN = 97.8%			% UP = 2.2%			Lamp = M400/C/U SC (along, across, 45°) = 1.7, 1.7, 1.7						
		0	0.86	0.86	0.86	0.84	0.84	0.84	0.80	0.80	0.80	0.76	0.76	0.76	0.73	0.73	0.73	0.71
		1	0.78	0.75	0.71	0.76	0.73	0.70	0.69	0.67	0.65	0.66	0.64	0.63	0.63	0.62	0.60	0.59
		2	0.71	0.65	0.60	0.69	0.63	0.59	0.60	0.56	0.53	0.58	0.54	0.52	0.55	0.53	0.50	0.49
		3	0.64	0.56	0.50	0.62	0.55	0.50	0.53	0.48	0.44	0.51	0.46	0.43	0.48	0.45	0.42	0.40
		4	0.59	0.50	0.43	0.57	0.49	0.42	0.47	0.41	0.37	0.45	0.40	0.36	0.43	0.39	0.36	0.34
		5	0.54	0.44	0.37	0.52	0.43	0.37	0.41	0.36	0.32	0.40	0.35	0.31	0.38	0.34	0.31	0.29
		6	0.49	0.39	0.33	0.48	0.39	0.32	0.37	0.31	0.27	0.36	0.31	0.27	0.34	0.30	0.26	0.25
		7	0.46	0.35	0.29	0.44	0.35	0.28	0.33	0.28	0.24	0.32	0.27	0.23	0.31	0.27	0.23	0.22
		8	0.42	0.32	0.26	0.41	0.31	0.25	0.30	0.25	0.21	0.29	0.24	0.21	0.28	0.24	0.21	0.19
		9	0.39	0.29	0.23	0.38	0.29	0.23	0.28	0.22	0.19	0.27	0.22	0.18	0.26	0.22	0.18	0.17
Low bay with drop lens, narrow		10	0.37	0.27	0.21	0.36	0.26	0.21	0.26	0.20	0.17	0.25	0.20	0.17	0.24	0.20	0.16	0.15
19 			EFF = 75.3%			% DN = 8.1			% UP = 91.9			Lamp = M175/C* SC (along, across, 45°) = 1.3, 1.3, 1.5						
		0	0.73	0.73	0.73	0.63	0.63	0.63	0.45	0.45	0.45	0.29	0.29	0.29	0.13	0.13	0.13	0.06
		1	0.66	0.63	0.60	0.57	0.55	0.52	0.39	0.38	0.36	0.25	0.24	0.23	0.11	0.11	0.11	0.05
		2	0.60	0.55	0.51	0.52	0.48	0.44	0.34	0.32	0.30	0.21	0.20	0.19	0.10	0.09	0.09	0.04
		3	0.55	0.48	0.43	0.47	0.42	0.37	0.30	0.27	0.25	0.19	0.17	0.16	0.09	0.08	0.07	0.03
		4	0.50	0.42	0.37	0.43	0.37	0.32	0.26	0.23	0.21	0.17	0.15	0.13	0.08	0.07	0.06	0.02
		5	0.46	0.37	0.32	0.39	0.33	0.28	0.23	0.20	0.18	0.15	0.13	0.11	0.07	0.06	0.05	0.02
		6	0.42	0.33	0.28	0.36	0.29	0.24	0.21	0.18	0.15	0.13	0.11	0.10	0.06	0.05	0.05	0.02
		7	0.39	0.30	0.24	0.33	0.26	0.21	0.19	0.16	0.13	0.12	0.10	0.09	0.05	0.05	0.04	0.02
		8	0.36	0.27	0.21	0.31	0.23	0.19	0.17	0.14	0.12	0.11	0.09	0.07	0.05	0.04	0.03	0.01
		9	0.33	0.24	0.19	0.28	0.21	0.17	0.15	0.12	0.10	0.10	0.08	0.07	0.05	0.04	0.03	0.01
Glowing suspended bowl, MH		10	0.31	0.22	0.17	0.26	0.19	0.15	0.14	0.11	0.09	0.09	0.07	0.06	0.04	0.03	0.03	0.01
20 			EFF = 81.5%			% DN = 15.3			% UP = 84.7			Lamp = (4) FT39* SC (along, across, 45°) = 1.3, 1.3, 1.5						
		0	0.81	0.81	0.81	0.71	0.71	0.71	0.52	0.52	0.52	0.35	0.35	0.35	0.20	0.20	0.20	0.13
		1	0.73	0.69	0.66	0.64	0.61	0.58	0.45	0.43	0.42	0.30	0.29	0.28	0.17	0.16	0.16	0.10
		2	0.66	0.60	0.55	0.58	0.53	0.49	0.39	0.36	0.34	0.26	0.25	0.23	0.15	0.14	0.13	0.08
		3	0.60	0.53	0.47	0.53	0.46	0.42	0.34	0.31	0.29	0.23	0.21	0.20	0.13	0.12	0.11	0.06
		4	0.55	0.47	0.40	0.48	0.41	0.36	0.30	0.27	0.24	0.20	0.18	0.17	0.11	0.10	0.09	0.05
		5	0.50	0.41	0.35	0.44	0.36	0.31	0.27	0.23	0.20	0.18	0.16	0.14	0.10	0.09	0.08	0.05
		6	0.46	0.37	0.30	0.40	0.32	0.27	0.24	0.20	0.18	0.16	0.14	0.12	0.09	0.08	0.07	0.04
		7	0.42	0.33	0.27	0.37	0.29	0.24	0.22	0.18	0.15	0.15	0.12	0.11	0.08	0.07	0.06	0.04
		8	0.39	0.30	0.24	0.34	0.26	0.21	0.20	0.16	0.13	0.13	0.11	0.09	0.08	0.06	0.05	0.03
		9	0.36	0.27	0.21	0.32	0.24	0.19	0.18	0.14	0.12	0.12	0.10	0.08	0.07	0.06	0.05	0.03
Glowing suspended bowl, CFL		10	0.34	0.25	0.19	0.30	0.22	0.17	0.16	0.13	0.11	0.11	0.09	0.07	0.06	0.05	0.04	0.03

Figure 9-28 *Continued*

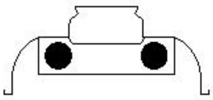
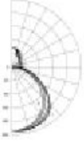
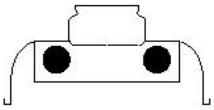
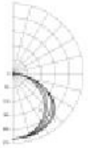
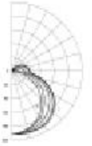
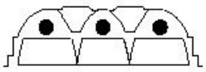
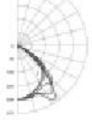
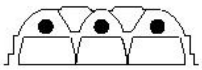
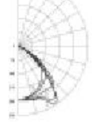
Typical Luminaire	Typical Intensity Distribution	ρcc →	80			70			50			30			10			0
		ρw →	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
		RCR ↓	EFF = 90.5%			% DN = 78.2%			% UP = 21.8%			Lamp = (2) F40T12 SC (along, across, 45°) = 1.3, 1.5, 1.5						
21  Industrial, white enamel reflector, 20% up		0	1.03	1.03	1.03	0.98	0.98	0.98	0.90	0.90	0.90	0.82	0.82	0.82	0.74	0.74	0.74	0.71
		1	0.93	0.89	0.85	0.89	0.85	0.81	0.77	0.74	0.72	0.70	0.68	0.66	0.64	0.62	0.61	0.58
		2	0.84	0.77	0.71	0.80	0.74	0.68	0.67	0.63	0.59	0.61	0.58	0.54	0.56	0.53	0.50	0.47
		3	0.77	0.67	0.60	0.73	0.64	0.58	0.59	0.53	0.49	0.54	0.49	0.45	0.49	0.45	0.42	0.40
		4	0.70	0.59	0.51	0.66	0.57	0.50	0.52	0.46	0.41	0.48	0.43	0.39	0.44	0.39	0.36	0.33
		5	0.64	0.53	0.45	0.61	0.51	0.43	0.46	0.40	0.35	0.43	0.37	0.33	0.39	0.35	0.31	0.29
		6	0.59	0.47	0.39	0.56	0.45	0.38	0.42	0.35	0.31	0.38	0.33	0.29	0.35	0.31	0.27	0.25
		7	0.55	0.43	0.35	0.52	0.41	0.34	0.38	0.32	0.27	0.35	0.30	0.26	0.32	0.28	0.24	0.22
		8	0.51	0.39	0.31	0.48	0.37	0.30	0.34	0.28	0.24	0.32	0.27	0.23	0.29	0.25	0.21	0.19
		9	0.47	0.35	0.28	0.45	0.34	0.27	0.32	0.26	0.21	0.29	0.24	0.20	0.27	0.23	0.19	0.17
		10	0.44	0.33	0.26	0.42	0.31	0.25	0.29	0.23	0.19	0.27	0.22	0.18	0.25	0.21	0.17	0.16
22  Industrial, white enamel reflector, down only			EFF = 86.9%			% DN = 100%			% UP = 0%			Lamp = (2) F40T12 SC (along, across, 45°) = 1.3, 1.5, 1.5						
		0	1.03	1.03	1.03	1.01	1.01	1.01	0.97	0.97	0.97	0.92	0.92	0.92	0.89	0.89	0.89	0.87
		1	0.94	0.90	0.86	0.92	0.88	0.84	0.84	0.81	0.79	0.81	0.79	0.76	0.78	0.76	0.74	0.72
		2	0.85	0.78	0.72	0.83	0.76	0.70	0.73	0.68	0.64	0.70	0.66	0.63	0.67	0.64	0.61	0.59
		3	0.77	0.68	0.60	0.75	0.66	0.59	0.64	0.58	0.53	0.61	0.56	0.52	0.59	0.55	0.51	0.49
		4	0.70	0.60	0.52	0.68	0.58	0.51	0.56	0.50	0.45	0.54	0.48	0.44	0.52	0.47	0.43	0.41
		5	0.65	0.53	0.45	0.63	0.52	0.44	0.50	0.43	0.38	0.48	0.42	0.38	0.47	0.41	0.37	0.35
		6	0.59	0.47	0.39	0.58	0.47	0.39	0.45	0.38	0.33	0.43	0.37	0.33	0.42	0.37	0.32	0.31
		7	0.55	0.43	0.35	0.53	0.42	0.35	0.41	0.34	0.29	0.39	0.33	0.29	0.38	0.33	0.29	0.27
		8	0.51	0.39	0.31	0.50	0.38	0.31	0.37	0.30	0.26	0.36	0.30	0.26	0.35	0.29	0.25	0.24
		9	0.48	0.36	0.28	0.46	0.35	0.28	0.34	0.28	0.23	0.33	0.27	0.23	0.32	0.27	0.23	0.21
		10	0.45	0.33	0.26	0.43	0.32	0.25	0.31	0.25	0.21	0.31	0.25	0.21	0.30	0.24	0.21	0.19
23  2-Lamp bare strip			EFF = 89.3%			% DN = 86.4%			% UP = 13.6%			Lamp = (2) F40T12 SC (along, across, 45°) = 1.3, 1.5, 1.6						
		0	1.03	1.03	1.03	1.00	1.00	1.00	0.92	0.92	0.92	0.86	0.86	0.86	0.80	0.80	0.80	0.77
		1	0.93	0.88	0.83	0.89	0.84	0.80	0.78	0.75	0.72	0.73	0.70	0.68	0.67	0.65	0.63	0.61
		2	0.83	0.75	0.68	0.80	0.72	0.66	0.67	0.62	0.58	0.62	0.58	0.55	0.58	0.55	0.52	0.49
		3	0.75	0.65	0.57	0.72	0.63	0.56	0.58	0.52	0.47	0.54	0.49	0.45	0.50	0.46	0.43	0.40
		4	0.69	0.57	0.49	0.65	0.55	0.47	0.51	0.45	0.40	0.48	0.42	0.38	0.44	0.40	0.36	0.34
		5	0.63	0.51	0.42	0.60	0.49	0.41	0.46	0.39	0.34	0.43	0.37	0.32	0.40	0.35	0.31	0.29
		6	0.58	0.45	0.37	0.55	0.44	0.36	0.41	0.34	0.29	0.38	0.32	0.28	0.36	0.31	0.27	0.25
		7	0.53	0.41	0.33	0.51	0.40	0.32	0.37	0.30	0.26	0.35	0.29	0.25	0.33	0.27	0.24	0.22
		8	0.50	0.37	0.29	0.47	0.36	0.29	0.34	0.27	0.23	0.32	0.26	0.22	0.30	0.25	0.21	0.19
		9	0.46	0.34	0.26	0.44	0.33	0.26	0.31	0.25	0.20	0.29	0.24	0.19	0.27	0.22	0.19	0.17
		10	0.43	0.31	0.24	0.41	0.30	0.23	0.29	0.22	0.18	0.27	0.21	0.18	0.25	0.20	0.17	0.15
24  2 × 4, 3-Lamp parabolic troffer with 3″ semi-spec. louvers, 18 cells			EFF = 72.7%			% DN = 100			% UP = 0			Lamp = (3) F32T8 SC (along, across, 45°) = 1.3, 1.6, 1.6						
		0	0.87	0.87	0.87	0.85	0.85	0.85	0.81	0.81	0.81	0.77	0.77	0.77	0.74	0.74	0.74	0.73
		1	0.81	0.78	0.76	0.79	0.77	0.74	0.74	0.72	0.70	0.71	0.69	0.68	0.68	0.67	0.66	0.65
		2	0.75	0.70	0.66	0.73	0.69	0.65	0.66	0.63	0.61	0.64	0.61	0.59	0.62	0.60	0.58	0.57
		3	0.69	0.63	0.58	0.68	0.62	0.57	0.60	0.56	0.52	0.58	0.54	0.52	0.56	0.53	0.51	0.49
		4	0.64	0.56	0.51	0.62	0.55	0.50	0.54	0.49	0.46	0.52	0.48	0.45	0.51	0.47	0.44	0.43
		5	0.59	0.51	0.45	0.58	0.50	0.44	0.48	0.44	0.40	0.47	0.43	0.40	0.46	0.42	0.39	0.38
		6	0.55	0.46	0.40	0.53	0.45	0.40	0.44	0.39	0.35	0.43	0.38	0.35	0.42	0.38	0.35	0.33
		7	0.51	0.42	0.36	0.50	0.41	0.36	0.40	0.35	0.31	0.39	0.35	0.31	0.38	0.34	0.31	0.30
		8	0.47	0.38	0.32	0.46	0.38	0.32	0.37	0.32	0.28	0.36	0.31	0.28	0.35	0.31	0.28	0.27
		9	0.44	0.35	0.29	0.43	0.35	0.29	0.34	0.29	0.25	0.33	0.29	0.25	0.32	0.28	0.25	0.24
		10	0.41	0.32	0.27	0.40	0.32	0.27	0.31	0.26	0.23	0.31	0.26	0.23	0.30	0.26	0.23	0.22
25  2 × 4, 3-Lamp parabolic troffer with 4″ semi-spec. louvers, 18 cells			EFF = 66.2%			% DN = 100			% UP = 0			Lamp = (3) F40T12 SC (along, across, 45°) = 1.3, 1.6, 1.5						
		0	0.79	0.79	0.79	0.77	0.77	0.77	0.74	0.74	0.74	0.70	0.70	0.70	0.68	0.68	0.68	0.66
		1	0.74	0.72	0.69	0.72	0.70	0.68	0.67	0.66	0.64	0.65	0.64	0.62	0.62	0.61	0.61	0.59
		2	0.69	0.64	0.61	0.67	0.63	0.60	0.61	0.58	0.56	0.59	0.57	0.55	0.57	0.55	0.53	0.52
		3	0.63	0.58	0.53	0.62	0.57	0.53	0.55	0.51	0.48	0.53	0.50	0.48	0.52	0.49	0.47	0.46
		4	0.59	0.52	0.47	0.57	0.51	0.47	0.50	0.46	0.42	0.48	0.45	0.42	0.47	0.44	0.41	0.40
		5	0.54	0.47	0.42	0.53	0.46	0.41	0.45	0.41	0.37	0.44	0.40	0.37	0.43	0.39	0.37	0.35
		6	0.50	0.43	0.37	0.49	0.42	0.37	0.41	0.36	0.33	0.40	0.36	0.33	0.39	0.35	0.33	0.31
		7	0.47	0.39	0.33	0.46	0.38	0.33	0.37	0.33	0.30	0.36	0.32	0.29	0.35	0.32	0.29	0.28
		8	0.44	0.35	0.30	0.43	0.35	0.30	0.34	0.30	0.26	0.33	0.29	0.26	0.33	0.29	0.26	0.25
		9	0.41	0.33	0.27	0.40	0.32	0.27	0.31	0.27	0.24	0.31	0.27	0.24	0.30	0.26	0.24	0.23
		10	0.38	0.30	0.25	0.37	0.30	0.25	0.29	0.25	0.22	0.28	0.24	0.22	0.28	0.24	0.22	0.20

Figure 9-28 *Continued*

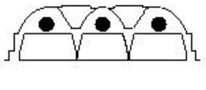
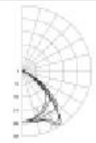
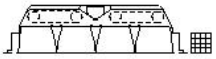
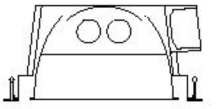
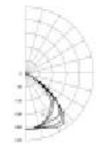
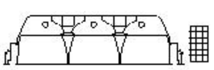
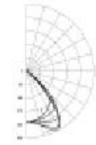
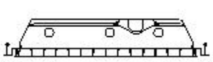
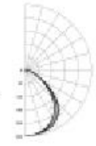
Typical Luminaire	Typical Intensity Distribution	ρcc →	80			70			50			30			10			0
		ρw →	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
		RCR ↓	EFF = 67.8%			% DN = 100%			% UP = 0%			Lamp = (3) FT40 SC (along, across, 45°) = 1.3, 1.6, 1.6						
26 		0	0.81	0.81	0.81	0.79	0.79	0.79	0.75	0.75	0.75	0.72	0.72	0.72	0.69	0.69	0.69	0.68
		1	0.75	0.73	0.71	0.74	0.71	0.69	0.69	0.67	0.66	0.66	0.65	0.64	0.64	0.63	0.62	0.60
		2	0.70	0.65	0.62	0.68	0.64	0.61	0.62	0.59	0.57	0.60	0.57	0.55	0.58	0.56	0.54	0.53
		3	0.65	0.59	0.54	0.63	0.58	0.53	0.56	0.52	0.49	0.54	0.51	0.48	0.52	0.50	0.47	0.46
		4	0.60	0.53	0.48	0.58	0.52	0.47	0.50	0.46	0.43	0.49	0.45	0.42	0.47	0.44	0.42	0.40
		5	0.55	0.47	0.42	0.54	0.47	0.42	0.45	0.41	0.38	0.44	0.40	0.37	0.43	0.40	0.37	0.35
		6	0.51	0.43	0.38	0.50	0.42	0.37	0.41	0.37	0.33	0.40	0.36	0.33	0.39	0.36	0.33	0.31
		7	0.47	0.39	0.34	0.46	0.39	0.33	0.38	0.33	0.30	0.37	0.32	0.29	0.36	0.32	0.29	0.28
		8	0.44	0.36	0.30	0.43	0.35	0.30	0.34	0.30	0.27	0.34	0.29	0.26	0.33	0.29	0.26	0.25
2 × 2, 3-Lamp with 3″ semi-spec. louvers, 9 cells		9	0.41	0.33	0.28	0.40	0.32	0.27	0.32	0.27	0.24	0.31	0.27	0.24	0.30	0.26	0.24	0.23
		10	0.39	0.30	0.25	0.38	0.30	0.25	0.29	0.25	0.22	0.29	0.25	0.22	0.28	0.24	0.22	0.20
27			EFF = 50.8%			% DN = 100%			% UP = 0%			Lamp = (2) F31T8/U/6 SC (along, across, 45°) = 1.2, 1.5, 1.4						
		0	0.61	0.61	0.61	0.59	0.59	0.59	0.56	0.56	0.56	0.56	0.56	0.56	0.54	0.54	0.54	0.52
		1	0.57	0.55	0.53	0.55	0.54	0.52	0.52	0.50	0.49	0.52	0.50	0.49	0.50	0.49	0.48	0.47
		2	0.53	0.49	0.47	0.51	0.48	0.46	0.47	0.45	0.43	0.47	0.45	0.43	0.45	0.43	0.42	0.42
		3	0.49	0.44	0.41	0.48	0.43	0.40	0.42	0.39	0.37	0.42	0.39	0.37	0.41	0.38	0.37	0.38
		4	0.45	0.40	0.36	0.44	0.39	0.36	0.38	0.35	0.32	0.38	0.35	0.32	0.37	0.34	0.32	0.34
		5	0.42	0.36	0.32	0.41	0.35	0.32	0.34	0.31	0.29	0.34	0.31	0.29	0.33	0.31	0.28	0.30
		6	0.39	0.33	0.29	0.38	0.32	0.28	0.31	0.28	0.25	0.31	0.28	0.25	0.30	0.27	0.25	0.27
2 × 2, 2-Lamp (U) parabolic troffer with 3″ semi-spec. louver, 16 cells		7	0.36	0.30	0.26	0.35	0.29	0.25	0.29	0.25	0.23	0.29	0.25	0.23	0.28	0.25	0.22	0.24
		8	0.33	0.27	0.23	0.33	0.27	0.23	0.26	0.23	0.20	0.26	0.23	0.20	0.26	0.22	0.20	0.22
		9	0.31	0.25	0.21	0.31	0.25	0.21	0.24	0.21	0.18	0.24	0.21	0.18	0.24	0.20	0.18	0.20
		10	0.29	0.23	0.19	0.29	0.23	0.19	0.22	0.19	0.17	0.22	0.19	0.17	0.22	0.19	0.17	0.19
28			EFF = 67.2%			% DN = 100%			% UP = 0%			Lamp = (2) F32T8 SC (along, across, 45°) = 1.3, 1.6, 1.5						
		0	0.80	0.80	0.80	0.78	0.78	0.78	0.75	0.75	0.75	0.72	0.72	0.72	0.69	0.69	0.69	0.67
		1	0.75	0.73	0.70	0.73	0.71	0.69	0.68	0.67	0.65	0.66	0.64	0.63	0.63	0.62	0.61	0.60
		2	0.70	0.65	0.61	0.68	0.64	0.61	0.62	0.59	0.56	0.59	0.57	0.55	0.58	0.56	0.54	0.53
		3	0.64	0.58	0.54	0.63	0.57	0.53	0.55	0.52	0.49	0.54	0.51	0.48	0.52	0.49	0.47	0.46
		4	0.59	0.52	0.47	0.58	0.52	0.47	0.50	0.46	0.43	0.49	0.45	0.42	0.47	0.44	0.42	0.40
		5	0.55	0.47	0.42	0.54	0.47	0.42	0.45	0.41	0.37	0.44	0.40	0.37	0.43	0.39	0.37	0.35
		6	0.51	0.43	0.37	0.50	0.42	0.37	0.41	0.36	0.33	0.40	0.36	0.33	0.39	0.35	0.33	0.31
1 × 4, 2-Lamp parabolic troffer with 3″ semi-spec. louver, 8 or 9 cells		7	0.47	0.39	0.34	0.46	0.38	0.33	0.37	0.33	0.29	0.36	0.32	0.29	0.36	0.32	0.29	0.28
		8	0.44	0.36	0.30	0.43	0.35	0.30	0.34	0.30	0.26	0.33	0.29	0.26	0.33	0.29	0.26	0.25
		9	0.41	0.33	0.27	0.40	0.32	0.27	0.31	0.27	0.24	0.31	0.27	0.24	0.30	0.26	0.24	0.22
		10	0.38	0.30	0.25	0.38	0.30	0.25	0.29	0.25	0.22	0.28	0.24	0.21	0.28	0.24	0.21	0.20
29			EFF = 67.2%			% DN = 100			% UP = 0			Lamp = (3) F32T8 SC (along, across, 45°) = 1.3, 1.5, 1.5						
		0	0.80	0.80	0.80	0.78	0.78	0.78	0.75	0.75	0.75	0.72	0.72	0.72	0.69	0.69	0.69	0.67
		1	0.76	0.74	0.72	0.74	0.72	0.70	0.69	0.68	0.67	0.67	0.66	0.65	0.64	0.64	0.63	0.62
		2	0.71	0.67	0.64	0.70	0.66	0.63	0.64	0.62	0.59	0.62	0.60	0.58	0.60	0.58	0.57	0.56
		3	0.67	0.62	0.58	0.65	0.61	0.57	0.59	0.56	0.53	0.57	0.54	0.52	0.55	0.53	0.51	0.50
		4	0.62	0.56	0.52	0.61	0.56	0.51	0.54	0.50	0.48	0.53	0.50	0.47	0.51	0.49	0.47	0.45
		5	0.58	0.52	0.47	0.57	0.51	0.47	0.50	0.46	0.43	0.49	0.45	0.43	0.47	0.44	0.42	0.41
		6	0.55	0.47	0.43	0.53	0.47	0.42	0.46	0.42	0.39	0.45	0.41	0.39	0.44	0.41	0.38	0.37
		7	0.51	0.44	0.39	0.50	0.43	0.39	0.42	0.38	0.35	0.41	0.38	0.35	0.41	0.37	0.35	0.34
2 × 4, 3-Lamp parabolic troffer, spec. louvers, 18 cells, RP-1		8	0.48	0.40	0.36	0.47	0.40	0.35	0.39	0.35	0.32	0.38	0.35	0.32	0.38	0.34	0.32	0.31
		9	0.45	0.37	0.33	0.44	0.37	0.32	0.36	0.32	0.29	0.36	0.32	0.29	0.35	0.32	0.29	0.28
		10	0.42	0.35	0.30	0.42	0.34	0.30	0.34	0.30	0.27	0.33	0.29	0.27	0.33	0.29	0.27	0.26
30			EFF = 51.4%			% DN = 100			% UP = 0			Lamp = (3) F32T8 SC (along, across, 45°) = 1.3, 1.3, 1.5						
		0	0.68	0.61	0.55	0.67	0.60	0.55	0.58	0.53	0.50	0.56	0.52	0.49	0.54	0.51	0.48	0.46
		1	0.63	0.55	0.49	0.61	0.54	0.48	0.52	0.47	0.43	0.50	0.46	0.42	0.49	0.45	0.42	0.40
		2	0.58	0.49	0.43	0.57	0.48	0.42	0.47	0.42	0.38	0.45	0.41	0.37	0.44	0.40	0.37	0.35
		3	0.54	0.44	0.38	0.52	0.44	0.38	0.42	0.37	0.33	0.41	0.37	0.33	0.40	0.36	0.33	0.31
		4	0.50	0.40	0.34	0.49	0.40	0.34	0.39	0.34	0.30	0.38	0.33	0.29	0.31	0.33	0.29	0.28
		5	0.47	0.37	0.31	0.46	0.37	0.31	0.36	0.30	0.27	0.35	0.30	0.26	0.34	0.30	0.26	0.25
		6	0.44	0.34	0.28	0.43	0.34	0.28	0.33	0.28	0.24	0.32	0.27	0.24	0.31	0.27	0.24	0.23
		7	0.41	0.32	0.26	0.40	0.31	0.26	0.30	0.25	0.22	0.30	0.25	0.22	0.29	0.25	0.22	0.21
2 × 4, 3-Lamp parabolic troffer, 1.5 × 1.5 × 1.0″ silver louvers, RP-1		8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		10	0.77	0.77	0.77	0.76	0.76	0.76	0.72	0.72	0.72	0.69	0.69	0.69	0.66	0.66	0.66	0.65

Figure 9-28 *Continued*

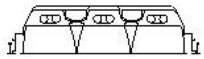
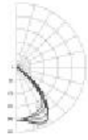
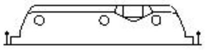
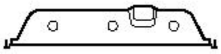
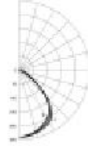
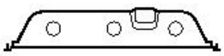
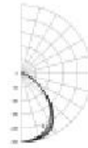
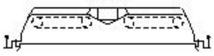
Typical Luminaire	Typical Intensity Distribution	ρcc →	80			70			50			30			10			0
		ρw →	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
		RCR ↓	EFF = 64.6%			% DN = 100%			% UP = 0%			Lamp = (3) F31T8/U/6 SC (along, across, 45°) = 1.3, 1.5, 1.3						
31  2 × 2, 3-Lamp troffer, spec. louvers, 12 cells, RP-1		0	0.77	0.77	0.77	0.75	0.75	0.75	0.72	0.72	0.72	0.69	0.69	0.69	0.66	0.66	0.66	0.65
		1	0.73	0.71	0.69	0.71	0.69	0.68	0.67	0.65	0.64	0.64	0.63	0.62	0.62	0.61	0.60	0.59
		2	0.68	0.65	0.62	0 67	0.64	0.61	0.61	0.59	0.57	0.59	0.58	0.56	0.58	0.56	0.55	0.54
		3	0.64	0.59	0.55	0.63	0.58	0.55	0.56	0.54	0.51	0.55	0.52	0.50	0.53	0.51	0.50	0.48
		4	0.60	0.54	0.50	0.59	0.53	0.50	0.52	0.49	0.46	0.51	0.48	0.45	0.49	0.47	0.45	0.44
		5	0.56	0.50	0.45	0.55	0.49	0.45	0.48	0.44	0.41	0.47	0.43	0.41	0.46	0.43	0.41	0.39
		6	0.53	0.46	0.41	0.51	0.45	0.41	0.44	0.40	0.37	0.43	0.40	0.37	0.42	0.39	0.37	0.36
		7	0.49	0.42	0.38	0.48	0.42	0.37	0.41	0.37	0.34	0.40	0.36	0.34	0.39	0.36	0.34	0.33
		8	0.46	0.39	0.34	0.45	0.39	0.34	0.38	0.34	0.31	0.37	0.33	0.31	0.36	0.33	0.31	0.30
		9	0.43	0.36	0.32	0.43	0.36	0.31	0.35	0.31	0.28	0.34	0.31	0.28	0.34	0.31	0.28	0.27
		10	0.41	0.33	0.29	0.40	0.33	0.29	0.33	0.29	0.26	0.32	0.28	0.26	0.32	0.28	0.26	0.25
32  2 × 4, 3-Lamp troffer with A12 lens			EFF = 75.6%			% DN = 100%			% UP = 0%			Lamp = (3) F32T8 SC (along, across, 45°) = 1.3, 1.3, 1.4						
		0	0.90	0.90	0.90	0.88	0.88	0.88	0.84	0.84	0.84	0.80	0.80	0.80	0.77	0.77	0.77	0.76
		1	0.83	0.79	0.76	0.81	0.78	0.75	0.75	0.72	0.70	0.72	0.70	0.68	0.69	0.67	0.66	0.65
		2	0.76	0.70	0.65	0.74	0.69	0.64	0.66	0.62	0.59	0.64	0.61	0.58	0.61	0.59	0.57	0.55
		3	0.70	0.62	0.57	0.68	0.61	0.56	0.59	0.54	0.51	0.57	0.53	0.50	0.55	0.52	0.49	0.47
		4	0.64	0.56	0.49	0.63	0.55	0.49	0.53	0.48	0.44	0.51	0.47	0.43	0.49	0.46	0.43	0.41
		5	0.59	0.50	0.44	0.58	0.49	0.43	0.48	0.42	0.38	0.46	0.41	0.38	0.45	0.41	0.37	0.36
		6	0.55	0.45	0.39	0.53	0.45	0.38	0.43	0.38	0.34	0.42	0.37	0.33	0.41	0.37	0.33	0.32
		7	0.51	0.41	0.35	0.50	0.41	0.35	0.39	0.34	0.30	0.38	0.33	0.30	0.37	0.33	0.30	0.28
		8	0.48	0.38	0.31	0.46	0.37	0.31	0.36	0.31	0.27	0.35	0.30	0.27	0.34	0.30	0.27	0.25
		9	0.44	0.35	0.29	0.43	0.34	0.28	0.33	0.28	0.24	0.33	0.28	0.24	0.32	0.27	0.24	0.23
		10	0.42	0.32	0.26	0.41	0.32	0.26	0.31	0.26	0.22	0.30	0.25	0.22	0.29	0.25	0.22	0.21
33  2 × 4, 3-Lamp troffer with A19 lens			EFF = 72.4%			% DN = 100%			% UP = 0%			Lamp = (3) F32T8 SC (along, across, 45°) = 1.3, 1.3, 1.3						
		0	0.86	0.86	0.86	0.84	0.84	0.84	0.80	0.80	0.80	0.77	0.77	0.77	0.74	0.74	0.74	0.72
		1	0.80	0.77	0.75	0.78	0.76	0.73	0.73	0.71	0.69	0.70	0.68	0.67	0.67	0.66	0.65	0.63
		2	0.74	0.69	0.65	0.72	0.68	0.64	0.65	0.62	0.59	0.63	0.60	0.58	0.61	0.59	0.57	0.55
		3	0.69	0.62	0.57	0.67	0.61	0.56	0.59	0.55	0.52	0.57	0.54	0.51	0.55	0.52	0.50	0.48
		4	0.64	0.56	0.50	0.62	0.55	0.50	0.53	0.49	0.45	0.52	0.48	0.45	0.50	0.47	0.44	0.43
		5	0.59	0.51	0.45	0.58	0.50	0.45	0.48	0.44	0.40	0.47	0.43	0.40	0.46	0.42	0.39	0.38
		6	0.55	0.46	0.40	0.54	0.45	0.40	0.44	0.39	0.36	0.43	0.39	0.35	0.42	0.38	0.35	0.34
		7	0.51	0.42	0.36	0.50	0.42	0.36	0.41	0.36	0.32	0.40	0.35	0.32	0.39	0.35	0.32	0.30
		8	0.48	0.39	0.33	0.47	0.38	0.33	0.37	0.32	0.29	0.36	0.32	0.29	0.36	0.32	0.29	0.27
		9	0.45	0.36	0.30	0.44	0.35	0.30	0.35	0.30	0.26	0.34	0.29	0.26	0.33	0.29	0.26	0.25
		10	0.42	0.33	0.28	0.41	0.33	0.28	0.32	0.27	0.24	0.31	0.27	0.24	0.31	0.27	0.24	0.23
34  2 × 2, 3-Lamp troffer with A12 lens			EFF = 68.4%			% DN = 100			% UP = 0			Lamp = (3) FT40 SC (along, across, 45°) = 1.2, 1.3, 1.3						
		0	0.81	0.81	0.81	0.80	0.80	0.80	0.76	0.76	0.76	0.73	0.73	0.73	0.70	0.70	0.70	0.68
		1	0.75	0.72	0.70	0.73	0.71	0.69	0.68	0.66	0.64	0.65	0.64	0.62	0.63	0.62	0.60	0.59
		2	0.69	0.64	0.60	0.68	0.63	0.59	0.61	0.58	0.55	0.59	0.56	0.54	0.56	0.54	0.52	0.51
		3	0.64	0.57	0.52	0.62	0.56	0.52	0.54	0.50	0.47	0.53	0.49	0.46	0.51	0.48	0.46	0.44
		4	0.59	0.52	0.46	0.58	0.51	0.46	0.49	0.45	0.41	0.47	0.44	0.41	0.46	0.43	0.40	0.39
		5	0.55	0.47	0.41	0.53	0.46	0.41	0.44	0.40	0.36	0.43	0.39	0.36	0.42	0.38	0.35	0.34
		6	0.51	0.42	0.37	0.49	0.42	0.36	0.40	0.36	0.32	0.39	0.35	0.32	0.38	0.35	0.32	0.30
		7	0.47	0.39	0.33	0.46	0.38	0.33	0.37	0.32	0.29	0.36	0.32	0.29	0.35	0.31	0.28	0.27
		8	0.44	0.35	0.30	0.43	0.35	0.30	0.34	0.29	0.26	0.33	0.29	0.26	0.32	0.29	0.26	0.24
		9	0.41	0.33	0.27	0.40	0.32	0.27	0.31	0.27	0.24	0.31	0.27	0.23	0.30	0.26	0.23	0.22
		10	0.39	0.30	0.25	0.38	0.30	0.25	0.29	0.25	0.22	0.29	0.24	0.21	0.28	0.24	0.21	0.20
35  2 × 2, 2-Lamp troffer with A12 lens			EFF = 57.1%			% DN = 100			% UP = 0			Lamp = (2) F31T8/U/6 SC (along, across, 45°) = 1.2, 1.3, 1.4						
		0	0.68	0.68	0.68	0.66	0.66	0.66	0.63	0.63	0.63	0.61	0.61	0.61	0.58	0.58	0.58	0.57
		1	0.64	0.62	0.60	0.62	0.60	0.59	0.58	0.57	0.55	0.56	0.55	0.54	0.54	0.53	0.52	0.51
		2	0.59	0.55	0.52	0.58	0.54	0.51	0.52	0.50	0.48	0.51	0.49	0.47	0.49	0.47	0.46	0.45
		3	0.55	0.50	0.46	0.53	0.49	0.45	0.47	0.44	0.42	0.46	0.43	0.41	0.44	0.42	0.40	0.39
		4	0.51	0.45	0.40	0.49	0.44	0.40	0.43	0.39	0.36	0.41	0.38	0.36	0.40	0.38	0.36	0.34
		5	0.47	0.40	0.36	0.46	0.40	0.36	0.39	0.35	0.32	0.38	0.34	0.32	0.37	0.34	0.31	0.30
		6	0.43	0.37	0.32	0.42	0.36	0.32	0.35	0.31	0.28	0.34	0.31	0.28	0.33	0.30	0.28	0.27
		7	0.40	0.33	0.29	0.39	0.33	0.29	0.32	0.28	0.25	0.31	0.28	0.25	0.31	0.27	0.25	0.24
		8	0.38	0.31	0.26	0.37	0.30	0.26	0.29	0.26	0.23	0.29	0.25	0.23	0.28	0.25	0.23	0.22
		9	0.35	0.28	0.24	0.34	0.28	0.24	0.27	0.23	0.21	0.27	0.23	0.21	0.26	0.23	0.21	0.20
		10	0.33	0.26	0.22	0.32	0.26	0.22	0.25	0.21	0.19	0.25	0.21	0.19	0.24	0.21	0.19	0.18

Figure 9-28 *Continued*

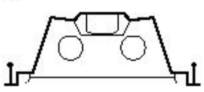
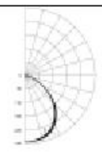
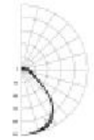
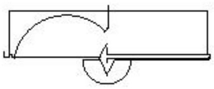
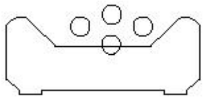
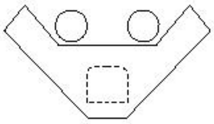
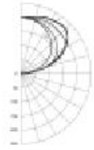
Typical Luminaire	Typical Intensity Distribution	ρcc →	80			70			50			30			10			0
		ρw →	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
36		RCR ↓	EFF = 65.1%			% DN = 100%			% UP = 0%			Lamp = (2) F32T8 SC (along, across, 45°) = 1.3, 1.3, 1.3						
		0	0.77	0.77	0.77	0.76	0.76	0.76	0.72	0.72	0.72	0.69	0.69	0.69	0.66	0.66	0.66	0.65
		1	0.71	0.69	0.66	0.70	0.67	0.65	0.64	0.62	0.61	0.62	0.60	0.59	0.59	0.58	0.57	0.56
		2	0.66	0.61	0.57	0.64	0.59	0.56	0.57	0.54	0.51	0.55	0.52	0.50	0.53	0.51	0.49	0.48
		3	0.60	0.54	0.49	0.59	0.53	0.48	0.51	0.47	0.44	0.49	0.46	0.43	0.48	0.45	0.42	0.41
		4	0.55	0.48	0.43	0.54	0.47	0.42	0.46	0.41	0.38	0.44	0.40	0.37	0.43	0.40	0.37	0.36
		5	0.51	0.43	0.38	0.50	0.43	0.37	0.41	0.37	0.33	0.40	0.36	0.33	0.39	0.35	0.33	0.31
		6	0.47	0.39	0.34	0.46	0.39	0.33	0.38	0.33	0.29	0.36	0.32	0.29	0.35	0.32	0.29	0.28
		7	0.44	0.36	0.30	0.43	0.35	0.30	0.34	0.30	0.26	0.33	0.29	0.26	0.33	0.29	0.26	0.25
		8	0.41	0.33	0.27	0.40	0.32	0.27	0.31	0.27	0.24	0.31	0.27	0.23	0.30	0.26	0.23	0.22
1 × 4, 2-Lamp troffer with A12 lens		9	0.39	0.30	0.25	0.38	0.30	0.25	0.29	0.25	0.21	0.28	0.24	0.21	0.28	0.24	0.21	0.20
		10	0.36	0.28	0.23	0.35	0.28	0.23	0.27	0.23	0.19	0.26	0.22	0.19	0.26	0.22	0.19	0.18
37			EFF = 68.9%			% DN = 91.4%			% UP = 8.6%			Lamp = (2) F32T8 SC (along, across, 45°) = 1.3, 1.5, 1.5						
		0	0.81	0.81	0.81	0.78	0.78	0.78	0.73	0.73	0.73	0.69	0.69	0.69	0.65	0.65	0.65	0.63
		1	0.74	0.71	0.68	0.71	0.68	0.66	0.64	0.62	0.60	0.61	0.59	0.58	0.57	0.56	0.55	0.53
		2	0.68	0.62	0.58	0.65	0.61	0.56	0.57	0.54	0.51	0.54	0.51	0.49	0.51	0.49	0.47	0.45
		3	0.62	0.55	0.50	0.60	0.54	0.49	0.51	0.47	0.44	0.48	0.45	0.42	0.46	0.43	0.41	0.39
		4	0.57	0.50	0.44	0.55	0.48	0.43	0.46	0.41	0.38	0.44	0.40	0.37	0.41	0.38	0.36	0.34
		5	0.53	0.45	0.39	0.51	0.43	0.38	0.41	0.37	0.33	0.39	0.35	0.32	0.38	0.34	0.31	0.30
		6	0.49	0.40	0.35	0.47	0.39	0.34	0.38	0.33	0.29	0.36	0.32	0.29	0.34	0.31	0.28	0.26
		7	0.46	0.37	0.31	0.44	0.36	0.31	0.34	0.30	0.26	0.33	0.29	0.26	0.31	0.28	0.25	0.24
		8	0.42	0.34	0.28	0.41	0.33	0.28	0.32	0.27	0.23	0.30	0.26	0.23	0.29	0.25	0.23	0.21
1 × 4, 2-Lamp lensed wrap-around, surface mounted		9	0.40	0.31	0.26	0.38	0.30	0.25	0.29	0.24	0.21	0.20	0.24	0.21	0.27	0.23	0.20	0.19
		10	0.37	0.29	0.23	0.36	0.28	0.23	0.27	0.22	0.19	0.26	0.22	0.19	0.25	0.21	0.19	0.17
38			EFF = 54.2%			% DN = 99.2%			% UP = 0.5%			Lamp = (2) FT36* SC (along, across, 45°) = 1.3, 1.5, 1.5						
		0	0.65	0.65	0.65	0.63	0.63	0.63	0.60	0.60	0.60	0.58	0.58	0.58	0.55	0.55	0.55	0.54
		1	0.58	0.55	0.53	0.57	0.54	0.52	0.52	0.50	0.48	0.49	0.48	0.46	0.47	0.46	0.45	0.44
		2	0.53	0.48	0.44	0.51	0.47	0.43	0.45	0.41	0.39	0.43	0.40	0.38	0.41	0.39	0.37	0.36
		3	0.48	0.42	0.37	0.46	0.41	0.36	0.39	0.35	0.32	0.37	0.34	0.31	0.36	0.33	0.31	0.30
		4	0.43	0.37	0.32	0.42	0.36	0.31	0.34	0.30	0.27	0.33	0.29	0.27	0.32	0.29	0.26	0.25
		5	0.40	0.33	0.27	0.39	0.32	0.27	0.31	0.26	0.23	0.30	0.26	0.23	0.28	0.25	0.23	0.21
		6	0.37	0.29	0.24	0.36	0.29	0.24	0.28	0.23	0.20	0.27	0.23	0.20	0.26	0.22	0.20	0.19
		7	0.34	0.26	0.21	0.33	0.26	0.21	0.25	0.21	0.18	0.24	0.20	0.18	0.23	0.20	0.17	0.16
		8	0.32	0.24	0.19	0.31	0.24	0.19	0.23	0.19	0.16	0.22	0.18	0.16	0.21	0.18	0.15	0.14
		9	0.29	0.22	0.17	0.29	0.22	0.17	0.21	0.17	0.14	0.20	0.17	0.14	0.20	0.16	0.14	0.13
2 × 2, semi-recessed troffer		10	0.28	0.20	0.16	0.27	0.20	0.16	0.19	0.15	0.13	0.19	0.15	0.13	0.18	0.15	0.13	0.12
39			EFF = 84.1%			% DN = 0			% UP = 100			Lamp = (2) F32T8 SC (along, across, 45°) = N/A						
		0	0.80	0.80	0.80	0.68	0.68	0.68	0.47	0.47	0.47	0.27	0.27	0.27	0.09	0.09	0.09	0.00
		1	0.73	0.69	0.66	0.62	0.59	0.57	0.41	0.39	0.38	0.23	0.23	0.22	0.07	0.07	0.07	0.00
		2	0.66	0.61	0.56	0.56	0.52	0.48	0.36	0.33	0.31	0.21	0.19	0.18	0.07	0.06	0.06	0.00
		3	0.60	0.53	0.48	0.51	0.46	0.41	0.31	0.28	0.26	0.18	0.17	0.15	0.06	0.05	0.05	0.00
		4	0.55	0.47	0.41	0.47	0.40	0.35	0.28	0.25	0.22	0.16	0.14	0.13	0.05	0.05	0.04	0.00
		5	0.50	0.41	0.35	0.43	0.36	0.30	0.24	0.21	0.19	0.14	0.12	0.11	0.05	0.04	0.04	0.00
		6	0.46	0.37	0.31	0.39	0.32	0.27	0.22	0.19	0.16	0.13	0.11	0.10	0.04	0.04	0.03	0.00
		7	0.42	0.33	0.27	0.36	0.28	0.23	0.20	0.16	0.14	0.11	0.10	0.08	0.04	0.03	0.03	0.00
		8	0.39	0.30	0.24	0.33	0.26	0.21	0.18	0.14	0.12	0.10	0.09	0.07	0.03	0.03	0.02	0.00
9″ Wide, thin profile, wide spread indirect		9	0.36	0.27	0.21	0.31	0.23	0.18	0.16	0.13	0.11	0.09	0.08	0.06	0.03	0.02	0.02	0.00
		10	0.34	0.24	0.19	0.29	0.21	0.16	0.15	0.11	0.09	0.08	0.07	0.06	0.03	0.02	0.02	0.00
40			EFF = 88.3%			% DN = 0			% UP = 100			Lamp = (2) F32T8 SC (along, across, 45°) = N/A						
		0	0.84	0.84	0.84	0.72	0.72	0.72	0.49	0.49	0.49	0.28	0.28	0.28	0.09	0.09	0.09	0.00
		1	0.76	0.73	0.70	0.65	0.62	0.60	0.43	0.41	0.40	0.25	0.24	0.23	0.08	0.08	0.07	0.00
		2	0.70	0.64	0.59	0.59	0.54	0.50	0.37	0.35	0.33	0.22	0.20	0.19	0.07	0.07	0.06	0.00
		3	0.63	0.56	0.50	0.54	0.48	0.43	0.33	0.30	0.27	0.19	0.17	0.16	0.06	0.06	0.05	0.00
		4	0.58	0.49	0.43	0.49	0.42	0.37	0.29	0.26	0.23	0.17	0.15	0.14	0.05	0.05	0.05	0.00
		5	0.53	0.43	0.37	0.45	0.37	0.32	0.26	0.22	0.20	0.15	0.13	0.12	0.05	0.04	0.04	0.00
		6	0.48	0.39	0.32	0.41	0.33	0.28	0.23	0.19	0.17	0.13	0.11	0.10	0.04	0.04	0.03	0.00
		7	0.45	0.35	0.28	0.38	0.30	0.24	0.21	0.17	0.15	0.12	0.10	0.09	0.04	0.03	0.03	0.00
		8	0.41	0.31	0.25	0.35	0.27	0.22	0.19	0.15	0.13	0.11	0.09	0.08	0.03	0.03	0.03	0.00
		9	0.38	0.28	0.22	0.32	0.24	0.19	0.17	0.13	0.11	0.10	0.08	0.07	0.03	0.03	0.02	0.00
V-shaped, completely indirect		10	0.35	0.26	0.20	0.30	0.22	0.17	0.15	0.12	0.10	0.09	0.07	0.06	0.03	0.02	0.02	0.00

Figure 9-28 *Continued*

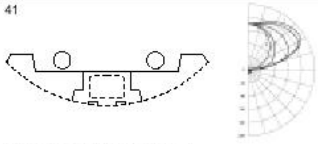
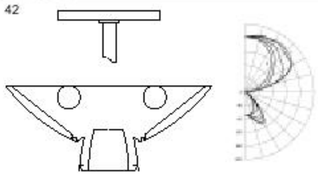
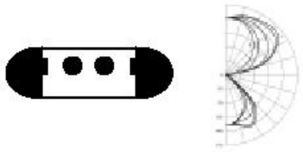
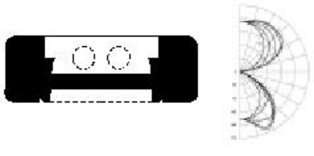
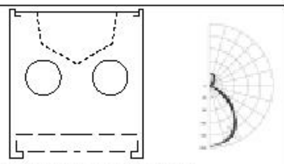
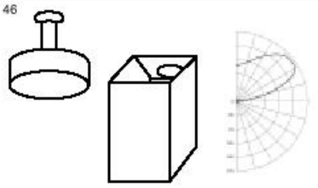
Typical Luminaire / Typical Intensity Distribution	ρcc →	80			70			50			30			10			0
	ρw →	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
41  Indirect with performated metal underside	RCR ↓	EFF = 82.4%			% DN = 5.4%			% UP = 94.6%			Lamp = (2) F32T8 SC (along, across, 45˚) = N/A						
	0	0.80	0.80	0.80	0.69	0.69	0.69	0.48	0.48	0.48	0.30	0.30	0.30	0.12	0.12	0.12	0.04
	1	0.72	0.69	0.66	0.62	0.59	0.57	0.42	0.40	0.39	0.27	0.25	0.24	0.11	0.10	0.10	0.04
	2	0.66	0.60	0.55	0.56	0.52	0.48	0.37	0.34	0.32	0.22	0.21	0.20	0.09	0.09	0.09	0.03
	3	0.60	0.53	0.47	0.51	0.45	0.41	0.32	0.29	0.27	0.20	0.18	0.17	8.08	0.08	0.07	0.02
	4	0.55	0.46	0.40	0.47	0.40	0.35	0.28	0.25	0.23	0.17	0.16	0.14	3 07	0.07	0.06	0.02
	5	0.50	0.41	0.35	0.43	0.36	0.30	0.25	0.22	0.19	0.16	0.14	0.12	0.07	0.06	0.05	0.02
	6	0.46	0.37	0.30	0.39	0.32	0.27	0.23	0.19	0.17	0.14	0.12	0.11	0.06	0.05	0.05	0.02
	7	0.42	0.33	0.27	0.36	0.28	0.23	0.20	0.17	0.14	0.13	0.11	0.09	0.05	0.05	0.04	0.01
	8	0.39	0.29	0.24	0.33	0.26	0.21	0.18	0.15	0.13	0.11	0.09	0.08	0.05	0.04	0.04	0.01
	9	0.36	0.27	0.21	0.31	0.23	0.18	0.17	0.13	0.11	0.10	0.08	0.07	0.04	0.04	0.03	0.01
	10	0.33	0.24	0.19	0.29	0.21	0.16	0.15	0.12	0.10	0.05	0.08	0.06	0.04	0.03	0.03	0.01
42  Semi-indirect, 2-lamp, v-shape, parabolic baffles		EFF = 83.2%			% DN = 21.6%			% UP = 78.4%			Lamp = (2) F32T8 SC (along, across, 45˚) = N/A						
	0	0.83	0.83	0.83	0.74	0.74	0.74	0.56	0.56	0.56	0.39	0.39	0.39	0.24	0.24	0.24	0.17
	1	0.76	0.73	0.70	0.67	0.65	0.62	0.49	0.48	0.46	0.35	0.34	0.33	0.22	0.21	0.21	0.15
	2	0.70	0.64	0.59	0.62	0.57	0.53	0.44	0.41	0.39	0.31	0.30	0.28	0.20	0.19	0.18	0.13
	3	0.64	0.57	0.51	0.56	0.50	0.46	0.39	0.36	0.33	0.28	0.26	0.24	0.18	0.17	0.16	0.12
	4	0.58	0.50	0.44	0.52	0.45	0.40	0.35	0.31	0.28	0.25	0.23	0.21	0.16	0.15	0.14	0.10
	5	0.54	0.45	0.39	0.47	0.40	0.35	0.31	0.27	0.25	0.23	0.20	0.18	0.15	0.13	0.12	0.09
	6	0.49	0.40	0.34	0.44	0.36	0.31	0.28	0.24	0.21	0.20	0.18	0.16	0.13	0.12	0.11	0.08
	7	0.46	0.36	0.30	0.40	0.32	0.27	0.25	0.22	0.19	0.19	0.16	0.14	0.12	0.11	0.10	0.07
	8	0.42	0.33	0.27	0.37	0.29	0.24	0.23	0.19	0.17	0.17	0.15	0.13	0.11	0.10	0.09	0.07
	9	0.39	0.30	0.24	0.35	0.27	0.22	0.21	0.17	0.15	0.16	0.13	0.11	0.10	0.09	0.08	0.06
	10	0.37	0.27	0.22	0.32	0.24	0.20	0.19	0.16	0.13	0.14	0.12	0.10	0.10	0.08	0.07	0.06
43  Semi-indirect, 2-lamp, thin profile, parabolic baffles, 70% up		EFF = 85.2%			% DN = 28.7%			% UP = 71.3%			Lamp = (2) F32T8 SC (along, across, 45˚) = N/A						
	0	3.87	0.87	0.87	0.78	0.78	0.78	0.61	0.61	0.61	0.45	0.45	0.45	0.31	0.31	0.31	0.24
	1	3.80	0.77	0.74	0.72	0.69	0.66	0.54	0.53	0.51	0.41	0.40	0.39	0.29	0.28	0.28	0.22
	2	0.73	0.68	0.63	0.66	0.61	0.57	0.48	0.46	0.44	0.37	0.35	0.34	0.26	0.25	0.24	0.20
	3	0.67	0.60	0.55	0.60	0.54	0.50	0.43	0.40	0.37	0.33	0.31	0.29	0.24	0.23	0.22	0.18
	4	0.62	0.54	0.48	0.55	0.49	0.43	0.39	3.35	0.32	0.30	0.28	0.26	0.22	0.20	0.19	0.16
	5	0.57	0.48	0.42	0.51	0.44	0.38	0.35	0.31	0.28	0.27	0.25	0.23	0.23	0.18	0.17	0.14
	6	0.53	0.43	0.37	0.47	0.39	0.34	0.32	0.28	0.25	0.25	0.22	0.20	0.18	0.17	0.15	0.13
	7	0.49	0.39	0.33	0.44	0.36	0.30	0.29	0.25	0.22	0.23	0.20	0.18	0.17	0.15	0.14	0.11
	8	0.45	0.35	0.29	0.41	0.32	0.27	0.26	0.22	0.20	0.21	0.18	0.16	0.15	0.14	0.12	0.10
	9	0.42	0.32	0.26	0.38	0.30	0.24	0.24	0.20	0.18	0.19	0.16	0.14	0.14	0.13	0.11	0.09
	10	0.39	0.30	0.24	0.35	0.27	0.22	0.22	0.18	0.16	0.18	0.15	0.13	0.13	0.12	0.10	0.09
44  Direct/indirect, 2-lamp, thin profile, parabolic baffles, 60% up		EFF = 88.3%			% DN = 40.3			% UP = 59.7			Lamp = (2) F32T8 SC (along, across, 45˚) = N/A						
	0	0.93	0.93	0.93	0.84	0.84	0.84	0.69	0.69	0.69	0.55	0.55	0.55	0.42	0.42	0.42	0.36
	1	0.85	0.82	0.79	0.77	0.75	0.72	0.61	0.60	0.58	0.49	0.48	0.47	0.38	0.37	0.37	0.31
	2	0.78	0.72	0.67	0.71	0.66	0.62	0.54	0.51	0.49	0.44	0.42	0.40	0.34	0.33	0.32	0.27
	3	0.71	0.64	0.58	0.65	0.58	0.53	0.48	0.45	0.42	0.39	0.37	0.34	0.31	0.29	0.28	0.24
	4	0.65	0.57	0.50	0.60	0.52	0.46	0.43	0.39	0.36	0.35	0.32	0.30	0.28	0.26	0.24	0.21
	5	0.60	0.50	0.44	0.55	0.46	0.40	0.39	0.34	0.31	0.32	0.28	0.26	0.25	0.23	0.21	0.18
	6	0.55	0.45	0.38	0.50	0.42	0.36	0.35	0.30	0.27	0.28	0.25	0.23	0.23	0.20	0.19	0.16
	7	0.51	0.41	0.34	0.47	0.38	0.32	0.32	0.27	0.24	0.26	0.23	0.20	0.21	0.18	0.16	0.14
	8	0.47	0.37	0.30	0.43	0.34	0.28	0.29	0.24	0.21	0.24	0.20	0.18	0.19	0.16	0.15	0.13
	9	0.44	0.34	0.27	0.40	0.31	0.25	0.26	0.22	0.19	0.22	0.18	0.16	0.17	0.15	0.13	0.11
	10	0.41	0.31	0.25	0.37	0.28	0.23	0.24	0.20	0.17	0.20	0.17	0.14	0.16	0.14	0.12	0.10

Figure 9-28 *Continued*

Typical Luminaire / Typical Intensity Distribution	ρcc →	80			70			50			30			10			0
	ρw →	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
45  6″ square x-section, mostly downlight	RCR ↓	EFF = 53.4%			% DN = 81.7%			% UP = 18.3%			Lamp = (2) F32T8 SC (along, across, 45˚) = 1.2, 1.2, 1.3						
	0	0.61	0.61	0.61	0.59	0.59	0.59	0.54	0.54	0.54	0.50	0.50	0.50	0.46	0.46	0.46	0.44
	1	0.57	0.55	0.53	0.55	0.53	0.51	0.49	0.48	0.47	0.45	0.44	0.44	0.42	0.41	0.41	0.39
	2	0.53	0.49	0.46	0.51	0.48	0.45	0.44	0.42	0.40	0.41	0.39	0.38	0.38	0.37	0.36	0.34
	3	0.49	0.44	0.41	0.47	0.43	0.39	0.40	0.37	0.35	0.37	0.35	0.33	0.35	0.33	0.32	0.30
	4	0.45	0.40	0.36	0.43	0.38	0.35	0.36	0.33	0.31	0.34	0.31	0.29	0.32	0.30	0.28	0.27
	5	0.42	0.36	0.32	0.40	0.35	0.31	0.33	0.30	0.27	0.31	0.28	0.26	0.29	0.27	0.25	0.24
	6	0.39	0.33	0.29	0.37	0.32	0.28	0.30	0.27	0.24	0.28	0.25	0.23	0.26	0.24	0.22	0.21
	7	0.36	0.30	0.26	0.35	0.29	0.25	0.27	0.24	0.22	0.26	0.23	0.21	0.24	0.22	0.20	0.19
	8	0.34	0.27	0.23	0.32	0.27	0.23	0.25	0.22	0.19	0.24	0.21	0.19	0.22	0.20	0.18	0.17
	9	0.32	0.25	0.21	0.30	0.24	0.21	0.23	0.20	0.18	0.22	0.19	0.17	0.21	0.18	0.17	0.16
	10	0.30	0.23	0.19	0.29	0.23	0.19	0.21	0.18	0.16	0.20	0.18	0.16	0.19	0.17	0.15	0.14
46  Completely indirect HID		EFF = 73%			% DN = 90%			% UP = 100%			Lamp = M400/U (coated)* SC (along, across, 45˚) = N/A						
	0	0.69	0.69	0.69	0.59	0.59	0.59	0.41	0.54	0.41	0.23	0.23	0.23	0.07	0.07	0.07	0.00
	1	0.63	0.60	0.58	0.54	0.52	0.43	0.35	0.34	0.33	0.20	0.20	0.19	0.06	0.06	0.06	0.00
	2	0.57	0.53	0.48	0.49	0.45	0.42	0.31	0.29	0.27	0.18	0.17	0.16	0.06	0.05	0.05	0.00
	3	0.52	0.46	0.41	0.45	0.39	0.36	0.27	0.25	0.23	0.16	0.14	0.13	0.05	0.05	0.01	0.00
	4	0.48	0.41	0.35	0.41	0.35	0.31	0.24	0.21	0.19	0.14	0.12	0.11	0.04	0.04	0.04	0.00
	5	0.44	0.36	0.31	0.37	0.31	0.26	0.21	0.18	0.16	0.12	0.11	0.10	0.04	0.04	0.03	0.00
	6	0.40	0.32	0.27	0.34	0.27	0.23	0.19	0.16	0.14	0.11	0.09	0.08	0.04	0.03	0.03	0.00
	7	0.37	0.29	0.23	0.31	0.25	0.20	0.17	0.14	0.12	0.10	0.08	0.07	0.03	0.03	0.02	0.00
	8	0.34	0.26	0.21	0.29	0.22	0.18	0.15	0.13	0.11	0.09	0.07	0.06	0.03	0.02	0.02	0.00
	9	0.31	0.23	0.18	0.27	0.20	0.16	0.14	0.11	0.09	0.08	0.07	0.05	0.03	0.02	0.02	0.00
	10	0.29	0.21	0.16	0.25	0.18	0.14	0.13	0.10	0.08	0.07	0.06	0.05	0.02	0.02	0.02	0.00
47  Fluorescent cove with specular reflector		EFF = 71.6%			% DN = 0.3%			% UP = 99.7%			Lamp = (1) F32T8 SC (along, across, 45˚) = N/A						
	0	0.42	0.35	0.30	0.40	0.34	0.30	0.32	0.28	0.26	0.30	0.27	0.25	0.29	0.26	0.24	0.23
	1	0.40	0.32	0.28	0.38	0.31	0.27	0.30	0.26	0.24	0.28	0.25	0.23	0.27	0.24	0.22	0.21
	2	0.37	0.30	0.26	0.36	0.29	0.25	0.28	0.24	0.22	0.26	0.23	0.21	0.25	0.22	0.20	0.19
	3	0.35	0.28	0.24	0.34	0.27	0.23	0.26	0.22	0.20	0.25	0.22	0.19	0.23	0.21	0.19	0.18
	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	6	0.67	0.67	0.67	0.64	0.64	0.64	0.58	0.58	0.58	0.53	0.53	0.53	0.48	0.48	0.48	0.46
	7	0.62	0.59	0.57	0.59	0.57	0.55	0.52	0.50	0.49	0.48	0.46	0.45	0.43	0.43	0.42	0.40
	8	0.57	0.53	0.50	0.55	0.51	0.48	0.47	0.45	0.43	0.43	0.41	0.40	0.40	0.38	0.37	0.35
	9	0.53	0.48	0.44	0.51	0.46	0.43	0.43	0.40	0.37	0.40	0.37	0.35	0.36	0.35	0.33	0.31
	10	0.50	0.44	0.39	0.47	0.42	0.38	0.39	0.36	0.33	0.36	0.34	0.32	0.34	0.32	0.30	0.28

Notes: EFF = efficiency; SC = spacing criteria.
For 6″ reflector with PAR-38, multiply by 0.98.
For A12 lens, 2 × 4's, ratio of F40 to T8, 0.96, 0.94, and 0.89 for 2, 3, and 4-lamp versions.
For A12 lens, 2 × 4's, ratio of 2 to 3-lamp effic. = 1.05; ratio of 4 to 3-lamp effic. = 0.98.
For parabolics, 2 lamp versions have 12 cells, 4 lamp versions have 32 cells.
For 3″ parabolic, 2 × 4's, ratio of 2 to 3-lamp effic. = 1.06; ratio of 4 to 3-lamp effic. = 0.96.
For 4″ parabolic, 2 × 4's, ratio of 2 to 3-lamp effic. = 0.98; ratio of 4 to 3-lamp effic. = 0.90.
CUs do not consider shadowing of the lighting fixture or cove.
* Different lamp types have been considered in determining the listed photometric report.

Figure 9-28 Coefficients of Utilization for Typical Luminaires

Average Exitance Calculations: The Lumen Method

Exitance calculations are greatly simplified through the use of exitance coefficients (ECs). These coefficients, like coefficients of utilization, may be computed for any luminaire, although they are somewhat rare in manufacturers' literature.

Exitance coefficients are similar to coefficients of utilization, except that they apply to the surfaces of the room cavity. They may be substituted into a variation of the lumen method formula in place of the coefficient of utilization. The result obtained is either the average wall exitance or the average ceiling cavity exitance, rather than illuminance on the workplane. Thus

$$\begin{aligned}&\text{average initial wall exitance}\\&\quad= \text{total bare-lamp lumens}\\&\qquad\times \frac{\text{ceiling exitance coefficient}}{\text{floor area}}\end{aligned} \tag{9-59}$$

and

$$\begin{aligned}&\text{average initial ceiling cavity exitance}\\&\quad= \text{total bare-lamp lumens}\\&\qquad\times \frac{\text{ceiling cavity exitance coefficient}}{\text{floor area}}\end{aligned} \tag{9-60}$$

% Effective Ceiling Cavity Reflectance, ρ_{cc}	80				70				50			30			10		
% Wall Reflectance, ρ_w	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10
For 30% Effective Floor Cavity Reflectance (20% = 1.00)																	
Room Cavity Ratio																	
1	1.092	1.082	1.075	1.068	1.077	1.070	1.064	1.059	1.049	1.044	1.040	1.028	1.026	1.023	1.012	1.010	1.008
2	1.079	1.066	1.055	1.047	1.068	1.057	1.048	1.039	1.041	1.033	1.027	1.026	1.021	1.017	1.013	1.010	1.006
3	1.070	1.054	1.042	1.033	1.061	1.048	1.037	1.028	1.034	1.027	1.020	1.024	1.017	1.012	1.014	1.009	1.005
4	1.062	1.045	1.033	1.024	1.055	1.040	1.029	1.021	1.030	1.022	1.015	1.022	1.015	1.010	1.014	1.009	1.004
5	1.056	1.038	1.026	1.018	1.050	1.034	1.024	1.015	1.027	1.018	1.012	1.020	1.013	1.008	1.014	1.009	1.004
6	1.052	1.033	1.021	1.014	1.047	1.030	1.020	1.012	1.024	1.015	1.009	1.019	1.012	1.006	1.014	1.008	1.003
7	1.047	1.029	1.018	1.011	1.043	1.026	1.017	1.009	1.022	1.013	1.007	1.018	1.010	1.005	1.014	1.008	1.003
8	1.044	1.026	1.015	1.009	1.040	1.024	1.015	1.007	1.020	1.012	1.006	1.017	1.009	1.004	1.013	1.007	1.003
9	1.040	1.024	1.014	1.007	1.037	1.022	1.014	1.006	1.019	1.011	1.005	1.016	1.009	1.004	1.013	1.007	1.002
10	1.037	1.022	1.012	1.006	1.034	1.020	1.012	1.005	1.017	1.010	1.004	1.015	1.009	1.003	1.013	1.007	1.002
For 10% Effective Floor Cavity Reflectance (20% = 1.00)																	
Room Cavity Ratio																	
1	.923	.929	.935	.940	.933	.939	.943	.948	.956	.960	.963	.973	.976	.979	.989	.991	.993
2	.931	.942	.950	.958	.940	.949	.957	.963	.962	.968	.974	.976	.980	.985	.988	.991	.995
3	.939	.951	.961	.969	.945	.957	.966	.973	.967	.975	.981	.978	.983	.988	.988	.992	.996
4	.944	.958	.969	.978	.950	.963	.973	.980	.972	.980	.986	.980	.986	.991	.987	.992	.996
5	.949	.964	.976	.983	.954	.968	.978	.985	.975	.983	.989	.981	.988	.993	.987	.992	.997
6	.953	.969	.980	.986	.958	.972	.982	.989	.977	.985	.992	.982	.989	.995	.987	.993	.997
7	.957	.973	.983	.991	.961	.975	.985	.991	.979	.987	.994	.983	.990	.996	.987	.993	.998
8	.960	.976	.986	.993	.963	.977	.987	.993	.981	.988	.995	.984	.991	.997	.987	.994	.998
9	.963	.978	.987	.994	.965	.979	.989	.994	.983	.990	.996	.985	.992	.998	.988	.994	.999
10	.965	.980	.989	.995	.967	.981	.990	.995	.984	.991	.997	.986	.993	.998	.988	.994	.999
For 0% Effective Floor Cavity Reflectance (20% = 1.00)																	
Room Cavity Ratio																	
1	.859	.870	.879	.886	.873	.884	.893	.901	.916	.923	.929	.948	.954	.960	.979	.983	.987
2	.871	.887	.903	.919	.886	.902	.916	.928	.926	.938	.949	.954	.963	.971	.978	.983	.991
3	.882	.904	.915	.942	.898	.918	.934	.947	.936	.950	.964	.958	.969	.979	.976	.984	.993
4	.893	.919	.941	.958	.908	.930	.948	.961	.945	.961	.974	.961	.974	.984	.975	.985	.994
5	.903	.931	.953	.969	.914	.939	.958	.970	.951	.967	.980	.964	.977	.988	.975	.985	.995
6	.911	.940	.961	.976	.920	.945	.965	.977	.955	.972	.985	.966	.979	.991	.975	.986	.996
7	.917	.947	.967	.981	.924	.950	.970	.982	.959	.975	.988	.968	.981	.993	.975	.987	.997
8	.922	.953	.971	.985	.929	.955	.975	.986	.963	.978	.991	.970	.983	.995	.976	.988	.998
9	.928	.958	.975	.988	.933	.959	.980	.989	.966	.980	.993	.971	.985	.996	.976	.988	.998
10	.933	.962	.979	.991	.937	.963	.983	.992	.969	.982	.995	.973	.987	.997	.977	.989	.999

Figure 9-29. Multiplying Factors for Effective Floor Cavity Reflectances Other Than 20% (0.2)

If the maintained average wall exitance or the maintained average ceiling cavity exitance is required, a light loss factor is introduced into these equations in the same manner as for maintained average illuminance. For suspended luminaires the average ceiling cavity exitance obtained is the average exitance of the imaginary plane at the level of the luminaires. This exitance does not include the weighted average exitance of the luminaires as seen from below. It is rather the average exitance of the background against which the luminaires are seen. In the case of recessed or ceiling-mounted luminaires, the average ceiling cavity exitance obtained is the average exitance of the ceiling between luminaires.

Limitations. The limitations for exitance calculations are similar to those for average illuminance. In addition, the wall reflectance used to enter the tables is a weighted average of the reflectances for the various parts of the walls; the wall exitance found from the wall exitance coefficient is the value that would occur if the walls were of a uniform and perfectly diffuse reflectance equal to the average reflectance used. Thus, many parts of the wall may have exitance values that differ from the calculated average value. A correction can be applied to determine the approximate exitance of any part of the wall. For any area on the wall,

$$\text{exitance} = \frac{(\text{average wall exitance}) \times (\text{reflectance of area})}{\text{average wall reflectance}} \qquad (9\text{-}61)$$

The Lumen Method Applied to Partitioned Spaces

The lumen method can be applied to partitioned spaces by separating the room cavity into both an upper cavity that extends from the top of the partitions to the luminaire plane, and a second cavity that is the cavity within the partitioned area. The upper cavity has an area that is equal to the area of the room, and the lower cavity covers only the area included within a single partitioned zone. Two lumen method calculations need to be made in order to perform a complete analysis (see Example 1 in "Examples of Basic Lighting Calculations," in this chapter).

	Floor Cavity Reflectance (ρ_{cc} = 20%)				
Wall Reflectance ρ_w (Percent)	70	50	30	10	0
RCR					
0	1.00	1.00	1.00	1.00	1.00
1	.90	.88	.86	.84	.84
2	.81	.77	.74	.71	.70
3	.74	.69	.64	.61	.59
4	.67	.61	.56	.52	.50
5	.61	.54	.49	.44	.42
6	.56	.44	.43	.38	.36
7	.52	.44	.38	.33	.31
8	.48	.39	.33	.29	.27
9	.44	.35	.29	.25	.23
10	.41	.32	.26	.22	.20

Figure 9-30. Coefficients of Utilization for a Perfectly Diffuse Emitter

First, the calculation is performed for the upper cavity to determine the illuminance falling on the top of the partitions. The floor cavity for this analysis is the area below the top of the partitions, and the effective floor cavity reflectance is that of a single partitioned space as viewed from above. All of the room's luminaires are used in this analysis, since presumably they all contribute to the illuminance on the plane at the top of the partitions. The CU is determined for the appropriate cavity ratio, and the average illuminance on the top of the partitions is then determined.

Next, the coefficient of utilization for the lower cavity, the area within a single partition, is considered. The coefficient of utilization is determined for a virtual luminaire that has a lambertian distribution, using Figure 9-30. The appropriate wall and effective floor cavity reflectances are used to obtain this value. The effective ceiling cavity reflectance assumed in this table is zero, since interreflections between the upper and lower room cavities were already considered in the determination of the illuminance on the top of the partitions. In many partitioned spaces, each cubicle has only three sides formed by the partitions, with the fourth side being open. For the wall reflectance, an area-weighted average of the cubicle walls should be used, where the opening is assigned a reflectance of zero. The illuminance obtained at the top of the partitions is then multiplied by the coefficient of utilization obtained for the cubicle area to obtain the average illuminance on the workplane. The equation is summarized below:

$$E = \frac{\begin{pmatrix}\text{total bare}\\ \text{lamp lumens}\end{pmatrix} \times \text{CU}_{\text{upper cavity}} \times \text{CU}_{\text{cubicle}} \times \text{LLF}}{\text{area of workplane}} \qquad (9\text{-}62)$$

This procedure is likely to be more accurate for indirect lighting systems than for direct, since the procedure assumes that flux is entering the partition from above in a perfectly diffuse manner. Luminaires that direct light predominantly downward are likely to exhibit slightly higher illuminance values that this procedure determines.

CALCULATION OF EQUIPMENT-RELATED QUANTITIES

So far in this chapter, quantities that characterize the lighting within a room have been discussed. Another set of quantities characterizes the luminaire. These include coefficients of utilization, optical efficiency, and the spacing criterion.

Lumen Method Coefficients of Utilization[31,45,82-84]

CU tables, wall exitance coefficients, and ceiling cavity exitance coefficients can be prepared. It is desirable to have standard tables for these values to prevent misunderstandings and to facilitate direct comparisons of the data for different luminaires. These coefficients are derived from the equations described in the above section, "Basic Principles." There are five basic assumptions used to develop the zonal-cavity coefficients:

- Room surfaces are lambertian reflectors.
- The incident flux on each surface is uniformly distributed over that surface.
- The luminaires are uniformly distributed throughout the room (uniformly dense but not necessarily in a uniform pattern).
- The room is empty.
- The room surfaces are spectrally neutral.

Figure 9-28 shows the recommended form for unabridged CU tables. It is recognized that space limitations often necessitate abridgements. In that case, only the columns for ρ_{CC} = 80, 50, and 10% are recommended for luminaires having 0 to 35% of their output in the 90 to 180° zone; and 80, 70, and 50% for luminaires having over 35% of their output in that zone. Also, the ρ_{CC} = 10% columns are not required for abridged tables. It is recommended that CUs be published to two decimal places, wall exitance coefficients to three decimal places, and ceiling cavity exitance coefficients to three decimal places. A wall direct radiation coefficient (WDRC) should be published to three decimal places for every room cavity ratio, adjacent to the wall exitance coefficient table. The three significant figures are not justified in terms of coefficient accuracy but are required because certain computational methods require the small differences between these coefficients.

Computation

1. Define 18 conic solid angle zones of 10° width from the nadir to the zenith about the luminaire as shown in Figure 9-31, where the index of each zone, N, is an integer between 1 and 18 inclusive.

2. Determine the flux Φ_N (lumens) in the various zones:

a. The flux in a conic solid angle (Figure 9-32) is given by

$$\Phi_N = 2\,\pi\, I_{\theta_N}\left(\cos(\theta_N) - \cos(\theta_{N+1})\right) \qquad (9\text{-}63)$$

where

$I_{\theta N}$ = midzone intensity, in cd, for the Nth zone, θ_N, θ_{N+1} = bounding cone angles.

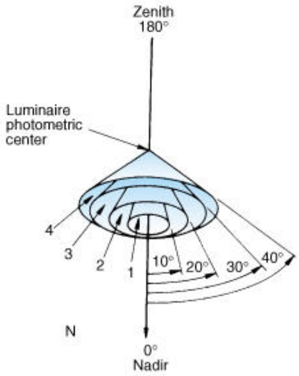


Figure 9-31. Conic solid angle zones of 10° width for use in calculating zonal flux.

b. If the intensity is not rotationally symmetric about the vertical axis, average the intensity about the vertical axis at each vertical angle θ. Note that the intensity must be sampled at equal angular intervals about the vertical axis. For example, if the intensity is known for three vertical planes [$I_{\theta,90°}$ (perpendicular), $I_{\theta,45°}$ and $I_{\theta,0°}$ (parallel)], then

$$I_\theta = \frac{1}{4}\left(I_{\theta,0^\circ} + 2I_{\theta,45^\circ} + I_{\theta,90^\circ}\right) \qquad (9\text{-}64)$$

Although three planes are sufficient for luminaires of nominal rotational symmetry, photometric data at 15° or 22.5° increments about the vertical axis are preferred for luminaires without this symmetry.

c. If the intensity is taken at 10° vertical intervals (θ = 5°, 15°, 25°, ...), then the flux Φ_N is determined by the application of the equation in part (a), above, to the full zone. It is preferred to have intensity values at 5° vertical angles (θ = 2.5°, 7.5°, 12.5°, ...). Then zone N is divided into two parts, the equation is applied to each part, and the resulting flux is summed.

3. Determine the additional flux functions:

$$\Phi_{\text{luminaire}} = \sum_{N=1}^{18} \Phi_N \qquad (9\text{-}65)$$

$$\eta_{\text{down}} = \frac{1}{\Phi_{\text{lamps}}} \sum_{N=1}^{9} \Phi_N \qquad (9\text{-}66)$$

$$\eta_{\text{up}} = \frac{1}{\Phi_{\text{lamps}}} \sum_{N=10}^{18} \Phi_N \qquad (9\text{-}67)$$

where

Φ_{lamps} = total flux emitted by the lamps,
$\Phi_{\text{luminaire}}$ = total flux emitted by the luminaire,
η_{down} = proportion of lamp flux leaving the luminaire in a downward direction,
η_{up} = proportion of lamp flux leaving the luminaire in an upward direction.

4. Determine the direct ratio, D_{RCR}, related to the fraction of luminaire flux below the horizontal that is directly incident on the workplane:

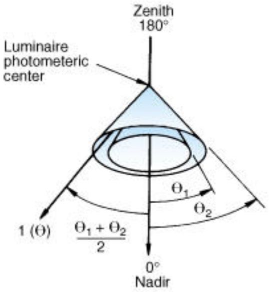


Figure 9-32. Angles used in calculating zonal flux.

$$D_{\mathrm{RCR}} = \frac{1}{\eta_{\mathrm{down}}\,\Phi_{\mathrm{lamps}}} \sum_{N=1}^{9} K_{\mathrm{RCR},N}\,\Phi_N \qquad (9\text{-}68)$$

where

RCR = room cavity ratio, used here as an integer between 1 and 10 inclusive,
$K_{\mathrm{RCR},N}$ = zonal multipliers.

The zonal multiplier is the fraction of downward-directed flux directly incident on the workplane (lower surface of room cavity) for each zone *N*. The zonal multipliers are functions of the RCR:

$$K_{\mathrm{RCR},N} = e^{-A \cdot \mathrm{RCR}^{B}} \qquad (9\text{-}69)$$

where *A* and *B* are constants and are given in Figure 9-33.

5. Determine the parameters C_1, C_2, C_3, and C_0 as an intermediate step. In the formulas below, ρ_W is the wall reflectance, ρ_{CC} is the ceiling cavity reflectance, and ρ_{FC} is the floor cavity reflectance, which is taken as 0.2 for standard coefficient tables. $F_{CC\rightarrow FC}$ is the form factor from the ceiling cavity to the floor cavity, described above in the discussion of flux transfer theory in the above section, "Basic Principles":

$$C_1 = \frac{(1-\rho_W)(1-f^2_{CC\rightarrow FC})\mathrm{RCR}}{2.5\rho_W(1-f^2_{CC\rightarrow FC}) + \mathrm{RCR}\,f_{CC\rightarrow FC}\,(1-\rho_W)} \qquad (9\text{-}70)$$

$$C_2 = \frac{(1-\rho_{CC})(1+f_{CC\rightarrow FC})}{1+\rho_{CC}\,f_{CC\rightarrow FC}} \qquad (9\text{-}71)$$

$$C_3 = \frac{(1-\rho_{FC})\,(1+F_{CC\rightarrow FC})}{1+\rho_{FC}\,f_{CC\rightarrow FC}} \qquad (9\text{-}72)$$

$$C_0 = C_1 + C_2 + C_3 \qquad (9\text{-}73)$$

6. Determine the coefficient of utilization (CU), the wall exitance coefficient (WEC), and the ceiling cavity exitance coefficient (CCEC) for each applicable combination of reflectances and RCR:

Zone (N)	A	B
1	0	0
2	0.041	0.98
3	0.070	1.05
4	0.100	1.12
5	0.136	1.16
6	0.190	1.25
7	0.315	1.25
8	0.640	1.25
9	2.10	0.80

Figure 9-33. Constants for the Zonal Multiplier Equation

$$\mathrm{CU} = \frac{2.5\rho_W C_1 C_3\,(1-D_{\mathrm{RCR}})\eta_{\mathrm{down}}}{\mathrm{RCR}\,(1-\rho_W)\,(1-\rho_{FC})\,C_0}$$

$$+\ \frac{\rho_{CC}\,C_2\,C_3\,\eta_{\mathrm{up}}}{(1-\rho_{CC})(1-\rho_{FC})\,C_0}$$

$$\left(1 - \frac{\rho_{FC}\,C_3\,(C_1+C_2)}{(1-\rho_{FC})\,C_0}\right)\frac{D_{\mathrm{RCR}}\,\eta_{\mathrm{down}}}{1-\rho_{FC}} \qquad (9\text{-}74)$$

$$\mathrm{WEC} = \frac{2.5\rho_W (1 - D_{\mathrm{RCR}})\,\eta_{\mathrm{down}}}{\mathrm{RCR}\,(1 - \rho_W)} \times \left(1 - \frac{2.5\rho_W C_1 (C_2 + C_3)}{\mathrm{RCR}\,(1 - \rho_W)\,C_0}\right) + \frac{2.5\rho_W \rho_{CC} C_1 C_2 \eta_{\mathrm{up}}}{\mathrm{RCR}\,(1 - \rho_W)(1 - \rho_{CC})\,C_0} + \frac{2.5\rho_W \rho_{FC} C_1 C_3 D_{\mathrm{RCR}} \eta_{\mathrm{down}}}{\mathrm{RCR}\,(1 - \rho_W)(1 - \rho_{FC})\,C_0} \qquad (9\text{-}75)$$

$$\mathrm{CCEC} = \frac{2.5\rho_W \rho_{CC} C_1 C_2 (1 - D_{\mathrm{RCR}})\,\eta_{\mathrm{down}}}{\mathrm{RCR}\,(1 - \rho_W)(1 - \rho_{CC})\,C_0} + \frac{\rho_{CC}\,\eta_{\mathrm{up}}}{1 - \rho_{CC}}\left(1 - \frac{\rho_{CC} C_2 (C_1 + C_3)}{(1 - \rho_{CC})\,C_0}\right) + \frac{\rho_{CC}\rho_{FC} C_2 C_3 D_{\mathrm{RCR}}\,\eta_{\mathrm{down}}}{(1 - \rho_{CC})(1 - \rho_{FC})\,\mathrm{C}_0} \qquad (9\text{-}76)$$

7. Determine the wall direct radiation coefficient (WDRC) for each RCR:

$$\mathrm{WRDC} = \frac{2.5\,\eta_{\mathrm{down}}\,(1 - D_{\mathrm{RCR}})}{\mathrm{RCR}} \qquad (9\text{-}77)$$

8. The above equations can be used to calculate the CU, WEC, and CCEC when the RCR equals zero, but the forms of the equations must be arranged to avoid division by zero. It is simplest to use the following relationships:

$$\mathrm{CU}_{\mathrm{RCR}\,=\,0} = \frac{\eta_{\mathrm{down}} + \rho_{CC}\eta_{\mathrm{up}}}{1 - \rho_{CC}\rho_{FC}} \qquad (9\text{-}78)$$

$$\mathrm{CCEC}_{\mathrm{RCR}\,=\,0} = \frac{\rho_{CC}\,(\eta_{\mathrm{up}} + \rho_{FC}\,\eta_{\mathrm{down}})}{1 - \rho_{CC}\rho_{FC}} \qquad (9\text{-}79)$$

Luminaire Efficiency

The luminaire efficiency is simply the ratio of the lumens leaving the luminaire to the total lumens produced by the lamps. From the expressions above, this quantity is

$$\text{luminaire efficiency} = \frac{\Phi_{\mathrm{luminaire}}}{\Phi_{\mathrm{lamps}}} \qquad (9\text{-}80)$$

The luminaire efficiency is considered in the determination of the CU.

Average Luminaire Luminance

The average luminaire luminance is a means of evaluating the effect that a luminaire has on visual comfort, as well as veiling reflections on task surfaces such as VDTs. A value can be easily determined in any direction, given the photometric characteristics of the luminaire. Since luminance is expressed in candelas per unit area, the average luminance in a direction (θ, ψ) (specified in spherical coordinates) is

$$L(\theta, \psi)_{\mathrm{avg}} = \frac{I(\theta, \psi)}{A_{\mathrm{luminaire}} \cos\theta} \qquad (9\text{-}81)$$

where

$I(\theta, \psi)$ = intensity of the luminaire in the direction (θ, ψ),
$A_{\mathrm{luminaire}}$ = surface area of the luminous element(s) of the luminaire.

Luminaire Spacing Criterion

The luminaire spacing criterion[85] (SC) is a classification technique for interior luminaires relating to the spread or distribution of the direct illuminance on a horizontal plane. It tests the uniformity of horizontal illuminance at two pairs of selected points to estimate the probable extreme limit of acceptable luminaire spacing. It is not a specification of the spacing-to-mounting-height ratio to be used in a lighting installation, and in fact, installation of luminaires at this nominal value may produce a poor lighting system.

The purpose of this classification technique is to aid designers in rapidly assessing one aspect of the potential of a luminaire with respect to its applications. It gives some idea about the distribution of flux from a luminaire and its subsequent effect on lighting system parameters, using only a single number. The basis of the luminaire spacing criterion is the horizontal illuminance on the workplane due to direct illuminance from nearby luminaires. As a first approximation, it is assumed that this represents a limiting case, since the reflected component of illuminance and the illuminance due to more distant luminaires generally increases the uniformity of horizontal illuminance from point to point.

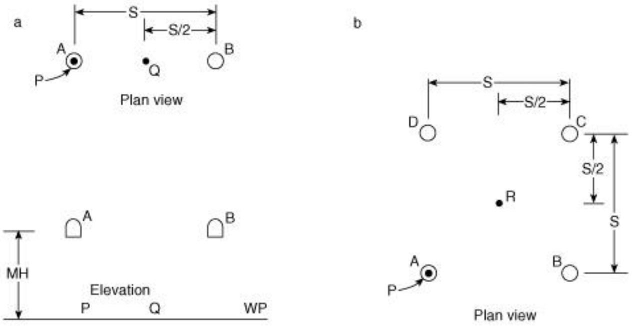


Figure 9-34. Points *Q* and *R* represent points of most probable low illuminance for (a) a configuration of 2 luminaires, and (b) a square array of 4 luminaires.

When two similar conventional luminaires are near their maximum spacing, the illuminance directly under a luminaire (*P*) is principally due to the overhead luminaire (*A*) (Figure 9-34a). Further, a very probable point of low illuminance is at the midpoint between two luminaires (*Q*). The maximum spacing at a given mounting height above the workplane is chosen such that the illuminance halfway between the two luminaires (*Q*) due to both luminaires (*A* and *B*) equals the illuminance under one (*P*) due to that one luminaire (*A*) only. Another likely point (*R*) for low illuminance is at the center of a square array of adjacent luminaires (Figure 9-34b). The maximum spacing at a given mounting height above the workplane is chosen such that the illuminance at the center of the luminaires (*R*) due to all four luminaires (*A*, *B*, *C*, and *D*) equals the illuminance under one (*P*) due to that one luminaire (*A*) only. The maximum spacing (expressed as a spacing-to-mounting-height ratio that is unitless) that fulfills each of the above conditions is easily determined on a special graph (Figure 9-35) using the intensity distribution of the luminaire. For the purpose of establishing this criterion, it is assumed that the inverse square law is valid. This is the only assumption for the computations.

Procedure. The procedure for calculating the luminaire spacing criterion is as follows:

A. For luminaires whose intensity distribution is nominally symmetric about the nadir:

1. Plot the relative intensity of the luminaire on the chart of Figure 9-35.

2. Locate the point of one-half the intensity at 0° on the ordinate, and draw a line through that point and parallel to the diagonal lines. If the intensity varies significantly in the vicinity of 0°, use an average of the intensity over the 0 to 5° polar angle.

3. Read scale *A* above the intersection of this line with the intensity curve.

4. Repeat step 2 using the point of one-quarter the intensity at 0°.

5. Read scale *B* above the intersection of this line with the intensity curve.

6. The lower of the values found in steps 3 and 5 is the luminaire spacing criterion. Round off the value to the nearest 0.1.

B. For luminaires with significantly asymmetric intensity distributions about the nadir:

1. Independently evaluate the intensity distributions in the parallel and perpendicular (0° and 90°) planes.

2. Apply steps 1, 2, and 3 from part A above for each of the intensity curves. Round off to the nearest 0.1.

3. In some cases, it may be appropriate to evaluate the intensity distribution in the 45° plane.

Interpretation. The value from scale *A* corresponds to the luminaire spacing criterion at point *Q* (Figure 9-34a), and the value from scale *B* corresponds to this criterion at point *R* (Figure 9-34b). Thus for symmetrical intensity distributions, the luminaire spacing criterion requires the direct horizontal illuminance at both test points to be equal to or greater than the illuminance directly below a single luminaire. For nonsymmetrical intensity distributions, it is generally found that independent testing at point *Q* for each orientation is adequate. A point directly under a luminaire has relatively high illuminance and receives its principal contribution from the luminaire overhead when the spacing is large. If the illuminance at a probable low point due to the closest luminaires is no lower than that at a probable high point, due to the main component, then it is likely that reasonable uniformity is achieved over the entire workplane. The luminaire spacing criterion only suggests a maximum spacing at which the horizontal illuminance is reasonably uniform. When other criteria are considered, such as overlap between luminaires, vertical illuminance, shadowing, and illuminance distribution above the workplane, it generally is found that luminaires must be installed at some spacing-to-mounting-height ratio less than the value of the luminaire spacing criterion.

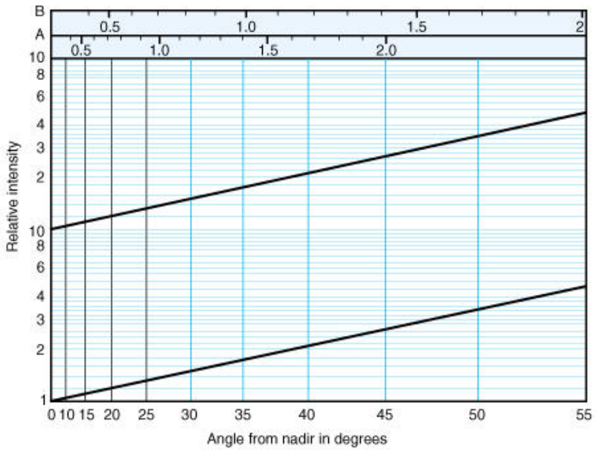


Figure 9-35. Chart for determining the luminaire spacing criterion.

In cases where uniformity is particularly important, the lighting designer must calculate the illuminance at several points throughout the room. It is suggested that a maximum value of 1.5 be assigned as the luminaire spacing criterion for any luminaire, since the use of larger values frequently does not produce acceptable lighting installations when all performance criteria are examined. Also, certain luminaires are designed to be installed only with specific spacing relations, and neither larger nor smaller spacings are desirable. In such cases, a luminaire spacing criterion is not applicable. Specific limits or ranges for the spacing-to-mounting-height ratios should be recommended by the manufacturer, and the basis for the recommendation should be stated, such as a certain degree of horizontal illuminance uniformity (determined by point calculations). In addition to the luminaire spacing criterion, it is possible to determine illuminance uniformity for specific installation conditions and report spacing-to-mounting-height limits for such conditions. If that is done, the luminaire layout, the room conditions, the uniformity criteria, and any application restrictions should be explicitly described.

INTERPRETATION AND LIMITS OF CALCULATED QUANTITIES

Calculated quantities can be used to provide the designer of a lighting system with information that could not otherwise be obtained except with an actual mock-up of a lighting installation. Information on illuminance, luminance, exitance, contrast, visual comfort probability, visibility, and visual performance metrics can be used to compare alternative designs and to verify that design criteria are met. These calculated quantities can also be used to protect or challenge a specification. Calculations are often required to meet strict design requirements imposed by labor unions, owners, local codes, or the like. If used correctly, computer models can be a valuable asset in designing a lighting system to meet particular design criteria.

With recent advances in the field of computer graphics, it is now possible to view the effects of a lighting system on a room through a computer-generated rendering of a space. At the heart of these renderings is a complex lighting analysis. The transformation from luminance data to a realistic-looking synthetic image requires special attention, since a computer screen has a limited range of available luminances. These tools are now being used by lighting professionals to evaluate and market their designs. Further improvements in this process will certainly make computer-generated visual methods more popular in the future.

In reviewing any lighting calculations, the results should first be screened for possible errors. Improper orientation or placement of a luminaire may produce incorrect results. Improper photometry, lamp lumen output, or light loss factors may also cause errors. If the results appear unreasonable, an error may be producing an inaccurate result. Assuming that the results are for the proper arrangement of lighting equipment and room surfaces, some advice is provided below to help evaluate computer output.

Illuminance

Often a designer has selected a target illuminance, and a detailed analysis is performed to determine if the target value is provided. For maintained illuminance, a design is generally acceptable if the illuminance is within 10% of the target value. For energy conservation purposes, values below the target value are preferred over values above.

It is difficult, however, to achieve a uniform value everywhere within a space, or even across a desk or workplane. A 15% variation in illuminance is generally considered to be tolerable. In all cases it is the responsibility of the designer to determine if a particular variation is acceptable.

In evaluating illuminance, it is important to focus on the actual task locations. Most general lighting systems provide a higher illuminance in the middle of the room than near the walls. If the principal task locations are against the walls, a more detailed analysis may be needed to properly evaluate the illuminance at those areas.

Obstructions in a space, such as partitions, should be considered in a lighting calculation model if possible. If an empty room is modeled, the illuminance near a vertical partition is likely to be much lower than predicted.

Luminance

Luminances can be used to evaluate the appearance of a space. Scallops, sharp luminaire cutoffs, and the general pattern of brightnesses can be studied through numerical and graphical models. Computer renderings or simple luminance contours for room surfaces can provide the needed information for a designer to evaluate the performance of lighting equipment.

Luminances can also be evaluated with respect to a luminance ratio criterion. In the lighting of spaces containing VDTs, the uniformity of the luminance on the ceiling and the maximum ceiling luminance are critical aspects to study (see Chapter 11, Office Lighting).

Contrast

The calculation of task contrast, particularly for specular tasks, provides an indication of where veiling reflections occur within a space. Contrast can also be used to compare the performance of two different lighting systems. Visibility and visual performance metrics that use task contrast can provide some insight into the significance of the contrast and the task luminance provided by a lighting system.

Visual Comfort Probability

Visual comfort probability (VCP) is a metric with limited application. It was developed for lensed fluorescent lighting equipment. It is not valid for use with incandescent or HID equipment. It also cannot be used with luminaires that have an upward component. The procedure has never been proven to accurately model the discomfort caused by parabolic fluorescent luminaires, although many lighting professionals continue to apply it in such situations. Parabolic luminaires are much less uniform in luminance than lensed luminaires, and the difference can have a noticeable effect on the comfort of occupants.

Small differences in VCP are not significant. VCP differences of less than 5 points do not indicate a meaningful difference in discomfort glare potential.

Comparison of Calculated and Measured Quantities

Although it seems reasonable to expect calculated values of quantities to be reproduced in the field, in practice it is very difficult to reconcile measured quantities with those provided by calculation. Assumptions inherent in any calculation model often represent conditions very different from those in an actual lighting installation.[1] Some of these conditions are listed below:

- Lambertian surfaces are assumed in most computer programs. Real-world surfaces may contain some degree of specularity.
- The room surface reflectance input to analysis software may not accurately represent what is present in the field.
- Reduced electrical voltage in the power system may produce reduced light output.
- The assumed ballast factor may be much different from that present in the field.
- Thermal effects in an installed luminaire may alter light output.
- Minor differences incurred in the manufacturing process or in the positioning of the lamp within a luminaire may alter the luminaire's photometric distribution.

Furniture and other absorbing and reflecting surfaces may not have been considered in the computer model. No analysis model is an exact representation of any real room. Simplifying assumptions in the calculation method may limit the accuracy of the results. Far-field photometric methods applied in a near-field situation may not accurately model the luminaire performance.

Another reason for disagreement can be errors in the measurement process. It is important to follow strict guidelines when measuring the photometric performance of lighting systems. For example, it is important that the lighting system be measured at a temperature that is representative of its thermal equilibrium condition. New lamps should operate for at least 100 h before measurements are taken. The operator of a photometer must ensure that his or her own presence does not influence the reading. Orientation and positioning of the photometer are also critical; a tripod with a leveling device is particularly useful when conducting horizontal illuminance measurements. Finally, all daylight should be eliminated from the measurements on interior lighting systems, perhaps by conducting measurements at night. Any attempt to subtract out daylight levels is difficult and is likely to introduce errors because of the temporal variations in daylight illuminance.

The magnitude of the differences between detailed analysis methods and field measurements varies. In general, differences of less than 20% can be expected, but in extreme cases, where a calculation method simply cannot handle the complexity of the lighting system, they may be greater. For a more complete discussion of the uncertainties, see reference 83.

EXAMPLES OF BASIC LIGHTING CALCULATIONS

The purpose of this section is to show how to apply some of the equations and procedures described in previous sections to lighting problems. Seven practical lighting problems demonstrate the calculation of basic quantities. With the exception of visual task contrast, the calculation of derived quantities is not demonstrated, nor are equipment-related quantities calculated, because these are normally calculated by manufacturers of lighting equipment.

The following outline helps organize the basic lighting calculation procedures and in fact represents the order in which basic calculations are often performed.

First-order calculations: illuminance

1. Direct calculations

    A. Diffuse, lambertian emission

    B. Real (nondiffuse) emission distributions

2. Interreflection calculations

    Second-order calculations: luminance

    1. Diffuse, lambertian reflection

    2. Real, (bidirectional) reflectance distributions

The first-order calculations are used to characterize the light reaching a surface, that is, the illuminance. The illuminance on a surface is a result of the light reaching that surface directly and by interreflections from surrounding surfaces. Luminance describes how light makes objects and surfaces appear and includes determination of contrast and luminance ratios. The determination of luminance is a second-order calculation because it almost always follows an illuminance calculation.

The first-order (illuminance) calculations are of two types. The first type is used to determine how much light reaches a surface or a point directly from a luminous source. The second type is used to determine how much light reaches the same surface or point from a secondary source of light that is, in fact, luminous by reflection.

Direct illuminance, either averaged over a surface or at a point on a surface, is treated as if produced by light emitted directly from a point source (as in the case of an incandescent lamp downlight), a line source (a narrow fluorescent lamp luminaire), or an area source (a window). These direct illuminance calculations assume one of two types of emitters, diffuse or nondiffuse.

Diffuse emitters are idealized approximations of reality that make calculations simpler to perform. Such emitters follow Lambert's cosine law of emission. This approximation is useful and appropriate for some reflective materials, such as cloth-covered partitions and flat-latex-painted walls, and for some transmissive materials, such as the face of a white plastic sign. Some self-luminous sources, such as the surface of a fluorescent lamp, can also be considered diffuse emitters.

Nondiffuse emitters have specific luminous intensity distributions determined by photometric measurement. In this section, they are referred to as real emitters. Luminaires are almost always treated as real emitters.

Interreflection is the repeated reflection of light among surfaces. For interreflection calculations, surfaces are always assumed to be diffuse reflectors. These surfaces are of finite area, their number and sizes dictated by the accuracy needed for the calculation. More surfaces of smaller size are specified for more accurate interreflection calculations. Interreflection calculations lead to surface exitance values, which are then used as sources of illumination. These values produce a quantity called the interreflected component in the illuminance calculation.

For some illuminance calculations, such as those for an indirect electric lighting system, only the interreflections are relevant. For some direct lighting systems, interreflections are negligible contributors to the total illuminance; in these cases, an experienced designer does not bother to calculate them (see the section "Characterizing Light for Calculation Purposes").

The second-order (luminance) calculations in this section are for luminance produced by reflection. That is, once light reaches a surface, the reflection characteristics of the surface determine its luminance. There are two types of luminance calculations: those for surfaces that can be approximated by diffuse reflection (that is, those that follow Lambert's cosine law of reflection), and those requiring specificity as to the bidirectional reflectance characteristics of the surface. Bidirectionality means that the reflectance of the surface depends on both the incident and the exitant directions of light. All real surfaces are characterized by a bidirectional reflectance distribution function (BRDF). Luminance calculations for real surfaces are the only ones for which the direction of incident light is important. Luminance by transmission is not considered in this section.

A General Algorithm for Lighting Calculations

The following discussion presents a general algorithm for lighting calculations. It consists of six steps:

1. Determine the quantity to be calculated.

2. Identify luminaires and the information describing them.

3. Determine the accuracy, complexity, and detail of the calculation.

4. Identify required geometric, reflectance, and other ancillary data.

5. Determine the appropriate equations or computational procedure.

6. Solve the equations or complete the procedure.

1. Determine the Quantity to Be Calculated. An evaluation of the proposed lighting system is the first step in the lighting calculation process. This evaluation includes a determination of what needs to be calculated and the required accuracy of the calculation. Listed in order of increasing complexity are the quantities considered in this section of example calculations:

- Average illuminance on a surface
- Illuminance at a point
- Average exitance and average diffuse luminance of a surface
- Exitance and diffuse luminance at a point
- Nondiffuse luminance

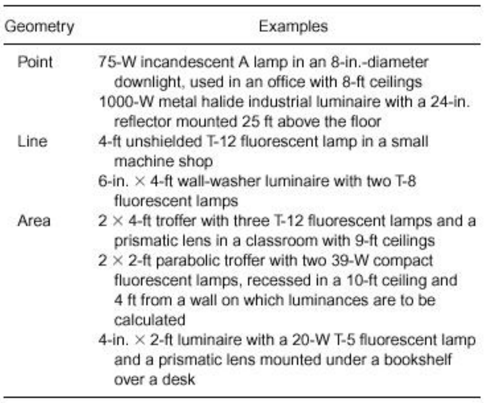
These basic quantities are used in a wide range of lighting applications. Computational procedures to determine them are independent of the specific lighting application in which they are used. Some applications, such as sports and roadway lighting, use coordinate systems and light loss factors in ways characteristic to those applications (see Chapter 20, Sports and Recreational Area Lighting, and Chapter 22, Roadway Lighting).

The value in performing these calculations is that they help demonstrate what is and is not important for a lighting design. For example, surface reflectances can significantly affect the lighting power density required to bring the illuminance levels to those required in an indoor space.

2. Identify Luminaire Geometry and Luminous Intensity Distribution. For computational purposes, sources can be categorized by the size and the dimensions they exhibit relative to the distances involved in the computation. It is usual to use the five-times rule to make this determination. This rule states that if the distance between the luminaire and the computation point is more than five times a luminaire's largest dimension, the luminaire can be treated as a point source. Thus, it is the ratio of luminaire size to computation distance that governs the computational size or geometry category of the luminaire (see the section "Photometry as the Basis for Calculations"). Assuming a luminaire to be a luminous rectangle, the following criteria hold:

- If both of its dimensions are smaller than one-fifth the computation distance, the luminaire is considered a point source.
- If only one dimension is larger than one-fifth the computation distance, the luminaire is considered a line source.
- If both dimensions are larger than one-fifth the computation distance, the luminaire is considered an area source.

Some examples of point, line, and area sources are:



Geometry	Examples
Point	75-W incandescent A lamp in an 8-in.-diameter downlight, used in an office with 8-ft ceilings 1000-W metal halide industrial luminaire with a 24-in. reflector mounted 25 ft above the floor
Line	4-ft unshielded T-12 fluorescent lamp in a small machine shop 6-in. × 4-ft wall-washer luminaire with two T-8 fluorescent lamps
Area	2 × 4-ft troffer with three T-12 fluorescent lamps and a prismatic lens in a classroom with 9-ft ceilings 2 × 2-ft parabolic troffer with two 39-W compact fluorescent lamps, recessed in a 10-ft ceiling and 4 ft from a wall on which luminances are to be calculated 4-in. × 2-ft luminaire with a 20-W T-5 fluorescent lamp and a prismatic lens mounted under a bookshelf over a desk

For computational purposes, luminous intensity distributions are considered either diffuse or nondiffuse. For computational purposes a diffuse luminous intensity distribution (Figure 9-36) is defined as

$$I(\theta, \psi) = I_n \cos \theta$$

where

I_n = luminous intensity normal ($\hat{n}$) to the luminous surface,
θ, = declination angle measured from the normal,
ψ = azimuthal angle.

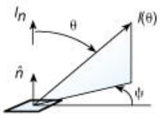


Figure 9-36. Illustration of angles for a diffuse intensity distribution.

A diffuse luminous intensity distribution does not depend on the azimuthal angle ψ and is axially symmetric about the normal to the luminous surface. It exhibits an intensity that varies only with the cosine of the declination angle θ .

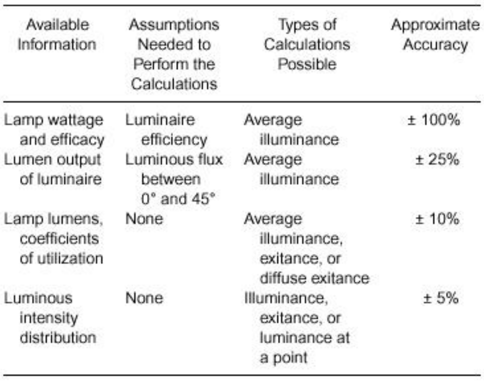
If a luminaire has a luminous intensity distribution given by $I(\theta, \psi)$, and if the ratio

$$\frac{I(\theta, \varphi)}{I(0°, 0°) \cos(\theta)}$$

differs from 1.0 by more than 10% for any of the intensities, then the distribution is considered to be nondiffuse. Large errors may result if such a distribution is treated as diffuse. Most luminous intensity distributions exhibited by electric lighting equipment are nondiffuse.

3. Determine the Accuracy and the Complexity

Accuracy. Accuracy requirements are different for different stages in the lighting design process. A preliminary determination of the type of source and required luminaire efficiency can be made, knowing the average illuminance that is required. An accuracy of ± 100% is generally sufficient for this determination. Then a preliminary choice of the general type and number of luminaires can be made, knowing the average illuminance that is required. An accuracy of ± 25% is generally sufficient for this stage. Illuminance calculations at a point require that both the specific luminous intensity distribution and location of the luminaire (s) be known. Figure 9-37 provides guidance about the required accuracy at different stages of the design process.



Available Information	Assumptions Needed to Perform the Calculations	Types of Calculations Possible	Approximate Accuracy
Lamp wattage and efficacy	Luminaire efficiency	Average illuminance	± 100%
Lumen output of luminaire	Luminous flux between 0° and 45°	Average illuminance	± 25%
Lamp lumens, coefficients of utilization	None	Average illuminance, exitance, or diffuse exitance	± 10%
Luminous intensity distribution	None	Illuminance, exitance, or luminance at a point	± 5%

Figure 9-37. Expected Accuracy of Lighting Calculations

The importance of the result and the consequences of uncertainty determine the accuracy required of a calculation. The accuracy, in turn, determines the complexity and cost of the calculation. For purposes of assessing illuminance as it relates to vision- and visibility-related lighting system characteristics, an accuracy of ± 25% is probably sufficient. Luminances used for determining the contrast of reading materials should be calculated with an accuracy of ± 10%. For specification, legal, or comparison purposes, calculations of ± 5% accuracy are often desired. A reasonable upper limit to what can be expected from computational accuracy is established by the uncertainty in measurement. Even with high-quality light measurement equipment, ± 5% accuracy is usually the best that can be expected. Computational accuracy greater than this cannot be verified by measurement.

Complexity. Calculation complexity is determined by the geometry of the problem. For example, an L-shaped room is computationally more complex than a rectangular room. Similarly, partition shadows and reflections add considerable complexity to the calculations; however, the complex calculations are more accurate.

The need for accuracy is often different for the direct and interreflected components. Although it may be necessary to calculate both the direct and interreflected components, the dominant component should always be calculated with much more accuracy. This, in turn, affects the complexity of the calculation.

4. Identify Required Geometric, Reflectance, and Ancillary Data

Geometric Data. Room dimensions, partition sizes and locations, and surface orientation information such as the slope of a ceiling are necessary geometric information for calculations. Similarly, the luminaire sizes and locations must be determined.

Reflectance Data. Surface reflectances are often unknown at lighting design and calculation time. Unknown reflectances produce an uncertainty that can be determined by calculation. In such cases, those quantities affected by reflectance are calculated twice, using the lowest and highest reasonable values of reflectance that are likely to be present. If these two values lie outside the accuracy requirements listed in Figure 9-37 and below in step 5, then a specification for surface reflectance is required. If the range is small, on the other hand, the reflectances can remain unknown, their values having been found not to significantly affect the lighting system's performance.

Ancillary Data. These data are often specific to a particular application. Examples of such data are BRDFs for visual tasks, r tables for roadway luminance calculations, application adjustment factors (AAFs) for sports lighting, and climate and site data for daylighting calculations. See the application chapters of this handbook for complete information on the ancillary data that might be required for a particular situation.

5. Determine Appropriate Equations. The appropriate equations for average workplane illuminance calculations are determined by the required accuracy. Note that the following equations should also include light loss factors in order to be accurate.

For direct lighting systems with an accuracy of ± 100%,

$$E_{\text{ave}} = \frac{\text{lamp watts} \times \text{efficacy} \times \text{luminaire efficiency} \times \text{number of lamps}}{\text{lighted area}}$$

For indirect lighting systems with an accuracy of ± 100%,

$$E_{\text{ave}} = \frac{\begin{array}{c}\text{lamp watts} \times \text{efficacy} \times \text{luminaire efficiency} \\ \times\ \text{number of lamps} \times 0.80 \times \text{ceiling reflectance}\end{array}}{\text{lighted area}}$$

The factor 0.80 above is a reasonable average value in most rooms for what is termed the form factor between the ceiling and floor. That is, for typical rooms, the fraction of luminous flux emitted by the ceiling that reaches the floor is 0.80.

For direct lighting systems and an accuracy of ± 25%,

$$E_{\text{ave}} = \frac{\text{lamp lumens} \times \text{luminaire efficiency} \times \text{number of lamps} \times \text{fraction of luminaire lumens between } 0° \text{ and } 45°}{\text{lighted area}}$$

The amount between 0° and 45° is a reasonable value for the luminaire lumens that reach the floor directly in rooms of typical proportions. There is no equation for indirect lighting systems and an accuracy of ± 25%.

For both direct and indirect lighting systems and an accuracy of ± 10%,

$$E_{\text{ave}} = \frac{\text{lamp lumens} \times \text{coefficient of utilization} \times \text{number of lamps}}{\text{lighted area}}$$

For an accuracy of ± 5%, the luminous intensity distribution must be known. The appropriate equations for direct component calculations follow from the geometry of the source, as shown in Figure 9-38.

The appropriate equations for interreflected component calculations are obtained from radiative transfer. The room surfaces are divided into discrete elements and an exitance is calculated for each. More and smaller elements are required for more accurate interreflection calculations.

Source Geometry	Equation	
	Diffuse distribution	Nondiffuse distribution
Point	Inverse square cosine law	Inverse square cosine law
Line	Configuration factor for a line to a point	Inverse square cosine law, where the line is discretized into pieces that are treated as point sources
Area	Configuration factor for an area to a point	Inverse square cosine law, where the area is discretized into pieces that are treated as point sources

Figure 9-38. Equations for Direct Component Calculations

6. Solve the Equations. Hand calculation is appropriate for small problems with straightforward equations. Spreadsheet programs can often be used. They are the useful option to specialized software, are easy to learn and use, and can be very powerful. More sophisticated computer programs are essential for complex, repetitive, or extended calculations.

COORDINATE SYSTEMS FOR LUMINAIRE PHOTOMETRY

Many lighting calculations involve using luminous intensity distribution data provided by manufacturers in photometric reports. The two basic coordinate systems for luminaire photometry are the spherical coordinate system and the polar coordinate system.

Directions relative to a lamp or luminaire are specified in a spherical coordinate system by angles θ (altitude) and θ (azimuth). The convention often is used that an azimuth direction along the lamp axis is $\psi = 0°$ or $\psi = 180°$, but when referring to data in a photometric report it is necessary to give careful attention to how the origin of ψ is defined. The terms and symbols used to describe a direction along the lamp axis are

along, parallel, | |,

and across the lamp axis

across, perpendicular, +.

A polar plot gives curves that specify the variation with θ of $I(\theta, \psi)$ in an azimuthal plane for stated angles θ . The polar plot is scaled in candelas (cd) measured radially from the photometric center. If the luminous intensity distribution is constant about the vertical axis (as with a round downlight having a vertical lamp orientation), only one curve is given and the angle ψ is not specified. If the luminous intensity distribution is symmetric about both the parallel and perpendicular horizontal axes (as with a horizontally mounted fluorescent lamp), curves may be given only for angles from 0 to 90°. Such a distribution is called quadrilaterally symmetric. In this case, equivalent values of ψ for angles that are between 90° and 360° are calculated as follows:

Range of ψ	Equivalent Angle
90° to 180°	$180° - \psi$
180° to 270°	$\psi - 180°$
270° to 360°	$360° - \psi$

This equivalent angle is the lookup angle used in the table of luminous intensity values.

With less symmetry and increasing optical control complexity, polar plots require more azimuthal planes (and therefore more curves) to adequately define the performance of the luminaire. Sometimes the luminous intensity of a luminaire is required at an angle that is not listed in the photometric report. In such cases interpolation is necessary to obtain accurate results. Linear interpolation is the simplest form of interpolation and is used here, though other more complicated procedures are available.[3,4]

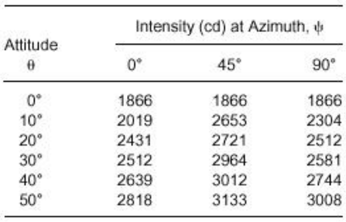
Figure 9-39 contains a partial luminous intensity table for an imaginary luminaire. Altitude angles are given at 10° intervals, and three azimuth angles are given (0°, 45°, and 90°). To determine the luminous intensity for an azimuth angle of 45° and an altitude angle of, for example, 42.7°, the following procedure can be used.

The fraction equal to the difference between 40° and 42.7° over the difference between 40° and 50° should be calculated:

$$\frac{42.7^\circ - 40^\circ}{50^\circ - 40^\circ} = \frac{2.7^\circ}{10^\circ}$$

From the table, the intensity at 40° is 3012 cd and the intensity at 50° is 3133 cd. The difference between these two values is 3133 − 3012 = 121 cd, and 27% of this difference is 32.7 cd. This value is then added to the intensity at 40°. Thus the intensity at an altitude of 42.7° and an azimuth of 45° is estimated to be 3012 + 32.7 = 3044.7, or 3045 cd. A way to check that the interpolated value is correct is that it must lie between the bounding points in the table (3045 cd lies between 3012 and 3133 cd).

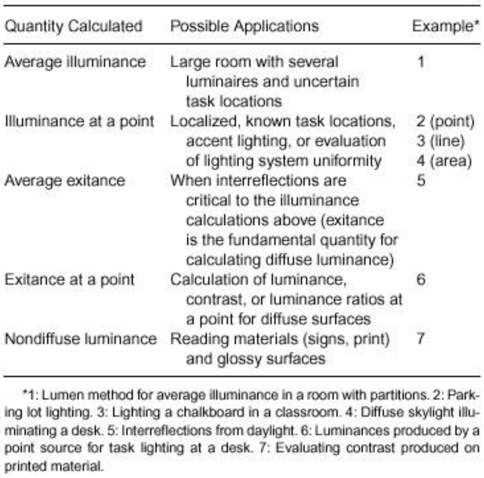
The examples that follow are taken from actual applications. They are intended to illustrate the general algorithm for lighting calculations discussed above. Only rarely would these examples represent a complete lighting calculation analysis. It is hoped, however, that the preceding discussion and the following examples lead to or augment an understanding of the invisible process of computer calculations. All of the following examples use English units of measurement (such as feet, inches, and footcandles). This is done to help facilitate an understanding of the basic calculations for the audience familiar with this system of units.



Attitude θ	Intensity (cd) at Azimuth, ψ		
	0°	45°	90°
0°	1866	1866	1866
10°	2019	2653	2304
20°	2431	2721	2512
30°	2512	2964	2581
40°	2639	3012	2744
50°	2818	3133	3008

Figure 9-39. Partial Example of a Luminous Intensity Distribution

Figure 9-40 summarizes the example calculations and their applications. The most useful and most widely applied calculations are those for illuminance, both at a point and averaged over a surface. All illustrations for these examples have been made using a computer drafting system similar to what might be used in many architectural and lighting design firms.



Quantity Calculated	Possible Applications	Example*
Average illuminance	Large room with several luminaires and uncertain task locations	1
Illuminance at a point	Localized, known task locations, accent lighting, or evaluation of lighting system uniformity	2 (point) 3 (line) 4 (area)
Average exitance	When interreflections are critical to the illuminance calculations above (exitance is the fundamental quantity for calculating diffuse luminance)	5
Exitance at a point	Calculation of luminance, contrast, or luminance ratios at a point for diffuse surfaces	6
Nondiffuse luminance	Reading materials (signs, print) and glossy surfaces	7

*1: Lumen method for average illuminance in a room with partitions. 2: Parking lot lighting. 3: Lighting a chalkboard in a classroom. 4: Diffuse skylight illuminating a desk. 5: Interreflections from daylight. 6: Luminances produced by a point source for task lighting at a desk. 7: Evaluating contrast produced on printed material.

Figure 9-40. Example Calculations and Their Applications

Example 1: Lumen Method for Average Illuminance

The setting for this example is a small open plan office with six workstations formed by partitions. VDTs are used extensively in this space. The office measures 36 × 30 ft with a 9.5-ft floor-to-ceiling height. The partitions are 5 ft high, and each workstation is 12 × 12 ft. The layout of the partitions and desks is shown in Figure 9-41a. The section showing the room cavities to be used is in Figure 9-41b.

1. Determine the Quantity to be Calculated. It is decided that an indirect lighting system is used in the space, with the goal of providing a maintained illuminance of 40 fc on the horizontal desk surfaces, which are 2.5 ft above the floor. High-angle light control is needed to suit VDT use in the space. The number of luminaires required to produce this illuminance on the desktops inside the partitioned workstations is the quantity to be calculated.

2. Identify Luminaires and the Information Describing Them. An indirect luminaire is used. The luminaire uses single in-line T-8 fluorescent lamps (lamp lumens = 2900 lm) and is available in continuous lengths that are multiples of 4 ft, up to a maximum length of 24 ft. A 1.5-ft pendant length is recommended by the manufacturer. Photometric data include the CUs that are shown in Figure 9-42.

3. Determine the Accuracy, Complexity, and Detail of the Calculation. The lumen method is used to determine the number of luminaires required, and the following light loss factors are defined: luminaire dirt depreciation factor, lamp lumen depreciation factor, and ballast factor. Other light loss factors are assumed to have a value of 1.0 for this example.

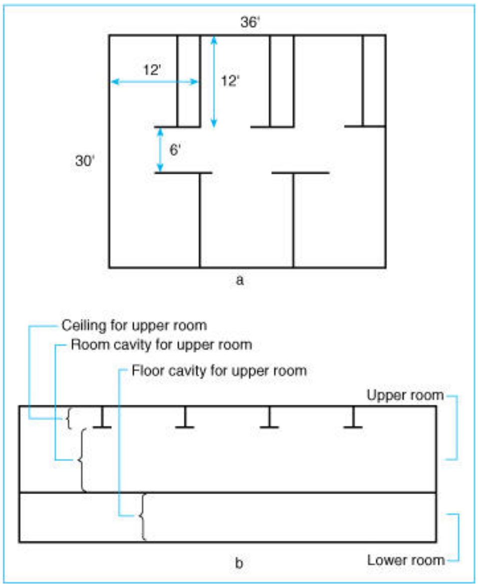


Figure 9-41. Open plan office for example 1: (a) layout, (b) section.

	$\rho_{floor} = 20$							
	$\rho_{ceiling} = 80$			70			50	
RCR	$\rho_{wall} = 70$	50	30	70	50	30	50	30
0	75	75	75	73	73	73	70	70
1	71	69	68	70	68	66	65	64
2	67	64	61	66	63	61	61	59
3	64	59	56	62	58	55	57	54
4	60	55	51	59	54	51	53	50
5	56	50	46	55	50	46	49	45
6	53	47	43	52	46	42	45	42
7	50	43	39	49	43	39	42	38
8	46	39	35	45	39	35	38	35
9	43	36	32	42	36	32	35	31
10	40	33	29	39	33	29	32	28

Figure 9-42. Coefficients of Utilization for Indirect Luminaire Used in Example 1

The following calculation strategy is used to take account of the light losses and shadowing produced by the partitions:

a) An individual partitioned workstation is treated as a small room.

b) An imaginary horizontal plane at the level of the top of the partitions represents the ceiling of an individual workstation. The partitions form the walls of this workstation, and the actual working plane is considered as the floor in the calculations. The ceiling reflectance is the effective cavity reflectance of the upper portion of the room, and the floor reflectance is the surface-area-weighted average of the desktop reflectance and effective cavity reflectance of the surfaces below the workplane. In both cases, the effective cavity reflectance is considered from a viewpoint between the workstation ceiling plane and the workplane.

c) The required illuminance on the desk surface is produced if, taking account of interreflections within the workstation, sufficient light crosses the workstation ceiling plane. This light is directed onto the ceiling plane from the portion of the room above the partitions.

d) Light crossing the workstation ceiling plane can be characterized both as an exitance from a viewpoint inside the workstation and as an illuminance from a viewpoint above the workstation ceiling plane. It is assumed that the distribution of the light crossing the workstation ceiling plane is diffuse.

e) For the purpose of lumen calculations within the workstation, the workstation ceiling plane can be considered a perfectly diffuse luminaire. Thus, the coefficients of utilization of a perfectly diffuse emitter can be used.

f) Working back from the illuminance required on the desk, the luminous output of the diffuse luminaire (that is, the diffuse exitance of the workstation ceiling plane) is calculated.

g) This exitance is numerically equal to the illuminance that must be produced by the upper part of the room onto the workstation ceiling plane. That is, the workstation ceiling plane can be considered the floor of the upper part of the room with a required illuminance. It has a reflectance that is the effective cavity reflectance of the partitioned workstation.

h) The lumen method is applied to the space above the partitions to determine the number of indirect luminaires required to produce this illuminance. Coefficients of utilization for the indirect luminaire are used for this calculation.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The diffuse reflectances of the room surfaces are as follows:

Floor	0.25
Walls	0.60
Ceiling	0.80
Partitions	0.65
Desktops	0.35

It is assumed that the fluorescent lighting system operates continuously through the working day, corresponding to 10 h of operation per start. A maintenance schedule whereby lamps and luminaires are cleaned every year is also assumed.

The luminaire dirt depreciation light loss factor is determined following the procedure given in Figure 9-14. Since the luminaire has an opaque bottom surface and no top enclosure, it is in maintenance category VI. Using the method given in Figure 9-15, the operating atmosphere must be classified, and for this situation is determined to be clean. The luminaire dirt depreciation light loss factor is then determined from Figure 9-17, and the depreciation curve for luminaires operating in a clean atmosphere. For a yearly maintenance cycle, the luminaire dirt depreciation factor is determined to be 0.85.

A more accurate determination can be made by referring to manufacturer's data for the specific lamp type to be used. Allowance can be made for the assumption that the lamps are operated for 10 h per start. The data in Chapter 6 are based on 3 h per start; thus it is assumed that the lamp lumen depreciation factor should be slightly adjusted to 0.88.

The ballast factor for the magnetic ballasts used in this luminaire is 0.95. The total light loss factor (LLF) is thus LLF = 0.85 × 0.88 × 0.95 = 0.711.

5. Determine Appropriate Equations. From Equation 9-50, the lumen method equation for determining the required number of luminaires is

$$\text{number of luminaires} = \frac{E_{\text{maintained}} \times \text{workplane area}}{\text{lamps per luminaire} \times \text{lamp lumens} \times \text{CU} \times \text{LLF}}$$

6. Solve the Equations. The lumen method is applied first to a workstation. The CU is determined from the room cavity ratio (RCR) and the surface reflectances (determined as shown in the section "Average Illuminance Calculation: The Lumen Method"):

$$\text{RCR} = \frac{5\,h\,(l + w)}{l \times w}$$

where h is the cavity height, l is the cavity length, and w is the cavity width. Because the ceiling of a workstation is at the level of the top of the partitions and the floor is at workplane level, the cavity height is 5 − 2.5 − 2.5 ft. This value and the workstation dimensions give

$$\text{RCR} = \frac{5 \times 2.5 \times (12 + 12)}{12 \times 12} = 2.08$$

Below the workplane level is a floor cavity, for which the effective cavity reflectance must be determined. It has a base reflectance of 0.25 (the actual floor) and a wall reflectance of 0.60, and the floor cavity ratio (FCR) is given by

$$\text{FCR} = \frac{5 \times 2.5 \times (12 + 12)}{12 \times 12} = 2.08$$

Figure 9-27 is read to determine the effective floor cavity reflectance (ρ_{FC}), using the floor cavity ratio 2.08 and the reflectances 0.25 and 0.60. By linear interpolation, the result is $\rho_{FC} = 0.23$.

In an area as small as the workstation, the size of the desk is significant. A surface-area-weighted average reflectance (ρ_{FCave}) can be determined for the floor or base of the cavity as shown in Equation 9-58. For the present case,

$$\rho_{FCave} = \frac{A_{FC}\,\rho_{FC} + A_{DT}\,\rho_{DT}}{A_{FC} + A_{DT}}$$

where the subscript DT indicates the desktop. A_{FC} and A_{DT} indicate the areas of the floor and desktop, respectively. If the area of the desktop is 18 ft^2, the effective floor cavity reflectance is

$$\rho_{FCave} = \frac{(12 \times 12 - 18) \times 0.23 + 18 \times 0.35}{(12 \times 12 - 18) + 18} = 0.245$$

The reflectance assigned to the workstation ceiling plane is the effective cavity reflectance of the upper portion of the room from a viewpoint inside the workstation. Because the room height is 9.5 ft and the partitions are 5 ft tall, the cavity height is 4.5 ft. The ceiling cavity ratio (CCR) is given by

$$\text{CCR} = \frac{5 \times 4.5 \times (36 + 30)}{36 \times 30} = 1.37$$

The base reflectance of this cavity is the ceiling reflectance of the room, 0.80, and the wall reflectance is the wall reflectance of the room, 0.60. Referring to Figure 9-27, the effective ceiling cavity reflectance for the workspace is 0.65.

Thus, the parameters for determining the CU in the workstation are RCR = 2.08, $\rho_{\text{ceiling}} = 0.65$, $\rho_{\text{walls}} = 0.60$, and $\rho_{FCave} = 0.245$. A CU table for a perfectly diffuse emitter is given in Figure 9-30. Linear interpolation gives the value CU = 0.80.

As stated in the CU table, all values assume a floor cavity reflectance of 0.20. Thus in this situation the CU value must be modified to take account of the high floor cavity reflectance. The multiplier for this purpose is interpolated from the table of multipliers in Figure 9-29. For $\rho_{FCave} = 0.245$, the result is multiplier = 1.06, and so CU = 0.80 × 1.06 = 0.85.

From the lumen method equation, the number of lumens required to pass through the workstation ceiling plane is

$$\text{lumens required} = \frac{E_{\text{maintained}} \times \text{workplane area}}{\text{CU}} = \frac{(40 \times 12 \times 12)}{0.85} = 6776 \text{ lm}$$

The illuminance that must be produced on this plane is thus

$$E_{\text{required}} = \frac{\text{required lumens}}{\text{area of workstation}} = \frac{6776}{(12 \times 12)} = 47 \text{ fc}$$

The lumen method is now applied to the upper portion of the room. The room cavity height is the distance between the partition tops and suspended luminaires, 3 ft. The RCR is

$$\text{RCR} = \frac{5 \times 3 \times (36 + 30)}{36 \times 30} = 0.916$$

Since the luminaires are suspended, an effective ceiling cavity reflectance must be determined. The CCR is

$$\text{CCR} = \frac{5 \times 1.5 \times (36 + 30)}{36 \times 30} = 0.458.$$

The base reflectance of this cavity is the room ceiling reflectance, 0.80, and the wall reflectance is the room wall reflectance, 0.60. Referring to Figure 9-27, the effective ceiling cavity reflectance is $\rho_{CC} = 0.74$.

The effective floor reflectance of the room is determined from the data on the workstations. The effective reflectance of the workplane has been calculated to be 0.245, and this plane forms the cavity base. The partitions, having a reflectance of 0.65, form the cavity walls. The cavity height is the height between the workplane and the workstation ceiling plane, 2.5 ft. The cavity ratio is

$$\text{CR} = \frac{5 \times 25 \times (12 + 12)}{12 \times 12} = 2.08.$$

Referring again to Figure 9-27, the effective floor cavity reflectance is $\rho_{FC} = 0.24$.

Thus, the parameters for determining the CU are RCR = 0.916, $\rho_{CC} = 0.74$, $\rho_{\text{walls}} = 0.60$, and $\rho_{FC} = 0.24$. Interpolation in the CU table for the indirect luminaire (Figure 9-42) gives CU = 0.67. As previously, a multiplier must be determined to correct for the difference between the assumed floor reflectance of 0.20 and the value 0.24. From Figure 9-29, the result is Multiplier = 1.08. Thus the corrected coefficient of utilization is CU = 0.67 × 1.08 = 0.72.

The other parameters for the lumen method equation are lamps per luminaire = 1 and lamp lumens = 2900 lm.

Finally, the number of luminaires is

$$\begin{aligned}\text{number of luminaires} &= \frac{E_{\text{maintained}} \times \text{workplane area}}{\text{lamps per luminaire} \times \text{lamp lumens} \times \text{CU} \times \text{LLF}} \\ &= \frac{47 \times 36 \times 30}{1 \times 2900 \times 0.72 \times 0.771} = 31.5\end{aligned}$$

An architecturally practical layout of these luminaires would involve 32 luminaires. One such arrangement is four rows, each 32 ft long, consisting of eight luminaires per row.

Example 2: Lighting a Small Parking Area

The setting for this example is a small parking lot near an office building.The parking lot measures 100 × 100 ft and is adjacent to a three-story office building. It is desired to keep the equipment height consistent with the architectural scale of the building. An analysis is to be performed to see if a single luminaire on a pole can sufficiently illuminate the entire parking lot. The pole is placed at the center of the area.

1. Determine the Quantity to be Calculated. A diagram of the parking area and the proposed lighting system appears in Figure 9-43. To evaluate the effectiveness of a single pole location, the illuminances are calculated at the points of a 5 × 5-ft rectangular grid on the pavement surface. This analysis is performed with three typical pole heights: 15, 20, and 25 ft. The evaluation criterion is the illuminance recommendation (see Chapter 22, Roadway Lighting) for a low-activity-level, open parking facility: a minimum horizontal illuminance of 0.2 fc, minimum vertical illuminance of 0.1 fc, and a uniformity criterion that the ratio of maximum to minimum illuminance is to be no greater than 20:1.

2. Identify Luminaires and the Information Describing Them. The luminaire to be used in the analysis is Type VS with a square distribution, using a 250-W clear metal halide lamp, and having a lumen rating of 20,500 lm. Photometric data are available and are shown in Figure 9-44 as they might appear in a photometric report.

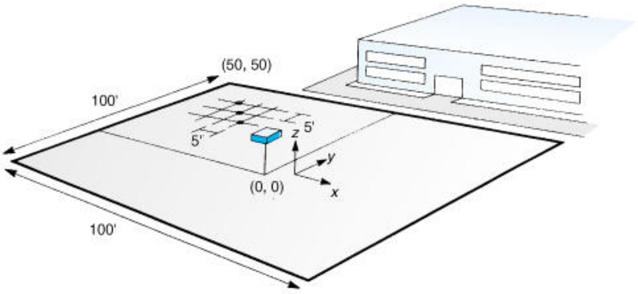
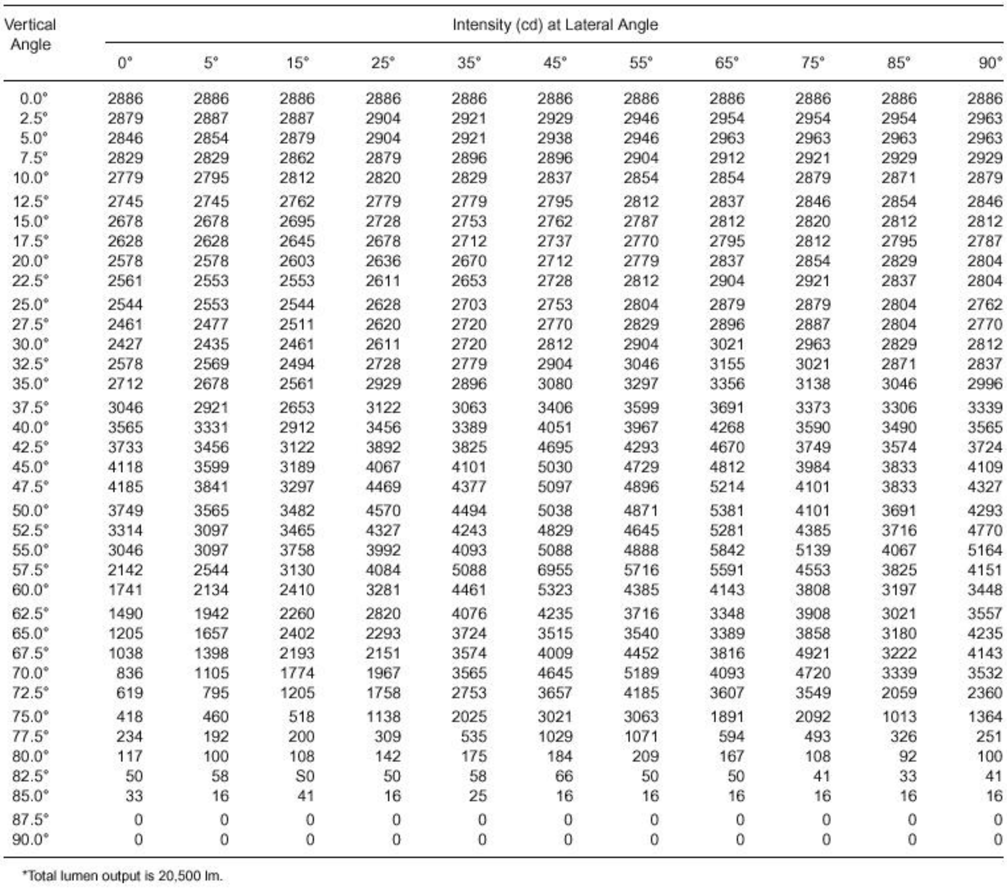


Figure 9-43. Diagram of parking area for Example 2.

3. Determine the Accuracy, Complexity, and Detail of the Calculation. Initial calculations are performed at the points along the diagonal of this grid. It is anticipated that the illuminance is likely to be lowest at the corners of the parking area because the distance from the luminaires is greatest at the corners.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The necessary dimensions are shown in Figure 9-43. On their photometric reports, manufacturers often recommend a total light loss factor to be used with their luminaires. In this case, the manufacturer recommended a total light loss factor of 0.85. Reflectances are unimportant, since this is an outdoor application.



Vertical Angle	Intensity (cd) at Lateral Angle										
	0°	5°	15°	25°	35°	45°	55°	65°	75°	85°	90°
0.0°	2886	2886	2886	2886	2886	2886	2886	2886	2886	2886	2886
2.5°	2879	2887	2887	2904	2921	2929	2946	2954	2954	2954	2963
5.0°	2846	2854	2879	2904	2921	2938	2946	2963	2963	2963	2963
7.5°	2829	2829	2862	2879	2896	2896	2904	2912	2921	2929	2929
10.0°	2779	2795	2812	2820	2829	2837	2854	2854	2879	2871	2879
12.5°	2745	2745	2762	2779	2779	2795	2812	2837	2846	2854	2846
15.0°	2678	2678	2695	2728	2753	2762	2787	2812	2820	2812	2812
17.5°	2628	2628	2645	2678	2712	2737	2770	2795	2812	2795	2787
20.0°	2578	2578	2603	2636	2670	2712	2779	2837	2854	2829	2804
22.5°	2561	2553	2553	2611	2653	2728	2812	2904	2921	2837	2804
25.0°	2544	2553	2544	2628	2703	2753	2804	2879	2879	2804	2762
27.5°	2461	2477	2511	2620	2720	2770	2829	2896	2887	2804	2770
30.0°	2427	2435	2461	2611	2720	2812	2904	3021	2963	2829	2812
32.5°	2578	2569	2494	2728	2779	2904	3046	3155	3021	2871	2837
35.0°	2712	2678	2561	2929	2896	3080	3297	3356	3138	3046	2996
37.5°	3046	2921	2653	3122	3063	3406	3599	3691	3373	3306	3339
40.0°	3565	3331	2912	3456	3389	4051	3967	4268	3590	3490	3565
42.5°	3733	3456	3122	3892	3825	4695	4293	4670	3749	3574	3724
45.0°	4118	3599	3189	4067	4101	5030	4729	4812	3984	3833	4109
47.5°	4185	3841	3297	4469	4377	5097	4896	5214	4101	3833	4327
50.0°	3749	3565	3482	4570	4494	5038	4871	5381	4101	3691	4293
52.5°	3314	3097	3465	4327	4243	4829	4645	5281	4385	3716	4770
55.0°	3046	3097	3758	3992	4093	5088	4888	5842	5139	4067	5164
57.5°	2142	2544	3130	4084	5088	6955	5716	5591	4553	3825	4151
60.0°	1741	2134	2410	3281	4461	5323	4385	4143	3808	3197	3448
62.5°	1490	1942	2260	2820	4076	4235	3716	3348	3908	3021	3557
65.0°	1205	1657	2402	2293	3724	3515	3540	3389	3858	3180	4235
67.5°	1038	1398	2193	2151	3574	4009	4452	3816	4921	3222	4143
70.0°	836	1105	1774	1967	3565	4645	5189	4093	4720	3339	3532
72.5°	619	795	1205	1758	2753	3657	4185	3607	3549	2059	2360
75.0°	418	460	518	1138	2025	3021	3063	1891	2092	1013	1364
77.5°	234	192	200	309	535	1029	1071	594	493	326	251
80.0°	117	100	108	142	175	184	209	167	108	92	100
82.5°	50	58	S0	50	58	66	50	50	41	33	41
85.0°	33	16	41	16	25	16	16	16	16	16	16
87.5°	0	0	0	0	0	0	0	0	0	0	0
90.0°	0	0	0	0	0	0	0	0	0	0	0

*Total lumen output is 20,500 lm.

Figure 9-44. Parking Lot Luminaire Luminous Intensity Distribution for Type A Photometry*

5. Determine Appropriate Equations. The smallest mounting height to be used is 15 ft, which is more than 5 times the largest dimension of the luminaire. Thus, the five-times rule is satisfied for any point on the calculation grid, and the luminaire can be treated as a point source. The inverse square cosine law can be used for illuminance computations:

$$E = \frac{I(\theta, \psi) \cos \theta}{D^2}$$

The geometry of this problem allows each of the trigonometric and distance quantities in this equation to be expressed in rectangular coordinates (Figure 9-43):

$$\theta = \arctan\left(\frac{\sqrt{x^2 + y^2}}{z}\right)$$

$$\psi = \arctan\left(\frac{x}{y}\right)$$

$$\cos \xi = \frac{z}{\sqrt{x^2 + y^2 + z^2}}$$

$$D^2 = x^2 + y^2 + z^2$$

These combine to give the following expression for the horizontal and vertical illuminances, *EH* and *EV*, respectively:

$$E_H = I(\theta, \psi) \frac{z}{(x^2 + y^2 + z^2)\sqrt{x^2 + y^2 + z^2}}$$

$$E_V = I(\theta, \psi) \frac{y}{(x^2 + y^2 + z^2)\sqrt{x^2 + y^2 + z^2}}$$

6. Solve the Equations. An analysis is performed at the grid points along a diagonal. Referring to Figure 9-43, the rectangular coordinates can be determined with respect to the luminaire. Three values of *z* are used for each pair of *x* and *y* coordinates, each value of *z* representing one of the three pole heights to be evaluated. The point ($x = 0$, $y = 0$) is directly underneath the luminaire. The point ($x = 50$, $y = 50$) is at the corner of the parking lot. The luminous intensity values are obtained by linear interpolation from Figure 9-44.

The intensity at ($\theta = 43.3°$, $\psi = 45.0°$) is estimated as 3801 cd. The results of all intermediate calculations are summarized in Figure 9-45. The horizontal and vertical illuminance at each position is calculated for each of the three pole heights.

At a distance of 50 ft, the horizontal illuminance near the corner of the lot is below 0.2 fc for a pole height of 15 or 20 ft. Only for a pole height of 25 ft is the minimum illuminance requirement of 0.2 fc met over the entire parking lot. This pole height also minimizes the maximum-to-minimum illuminance ratio over the parking area, which meets the required maximum ratio of 20:1 from Chapter 22, Roadway Lighting, as demonstrated below. Additionally, the 25-ft pole height produced a minimum vertical illuminance of 0.26 fc, which meets the minimum requirement.

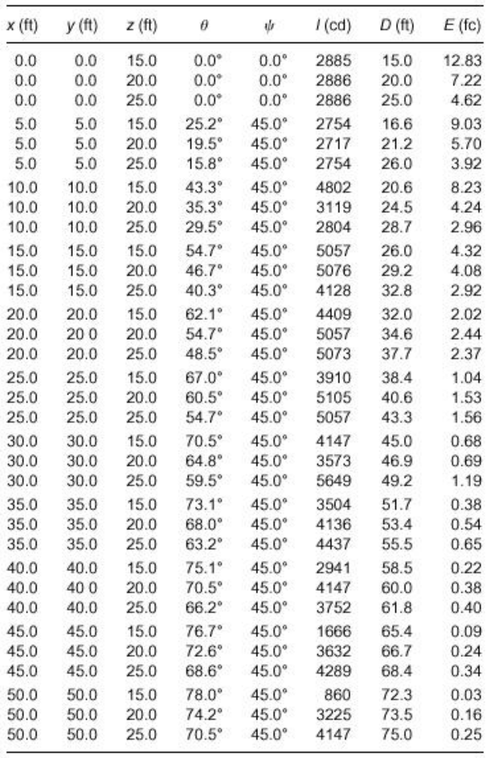
The maximum-to-minimum ratio for the pole height of 25 ft is calculated as follows:

$$\frac{\text{maximum illuminance}}{\text{minimum illuminance}} = \frac{4.54 \text{ fc}}{0.23 \text{ fc}} = \frac{19.7}{1}$$

Thus the ratio is 19.7:1, which meets IESNA recommendations for uniformity.

Example 3: Calculation of Illuminance at a Point: Direct and Interreflected Components

This example concerns lighting a chalkboard.



x (ft)	*y* (ft)	*z* (ft)	*θ*	*ψ*	*I* (cd)	*D* (ft)	*E* (fc)
0.0	0.0	15.0	0.0°	0.0°	2885	15.0	12.83
0.0	0.0	20.0	0.0°	0.0°	2886	20.0	7.22
0.0	0.0	25.0	0.0°	0.0°	2886	25.0	4.62
5.0	5.0	15.0	25.2°	45.0°	2754	16.6	9.03
5.0	5.0	20.0	19.5°	45.0°	2717	21.2	5.70
5.0	5.0	25.0	15.8°	45.0°	2754	26.0	3.92
10.0	10.0	15.0	43.3°	45.0°	4802	20.6	8.23
10.0	10.0	20.0	35.3°	45.0°	3119	24.5	4.24
10.0	10.0	25.0	29.5°	45.0°	2804	28.7	2.96
15.0	15.0	15.0	54.7°	45.0°	5057	26.0	4.32
15.0	15.0	20.0	46.7°	45.0°	5076	29.2	4.08
15.0	15.0	25.0	40.3°	45.0°	4128	32.8	2.92
20.0	20.0	15.0	62.1°	45.0°	4409	32.0	2.02
20.0	20.0	20.0	54.7°	45.0°	5057	34.6	2.44
20.0	20.0	25.0	48.5°	45.0°	5073	37.7	2.37
25.0	25.0	15.0	67.0°	45.0°	3910	38.4	1.04
25.0	25.0	20.0	60.5°	45.0°	5105	40.6	1.53
25.0	25.0	25.0	54.7°	45.0°	5057	43.3	1.56
30.0	30.0	15.0	70.5°	45.0°	4147	45.0	0.68
30.0	30.0	20.0	64.8°	45.0°	3573	46.9	0.69
30.0	30.0	25.0	59.5°	45.0°	5649	49.2	1.19
35.0	35.0	15.0	73.1°	45.0°	3504	51.7	0.38
35.0	35.0	20.0	68.0°	45.0°	4136	53.4	0.54
35.0	35.0	25.0	63.2°	45.0°	4437	55.5	0.65
40.0	40.0	15.0	75.1°	45.0°	2941	58.5	0.22
40.0	40.0	20.0	70.5°	45.0°	4147	60.0	0.38
40.0	40.0	25.0	66.2°	45.0°	3752	61.8	0.40
45.0	45.0	15.0	76.7°	45.0°	1666	65.4	0.09
45.0	45.0	20.0	72.6°	45.0°	3632	66.7	0.24
45.0	45.0	25.0	68.6°	45.0°	4289	68.4	0.34
50.0	50.0	15.0	78.0°	45.0°	860	72.3	0.03
50.0	50.0	20.0	74.2°	45.0°	3225	73.5	0.16
50.0	50.0	25.0	70.5°	45.0°	4147	75.0	0.25

Figure 9-45. Intermediate Calculations for Example 2

1. Determine the Quantity to Be Calculated. The quantity of interest is the illuminance at a point on a chalkboard. This is used to determine if a design illuminance criterion of 20 fc on the chalkboard is met. It is assumed that the point at the center of the chalkboard is representative; this point is used for calculations. The layout is shown in Figures 9-46 and 9-47.

2. Identify Luminaires and the Information Describing Them. A pair of 1 × 4-ft recessed troffers, each with two T-12 fluorescent lamps, are used. The total produced by a single luminaire is 3791 lm. The luminous intensity distribution for this luminaire is shown in Figure 9-48 as it might appear in a photometric report.

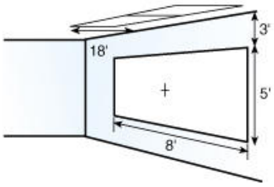


Figure 9-46. Pertinent room dimensions for Example 3, lighting a chalkboard.

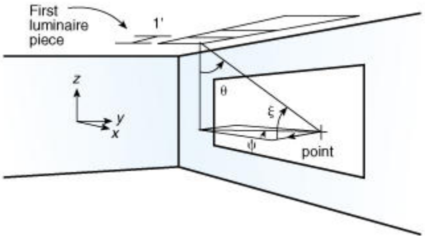


Figure 9-47. Illustration of angles and dimensions for Example 3.

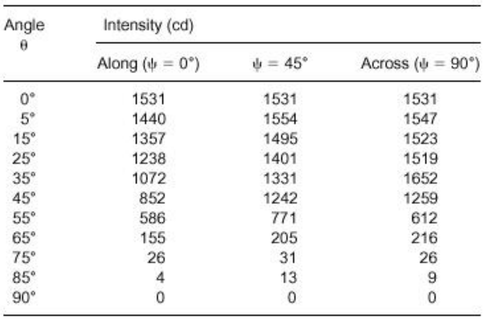
3. Determine the Accuracy, Complexity, and Detail of the Calculation. The direct component of illuminance is calculated from the two luminaires. It is not possible to treat the luminaires as point sources because of their size and proximity to the chalkboard. Because of their shape, they are considered to be line sources. Therefore the five-times rule is used to determine the number of discrete pieces of luminaire that must be considered.

The distance *D* from the center of one of the luminaires to the center of the chalkboard, as can be seen in Figures 9-46 and 9-47, is

$$D = \sqrt{x^2 + y^2 + z^2} = \sqrt{2^2 + 1.5^2 + 5.5^2} = 6.04 \text{ ft}$$

The five-times rule requires the dimensions of the discrete pieces of the luminaire to be no greater than 6.04/5 = 1.2 ft. Since the luminaires measure approximately 1 × 4 ft, each can be discretized into four sections of 1 ft^2 along its length. Each discrete piece of the luminaire is assumed to emit 25% of the luminaire lumens. Therefore, each has a luminous intensity distribution equal to 25% that of the entire luminaire.

The interreflected component is determined using the average interreflected illuminance over the chalkboard, since the average interreflected illuminance variation is likely to be small. It is assumed that the principal interreflection is between the chalkboard and a section of the ceiling nearby. The floor is very likely to have a low reflectance and is ignored for purposes of interreflected component calculations. Other walls are assumed to be sufficiently far from the chalkboard to give a negligible contribution to the interreflected component. Note that luminaires in the room other than those used to directly light the chalkboard may also produce direct and interreflected illuminance on the chalkboard. Other sources of illumination are not considered in this example.



Angle θ	Intensity (cd)		
	Along (ψ = 0°)	ψ = 45°	Across (ψ = 90°)
0°	1531	1531	1531
5°	1440	1554	1547
15°	1357	1495	1523
25°	1238	1401	1519
35°	1072	1331	1652
45°	852	1242	1259
55°	586	771	612
65°	155	205	216
75°	26	31	26
85°	4	13	9
90°	0	0	0

Figure 9-48. Luminous Intensity Distribution for Schoolroom Luminaire

4. Identify Required Geometric, Reflectance, and Ancillary Data. The chalkboard reflectance ρ_1 is 0.25. The ceiling reflectance ρ_2 is 0.80. The pertinent room dimensions are as shown in Figure 9-46.

5. Determine Appropriate Equations

Direct Component. The discrete luminaire pieces are small enough for the inverse square cosine law to be applied for each of the eight pieces (two four-foot luminaires, each divided into one-foot sections), and the illuminances (calculated using Equation 9-4) added together to give the total illuminance:

$$E = \sum_{i=1}^{8} \frac{I_i \cos \xi_i}{D^2{}_i}$$

where

I_i = intensity of the *i*th piece in the direction to the center of the chalkboard,
ξ_i = angle between the normal to the chalkboard surface and a line from the *i*th piece to the center of the chalkboard,
D_i = distance between the center of the chalkboard and the *i*th piece.

Interreflected Component. A general equation for interreflected illuminance between two diffuse surfaces is used, based on Equation 9-23a:

$$\bar{E}_{1\ \text{inter}} = \frac{\bar{E}_{1\ \text{dir}} + \bar{E}_{2\ \text{dir}} f_{1\to 2}}{1 - \rho_1 \rho_2 f_{1\to 2} f_{2\to 1}} - \bar{E}_{1\ \text{dir}}$$

where

$E_{1\ \text{dir}}$ = direct illuminance onto surface 1,
$E_{2\ \text{dir}}$ = direct illuminance onto surface 2,
$f_{1\to 2}$ = radiative exchange form factor from surface 1 to surface 2,
$f_{2\to 1}$ = radiative exchange form factor from surface 2 to surface 1,
ρ_1, ρ_2 = diffuse reflectances of surfaces 1 and 2.

In the present application, surface 1 is the chalkboard and surface 2 is the ceiling near the chalkboard. In this case only the chalkboard has an initial illuminance, and the general equation becomes

$$\bar{E}_{\text{inter}} = \frac{\bar{E}_{\text{dir}}}{1 - \rho_{cb}\rho_c f_{cb\to c} f_{c\to cb}} - \bar{E}_{\text{dir}}$$

where

$\bar{E}_{\text{dir}}$ = direct illuminance on the chalkboard,
$f_{cb\to c}$ = radiative exchange form factor between the chalkboard (*cb*) and the ceiling (*c*)
$f_{c\to cb}$ = radiative exchange form factor between the ceiling and the chalkboard,
ρ_{cb}, ρ_c = diffuse reflectances of the chalkboard and ceiling.

6. Solve the Equations

Direct Component. The intermediate quantities required to calculate the direct component of illuminance are shown below and in Figure 9-49:

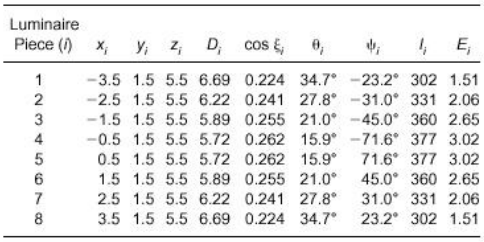
$$D_i = \sqrt{x_i^2 + y_i^2 + z_i^2}$$

$$\theta_i = \arccos\left(\frac{z_i}{D_i}\right)$$

$$\psi_i = \arctan\left(\frac{y_i}{x_i}\right)$$

$$\cos \xi = \frac{y_i}{D_i}$$

The angle ψ is measured from the lamp axis of the luminaire. The plane of data corresponding to a value of zero for this angle is identified as "along" in Figure 9-48. Intensities for angles not between 0 and 90° are obtained as discussed above. Negative angles can be converted to positive angles by adding 360°. The luminous intensities are linearly interpolated from the luminous intensity distribution data in Figure 9-48 and divided by 4 because of the discretization of each luminaire into four pieces. All of the calculated values for each of the eight luminaire pieces are shown in Figure 9-49. The total direct illuminance is then the sum of the partial illuminances in the column at the far right of the table, or 18.5 fc.



Luminaire Piece (i)	x_i	y_i	z_i	D_i	$\cos \xi_i$	θ_i	ψ_i	I_i	E_i
1	−3.5	1.5	5.5	6.69	0.224	34.7°	−23.2°	302	1.51
2	−2.5	1.5	5.5	6.22	0.241	27.8°	−31.0°	331	2.06
3	−1.5	1.5	5.5	5.89	0.255	21.0°	−45.0°	360	2.65
4	−0.5	1.5	5.5	5.72	0.262	15.9°	−71.6°	377	3.02
5	0.5	1.5	5.5	5.72	0.262	15.9°	71.6°	377	3.02
6	1.5	1.5	5.5	5.89	0.255	21.0°	45.0°	360	2.65
7	2.5	1.5	5.5	6.22	0.241	27.8°	31.0°	331	2.06
8	3.5	1.5	5.5	6.69	0.224	34.7°	23.2°	302	1.51

Figure 9-49. Intermediate Calculations for Example 3

Interreflected Component. As shown above, this calculation requires the initial average illuminance on the chalkboard. For the purpose of calculating the interreflected component, it is assumed to be the same as the average illuminance on the entire wall. This average illuminance can be calculated from (luminaire lumens incident onto the chalkboard)/(area of the chalkboard wall). The luminaires have intensity distributions that are symmetric both along and across the lamp axis and are mounted close to the chalkboard wall. Thus it can be assumed that approximately 50% of the luminaire lumens reach this surface directly. For each luminaire, 50% of 3791, or 1895.5 lm, reaches the chalkboard wall directly. Because there are two luminaires, the total flux incident on the chalkboard wall is assumed to be 3791 lm. The area of the chalkboard wall is 64 ft^2 (8 × 8 ft). Therefore,

$$\bar{E}_{\text{dir}} = \frac{\text{incident flux}}{\text{area}} = \frac{3791\ \text{lm}}{64\ \text{ft}^2} = 59\ \text{fc}$$

Solving for the interreflected illuminance component gives

$$\bar{E}_{\text{inter}} = \frac{\bar{E}_{\text{dir}}}{1 - \rho_{cb}\, \rho_c f_{cb} \to c\, f_{c\to cb}} - \bar{E}_{\text{dir}}$$

where $\bar{E}_{\text{dir}}$, ρ_{cb}, and ρ_c have been previously defined, and $f_{cb\text{-}c}$ and $f_{\text{c-cb}}$ are both assumed to equal 0.2. Hence $\bar{E}_{\text{inter}}$ = 0.5 fc. The total illuminance at the point is then $E = \bar{E}_{\text{dir}} + E_{\text{inter}}$ = 18.5 fc + 0.5 fc = 19 fc.

Given the accuracy of the equations used (which is no better than 5%, as discussed in the description of the algorithm above), the calculated illuminance of 19 fc may or may not meet the established design criterion of 20 fc. Further analysis on the part of the designer is probably necessary in this borderline case.

Note that the interreflected component is significantly smaller than the direct component. Because of this, a more elaborate calculation of the interreflected component produced by these luminaires is not required.

Example 4: Calculation of Illuminance at a Point from an Area Source: Direct Component Only

This example addresses skylights in a small classroom in Denver, Colorado.

1. Determine the Quantity to Be Calculated. The quantity of interest is the direct component of illuminance at a point on a desk in a small classroom. The calculation point is at the center of the room on a desk 2.5 ft high. The room is 28 × 28 ft with a floor-to-ceiling height of 10 ft. It has a ceiling reflectance of 0.80, a wall reflectance of 0.46, and a floor reflectance of 0.20.

2. Identify Sources and the Information Describing Them. The room is lighted by an array of four domed skylights, as shown in Figure 9-50. Each skylight is made of plastic that exhibits a diffuse transmittance of 0.15 for light incident perpendicular to the surface. For light incident at other angles, the transmittance is diffuse but the value is reduced. This diffuse directional transmittance is given by the equation $T(\theta) = 0.15 \cos^2 \theta$, where θ is the angle of incidence. This equation is used for the direct solar contribution. The total diffuse transmittance T for light incident equally from all directions is 0.10.

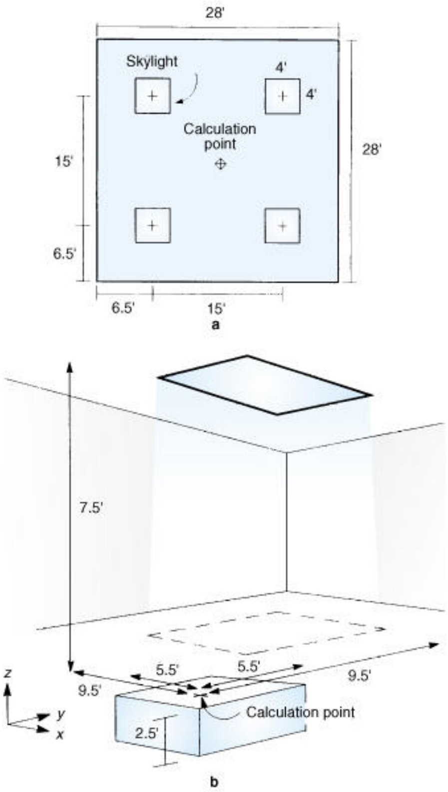


Figure 9-50. Classroom and skylights for Examples 4 and 5: (a) plan, (b) perspective.

3. Determine the Accuracy and Complexity. The direct component is calculated from the skylights, assuming that they are diffuse area sources. The equation for the illuminance produced by a diffuse area source is used (Equation 9-9). This equation requires the source exitance, which in this case is the skylight exitance. This exitance is produced by sunlight and sky light transmitted through the dome of the skylight.

Since the skylight is domed, the transmittance is almost independent of the direction from which the light arrives onto the skylight. This would not be true if the skylight were flat. Domed skylights exhibit a transmittance change due to the thinning of material at the top of the dome. The effect of domed skylights is determined by evaluating the change in transmittance.

The illuminance produced by the skylights is a function of their exitance, which in turn is a function of the daylight illuminance on them and their transmittance. Both of these quantities are affected by the sun's position. Thus the calculation must be made for a specific date, time, and sky condition as described in Chapter 8, Daylighting.

The calculation for the interreflected component is shown in example 5.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The date and time of the example calculation is April 10, 12 noon for Denver, Colorado. The sky condition is assumed to be clear. The available horizontal illuminance, as calculated according to the method described in Chapter 8, Daylighting, is $E_{\text{sun}} = 9150$ fc and $E_{\text{sky}} = 1400$ fc. The solar altitude for these conditions is 57.5°, so the sun is 32.5° from the zenith.

5. Determine Appropriate Equations. The equation for the illuminance produced by a diffuse area source is $E = Mc$, where M is the diffuse exitance of the source and c is the configuration factor for the area to the point. In this case the configuration factor is for a rectangle to a point in a plane parallel to the plane of the rectangle. The general equation, from Figure 9-3, is:

$$c = \frac{1}{2\pi} \sum_{i=1}^{2} \sum_{j=1}^{2} F(x_i, y_j)\,(-1)^{i+j}$$

where

$$F(x_i, y_j) = \frac{x_i}{\sqrt{x_i^2 + z^2}} \arctan\left(\frac{y_j}{\sqrt{x_i^2 + z^2}}\right) + \frac{y_j}{\sqrt{y_j^2 + z^2}} \arctan\left(\frac{x_i}{\sqrt{y_j^2 + z^2}}\right)$$

x_i = distance from the calculation point to the ith edge of the rectangular source in the x direction,
y_j = distance from the calculation point to the jth edge of the rectangular source in the y direction,
z = distance between the plane containing the calculation point and the plane of the source.

Since there is more than one diffuse area source, the total direct component of illuminance is

$$E = \sum_{i=1}^{4} M_i c_i$$

All four skylights have the same transmittance characteristics, and their proximity means that they have the same sky and sun illuminance. Thus they exhibit the same exitance. This gives

$$E = M \sum_{i=1}^{4} c_i$$

In the present example, the calculation point is at the center of the room and is thus symmetrically placed with respect to the skylights, and the four configuration factors are the same. The illuminance is then $E = 4Mc$.

The exitance M of the skylight within the room is

$$M = E_{\text{sun}} T_{\text{net}} + E_{\text{sky}} T$$

where

E_{sun} = horizontal illuminance produced by the sun,
E_{sky} = horizontal illuminance produced by the sky,
T_{net} = net directional transmittance of the skylight,
T = total diffuse transmittance of the skylight.

The equation for the net directional transmittance T_{net} of a domed skylight for directional light (i.e., from the sun) is $T_{\text{net}} = 1.25\, T(0)\, [1.18 - 0.416T(0)]$, where $T(0)$ is the diffuse transmittance for light incident perpendicularly to the surface of the plastic (see Chapter 8, Daylighting).

6. Solve the Equations. The skylight net transmittance is $T_{\text{net}} = 1.25(0.15)[1.18 - 0.416(0.15)] = 0.210$. The skylight exitance M is M = (9150)(0.210) + (1400)(0.10) = 2057 lm/ft^2.

The configuration factor from one of the skylights to the point is calculated from the equation shown above in step 5. The distances involved are x_1 = 5 ft, x_2 = 9.5 ft, y_1 = 5.5 ft, y_2 = 9.5 ft, and z = 7.5 ft. The resulting configuration factor c is 0.0104.

The illuminance at the calculation point from the four skylights is $E = 4Mc = 4(2057)(0.0104) = 85.5$ fc. Thus, for a clear sky condition at 12 noon on April 10 in Denver, the four skylights produce a direct illuminance of 86 fc on the desk in the middle of the room.

Example 5: Calculation of Illuminance at a Point from an Area Source: Interreflected Component

This example also addresses skylights in a small classroom in Denver, Colorado.

1. Determine the Quantity to Be Calculated. The quantity of interest is the interreflected component of illuminance at a point on a desk in a small classroom. The direct illuminance component has been calculated in Example 4 and is 86 fc. The calculation point is the same as for Example 4: at the center of the room, on a desk 2.5 ft above the floor. The room is 28 × 28 ft with a floor-to-ceiling height of 10 ft. It has a ceiling reflectance of 0.80, a wall reflectance of 0.46, and a floor reflectance of 0.20.

2. Identify Sources and the Information Describing Them. The room is lighted by an array of four domed skylights, as shown in Figure 9-50. The skylights are described in Example 4.

3. Determine the Accuracy and Complexity. The interreflected component due to the skylights is calculated assuming that they are diffuse area sources. The interreflections in the room are likely to produce uniform room surface exitances, so a simple three-surface radiative transfer model is used. That is, the ceiling and floor are each treated as separate surfaces, and the four walls are grouped together and treated as the third surface. Calculating the interreflection of light results in a single final exitance for the floor, walls, and ceiling.

The ceiling and walls are then treated as diffuse area sources, and the illuminance they produce at the calculation point is the interreflected component. The equation for the illuminance produced by a diffuse area source is used.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The date and time of the example calculation is April 10, 12 noon for Denver, Colorado. The sky condition is assumed to be clear. The available horizontal illuminance, calculated as described in Chapter 8, Daylighting, is E_{sun} = 9150 fc and E_{sky} = 1400 fc. The reflectance data are described above in step 1.

5. Determine Appropriate Equations. Equations 9-24 through 9-26 governing the interreflection of light in a three-surface model are

$$M_c = M_{0c} + \rho_c(M_w f_{c\to w} + M_f f_{c\to f})$$

$$M_w = M_{0w} + \rho_w(M_c f_{w\to c} + M_w f_{w\to w} + M_f f_{w\to f})$$

$$M_f = M_{0f} + \rho_f(M_c f_{f\to c} + M_w f_{f\to w})$$

where

M_c = final ceiling exitance,
M_w = final wall exitance,
M_f = final floor exitance,
M_{0c} = initial ceiling exitance,
M_{0w} = initial wall exitance,
M_{0f} = initial floor exitance,
ρ_c = ceiling reflectance,
ρ_w = wall reflectance,
ρ_f = floor reflectance,
$f_{f\to c}$ = form factor from the floor to the ceiling,
$f_{f\to w}$ = form factor from the floor to the walls,
$f_{w\to c}$ = form factor from the walls to the ceiling,
$f_{w\to w}$ = form factor from the walls to the walls,
$f_{w\to f}$ = form factor from the walls to the floor,
$f_{c\to w}$ = form factor from the ceiling to the walls,
$f_{c\to f}$ = form factor from the ceiling to the floor.

As discussed above, reciprocity between radiative exchange form factors and the simple geometry of the three-surface model permits six of the seven form factors to be calculated from the single form factor $f_{f\to c}$, the radiative exchange form factor between floor and ceiling. This is the fraction of flux leaving the ceiling that reaches the floor directly. $f_{f\to c}$ is calculated using the equation for identical, parallel, directly opposed rectangles.

The initial exitances M_{0c}, M_{0w}, and M_{0f} are determined from

$$\mathrm{M} = \frac{\Phi_{\mathrm{onto}}\,\rho}{\mathrm{area}}$$

where Φ_{onto} is in this case, the flux directly from the skylights onto the surface.

The three simultaneous equations can then be solved for the final exitances M_c, M_w, and M_f. Finally, the illuminance produced at the desk by the ceiling and walls is calculated from

$$E = M_c c_{c\to p} + M_w c_{p\to w}$$

where

$c_{c\to p}$ = configuration factor from the ceiling to the point,
$c_{p\to w}$ = configuration factor from the walls to the point.

In this case the configuration factor is for a rectangle to a point in a plane parallel to the plane of the rectangle. This equation is found in Figure 9-3.

Since the sum of the configuration factors from all the surfaces enclosing a point is 1.0,

$$c_{p\to w} = 1.0 - c_{c\to p}$$

6. Solve the Equations. The radiative exchange form factor between floor and ceiling, $f_{f\to c}$, is calculated using Figure 9-5. Substituting the dimensions determined in step 1 into the appropriate equation, it is determined that $f_{f\to c} = 0.52571$.

We now use the relationships among the other form factors (from Equations 9-28 through 9-31):

$$f_{c\to f} = f_{f\to c} = 0.52571,$$

$$f_{c\to w} = f_{f\to w} = 1 - f_{c\to f} = 0.47429,$$

$$f_{w\to c} = f_{w\to f} = \frac{A_c}{A_w}(1 - f_{c\to f}) = 0.33200,$$

$$f_{w\to w} = 1 - 2\,f_{w\to c} = 0.33599,$$

where A_c is the area of the ceiling and A_w is the area of the walls. The equations for M_c, M_w, and M_f become

$$M_c = M_{0c} + 0.80(M_w 0.47429 + M_f 0.52571),$$

$$M_w = M_{0w} + 0.46(M_c 0.33200 + M_w 0.33599 + M_f 0.33200),$$

$$M_f = M_{0f} + 0.20(M_c 0.52571 + M_w 0.47429).$$

The initial exitance of the ceiling, M_{0c}, is zero, since the skylights cannot directly illuminate the ceiling: $M_{0c} = 0.0$. The initial exitance of the floor, M_{0f}, is given by

$$M_{0f} = \frac{\Phi_{\text{skylights}\to\text{floor}}\,\rho_f}{A_f}$$

where

$\Phi_{\text{skylights} \to \text{floor}}$ = flux emitted by the skylights that reaches the floor directly,
A_f = area of the floor.

The flux from the skylights to the floor is calculated from the total flux leaving the skylights and the radiative exchange form factors from the skylights to the floor:

$$\Phi_{\text{skylights} \to \text{floor}} = \sum_{i=1}^{4} \Phi_{\text{skylight}_i} f_{\text{skylight}_i \to \text{floor}}$$

The summation is over the four skylights in the room. Since the skylights are identical and placed symmetrically with respect to the calculation point and the center of the room, each emits the same number of lumens, and the form factors from each skylight to the floor are identical. Thus

$$\Phi_{\text{skylights} \to \text{floor}} = 4\,\Phi_{\text{skylight}} f_{\text{skylight} \to \text{floor}}$$

Φ_{skylight} is calculated from $\Phi_{\text{skylight}} = M_{\text{skylight}}\, A_{\text{skylight}}$. Thus

$$M_{0f} = \frac{4\,M_{\text{skylight}}\,A_{\text{skylight}}\,f_{\text{skylight} \to \text{floor}}\,\rho_f}{A_f}$$

The skylight exitance M_{skylight}, as calculated in example 4, is 2057 lm/ft^2. The radiative exchange form factor from a skylight to the floor is calculated from the appropriate equation in Figure 9-6. The resulting value of $f_{\text{skylight} \to \text{floor}}$ is 0.556. Solving for M_{0f}, then, we have

$$M_{0f} = \frac{4(2057)(16)(0.556)(0.20)}{(28)(28)} = 18.7\,\frac{\text{lm}}{\text{ft}^2}$$

The initial wall exitance is treated similarly:

$$M_{0w} = \frac{4\,M_{\text{skylight}}\,A_{\text{skylight}}\,f_{\text{skylight} \to \text{walls}}\,\rho_w}{A_w}$$

The radiative exchange form factor from the skylight to the walls is found by closure; that is, all of the flux emitted by a skylight that does not reach the floor must reach the walls: $f_{\text{skylight} \to \text{walls}} = 1 - f_{\text{skylight} \to \text{floor}} = 1 - 0.556 = 0.444$. Thus

$$\text{M} = \frac{4(2057)(16)(0.444)(0.50)}{(4)(28)(10)} = 26.1\,\frac{\text{lm}}{\text{ft}^2}$$

With these three values of initial exitance, the three simultaneous equations become

$$\begin{aligned}
M_w &= 26.1 + M_c 0.15372 + M_w 0.15556 + M_f 0.15372\\
M_f &= 18.7 + M_c 0.10514 + M_w 0.09486\\
M_c &= 0.0 + M_w 0.37943 + M_f 0.42057
\end{aligned}$$

The solution of these three equations yields $M_c = 25.87$ lm/ft^2, $M_w = 40.21$ lm/ft^2, and $M_f = 25.23$ lm/ft^2.

The configuration factor from the calculation point to the ceiling, $c_{c \to p}$, is calculated as described in Figure 9-2. Its value is 0.811. By closure, the configuration factor from the calculation point to the walls, $c_{p \to w}$, equals $1.0 - c_{c \to p} = 0.189$. Finally, solving for the interreflected illuminance E, we have $E = M_c c_{c \to p} + M_w c_{p \to w} = 25.87(0.811) + 40.21(0.189) = 28.76$ fc.

The sum of the direct (from example 4) and interreflected illuminance components is $E_{\text{total}} = 86 + 28.76 = 115$ fc. Thus the calculated value for the illuminance is 115 fc for the prescribed time, location, and sky.

Example 6: Calculation of Luminances Produced by a Point Source

This example illustrates the task lighting analysis of a desk. A small desk luminaire is to be used for lighting desks in workstations (Figure 9-51).

1. Determine the Quantity to be Calculated. The analysis of the performance of a task light on a desk consists, in part, of a determination of the luminance of a white piece of paper.

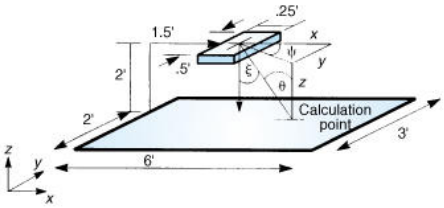
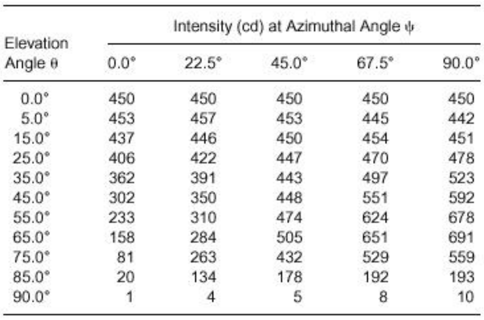


Figure 9-51. Desk layout for Example 6.

2. Identify Luminaires and the Information Describing Them. The luminaire used is a single 13-W compact fluorescent lamp with a reflector that produces a very directional luminous intensity distribution. The luminaire is 6 in. long, 3 in. wide, and 1.5 in. high. It is mounted on a movable arm designed to permit it to be placed off to the side of the desk. The photometric data are shown in Figure 9-52.



Elevation Angle θ	Intensity (cd) at Azimuthal Angle ψ				
	0.0°	22.5°	45.0°	67.5°	90.0°
0.0°	450	450	450	450	450
5.0°	453	457	453	445	442
15.0°	437	446	450	454	451
25.0°	406	422	447	470	478
35.0°	362	391	443	497	523
45.0°	302	350	448	551	592
55.0°	233	310	474	624	678
65.0°	158	284	505	651	691
75.0°	81	263	432	529	559
85.0°	20	134	178	192	193
90.0°	1	4	5	8	10

Figure 9-52. Luminous Intensity Distribution of Desk Luminaire

3. Determine the Accuracy, Complexity, and Detail of the Calculation. The luminance of the paper is assumed to be diffuse, so the luminance calculation requires only a determination of the illuminance and a measurement of the paper's diffuse reflectance.

As shown in Figure 9-51, the luminaire arm is mounted at the side of a desk whose dimensions are 6 ×3 ft. The luminaire is located at a height of 2 ft above the desk surface, 1.5 ft to the left of the center of the desk, and 2 ft from the front of the desk. The distance from the center of the luminaire to the center of the desk is given by

$$D = \sqrt{x^2 + y^2 + z^2} = \sqrt{1.5^2 + 0.5^2 + 2^2} = 2.55 \text{ ft}$$

This distance is larger than 5 times the maximum luminous dimension of the luminaire (0.5 ft), so the inverse square cosine law for the illuminance from a point source can be used.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The geometric dimensions are shown in Figure 9-51. The white paper is a diffusely reflecting object with a reflectance ρ = 0.83.

5. Determine Appropriate Equations. The luminance (L) of a diffusely reflecting surface is given by the following formula:

$$L = \frac{M}{\pi} = \frac{\rho_{\text{paper}} E}{\pi}$$

The illuminance at the center of the desk is given by

$$E = \frac{I(\theta,\psi) \cos \theta}{D^2}$$

The luminous intensity distribution data are shown in Figure 9-52. The angles required to determine the luminous intensity are calculated as follows from geometric principles (Figure 9-51):

$$\theta = \arctan\left(\frac{\sqrt{x^2 + y^2}}{z}\right)$$

$$\psi = \arctan\left(\frac{y}{x}\right)$$

$$\xi = \arctan\left(\frac{\sqrt{x^2 + y^2}}{z}\right)$$

6. Solve the Equations. First, the illuminance produced by the luminaire is calculated. Using the dimensions in Figure 9-51,

$$\theta = \arctan\left(\frac{\sqrt{1.5^2 + 0.5^2}}{2}\right) = 38.3^\circ$$

$$\psi = \arctan\left(\frac{0.5}{1.5}\right) = 18.4^\circ$$

Linearly interpolating in the table of luminous intensities (Figure 9-52), the intensity at ($\theta = 38.3^\circ$, $\psi = 18.4^\circ$) has a value of 356 cd.

The incident angle is given by

$$\xi = \arctan\left(\frac{\sqrt{1.5^2 + 0.5^2}}{2}\right) = 38.3^\circ$$

The illuminance E is calculated as follows:

$$E = \frac{I(\theta, \psi)\cos\theta}{D^2} = \frac{356\cos(38.3^\circ)}{1.5^2 + 0.5^2 + 2^2} = 42.9 \text{ fc}$$

The luminance of the paper is

$$L_{\text{paper}} = \frac{\rho_{\text{paper}} E}{\pi} = \frac{(0.83)(42.9)}{\pi} = 11.4 \text{ cd / ft}^2$$

7: Calculation of Contrast Produced on Printed Material

This example also illustrates the task lighting analysis of a desk. A small desk luminaire is to be used for task lighting desks in workstations.

1. Determine the Quantity to be Calculated. The analysis of the performance of a task light on a desk consists, in part, of a determination of the visual task contrast that is produced on the horizontal desk surface. The contrast determined here is that for black print on white glossy paper, such as is commonly found in journals and magazines.

2. Identify Luminaires and the Information Describing Them. The same luminaire is used for this example was for Example 6. The luminous intensity distribution is shown in Figure 9-52.

3. Determine the Accuracy, Complexity, and Detail of the Calculation. Calculating the contrast requires determining the luminance of both the task and its background. Neither the paper nor the print ink is assumed to have a diffuse reflectance for this example. Therefore, the calculation of these luminances requires both the illuminance and the bidirectional reflectance distribution function (BRDF) of the task and its background.

The layout of the task is shown in Figure 9-53. As calculated in Example 6, the distance from the task (at the center of the desk) to the center of the luminaire is 2.55 ft, which is larger than 5 times the maximum luminous dimension of the luminaire. Thus the inverse square cosine law is valid in this case.

4. Identify Required Geometric, Reflectance, and Ancillary Data. The necessary dimensions are shown in the figure. The BRDFs for the paper and for the printed ink are shown in Figures 9-54 and 9-55, for a typical viewing angle of 10° from vertical. The irregular spacing of the azimuth and declination angles in the BRDF tables reflects the degree of specularity for the material. Where angles are spaced closer together, the BRDF is more sensitive to small changes in these angles.

5. Determine Appropriate Equations. The luminance contrast C of a task is given by

$$C = \frac{|L_b - L_t|}{L_b}$$

where L_b is the luminance of the background and L_t is the luminance of the target. In this example, the luminances are of nondiffusely reflecting surfaces. The luminance of a nondiffusely reflecting surface illuminated by an unpolarized source is described earlier in this chapter, and is

$$L(\theta_v) = \sum_i \sum_j E(\theta_i, \psi_j) f_r(\theta_v; \theta_i, \psi_j)$$

where

θ_v = viewing declination angle, in this case equal to 10°,
θ_i = incident declination angle,
ψ_j = incident azimuthal angle, measured from the plane containing the direction of view and given by $\psi_j = 90^\circ + \arctan(y/x)$.

The sum is taken over all the discrete values of illuminance. The number of discrete steps determines the accuracy of the approximation. The step size in these approximations is determined by the need to model high gradients of either the illuminance or the BRDFs. In the present case, the largest declination angle subtended by the luminaire to the calculation point is 6.9°, and the largest azimuthal angle subtended by the luminaire is 19.9°. The azimuthal and declination incident angles from the center of the luminaire are used to determine the region of the BRDFs being used. Examination of this region reveals whether discretization is necessary for an illuminating field that measures 6.9° × 19.9°.

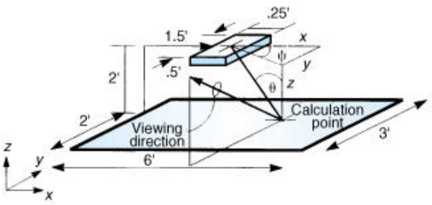


Figure 9-53. Desk lamp drawing for Example 7.

6. Solve the Equations. The illuminance at the center of the desk is 42.9 fc, as shown in example 6. The luminances of task and background require determining the BRDFs of the paper and of the printed ink at the specified angles. The incident azimuthal angle ψ_i must be determined: $\psi_j = 90° + \arctan (1.5/0.5) = 161.5°$.

The incident declination angle has been determined to be 38.3° in Example 6. Given the viewing angle of 10°, the BRDF tables in Figures 9-54 and 9-55 for the paper and ink are interpolated to obtain the values $f_{\text{ink}}(10°; 38.3°, 161.5°) = 0.0001$ and $f_{\text{paper}}(10°; 38.3°, 161.5°) = 0.2182$.

Azimuth	BRDF (sr $^{-1}$) at Declination					
	24°	28°	34°	44°	52°	60°
0°	0.226	0.221	0.215	0.216	0.205	0.194
130°	0.240	0.226	0.220	0.217	0.208	0.197
150°	0.249	0.231	0.224	0.214	0.208	0.196
160°	0.252	0.231	0.221	0.214	0.200	0.196
170°	0.253	0.233	0.222	0.216	0.212	0.196
176°	0.250	0.234	0.223	0.216	0.206	0.197
177°	0.261	0.235	0.224	0.217	0.205	0.198
178°	0.262	0.236	0.223	0.218	0.211	0.198
179°	0.263	0.235	0.223	0.219	0.213	0.200
180°	0.263	0.234	0.222	0.219	0.210	0.193

*Viewing declination angle = 10°, viewing azimuth angle = 0°.

Figure 9-54. Partial Bidirectional Reflectance Distribution Function (BRDF) Data for White Paper*

Azimuth	BRDF (sr $^{-1}$) at Declination					
	22°	28°	36°	44°	52°	60°
0°	0.004	0.003	0.002	0.001	0.000	0.000
130°	0.013	0.002	0.000	0.000	0.000	0.000
150°	0.034	0.006	0.000	0.000	0.000	0.000
160°	0.056	0.010	0.000	0.000	0.000	0.000
170°	0.089	0.015	0.001	0.000	0.000	0.000
176°	0.109	0.018	0.001	0.000	0.000	0.000
177°	0.111	0.019	0.001	0.000	0.000	0.000
178°	0.113	0.019	0.002	0.000	0.000	0.000
179°	0.116	0.020	0.002	0.000	0.000	0.000
180°	0.118	0.020	0.002	0.000	0.000	0.000

*Viewing declination angle = 10°, viewing azimuth angle = 0°.

Figure 9-55. Partial BRDF Data for Black Printed Ink*

The units of BRDFs are inverse steradians (sr^{-1}). The luminance of the ink at the calculation point is then $L_{\text{ink}} = E(\theta_i, \psi_i)\, f_r(\theta_v; \theta_i, \psi_i) = (42.9 \text{ fc})(0.0001 \text{ sr}^{-1}) = 0.0043 \text{ cd/ft}^2$. The luminance of the paper at the calculation point is $L_{\text{paper}} = E(\theta_i, \psi_i)\, f_r(\theta_v; \theta_i, \psi_i) = (42.9 \text{ fc})(0.2182 \text{ sr}^{-1}) = 9.36 \text{ cd/ft}^2$. The luminance contrast of the task and background is then

$$C = \frac{|9.36 - 0.0034|}{9.36} = 0.999$$

Calculations of contrast for the extreme azimuth and declination angles subtended by the luminaire result in the following contrasts at the calculation point:

$$\begin{aligned} C(38.3° + 3.45°, 161.5° + 9.95°) &= C(41.75°, 171.45°) = 0.999 \\ C(38.3° + 3.45°, 161.5° - 9.95°) &= C(41.75°, 151.55°) = 1.000 \\ C(38.3° - 3.45°, 161.5° + 9.95°) &= C(34.85°, 171.45°) = 0.986 \\ C(38.3° - 3.45°, 161.5° - 9.95°) &= C(34.85°, 151.55°) = 0.970 \end{aligned}$$

Each of these lies within 10% of the contrast calculated using a single point at the center of the luminaire, so discretization of the luminaire into several elements is not required.

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10

Quality of the Visual Environment

LIGHTING QUALITY

Patterns of light and dark affect both our perceptions of the world and our emotional and physiological responses, and thus they are essential in gathering information about the physical world. Good-quality lighting can support visual performance and interpersonal communication and improve our feelings of well-being (Figure 10-1). Poor-quality lighting can be uncomfortable and confusing and can inhibit visual performance. This chapter defines and discusses lighting quality.

The overall purpose of lighting is to serve the needs of people. The role of the lighting designer is to match and rank the needs of the people using the space with the economic and environmental considerations and the architectural objectives, and then to translate the results into a workable design and functional installation. The human needs served by lighting are identified in Figure 10-2.

Lighting for Human Needs

The needs of people are complex. Emotions, actions, perceptions, and health are influenced by lighting. Central to human needs is visibility, because it is the detection and organization of light patterns that allow a person to analyze and evaluate the environment. Once objects and patterns are visible, one can use a pencil to write a note, learn to pronounce new words by following the facial expressions of a teacher, walk down a corridor without bumping into a vacuum cleaner on the floor, appreciate a painting, or feel relaxed in a dimly lighted restaurant. Figure 10-2 illustrates that visibility is central to a larger number of human needs: task performance; mood and atmosphere; visual comfort; aesthetic judgment; health, safety, and well-being; and social communication.

Visibility. Visibility is the ability to extract information from the field of view, whether that information is the location of a curb or of a flower arrangement. It is a necessary condition for good-quality lighting. Lighting installations exist to enable sight. For many years this fact led to a heavy emphasis on visibility over all other goals for lighting design. As a result, research was focused in this direction, and we have a good understanding of visibility and its importance. Contrast, luminance, time, and size are the most powerful variables influencing the visibility of objects. Age modifies this relationship; for the older viewer, the task must be larger and brighter and its contrast higher in order to achieve visibility levels equivalent to those of younger viewers. In general, high illuminances can offset visibility losses for tasks of low contrast and small size.

Task Performance. Task performance is an essential human need. The task is the user's activity, whether measuring the size of a room, washing mud off hands, reading room numbers posted in a corridor to find a doctor's office, or seeing the details in the etchings displayed in a museum. Lighting must enable users to perform the "work" they came to do. Task performance and visual performance are not synonymous; in fact, several nonvisual factors contribute significantly to task performance. Training, motor skills, motivation, and many other human factors interact with visibility to affect the level of task performance. Visual performance, on the other hand, eliminates these factors from consideration in assessing the impact of visual stimuli, including lighting variables, on a behavioral response.[1,2] Illuminance selection, discussed in its own section below, is largely based on visual performance, not task performance.

Mood and Atmosphere. Needs for mood and atmosphere encompass the emotional response to the luminous environment.[3] Preference, satisfaction, relaxation, and stimulation are influenced by lighting. These mood states can indirectly influence other behaviors, such as task performance.[4]

Visual Comfort. Visual comfort is an essential human need that can affect task performance, health and safety, and mood and atmosphere. Office workers may find themselves more fatigued in a glaring lighting installation, but flashing lights in a discotheque can temporarily excite and please that same person.

Aesthetic Judgment. Aesthetic judgment needs differ from emotional responses. Humans appear to need to make sense of what they see, so the information must be either immediately available in a scene or implied. Lighting can communicate meaning, reinforce rhythmic patterns in the architecture, and enhance color, thereby creating a hierarchy of social significance in the visual field. Lighting can also hinder understanding by introducing patterns that conflict with the underlying scene. One research model that attempts to quantify aesthetic judgments uses four dimensions of appraisal: coherence, legibility, mystery, and complexity.[5,6] Another uses visual interest and visual lightness (room surface brightness).[7,8,9] These studies conclude that preference for a scene increases when the lighting is nonuniform; however, high levels of one quality can reduce levels of another. For example, a scene that is complex may rank low in coherence.

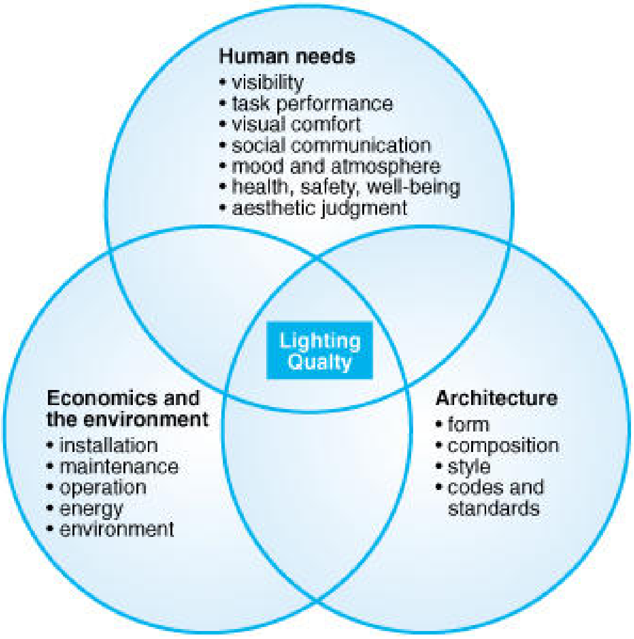


Figure 10-1. Lighting quality: the integration of human needs, architecture, and economics and the environment.

Health, Safety, and Well-Being. Although they are needs of primary importance, health, safety, and well-being are often overlooked. As an example, flicker from some electric lighting can produce a stroboscopic effect with moving machinery, making the machine appear to move at a different rate. Electronic ballasts for fluorescent lamps reduce the perception of flicker, and it also appears that they reduce the incidence of headaches and eyestrain.[10] Safety is an important need, but emergency lighting is only one aspect of it. Lighting also affects the visibility of curbs, stair edges, train platforms, roadway intersections, and labels of critical chemicals and pharmaceuticals.

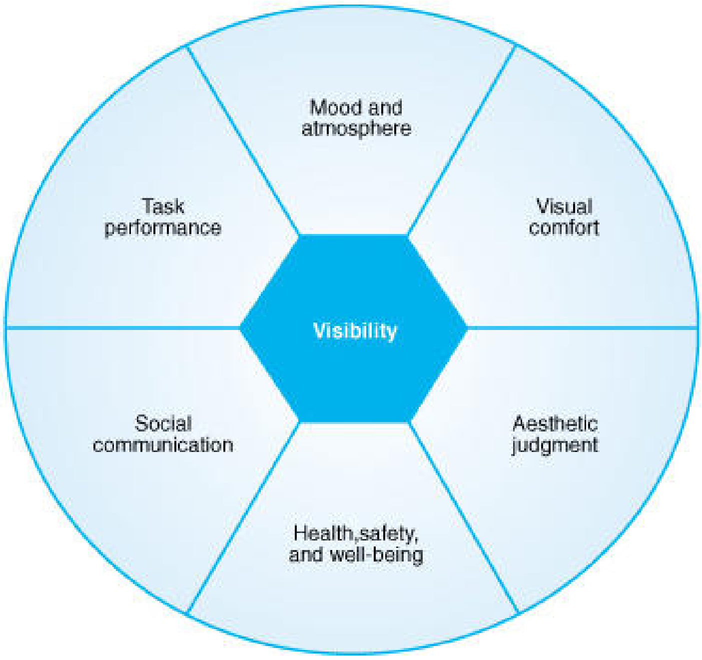


Figure 10-2. Human needs served by lighting.

Light also has a direct impact on wakefulness and the state of the circadian system (i.e., sleep-wake cycle) by suppression of melatonin in the brain. Recent evidence suggests that disruption of the circadian system may have long-term consequences for different types of cancer.[11] This is a new field of research and should be carefully monitored by the lighting designer.

The relative importance of these needs differs for each setting. In a factory, aesthetic judgments are likely to be less important than health and safety or task performance. In a restaurant, social and communication needs, aesthetic judgments, mood, and comfort are all important; however, visual tasks such as reading the menu also need to be considered. One of the challenges in lighting design is to determine which human needs are to be served. In some cases, needs conflict and require careful thought to establish priorities.

Social Communication. Social communication needs include the creation of luminous conditions conducive to such communications in a setting, especially by facial appearance. Much human communication occurs by nonverbal means, but these cues are missed if the lighting distracts from or masks the information. Facial recognition, for example, which is a critical element of security lighting, is influenced not only by the amount of light needed to detect a face, but also by the modeling of facial features created by the pattern of the light and shadow on the subject's face.

Balancing Human Needs with Architecture and Economics and the Environment

Architecture. Lighting occurs in an architectural context, whether interior or exterior. High-quality lighting is responsive to the architectural form, composition, and style.[3] The integration with the architecture conveys meaning and contributes to the observer's understanding of the space.

Light that ignores architecture can violate human needs. For example, emergency lighting that is not coordinated with the building layout can slow down or prevent egress.[12] Specifying luminaires that are too tall to fit in the plenum space could delay the completion of a construction project.

Economics and the Environment

Costs frequently influence and constrain lighting system choices. Purchasers tend to be very sensitive to first costs, but installation, operation, and maintenance costs can outweigh first costs in a complete economic analysis. Any lighting solution fails if maintenance or operating costs are higher than common practice.

In recent years, codes and standards have mandated lighting power density limits (e.g., ASHRAE/IESNA

Standard 90.1).[13] But reduced energy use should not be regarded merely as a compliance with regulation; this is a responsibility toward the ongoing environmental health of our planet and the well-being of future generations.

HOW TO USE THE IESNA LIGHTING DESIGN GUIDE

Previous editions of the *Illuminating Engineering Society of North America (IESNA) Lighting Handbook* have discussed important criteria for assessing and designing the visual environment, but a formal system for considering these criteria had never been developed by the IESNA. However, the IESNA has always recommended illuminances for specific applications or visual tasks. As a result, lighting specifiers often mistook the IESNA system of recommended illuminances as the primary or even sole criterion for lighting design. This edition of the *IESNA Lighting Handbook* introduces a new, formal system for considering a wide range of lighting design criteria. If followed, the recommended design criteria will increase the quality of the visual environment throughout North America. In engineering terms, the goal is to raise the "minimum standard of care" required of lighting designers.

This chapter, which includes the new IESNA Lighting Design Guide, focuses on criteria important for a high-quality visual environment. It should be emphasized, however, that a high-quality lighting design should also be energy-efficient, cost-effective, and require minimum maintenance. Future editions of the *IESNA Lighting Handbook* may include these other criteria. In the meantime, the lighting designer should employ information presented in this edition of the *IESNA Lighting Handbook* on energy efficiency, safety and security, and maintenance to establish the best possible lighting design for the client. The reader should also consult other IESNA publications such as the series of Recommended Practices for various lighting applications.

The IESNA Lighting Design Guide at the end of this chapter is divided into the following sections:

I. Interior

II. Industrial

III. Outdoor

IV. Sports and Recreation

V. Transportation

VI. Emergency, Safety, and Security

Within each section there are different headings, subheadings, and location or task listed alphabetically and presented in rows of the Design Guide. For example, in the "Interior" section, "Educational Facilities" is listed, and under this heading is a subheading called "classrooms," under which is a location called "science laboratories."

The columns in the Design Guide represent the criteria important for a high-quality visual environment, including both horizontal and vertical illuminance. There are 23 criteria defined in this chapter and discussed in other chapters of this edition of the *IESNA Lighting Handbook*.

One of four levels of "importance" is entered in the cells of the Design Guide: "very important," "important," "somewhat important," and "not important or not applicable." Each cell entry represents the relative importance of one criterion for a particular location or task. The IESNA Lighting Design Guide and the entries ranking the relative importance of the criteria for specific locations or tasks were developed through consensus by the IESNA.

A simple example of how to use the IESNA Lighting Design Guide may be helpful. Suppose a lighting designer is asked to design the lighting of an open-plan office. The designer should go to the "Interior" section in the Design Guide and look for "Offices." Within "Offices," the designer should look for the "open-plan offices" subheading. The lighting designer can learn from the Design Guide that, in offices with intensive use of visual display terminals (VDTs), in addition to vertical illuminance, factors such as source/task/eye geometry, reflected glare, direct glare, and luminances of room surfaces are "very important" and should be considered in the design.

The user of the IESNA Lighting Design Guide should read the section "Discussions of Design Issues" below for a better understanding of every design criterion. The user can consult the section "Illuminance Selection" below for a more detailed understanding of the recommended horizontal and vertical illuminances. The other chapters in this edition of the *IESNA Lighting Handbook* should also be consulted to learn more about the bases and the applications of the design criteria. Finally, the designer, with specific knowledge of the project and past experience, can deviate from any lighting design recommendations in the matrix. Factors that might lead to deviations from the recommendations include the following:

- Life, health, and safety issues
- Security
- Energy requirements
- Historical context
- Reduced visual function (e.g., macular degeneration)
- Melatonin suppression at night
- Mental dysfunction
- Unusual maintenance requirements
- Nonhuman requirements (e.g., for plants, animals, cameras)
- Material degradation
- Unusual client specifications

The lighting designer is strongly advised, however, to document and explain all deviations from the recommendations given in this edition of the *IESNA Lighting Handbook*.

In summary, the reader should follow these six steps:

1. Go to the Design Guide and find the location or task (row) under consideration.

2. Learn about the design criteria (columns) that are very important, important, and somewhat important for that location or task.

3. Go to the section "Discussions of Design Issues" of this chapter to understand every design criterion.

4. Go to other chapters for discussions of how to apply the relevant design criteria in the location or for the task under consideration and for a better understanding of issues that are not included in the Design Guide, such as energy efficiency, economics, and maintenance.

5. Consult the section "Illuminance Selection" in this chapter regarding the recommended horizontal and vertical illuminances. Use professional judgment to determine whether a change in these values is justified given the specific situation and the relative importance of the other design issues.

6. Document the lighting design process, especially any justifications for any changes to the recommendations provided in the *IESNA Lighting Handbook*.

DISCUSSIONS OF DESIGN ISSUES

The following are brief discussions of the design issues that appear in the IESNA Lighting Design Guide.

Appearance of Space and Luminaires. Appearance includes both the arrangement of elements such as furnishings and luminaires in a space and their relationship to one another. These elements can provide visual cues that assist occupant orientation. It is important that the style of the luminaires coordinate with and enhance the design and architecture of the space. Lighting systems can also help create an image for the space (e.g., "corporate," "casual," "luxurious," "industrial," or "avant garde").

Another important issue is "visual clutter," that is, confusing or distracting details in the visual field. For instance, lighting equipment can interfere with the view of a natural landscape or a carefully designed visual composition. The eye is drawn to areas of greater brightness. Bright areas should be important to the composition, and preferably they impart some visual information (e.g., identify key paths for wayfinding, define boundaries, and delineate circulation patterns). Color patterns should also lead the eye to the areas of greatest importance.

Color Appearance (and Color Contrast). Color appearance can affect visibility and aesthetics. For example, fluorescent paint can enhance visibility of an object but clash with the aesthetic composition in the space. Factors that contribute to color appearance include the spectral power distribution of the light source, the color perception abilities of the observer, and the transmission and reflection properties of objects and surfaces in the room or area. Color contrast, the difference in perceived color between a task and its background, is often an important issue for industrial tasks and for safety signage or markings.

Generally, lamps with a color rendering index (CRI) greater than 80 should be used to ensure a pleasant appearance of skin tones, food, and merchandise. For most office, educational, health care, and institutional workplaces, a CRI of 70 or above is acceptable. A CRI of 50 provides adequate color rendering for most industrial tasks. If color matching, paint mixing, or color selection is involved, a lamp with a CRI of 90 or above should be used.

Daylighting Integration and Control. A view of the outdoors is believed to be important for psychological and physiological reasons by providing cues about the time of day and weather, and by providing distant objects on which to focus, thereby allowing people to relax the muscles of their eyes. Diffusing window glass should be avoided because it obscures views of the outdoors.

Daylight and sunlight can be used to help light a space, but care should be taken to control the quantity and distribution of the light and to control heat gain. Overhangs, light shelves, window blinds, and shades are all useful. It should be noted that more illumination is sometimes needed on interior surfaces near windows to reduce the brightness contrasts between those surfaces and the windows. For example, occupants' faces and other important surfaces can appear in dark silhouette against a window unless illuminated by electric lighting. Daylighting is most effective when used as ambient illumination, but it is too variable as a reliable source for task illuminance.

Automatic photoelectric controls as well as manual dimming and switching are effective energy-saving strategies to be used with daylight. Automatic controls are often unacceptable to occupants, however, so special consideration must be given to commissioning these systems to meet both energy-saving goals and occupant satisfaction (see also the section "System Control and Flexibility" below).

Transitioning from daylight conditions to interior or enclosed spaces requires time for eyes to adapt. Visual "transition zones" are effective design features that allow occupants time to adapt comfortably as they move between areas of high and low brightness.

Direct Glare. Glare can cause discomfort and interfere with visibility. Direct glare occurs when the light travels directly from the source to the eye. This may include "disability glare," "discomfort glare," and "overhead glare" (see also the section "Reflected Glare" below).

Luminaires, windows, and skylights can be uncomfortable to view, but there appears to be more tolerance of window brightness than of comparable luminaire brightness. Presumably this is due to viewers' preference for the visual information attained from windows.

Glare criteria for luminaire luminances between 50° and 90° from luminaire nadir (i.e., 0° to 40° above horizontal) have been established. Light from other angles can also produce glare if luminances exceed 10,000 cd/m^2. As a rule, luminaire luminances should not be more than 100 times those of surrounding surfaces to minimize glare. This can be achieved with luminaires that illuminate the ceiling as well as the task and by increasing ceiling reflectance.

Flicker (and Strobe). Flicker is the rapid variation in light source intensity, usually most noticeable in peripheral vision. Individuals vary widely in flicker sensitivity. Lamp flicker may interact with the movement of industrial machinery or with moving balls in various sports to produce a stroboscopic effect, where the machinery or ball appears to move at a rate different from its actual movement. The flashing seen in lamp startup is not considered flicker.

In industrial applications, flicker can be mitigated by using a three-phase electric distribution system with circuiting adjacent luminaires on alternate phases. High-frequency (20 to 60 kHz) electronic ballasts effectively eliminate flicker.

Illuminance (Horizontal). Horizontal illuminance is the density of luminous flux falling onto a horizontal surface, measured in lux (lumens per square meter) or footcandles (lumens per square foot). Unless otherwise indicated, the plane on which the illuminance is specified and measured is assumed to be a horizontal plane 0.76 m (30 in.) above the floor for interior and industrial locations and tasks, 0.91 m (36 in.) above the ground for sports and recreational locations and tasks, and at grade for the outdoors.

Illuminance (Vertical). Vertical illuminance is the density of luminous flux falling onto a vertical surface, measured in lux (lumens per square meter) or footcandles (lumens per square foot).

Intrinsic Material Characteristics. Visual cues about surfaces and materials, such as texture or transparency, are revealed by lighting. The ability to see these cues, like nap and grain, may be critical to evaluating the type or quality of material, or the degree of consistency.

Light Distribution on Surfaces. Patterns of light resulting from the spacing and light distribution of the luminaires, as well as from objects that can cast shadows, can affect task visibility, comfort, and perceptions. Harsh striated patterns of excessive brightness or noticeable shadow should be avoided. Illuminance patterns should correspond with architectural features (e.g., a regular pattern of glowing sconces) or objects (e.g., lighting art on the walls). Random patterns can be confusing or distracting.

Surfaces should not have extremely different brightnesses. For example, ceiling and walls should have luminances within a 3:1 ratio. Spaces with totally uniform brightness, however, lack visual interest. "Luminance ratios" refer to the relative luminances of any two areas in the visual field (e.g., ceiling-to-wall luminance ratios or immediate-surround-to-task luminance ratios).

Light Distribution on Task Plane (Uniformity). Patterns of light on the task plane can be distracting, confusing, or beneficial. The task plane varies according to the application. In an office, the task plane is most often the desk top; in a corridor, it may be the floor; in an industrial plant, the cutting table; in a parking lot, the pavement surface. These patterns of light and shadow can affect task visibility, comfort, and perception. Task illuminance should be higher than the immediate surround. Work surface illuminances that are 1.5 to 3 times higher than those in the surrounding areas assist in directing occupants' attention to the task. Greater luminance ratios must be avoided to minimize visual fatigue. Descriptive statistics about illuminance or luminance distributions such as maximum-to-average or average-to-minimum are used to quantify the luminous uniformity of a surface. Use photometric data and luminaire manufacturer's guidelines to achieve the uniformity recommended for the application.

Light Pollution/Trespass. Light that is directed upward to the sky or reflected from surfaces that interferes with astronomical observations or appreciation of the night sky is termed "light pollution." "Light trespass" is unwanted light that falls beyond the property line or area intended to be illuminated.

Luminaire Noise. Sound generated by the internal parts of a luminaire can be annoying and distracting. Electromagnetic ballasts are the usual sources of sound, but incandescent lamps operated on certain types of dimmers and air moving through air-handling luminaires can also produce noise.

Luminances of Room Surfaces. Room surface luminances influence the perception of brightness in a space. Illuminance and reflectance affect luminance. Matte surfaces of high reflectance (e.g., white-painted walls and light-colored furniture finishes) are effective materials for increasing room surface luminances. Luminaires expressly designed for lighting walls or ceilings are effective tools for increasing room surface luminances.

Average wall luminances of at least 30 to 100 cd/m^2 are preferred in typical office work spaces (where 300 to 1000 lx [30 to 100 fc] is provided on the workplane). Minimize dark areas at tops of walls. If there are no luminaires dedicated to illuminating the walls, locate general lighting luminaires close to walls and utilize lenses, reflectors, or louvers to soften the pattern of light and distribute more light to the top of walls.

Spaces that deliver both direct and diffuse light to the occupant and task increase user comfort and satisfaction. This approach reduces distracting shadows from hands, desk objects, partitions, and overhead cabinets; reduces overhead glare; and improves facial modeling.

Modeling of Faces or Objects. Lighting can reveal the depth, shape, and texture of an object. Through the creation or elimination of shadows, faces and objects can have more or less contrast.

The distribution of light in a retail display is critical to attracting attention and making the merchandise look appealing. Appropriate direction and distribution depends on the type of merchandise, but generally a combination of diffuse light and directional light will enhance appearance.

In industrial applications, modeling is critical to assessing material quality, finish quality, and degree of consistency. Appropriate direction and distribution of light vary depending on material and task. Often diffuse ambient lighting is inadequate for assessing fine texture; task lighting is therefore used to provide the required direction, distribution, and intensity of light.

A high percentage of communication is nonverbal. It is important that the pattern of light on faces enables clear recognition and interpretation of expressions by enhancing contrast in certain areas around the mouth and eyes. Concentrated downlighting, which creates harsh facial shadows and accentuates blemishes and wrinkles, should be avoided because it creates too much contrast on the face. Multidirectional lighting improves facial modeling. Interreflected light from walls, partitions, ceiling, and light-colored work surfaces helps increase vertical illuminance on faces, filling in sharp shadows and rendering faces in a more pleasing way with easier-to-read facial expressions.

Peripheral Detection. The human visual system is designed to detect movement in the periphery of the visual field and to guide the fovea to that movement for inspection and interpretation.

Point(s) of Interest. A point of interest is the object or place to which attention is drawn, using movement, luminance contrast, and color contrast.

Reflected Glare. Bright reflections from polished or glossy surfaces are uncomfortable and reduce task visibility; this is known as "reflected glare." "Veiling reflections" are contrast-reducing reflections from semi-specular surfaces that reduce task visibility. The possible negative impact of reflected glare and veiling reflections can be estimated. The ratio of illuminance on the task from the mirror angle relative to the total illuminance on the task should be less than 0.3 for satisfactory results, whereas unsatisfactory results can occur if the ratio exceeds 0.7. Both reflected glare and veiling reflections can be mitigated by providing illuminance from the sides of the task or by special luminaire optical designs. It should be noted, however, that reflected glare can improve visibility for some tasks such as paint inspection for defects or reading increment marks on a steel rule (see also the section "Source/Task/Eye Geometry" below). For VDT applications the most practical solution to both veiling reflections and reflected glare is to select a VDT monitor with a diffuse reflecting screen and one that provides a bright background and dark text.

Shadows. Shadows can interfere with task visibility by placing detail in darkness (e.g., a body shadow on a paper task), and they can also enhance definition of three-dimensional details (e.g., imperfections in a piece of cloth). Point sources (e.g., incandescent or high-intensity discharge [HID] lamps) can cause sharp shadows from obstructions, whereas linear or area sources (e.g., luminaires with a large uplight component, fluorescent lamp luminaires with large prismatic lenses and white reflectors) produce more diffuse shadows. Local task lighting can increase illuminances to minimize shadows on machinery or under cabinets.

Source/Task/Eye Geometry. The angular relationships between the viewer, the task, and the luminaire are frequently critical to task visibility. This geometry can both enhance contrast (e.g., scribed marks on a micrometer) and reduce it (e.g., viewing a meter dial through glass).

Sparkle/Desirable Reflected Highlights. Small points of high luminance can enhance visual interest (e.g., a candle flame or decorative tree lights).

Special Considerations. Often there are special issues associated with a specific location or task (e.g., photodegradation or hazardous location requirements).

Surface Characteristics. Object characteristics such as texture, color, and specularity and reflectance values of surfaces can affect the perceived brightness of walls, ceilings, exterior building facades, and pavement. Interior workspaces should have high reflectances (walls, 50 to 70%; ceiling, 75 to 90%) to increase interreflections and thus help reduce the undesirable contrast of luminaires against their background. High reflectances also allow the designer to produce an effective lighted environment with fewer watts and fewer luminaires.

Surfaces should be matte or satin finished to avoid reflected glare. Dark surfaces (20 to 50%), saturated colors, and glossy finishes can maintain visual interest and stimulation, but they should be used to a limited degree. The Finish Schedule of construction documents should include material reflectances available from manufacturers of paint, wall covering, fabrics, and ceiling tiles.

System Control and Flexibility. Many spaces require different light levels for a variety of tasks. Conference rooms and auditoriums in particular need to have equipment that provides for different settings for slide shows, personnel interviews, financial meetings, presentations, and cleaning. Two or more lighting circuits can be used separately or together to achieve a wide range of appearances and light levels. One system can light walls, another can provide downlight on the workplane, and a third can provide general ambient illumination from a decorative luminaire mounted over a table. Preset scene controls can be employed with combinations of circuits. Dimming provides additional flexibility.

There are widely differing personal preferences for illuminance in work areas. User satisfaction can be enhanced through control of illuminance with switching or dimming of task or overhead lighting. Task lights can also be used so that the occupants can control the location, direction, and intensity of light. This is particularly important in spaces where both VDT and paper tasks are used.

DESIGN ISSUES APPLIED TO COMMON LIGHTING SITUATIONS

Lighting quality issues should be considered for the whole space and for every visual task within an indoor or outdoor lighted environment. These considerations should have an impact on the design, finishes, and furniture and equipment layout of the space. Six applications are discussed in this section, illustrating how lighting design issues affect the visual environment. The lighting issues are noted on the illustrations and discussed along with design strategies and guidelines that the designer can use to satisfy the design objectives. It should be noted, however, that these illustrations are not necessarily representative of typical spaces, so the emphasis on certain design issues may not be relevant to all applications.

These guidelines were developed by lighting professionals with many years of design experience. It should be noted, however, that the same design objectives can be achieved in these examples with different lighting equipment and layouts.

Figure 10-3 is an illustration of an industrial machine shop, with open trusswork on the ceiling and suspended HID high-bay luminaires. The visual tasks are reading drawings and using lathes, drill presses, and other machinery. A series of design issues should be considered in the design of the lighting and the space. Several of these are noted on the illustration and also listed below, with simple guidelines for dealing with each issue:

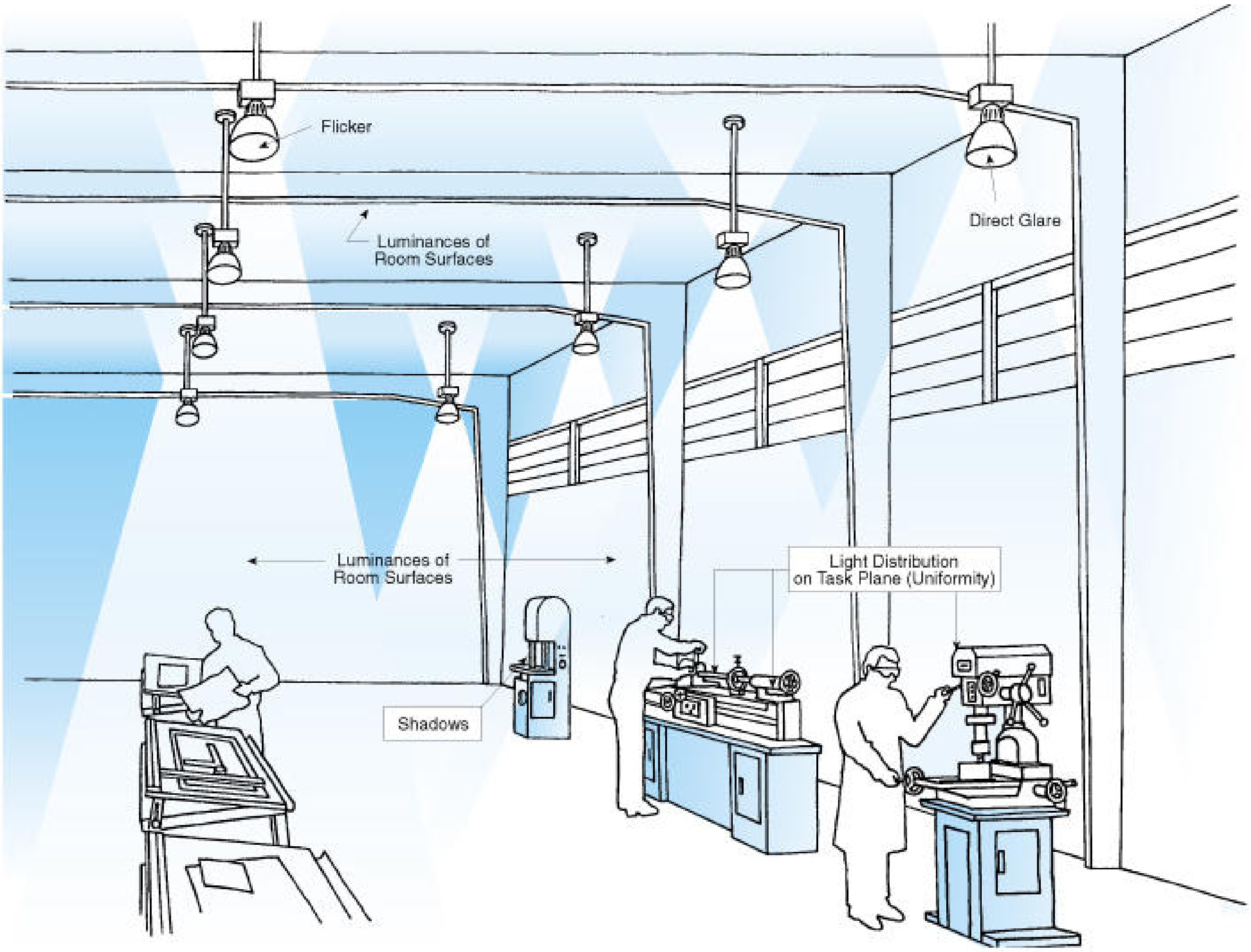


Figure 10-3. Industrial machine shop.

- *Flicker (and Strobe).* Unless operated at high frequencies, HID lamps can be a source of flicker, which can be both annoying and a potential hazard for operators of moving machinery. Consider putting alternate HID luminaires on different phases of a three-phase electrical system to minimize the stroboscopic effect.
- *Luminances of Room Surfaces.* Industrial spaces can appear dark and the luminaires excessively bright if the ceilings are dark. Paint the ceiling a light color and choose luminaires that direct some light upward. This can make the space feel brighter and the luminaires appear less glaring by reducing the contrast between the lighted luminaire and the surrounding ceiling. Indirect light in an industrial space can minimize shadows. Walls painted a light color reflect more diffuse light onto task areas, mitigating shadows and increasing the general brightness of the space.
- *Light Distribution on the Task Plane (Uniformity).* Illuminances on the floor or work plane should not vary widely, or else it will be hard for workers to see details in the darker areas. Use the luminaire manufacturer's photometry and spacing recommendations, along with calculation procedures that account for tall obstructions, to ensure reasonable uniformity.
- *Direct Glare.* Glare affects both visual comfort and the viewer's ability to see. Consider using low-brightness luminaires that minimize the occupants' direct view of bright lamps from normal angles.
- *Shadows.* Industrial machinery or the operator's body can shadow the visual task from the general lighting. Consider fitting the machines with individual task lights.

Figure 10-4 shows an office space with a VDT, windows, and an acoustical lay-in ceiling. Pendant luminaires with a direct/indirect distribution provide ambient lighting. The workstation has linear fluorescent lamp undercabinet lighting. An adjustable task light provides illumination for a variety of tasks. The following design issues should be considered:

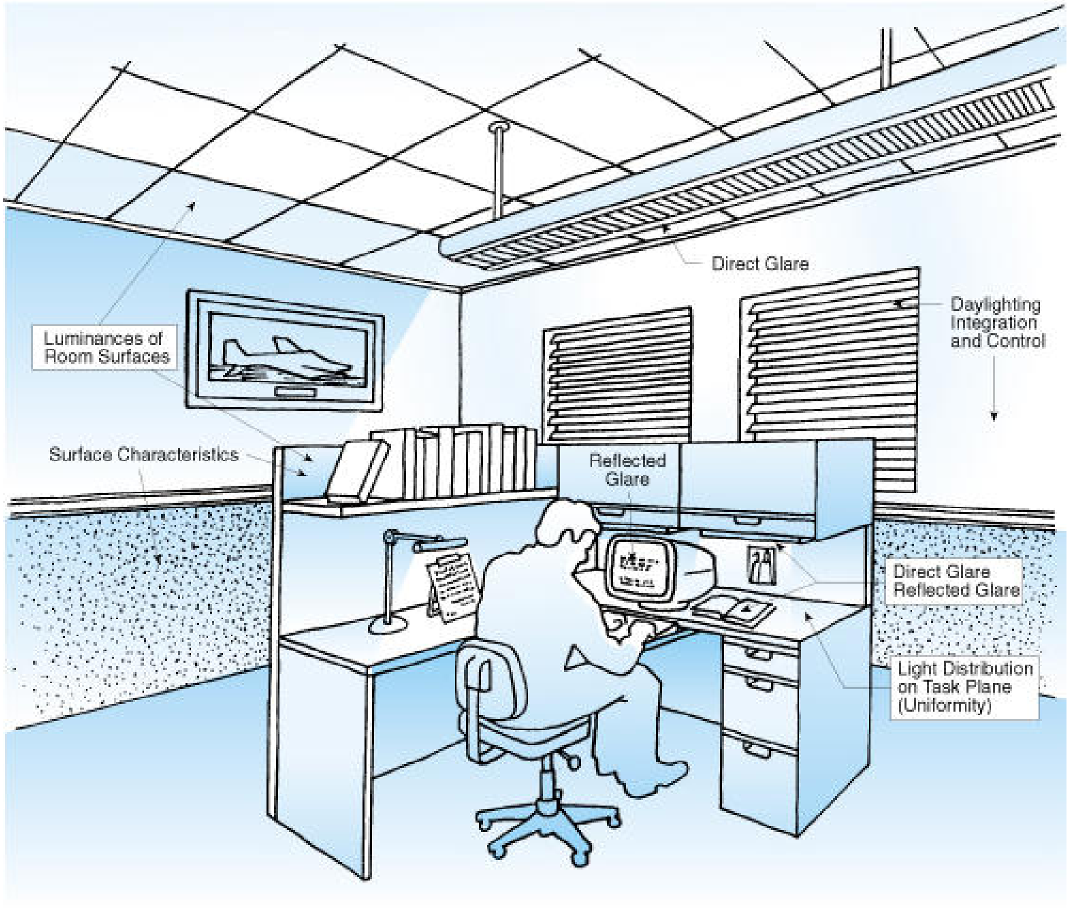


Figure 10-4. Office with work at the VDT as the primary visual task.

- *Direct Glare*
    - Ceiling. Choose a luminaire that limits glare at viewing angles the office worker would commonly experience. Semi-specular or white louvers can reduce the contrast between the lamp and the luminaire. Avoid luminaires with specular louvers where the worker's viewing angle permits seeing the lamp reflection. Luminaires that illuminate the ceiling as well as the task and higher ceiling reflectance help to reduce the contrast between the luminaire and the ceiling.
    - Undercabinet task light. Choose a luminaire that has an opaque front so that the seated worker has no direct view of the lamp or lens.
    - Adjustable task light. Choose a luminaire that is flexible enough to illuminate the visual task so that the bare source is not visible to the occupant or to adjacent workers.
- *Reflected Glare*
    - Undercabinet task light. Locate the luminaire to minimize reflected glare and veiling reflections from the desk top. A movable luminaire or special optics can help achieve this goal if luminaire location is restricted.
    - VDT screen. Computer screens with diffusing finishes, anti-reflection (AR) coatings, and high background luminances can be beneficial. The screen should not be oriented toward windows.
- *Light Distribution on Task Plane (Uniformity)*
    - Luminaire spacing. The pattern of light on the workplane is strongly affected by the photometric distribution of the luminaire. Space the luminaires so that the illuminance pattern on the workplane is within the recommended uniformity range. Luminaire spacing should be reduced if partial height furniture partitions are used. It should be noted, however, that luminaire spacing can be increased if indirect or direct/indirect lighting is used.
    - Luminaire selection. Avoid narrow-distribution luminaires, especially if the light from the luminaire produces a sharp scallop of light on the wall. This light pattern can be distracting if it serves no design purpose.
    - Workstation. Avoid extreme differences in luminance between the workplane and other surfaces in the visual field.

    - Desk top. Provide uniform illuminance on the desktop from undercabinet task lighting. Consider using a dimming electronic ballast to allow the occupant to control the location, direction, and intensity of light.
- *Luminances of Room Surfaces.* Provide uniform illuminance on the walls, ceilings, and furniture partitions to reduce contrast and achieve visual comfort in the workplace. If there are no dedicated luminaires for illuminating the walls (wall washing), space the ceiling luminaires less than 1 m (3 ft) from the wall and use white or semi-specular louvers and reflectors. Harsh striated patterns of excessive brightness or noticeable shadow should be avoided.
- *Surface Characteristics.* Interior workspaces should have high reflectances (walls, 50 to 70%; ceiling, 75 to 90%) to increase interreflections and thus help reduce contrast of luminaires against their background. High reflectances also allow the designer to produce an effective lighted environment with fewer watts and fewer luminaires.
- *Daylighting Integration and Control.* Use blinds or shades on windows to control glare and thermal discomfort from sun and sky. Use high-reflectance walls to reduce the contrast between the bright windows and the walls.

Figure 10-5 shows the produce department of a supermarket, with wet produce cases, grocery shelves, produce bins, and a feature display. The grocery shelves and wet cases utilize valance lighting, and track-mounted accent lights illuminate the bins. There is additional uplighting from above the grocery shelves and wet cases. The following are some relevant design issues:

Figure 10-5. Supermarket produce section.

- *Direct Glare*
    - Accent lights. Use narrow-beam track lights and careful aiming to illuminate the produce but reduce glare for shoppers. Use louvers if necessary.
    - Valance lighting. For visual comfort and improved visibility of produce, conceal the lamps mounted in wet cases.
- *Light Distribution on Task Plane (Uniformity).* The ratio of illuminances between merchandise and aisle should not exceed 3:1, so that shoppers can alternatively see the merchandise in their baskets and on the shelves.
- *Luminances of Room Surfaces.* Uplights on top of perimeter cases and on top of grocery gondolas help reduce shadows and make the space appear uniformly illuminated.

- *Color Appearance (and Color Contrast).* Use high-color-rendering lamps (CRI > 80) to make produce look appealing and help shoppers evaluate the freshness of the produce.
- *Illuminance (Vertical).* Vertical illuminance is important for grocery shelves.
- *Point(s) of Interest.* The feature display should have at least 3 to 5 times higher illuminance than the surrounding areas to attract the shopper's attention.

Figure 10-6 shows a building exterior with a canopied restaurant entrance and parking lot. There are shrubs and trees around the perimeter of the parking lot, wall sconces illuminating the entry stairs, uplights on specimen trees next to the building, and decorative post-top luminaires in the parking lot. The following design issues are important:

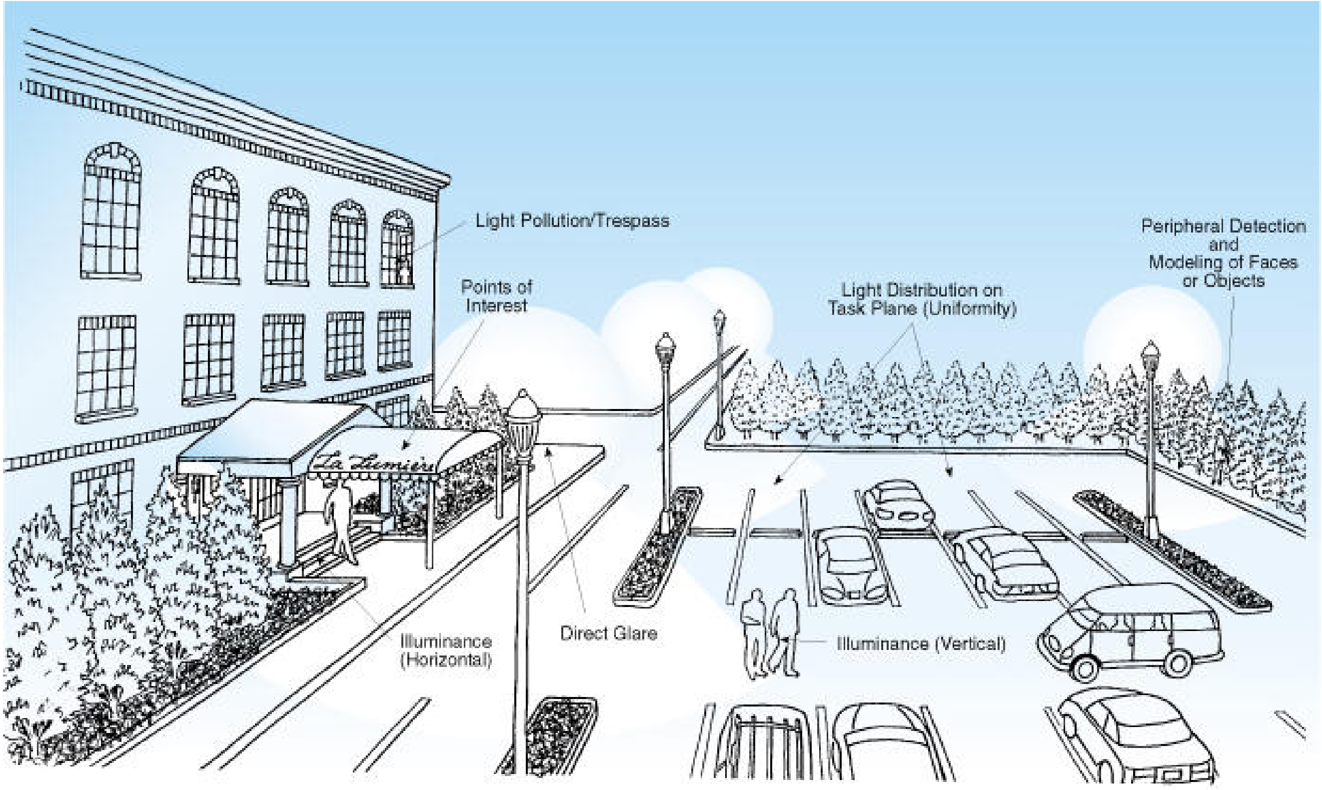


Figure 10-6. Restaurant entry/parking lot.

- *Direct Glare.* Use cutoff optics or a semi-cutoff optical system to control glare. Avoid using luminaires where the bare lamp can be seen.
- *Light Distribution on Task Plane (Uniformity).* Make sure parking lot is uniformly illuminated (usually a 4:1 average-to-minimum illuminance ratio is preferred).
- *Peripheral Detection.* Illuminate the perimeter of the area so that pedestrians and motorists can see potential danger in their peripheral vision.
- *Modeling of Faces or Objects.*[14] If it is important to identify faces, provide adequate vertical as well as horizontal illuminance. Diffuse illumination from luminaires and from surface reflections is helpful.
- *Illuminance (Vertical).* This helps motorists see obstacles and pedestrians in their path more quickly.
- *Light Pollution/Trespass.* Avoid using luminaires that emit light above the horizontal plane. Minimize direct light onto nearby windows and illumination onto adjacent properties.
- *Illuminance (Horizontal).* Follow guidelines for illuminance on steps and entry areas, including provisions for transitional illuminances from dark spaces to light spaces and vice versa.
- *Point(s) of Interest.* Make sure signs, special landscaping, and other points of interest are clearly visible to attract attention.

Figure 10-7 illustrates the passenger cabin of an airplane. The lighting must enable many activities that can occur day or night, such as boarding the aircraft and stowing luggage, reading and handwriting, viewing television or projection screens, and sleeping. The following are important design issues:

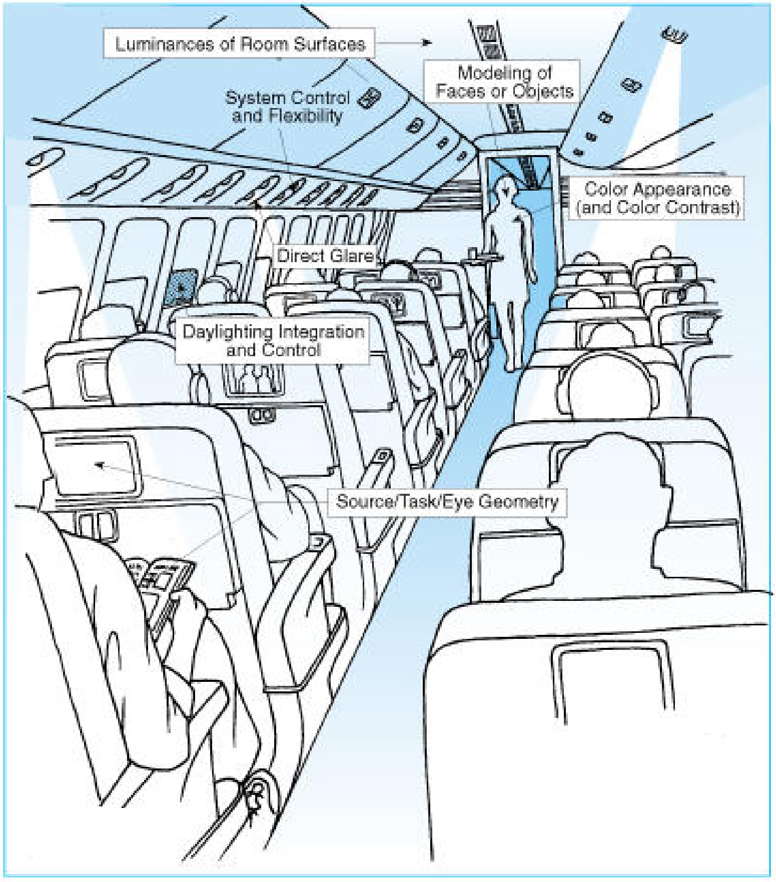


Figure 10-7. Aircraft passenger cabin.

- *System Control and Flexibility*. General illumination required for stowing luggage could be too bright for comfortable television viewing or sleeping, so it is essential that there be a flexible control system that allows the crew to reduce ambient illumination throughout the cabin. Also, individual control of reading lights accommodates different activities, including sleeping.
- *Daylighting Integration and Control*. The cabin windows provide a view and, during the day, light onto surfaces inside the cabin, but blackout shades should be provided to minimize brightness.
- *Source/Task/Eye Geometry*. The passenger reading light needs to be carefully located with the user and task locations in mind. A good reading light position, distribution, and aiming angle helps avoid veiling reflections and shadows on reading and writing surfaces.
- *Direct Glare*. For comfort and visibility, brightness should be minimized at normal viewing angles for the cabin attendants and the passengers. Solutions include aiming luminaires away from passengers' eyes, lensing or louvering luminaires, and using indirect lighting.
- *Luminances of Room Surfaces*. An airplane cabin is a confined space. Consider light colored, matte finishes and washing light across ceiling, wall, and overhead bin surfaces to effect a perception of spaciousness.
- *Color Appearance (and Color Contrast)*. Choose light sources that deliver good color rendering of skin tones and interior finishes.
- *Modeling of Faces or Objects*.[14] Good facial modeling assists communication between crew and passengers. For general lighting, use some indirect illumination reflected from light-colored surfaces to help wash out harsh shadows on faces.

Figure 10-8 shows an indoor tennis court. It is important that the players see their opponents and team members clearly, see the ball in motion, and not be confused by glare or shadows. The following design issues are common to many interior sports facilities.

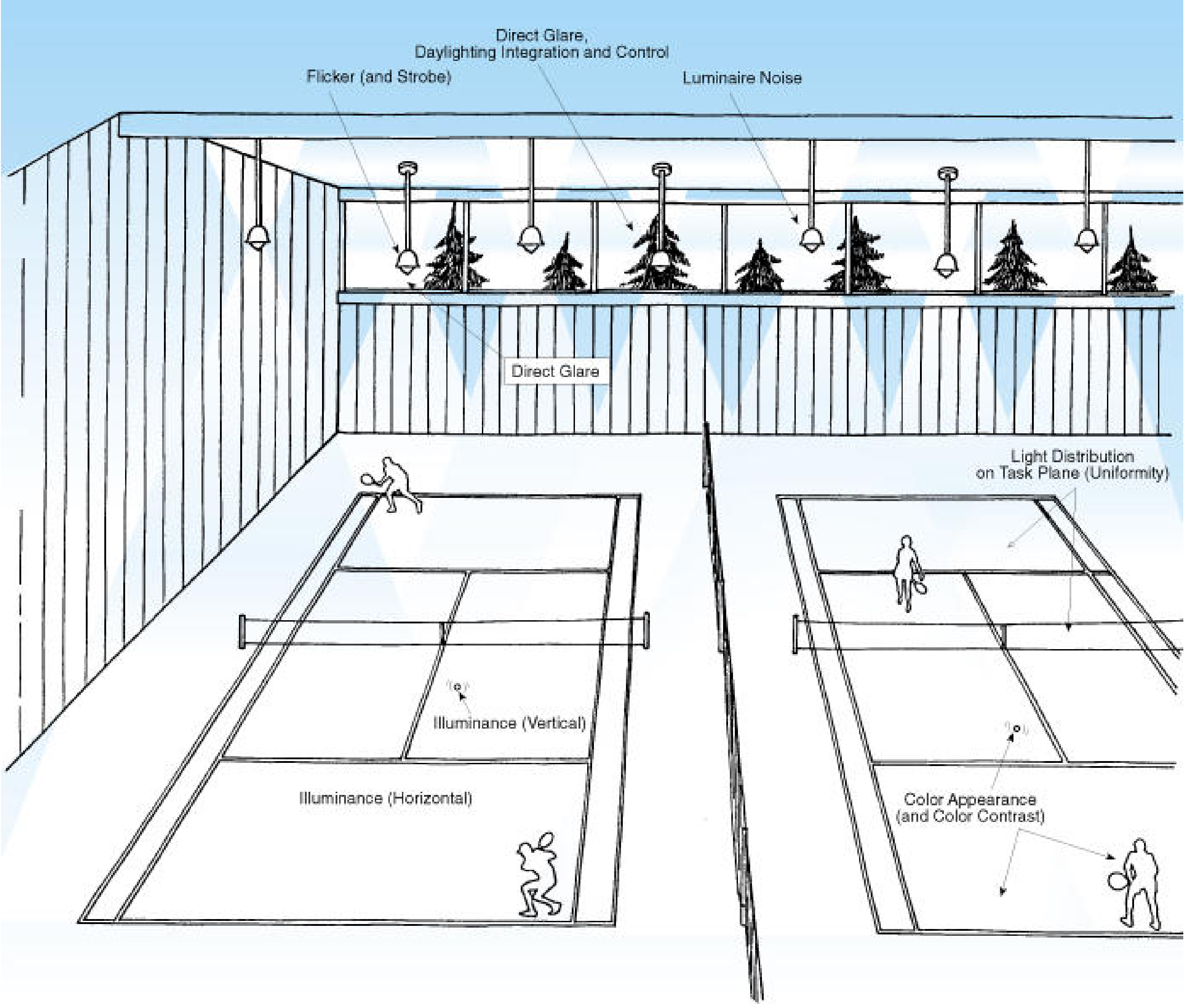


Figure 10-8. Indoor tennis court.

- *Light Distribution on Task Plane (Uniformity).* It is important to keep the illuminance on the tennis court within the uniformity ratios suggested in Chapter 20, Sports and Recreational Area Lighting.
- *Illuminance.* Illuminances, both horizontal and vertical, are important for observing player action and ball movement. Vertical illuminance above the court is important so that the ball trajectory can be seen.
- *Direct Glare.* Bright luminaires, especially those with exposed lamps, can produce glare and after-image that can severely limit a player's ability to track the ball. Consider using indirect lighting or control lamp brightness with lenses or louvers.
- *Color Appearance (or Color Contrast).* Use light sources that render skin tones well. Also, color contrast between the ball and the surrounding surfaces can help make the ball easier to see.
- *Flicker (and Strobe).* In order to avoid the stroboscopic effect with the ball, use light sources with high-frequency ballasts, or put adjacent luminaires on alternate phases of a three-phase electrical system.
- *Daylighting Integration and Control.* If daylight is admitted to the sports facility, ensure that glare from windows and skylights does not interfere with the visual comfort of the players or the visibility of the ball.
- *Luminaire Noise.* The noise from ballasted luminaires can be very distracting to players and spectators. Use remote-mounted ballasts, "potted" ballasts in enclosures that isolate ballast vibrations, or electronic ballasts.

ILLUMINANCE SELECTION

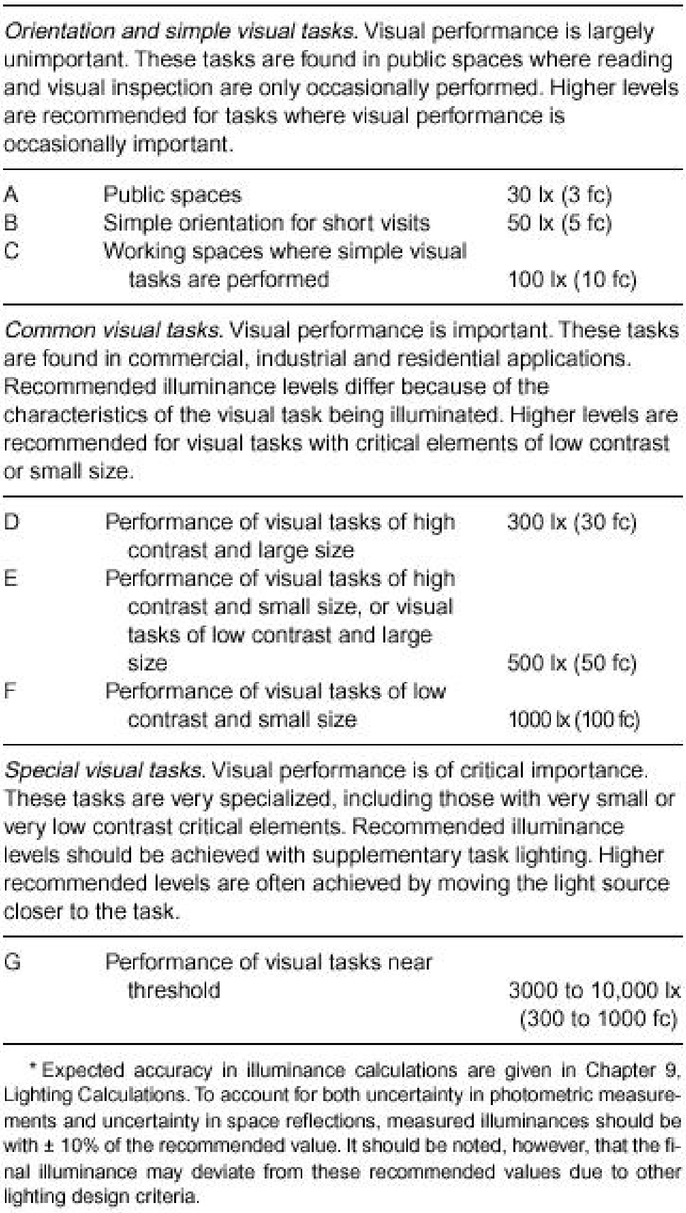
In 1979, the IESNA established an illuminance selection procedure, which was published in the 6th, 7th, and 8th editions of its *Lighting Handbook*. The philosophy of that procedure was to enable the lighting designer to select illuminances based on a knowledge of space and occupant characteristics as well as the task and worker characteristics.

The philosophy of that procedure has been embraced again in this edition, but the procedure has been modified and simplified to place visual performance and therefore illuminance selection more in balance with the other important lighting design criteria presented in this chapter and discussed throughout this edition of the *IESNA Lighting Handbook*. Specifically, the recommended illuminances provided in the Design Guide are based on the Society's judgment of best practice for "typical" applications. Every situation is unique so, naturally, typical conditions may not be appropriate for a specific application. As a professional, the lighting designer should have a better understanding of the particular space and the needs of the occupants and clients than what can be presented in a recommended illuminance value for a typical space.

Illuminance Recommendations

In 1979, the IESNA established nine illuminance categories, "A," the lowest set of recommended illuminances, through "I," the highest set. Each of the nine categories had general descriptions of the visual task, irrespective of the application. Generally, the same approach has been employed in this edition of the *IESNA Lighting Handbook* to help lighting designers establish the best task illuminance. However, four important modifications have been adopted.

1. The recommended illuminances are no longer provided without reference to a specific application. Every application in the Design Guide has a specific recommended illuminance (horizontal, vertical, or both) representing best practice for a typical application.
2. The nine illuminance selection categories established earlier by the IESNA have been reduced to seven categories and organized into three sets of visual tasks (orientation and simple, common, and special). These groupings provide additional clarity to the category descriptions (Figure 10-9).
3. Additional precision has been given to the task descriptions in each category. In the previous three editions it was impossible for the lighting designer to unambiguously ascertain what constituted, for example, "low contrast" or "small size." Specific ranges of contrast and size have been established for this edition (Figures 10-10 and 10-11).
4. Recommended illuminances increase roughly logarithmically with increasing task difficulty by combined changes in task contrast and task size, as defined in Figure 10-10. These recommendations are guided by both the scientific literature and practical experience.



Orientation and simple visual tasks. Visual performance is largely unimportant. These tasks are found in public spaces where reading and visual inspection are only occasionally performed. Higher levels are recommended for tasks where visual performance is occasionally important.

A	Public spaces	30 lx (3 fc)
B	Simple orientation for short visits	50 lx (5 fc)
C	Working spaces where simple visual tasks are performed	100 lx (10 fc)

Common visual tasks. Visual performance is important. These tasks are found in commercial, industrial and residential applications. Recommended illuminance levels differ because of the characteristics of the visual task being illuminated. Higher levels are recommended for visual tasks with critical elements of low contrast or small size.

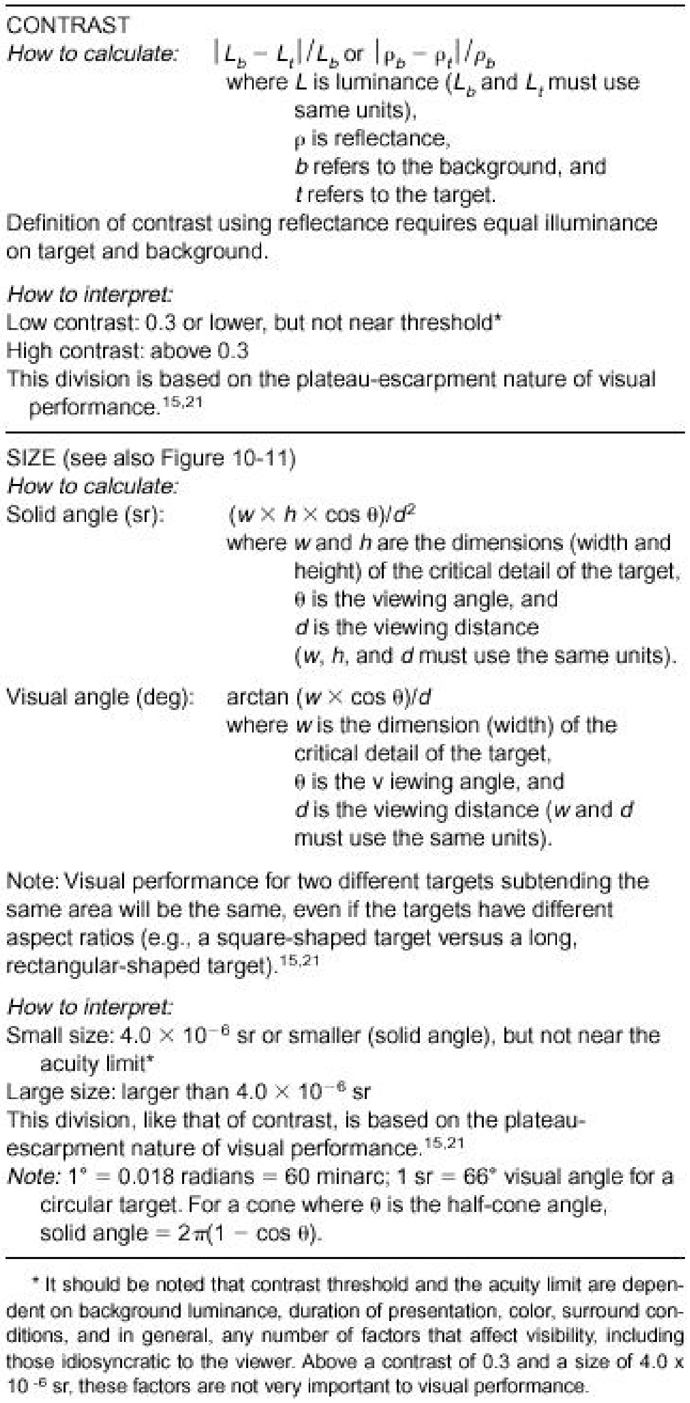
D	Performance of visual tasks of high contrast and large size	300 lx (30 fc)
E	Performance of visual tasks of high contrast and small size, or visual tasks of low contrast and large size	500 lx (50 fc)
F	Performance of visual tasks of low contrast and small size	1000 lx (100 fc)

Special visual tasks. Visual performance is of critical importance. These tasks are very specialized, including those with very small or very low contrast critical elements. Recommended illuminance levels should be achieved with supplementary task lighting. Higher recommended levels are often achieved by moving the light source closer to the task.

G	Performance of visual tasks near threshold	3000 to 10,000 lx (300 to 1000 fc)

* Expected accuracy in illuminance calculations are given in Chapter 9, Lighting Calculations. To account for both uncertainty in photometric measurements and uncertainty in space reflections, measured illuminances should be with ± 10% of the recommended value. It should be noted, however, that the final illuminance may deviate from these recommended values due to other lighting design criteria.

Figure 10-9. Determination of Illuminance Categories*



CONTRAST

How to calculate: $|L_b - L_t|/L_b$ or $|\rho_b - \rho_t|/\rho_b$

where L is luminance (L_b and L_t must use same units),

ρ is reflectance,

b refers to the background, and

t refers to the target.

Definition of contrast using reflectance requires equal illuminance on target and background.

How to interpret:

Low contrast: 0.3 or lower, but not near threshold*

High contrast: above 0.3

This division is based on the plateau-escarpment nature of visual performance.[15,21]

SIZE (see also Figure 10-11)

How to calculate:

Solid angle (sr): $(w \times h \times \cos\theta)/d^2$

where w and h are the dimensions (width and height) of the critical detail of the target,

θ is the viewing angle, and

d is the viewing distance

(w, h, and d must use the same units).

Visual angle (deg): $\arctan(w \times \cos\theta)/d$

where w is the dimension (width) of the critical detail of the target,

θ is the v iewing angle, and

d is the viewing distance (w and d must use the same units).

Note: Visual performance for two different targets subtending the same area will be the same, even if the targets have different aspect ratios (e.g., a square-shaped target versus a long, rectangular-shaped target).[15,21]

How to interpret:

Small size: 4.0×10^{-6} sr or smaller (solid angle), but not near the acuity limit*

Large size: larger than 4.0×10^{-6} sr

This division, like that of contrast, is based on the plateau-escarpment nature of visual performance.[15,21]

Note: 1° = 0.018 radians = 60 minarc; 1 sr = 66° visual angle for a circular target. For a cone where θ is the half-cone angle, solid angle $= 2\pi(1 - \cos\theta)$.

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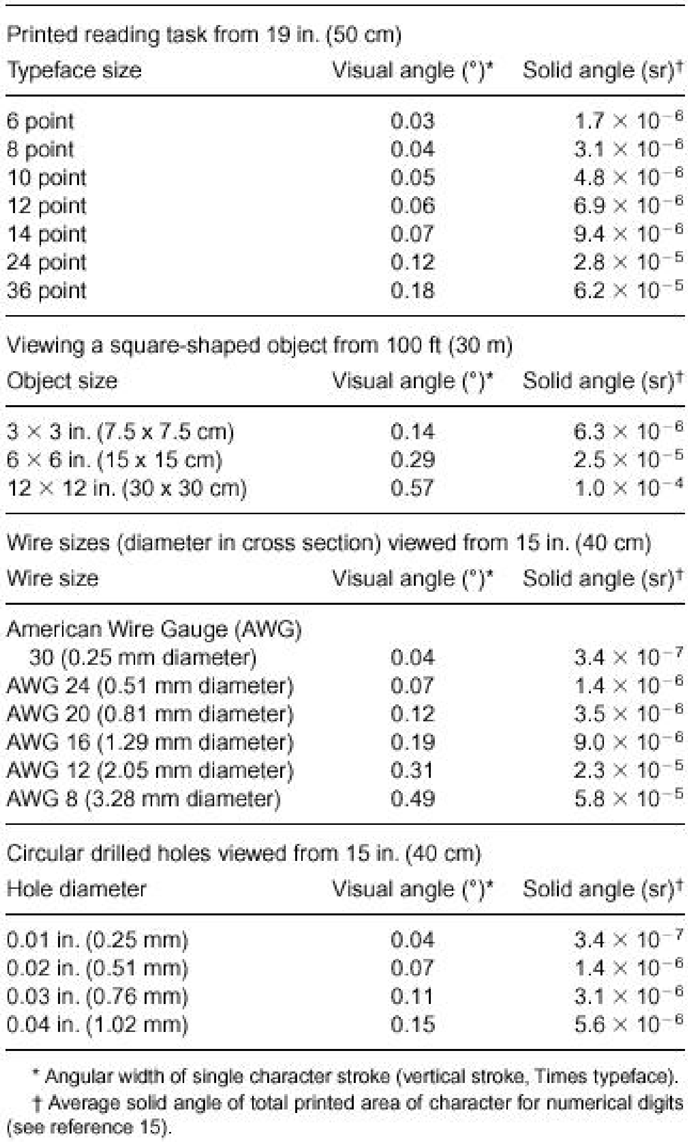
* It should be noted that contrast threshold and the acuity limit are dependent on background luminance, duration of presentation, color, surround conditions, and in general, any number of factors that affect visibility, including those idiosyncratic to the viewer. Above a contrast of 0.3 and a size of 4.0×10^{-6} sr, these factors are not very important to visual performance.

Figure 10-10. Determination of Visual Task Parameters



Printed reading task from 19 in. (50 cm)

Typeface size	Visual angle (°)*	Solid angle (sr)†
6 point	0.03	1.7×10^{-6}
8 point	0.04	3.1×10^{-6}
10 point	0.05	4.8×10^{-6}
12 point	0.06	6.9×10^{-6}
14 point	0.07	9.4×10^{-6}
24 point	0.12	2.8×10^{-5}
36 point	0.18	6.2×10^{-5}

Viewing a square-shaped object from 100 ft (30 m)

Object size	Visual angle (°)*	Solid angle (sr)†
3 × 3 in. (7.5 x 7.5 cm)	0.14	6.3×10^{-6}
6 × 6 in. (15 x 15 cm)	0.29	2.5×10^{-5}
12 × 12 in. (30 x 30 cm)	0.57	1.0×10^{-4}

Wire sizes (diameter in cross section) viewed from 15 in. (40 cm)

Wire size	Visual angle (°)*	Solid angle (sr)†
American Wire Gauge (AWG) 30 (0.25 mm diameter)	0.04	3.4×10^{-7}
AWG 24 (0.51 mm diameter)	0.07	1.4×10^{-6}
AWG 20 (0.81 mm diameter)	0.12	3.5×10^{-6}
AWG 16 (1.29 mm diameter)	0.19	9.0×10^{-6}
AWG 12 (2.05 mm diameter)	0.31	2.3×10^{-5}
AWG 8 (3.28 mm diameter)	0.49	5.8×10^{-5}

Circular drilled holes viewed from 15 in. (40 cm)

Hole diameter	Visual angle (°)*	Solid angle (sr)†
0.01 in. (0.25 mm)	0.04	3.4×10^{-7}
0.02 in. (0.51 mm)	0.07	1.4×10^{-6}
0.03 in. (0.76 mm)	0.11	3.1×10^{-6}
0.04 in. (1.02 mm)	0.15	5.6×10^{-6}

* Angular width of single character stroke (vertical stroke, Times typeface).

† Average solid angle of total printed area of character for numerical digits (see reference 15).

Figure 10-11. Examples of Common Visual Angles and Solid Angles

High illuminances can partially compensate for small size and low contrast to maintain high levels of visual performance. Changes in visual performance as a function of task contrast and size, background reflectance, and observer age can be calculated precisely.[15] For well-controlled situations, this procedure can be a useful predictive tool. However, performance at a visual task depends on many uncontrolled visual and nonvisual factors that are highly variable and largely indeterminable by the lighting designer. For example, it is often difficult or impossible to know the age, retinal health, and optical refraction of the worker. Moreover, worker motivation, education, manual dexterity, posture, stature, and level of fatigue are highly variable and usually unmeasurable. Therefore, a precise calculation method for visual performance cannot be justified for typical areas or activities. For this reason, the IESNA currently believes that the recommended illuminances in the Design Guide and in Figure 10-9 are adequate and appropriate guidelines for lighting design.

The Basis for Deviating from the Recommended Illuminances

Every visual task identified in the Design Guide has provisions for horizontal and vertical illuminance recommendations. Depending on the task, one or both illuminance recommendations are provided. Occasionally, the Guide refers the reader to an application chapter for recommended illuminances. The recommended values throughout the Design Guide represent consensus values formally obtained by the appropriate application committee.

Occasionally the visual task in a specific space is not typical, and Figures 10-10 and 10-11 should be used to adjust the illuminance for that task. Indeed, it is extremely important that the lighting designer have a clear understanding of the visual task being illuminated and then determine whether, in fact, the recommended illuminance is appropriate. It is also possible that more than one visual task is performed in a space. The lighting designer should make provisions to illuminate these tasks to the recommended levels unless other design criteria supercede illuminance as a design criterion.

The IESNA recognizes that illuminance is not the sole lighting design criterion. Other criteria in the design guide may be more important than illuminance; to address the primary design criteria, the lighting designer can deviate from the recommended illuminance. Further, and as listed in the section "How to Use the IESNA Lighting Design Guide" above, there are many other factors that might lead to deviation from the recommendations made in the Design Guide. Given the complexity and diversity of design goals for a specific application, it is impossible to formulate a formal, precise method for deviating from the recommended illuminances in the Design Guide. However, some guidance, based on descriptive statistics, is offered by the IESNA with regard to what might be considered "dramatic" deviations from a recommended illuminance.

Consider a hypothetical example. A survey of task illuminances was obtained for a large sample of open-plan offices where the primary visual task is reading 8- and 10-point print, and the recommended illuminance is 300 lx. Figure 10-12 illustrates the results of the survey. Illuminances ranged from 150 lx to 450 lx with a peak frequency of 300 lx. Roughly two-thirds of the illuminances (i.e., one standard deviation) were between 250 and 350 lx, and approximately 95% (i.e., two standard deviations) of the illuminances were between 200 and 400 lx. Dramatic deviations were those illuminances below 200 or above 400 lx and, in total, represented less than 5% of all illuminances surveyed.

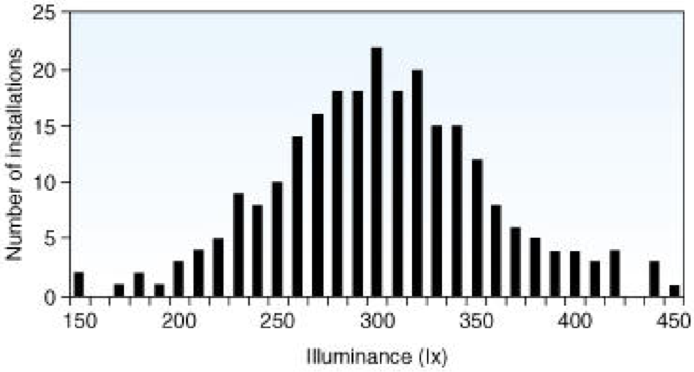


Figure 10-12. Hypothetical distribution of surveyed illuminances.

In general, the IESNA believes that a dramatic difference between an actual and a recommended illuminance (i.e., a difference of two standard deviations or more) would be 1/3 more or 1/3 less than the recommended value. It should be noted again that an experienced lighting designer can produce a satisfactory illuminance outside this range, but it would be an exceptional achievement. As already noted above, the IESNA believes that any dramatic deviations from the recommended value should be carefully documented by the lighting designer, not only because documentation is good professional practice, but it is also good to have in case the design illuminance is ever challenged.

Age

Finally it should be noted that the recommendations for illuminances provided in the Design Guide are not made with respect to the age of the occupants. Generally, the visual requirements of older persons are significantly different from those of younger persons in the two ways[16,17]: (1) there is a thickening of the yellow crystalline lens, which decreases the amount of light reaching the retina, increases scatter within the eye, and reduces the range of distances that can be properly focused (presbyopia); and (2) there is a reduction of pupil size, decreasing the amount of light reaching the retina.

The retinal illuminance of a typical 60-year-old person is only about one-third of the retinal illuminance of a typical 20-year-old person due to smaller pupil sizes and thicker lenses (Figure 10-13).[18] Additionally, the near point of a typical 20-year-old person is 10 cm (4 in.), compared to more than 1 m (3 ft) for a typical 60-year-old person (Figure 10-14). Consequently, older persons tend to require higher task illuminances for the same retinal illuminances and, because of reduced clarity in the lens, have reduced image quality. Similarly, greater attention to sources of glare within the field of view is more important for older than for younger persons.

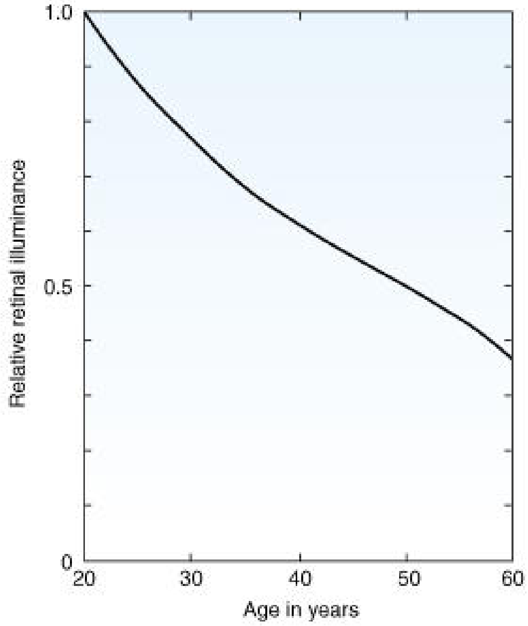


Figure 10-13. An estimate of relative decline in retinal illuminance with age.

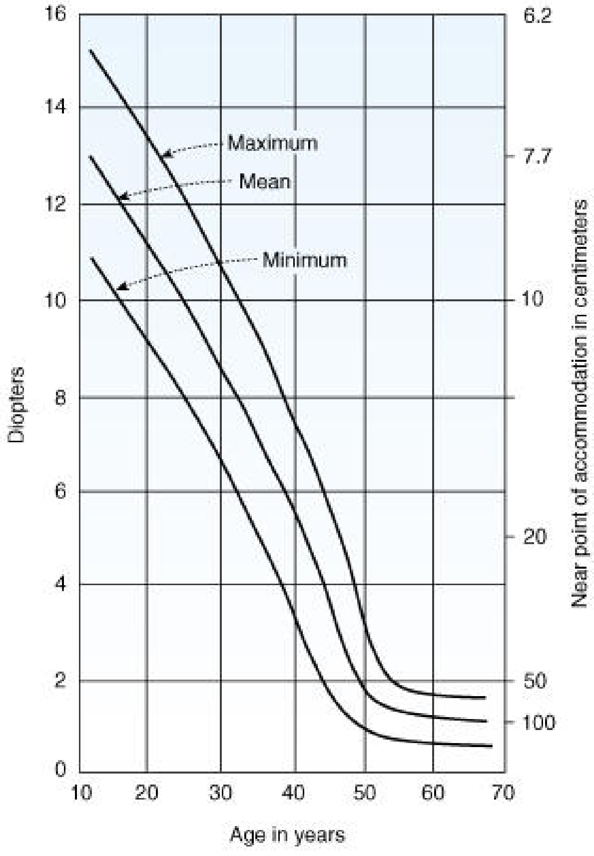


Figure 10-14. The decrease of the amplitude of accommodation with age.

The population of persons older than 60 years is growing, and this means that the lighting specifier must consider the possibility of increasing the recommended illuminances and take measures to avoid glare and excessive luminance ratios in the field of view (see the sections "Direct Glare" and "Reflected Glare" above for additional information about glare). It should be noted too that after age 65, neurological factors (e.g., macular degeneration, diabetic retinopathy) become increasingly problematic. These changes demand even more sophisticated lighting design. It is recommended that other resources be consulted for guidance on the effects of age on the quantity and quality of illumination, and that this information, like that for other lighting design criteria, be factored into the final design.[19-21]

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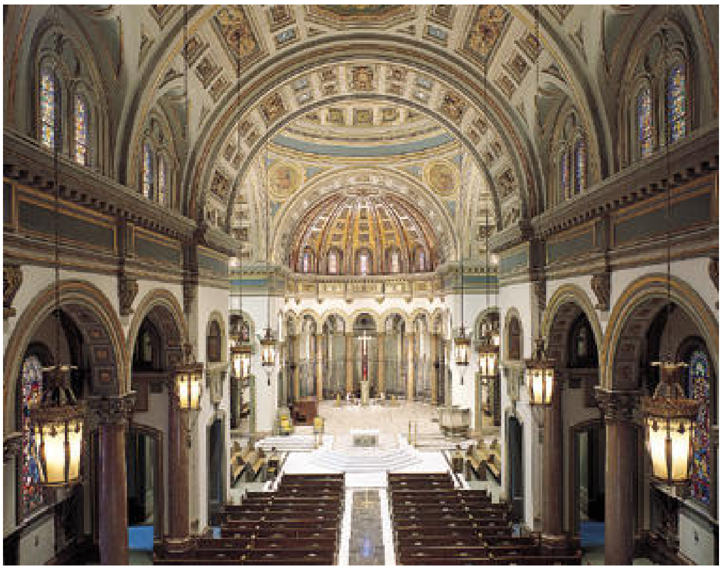


Plate 1. The magnificence of the architecture has been redefined by a new lighting system in this cathedral. Lanterns from 1929 were refurbished, 1949 downlights were retrofitted with tungsten-halogen lamps, a new indirect lighting system was installed to emphasize the ceiling vault and dome, and a television lighting system was added, all controlled to allow lighting level flexibility from 0 to 100%.

Plate 2. This sanctuary features a spiral ceiling, a centrum (altar), an organ, and a clerestory. The space is lighted for general assembly, with the organ and centrum serving as illuminated focal points. Floodlights provide ambient illumination. Warm white cold cathode lamps, concealed in a continuous architectural cove, uplight the spiral to its 200 ft peak.

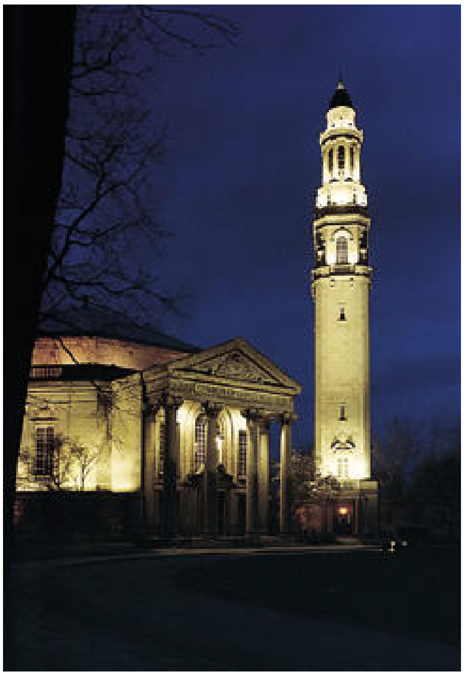


Plate 3. Lighting the exterior of this historic church and bell tower emphasizes the structure's uniqueness and significance, highlights their graceful architectural features, and provides drama to a nighttime view.

Plate 4. The lighting on vertical surfaces in the pulpit area can be raised to 70 fc, sufficient for color television broadcasting. The surrounding ambient light is then raised to about one-third of the broadcast level to mitigate any unpleasant glare from the television lighting for either the clergy or the congregation.

Plate 5. A festive, yet elegant mood was created for an entrance to a hotel and casino. The main lighting features include strings of low-wattage incandescent lights inserted into column slots, translucent alabaster column capitals that conceal fluorescent striplights, halogen wall sconces, blue neon coved uplight, incandescent bowl pendants, and PAR38 halogen downlights.

Plate 6. Main Concourse and restored Sky Ceiling, Grand Central Terminal, New York, New York. The new lighting scheme for this renowned architectural jewel incorporates new lighting technologies with classical structural elements. Beneath the decorative lunettes and cornice, a row of more than two hundred 25-W compact fluorescent lamps, set in custom cylindrical containers, spans the perimeter of the vast concourse. A fiber-optic system illuminates the constellations in the vaulted-ceiling firmament. The ceiling was painted a blue-green to simulate the night sky.

Plate 7. The main banking hall of a landmark bank building features a stained-glass ceiling, decorative multi-arm bowl pendants, and task lights on the desks. In the main traffic areas and at the teller’s station, fluorescent lamp luminaires with parabolic louvers provide general illumination.

Plate 8. Shoppers use mall areas to rest and congregate. Lighting must address a variety of purposes: provide general ambient lighting; add emphasis where appropriate, yet not compete with individual store windows and entrances; and be flexible to accommodate special displays and attractions. Landscape lighting adds aesthetic beauty and serenity, and contributes to a desired image.

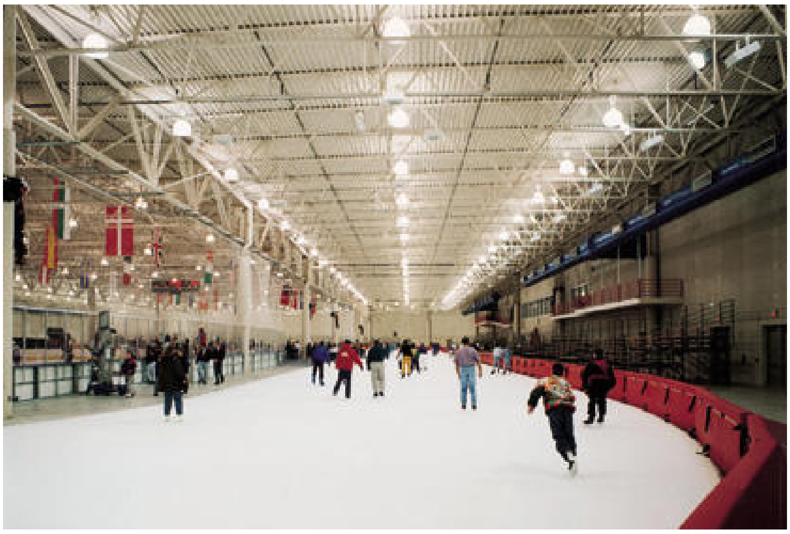


Plate 9. Metal halide lighting in industrial luminaires installed over this skating rink provides good general illumination for skaters and a glare-free ice surface. The uplight contribution creates a feeling of spaciousness and pleasantness in the space.

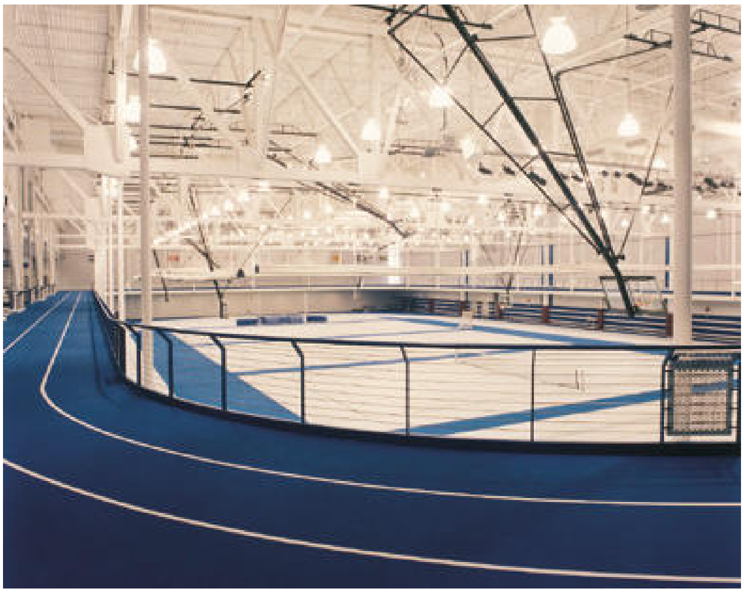


Plate 10. This sports facility features a multipurpose gymnasium surrounded by an indoor track. Metal halide lighting is used for ambient illumination.

Plate 11. The outdoor lighting of this shopping mall not only emphasizes the architecture, but it serves to attract customers to the mall's stores and restaurants.


a

b

c d

Plate 12 a, b, c, and d. Paintings, sculptures, and art objects are effectively lighted with track lights, which can be aimed to provide an even wash of light over an object (a) or to emphasize certain features, such as color or texture (b). In (c) light from several directions models the sculpture and provides a dramatic background of shadows that are as interesting to look at as the sculpture itself. In (d) daylight is admitted into this gallery through a translucent skylight, and the amount of light transmitted is carefully controlled. Track lighting provides both supplementary general illumination and accent lighting for the ornamental objects (hand-painted screens) in this exhibit.

11

Office Lighting

THE IMPORTANCE OF LIGHTING IN THE OFFICE ENVIRONMENT

Offices are designed to house working people engaged in thought and in a number of forms of communication (written, visual, telephone, computer, and face to face). Office lighting should enable workers to perform these tasks effectively.

Since feelings of well-being, interest, and enthusiasm are affected by the environment, consideration should be given to the design of office interiors in an effort to achieve a stimulating work place. Office lighting affects the appearance of the space and its occupants, and therefore their mood and productivity. Naturally, lighting should provide good visibility for the visual tasks. Although it is important to consider the luminous environment and the lighting of visual tasks separately, these aspects must work together. The same lighting system may contribute to both, but typically, separate luminaires should provide or augment the visual task illumination.

Energy-efficient lighting is critical to office lighting design. Good lighting design and applications go hand in hand with energy-efficient technologies to reduce operating costs and environmental pollution.

THE LUMINOUS ENVIRONMENT

Composition of the Luminous Environment

The visual effect of an office space depends on variations in perceived brightness and color. The effects can be achieved by varying surface reflectances and illuminance. Shadow and light are both design elements. One example is wall washing, whereby the wall has a greater luminance than the ceiling or floor. Another example is local task lighting, which provides pools of higher brightness within a large space. This latter approach helps give office workers a sense of place at a workstation within an otherwise uniform open office. Careful design provides interesting variations without producing distracting or uncomfortable luminance differences.

Color

Both surface reflectances and light source spectral power distribution (SPD) play important roles in the color of the office lighting environment. Color adds visual interest to a space, making it a more inviting and pleasant place to work. High color rendering by the light source is critical if fine color discriminations are being performed. The spectral composition of the light source can also determine the general overall appearance of a space, particularly the furnishings, room surfaces, and people in that space, and so should be considered when selecting a light source.

OFFICE LIGHTING DESIGN ISSUES

Open Plan Office, Intensive VDT Use

- Direct glare
- Illuminance (Vertical)
- Luminances of Room Surfaces
- Reflected Glare
- Source/Task/Eye Geometry

Private Office

- Daylighting Integration and Control
- Direct Glare
- Luminances of Room Surfaces
- Reflected Glare

Conference Rooms

- Appearance of Space and Luminaires
- Direct Glare
- Modeling of Faces or Objects

Video Conferencing

- Direct Glare
- Illuminance (Vertical)
- Modeling of Faces or Objects
- Reflected Glare
- Source/Task/Eye Geometry

Drafting Areas

- Color Appearance (and Color Contrast)
- Direct Glare
- Flicker (and Strobe)
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Luminances of Room Surfaces
- Reflected Glare
- Shadows
- Source/Task/Eye Geometry

Surface Reflectances. Some believe that, where workers are exposed to the same environment for long periods of time, the color in that environment can affect performance positively or negatively, even if workers are not aware of this effect. Some also believe that small offices can be made to appear larger and less crowded if woodwork and furniture placed against walls have the same hue or a similar reflectance. Touches of accent color give vitality and dramatic interest to any office area. Contrasting colors, or light and dark values of the same color, can be used at some point or points in the room. These may be in wall coverings, furniture upholstery, or pictures or tapestries. Colors selected for large surface areas should have reflectances as recommended in Figure 11-1. Color contrast, through the use of more colorful surfaces, may also make interior spaces appear brighter at low light levels.

Light Source Spectral Power Distribution (SPD). There are two distinct application considerations with respect to light source SPD. These are the chromaticity (correlated color temperature, or CCT) and the color rendering properties of the light source.

Chromaticity refers to the color appearance of the lighted source and is designated by its CCT in kelvin

(K) (see Chapter 4, Color, and Chapter 6, Light Sources). In interior spaces such as offices, a source will create a "warm" environment if its CCT is about 3000 K or lower, and a "cool" environment if it is 5000 K or higher. A CCT between these two is considered neutral. Individual preferences vary in regard to warm, neutral, or cool environments.

The perceived color of an object is affected by the color rendering properties of the lamp. The color rendering index (CRI) is a measure of the color shift induced by a given lamp relative to a standard lamp of the same CCT. The maximum CRI value is 100. Where color discrimination is an important part of the work (for example, color matching in an advertising agency), a source with a CRI of 90 or higher should be employed.

Two lamps with the same chromaticity may have different color rendering characteristics. Fluorescent lamps that are now available offer the designer several chromaticities with good to excellent color rendering and high luminous efficacy. The color rendering properties of various lamps can be demonstrated by installing them in display boxes or rooms, each having an identical presentation of colored objects.

Light source selection depends on the importance given to color rendering, initial cost, lamping and maintenance costs, and energy costs. Because different sources render colors differently, it is important that the sources be viewed in a similar space before being specified. If daylight is present in the office, the colored objects should be viewed under the electric light source with and without the expected daylight contribution (taking into account possible tinting of the fenestration).

Color, Luminance, and Brightness Differences

Luminous differences and color contrast are necessary for vision. Achromatic print can be seen because of the difference in luminance between the white page and black print. Similarly, an interior space is visible because of the brightness differences of the surfaces. Brightness variations are a function of the absolute and spectral reflectances of the surfaces and of the distribution of light on those surfaces.

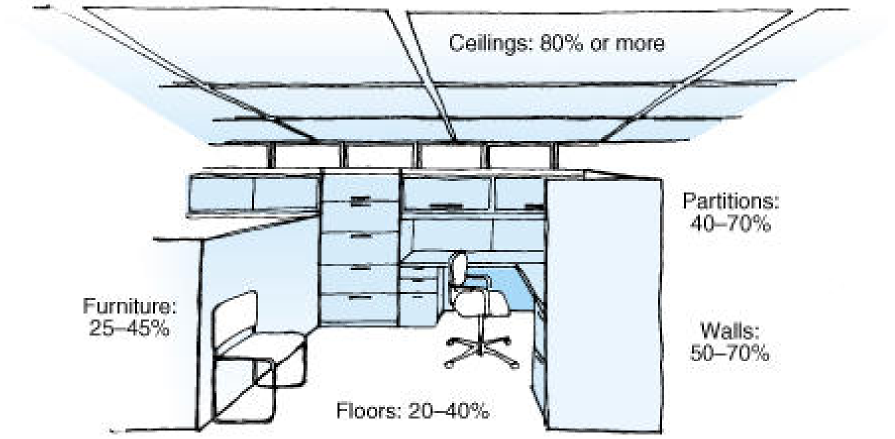
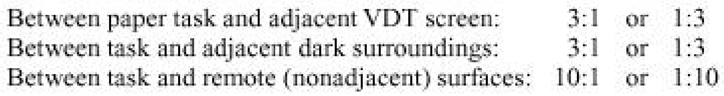


Figure 11-1. Reflectances recommended for room and furniture surfaces in offices.

Large brightness variations can be problematic. Office interiors should be lighted to provide for good visibility with no distracting glare. Direct and reflected glare should be avoided; however, it is important to provide enough variation in luminance or color to contribute to a stimulating, attractive environment. Where there are no prolonged visual tasks, such as in lobbies and corridors and in reception, conference, lounge, and dining areas, variations in brightness are encouraged, using attractive colors and appropriate focal points of high illuminances to catch the eye.

Luminance Ratios. For an office environment, luminances near each task and in other parts of the office interior within the field of view should be balanced with the task luminance. Two separate phenomena are influenced by the luminance ratios within the field of view: dark and light adaptation and disability glare (see Chapter 3, Vision and Perception). To limit the effects of these phenomena, the luminance ratios generally should not exceed the following:



Between paper task and adjacent VDT screen:	3:1	or	1:3
Between task and adjacent dark surroundings:	3:1	or	1:3
Between task and remote (nonadjacent) surfaces:	10:1	or	1:10

However, it is not practical or aesthetically desirable to maintain these ratios throughout the entire environment. For visual interest and distant eye focus (for periodic eye muscle relaxation throughout the day), small visual areas that exceed the luminance-ratio recommendations are desirable. This would include artwork, accent finishes on walls, ceilings or floors, small window areas, accent finishes on chairs and accessories, and accent focal lighting.

Transient Adaptation. The visual system adjusts its operating characteristics as a result of changes in the brightnesses within the field of view. Photochemical, neurological, and pupillary changes occur in this adaptation process. Neural changes occur most quickly, although visual capabilities are temporarily impaired while the visual system readjusts. This is known as transient adaptation, which is completed after a very short time (less than 200 ms). Photochemical changes occur much more slowly and are most noticeable when there is a dramatic change in ambient light level, such as moving from full daylight into a dark theater. Pupillary changes are relatively insignificant in the adaptation process (see Chapter 3, Vision and Perception).

Disability Glare. Glare sources within the field of view may cause stray light within the ocular media of the eye. This light is in turn superimposed on the retinal image. This reduces the contrast of the image and can reduce visibility and performance.

Reflectances and Finishes. The brightnesses of objects depend on illuminance as well as surface reflectance. For example, reading 80%-reflectance white paper on an evenly illuminated desk top requires that the desk top have a reflectance of at least 27% (one-third of 80%) in order to comply with the 3:1 guideline for the ratio between the luminance of the task and its immediate surrounding. Dark wood or veneer work surfaces often have lower reflectance values and exceed the recommended value. Thus, reflectance as well as illuminance levels are important in office lighting design.

Surface specularity, or gloss, must also be considered. Glossy surfaces are mirrorlike and can produce images of the luminaires that can result in reflected glare, a patch of very high brightness. Glossy horizontal work surfaces are particularly troublesome (Figure 11-2). For this reason, shiny work surfaces should be avoided.

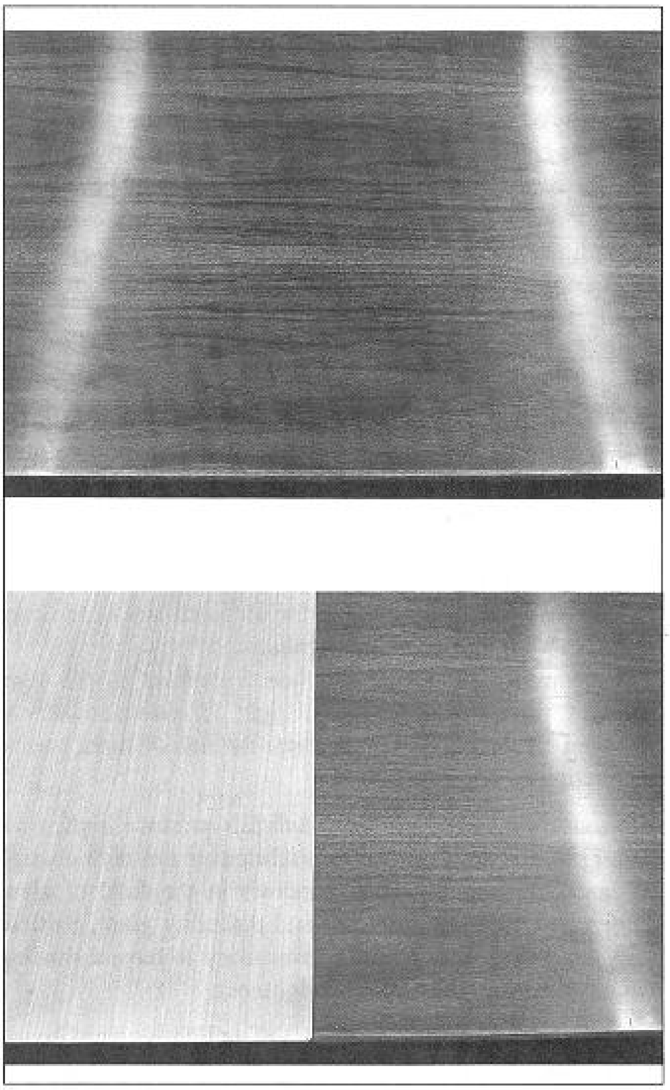


Figure 11-2. The streaks of light are reflected images of two continuous rows of luminaires. A very severe glare condition is produced by a desk top that is both dark and specular. The reflected glare disappears when a piece of light matte material is placed over the dark specular top.

If shiny horizontal surfaces cannot be avoided, a relatively low-brightness, indirect lighting system can be used to provide ambient illuminance. It is important that the luminaires have a broad light distribution pattern to provide essentially even ceiling luminance. The ratio of 5:1 or better between the darkest area between luminaires and the brightest area directly above the luminaire can be considered even ceiling luminance. If the maximum ceiling luminance is less than 425 cd/m^2, the potential for harmful reflections is very low. Local task lighting located on one or both sides of the task can be used to supplement the ambient illuminance. By placing task lighting luminaires to the sides of the work area, reflected glare from a shiny desk top is eliminated at the worker's viewing position.

In private offices, if the furniture location is known, direct ceiling-mounted luminaires can be located so that, again, specular reflections from the luminaires off the desk top are minimized for the worker.

Visual Comfort

Discomfort glare is a sensation of annoyance produced by brightnesses in the visual field that are significantly higher than the brightnesses of the surrounding areas. The magnitude of the sensation depends on the size, position, relative brightness, and number of sources in the field of view.

Luminaires. A comparison of glare control from various luminaires can be made from photometric reports by comparing the average luminance values produced at 0° (vertical), 45°, 55°, 65°, 75°, and 85° in the lengthwise, crosswise, and (sometimes) diagonal planes.

Another comparison can be made by using the visual comfort probability (VCP) calculation (see Chapter 9, Lighting Calculations). It is recommended that office lighting systems should have a VCP of 70 or greater. Since the operation of a visual display terminal (VDT) requires a heads-up, near-horizontal viewing position, several luminaires may be in view behind the VDT. To minimize discomfort glare for VDT tasks, a VCP of 80 or greater is recommended. VCP tables are available from most luminaire manufacturers. It should be noted, however, that VCP calculations may not be applicable for all luminaire types even though a VCP value can be calculated.

Discomfort glare becomes less important as the light source is farther from the line of sight. However, sources of intense brightness, even well above the line of sight, can be distracting or unpleasant.

Fenestration. Windows and skylights produce high, variable brightnesses. Frequently brightnesses are high enough to cause glare, particularly windows in the field of view. They can also cause reflected and disability glare, particularly for VDTs. It is therefore necessary to have a shading device to control the window brightness.

Electric Lighting and Daylight. Office lighting must be adequate for work after dusk. During the day, with proper controls, daylight can replace some electric lighting. One way of integrating daylight with electric light is to circuit perimeter luminaires on a separate circuit that can be manually or photoelectrically switched or dimmed. Horizontal blinds or refractors can control brightness and, to some extent, redirect light in useful directions.

VISUAL TASK CONSIDERATIONS

The Importance of Visual Tasks in Offices

Office work entails a variety of visual tasks. In addition to creating a pleasant and stimulating environment, office lighting should support the various visual tasks performed. The visibility of task details is determined by their size and contrast with the background, the absolute luminance of the background, and the viewing duration. Although visual performance follows a law of diminishing returns, one can say that in general the greater the contrast and size of the task details, the higher the background luminance, the longer the viewing duration, and the higher the level of visual performance.[1-3]

Within limits, a given level of visual performance can be maintained by trading off reductions in the magnitude of one factor with improvements in another. So, for example, leaning forward to make task details appear larger can offset reduced background luminance caused by low illuminances.[4]

Visibility also depends on the age of the worker. As a person ages, the pupil becomes progressively smaller (for a fixed level of ambient illumination) and the crystalline lens becomes thicker and less transparent. For example, a typical 50-year-old needs twice the illuminance falling on a task that a typical 20-year-old needs for that task to provide the same amount of light falling on the retina.[5,6]

Illuminance Selection

Illuminance levels should be determined based on visual performance research[1,2,6,7] as well as on design experience. The procedure is task specific, and knowledge of the task is important. If a specific task is unknown, then the designer must design for typical office tasks. If possible, a survey of future occupants should be conducted to gather information about the activities that will occur in the space and the ages of the people who will perform them.

For a given office task, illuminance design levels are provided in Chapter 10, Quality of the Visual Environment. The designer can tailor the illuminance to the specific situation. The designer is provided with this flexibility in order to specify a level that is suited to the visual task, keeping in mind the lighting design issues listed at the beginning of this chapter and in Chapter 10, Quality of the Visual Environment.

In determining an appropriate illuminance level, the designer must also consider how the illuminance is to be delivered, and to what locations. It is essential to differentiate between general lighting for the space and the illuminance specifically on the task or at the task location. In open plan offices, providing task-level illumination only at specific task locations and at a lower illuminance level throughout the space is typically appropriate. In private offices with free standing desks, it is more likely that the general illumination of the room provides the task level illumination.

The general illumination level of an office facility should be determined by several factors. The reflectance values of surfaces surrounding the task area should be considered to create a visually comfortable environment. Luminance levels surrounding the task should not be greater than three times the luminance value of the task, or less than one-third the luminance value of the task. If the offices contain VDTs, the general illumination should meet the guidelines established for that specific type of task (see the section "Offices with Video Display Terminals" in this chapter). Additionally, the general illumination should meet the psychological need for light of the occupants of the space. It should be remembered that room reflectance values and the distribution characteristics of the luminaire may be as important as illuminance level.

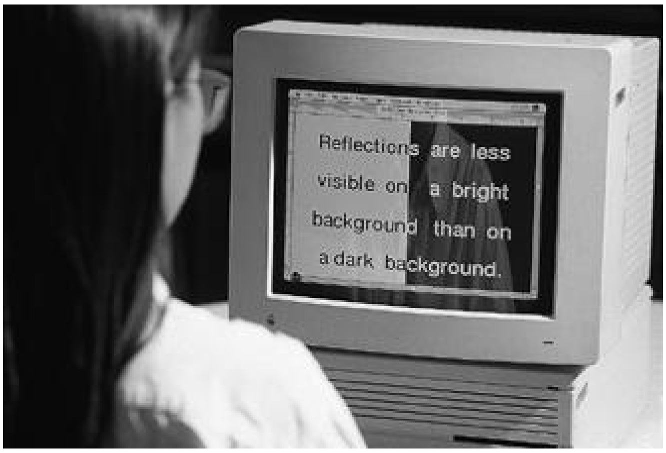


Figure 11-3. In a VDT screen, veiling reflections from bright objects, which reduce contrast, are prominent on a white-on-black display (right side of screen). These reflections are less noticeable on a black-on-white display (left side of screen).

If there is more than one task in the space, with each requiring a different illuminance, the designer must choose among them. There are several alternative methods for combining different target values.

The illumination requirements of different tasks may be satisfied by providing different task lights. A flexible lighting system, individual dimming controls, and multilevel switching are other available alternatives, depending on furniture layout and architecture. For locations with multiple tasks, designers can design for the task requiring the highest level of illumination and provide dimming capabilities that allow the user to adjust the lighting level in various areas to suit different tasks. Multilevel lighting systems also may be appropriate. If flexibility is not possible, the designer may be forced to choose one criterion over another for the entire system. However, it should be noted that most task lights provide more than enough illuminance.

Often, office buildings are built on speculation, so that the visual tasks and the occupants are unknown. A building in which the lighting has been thoughtfully designed for today's typical office tasks is more attractive for prospective tenants. A logical recourse is to design for the modern electronic office in which a combination of paper and VDT tasks will be performed. Ambient illuminances throughout the office space should not exceed 500 lx (50 fc), where VDTs are used, and extreme care should be given to providing a general lighting system that does not create disability glare, or reflected glare off of VDT screens (see the section "Offices with Video Display Terminals" in this chapter). Higher illuminances at task locations can be provided by task-light luminaires.

Quality of Lighting

It should be remembered that task visibility can be affected by the quality of light. Poor lighting quality can provide veiling reflections, reflected glare, and shadows, resulting in reduced visibility. The angle at which light strikes the task, the location of the luminaires relative to the task, the distribution of the light emitted from the luminaires, the location of luminaires in the office, and the specific properties of the task and work surface all affect lighting quality.

Veiling Reflections, Reflected Glare, and Shadows. The contrast of a visual task depends on the glossiness of the task surface and on the geometric relationships between the light sources, the task, and the eyes. If the visual task produces a mirror angle between the eye and the luminaire or another bright object, contrast is reduced. This effect is called veiling reflections (Figure 11-3). The area from which a luminaire or bright object can reflect light off the task and into the viewer's eyes is termed the offending zone. This may be a specific area of the ceiling or, often in open-plan workstations, the area directly in front and above the occupant, which is a common area for placement of task-light luminaires (Figure 11-4).

Task Lighting. Like ceiling luminaires, task lighting, either as desk luminaires or as part of open-plan furniture systems, ordinarily should not be placed in the offending zone. However, the light distribution characteristics of some luminaires minimize veiling reflections through optical design elements. Such luminaires may be placed in the offending zone if they use an optical system that redirects light so that these veiling reflections are eliminated or at least reduced. This can be accomplished with lenses and/or reflectors. Many task lights use a batwing lens. This type of lens is made up of a series of linear prisms that minimize the light output at nadir (straight ahead) and redirect light out to the sides. As a result most of the light striking the task originates from the sides or ends of the task light (Figure 11-5).

Free-standing or mobile-arm task lights allow the user to position the light for best task visibility (Figure 11-6). This may be a useful approach when linear task lights cannot be used. Many of these portable task lights offer little optical control; a shade can block light from the user's eyes, and generally most of the light is concentrated directly below the unit.

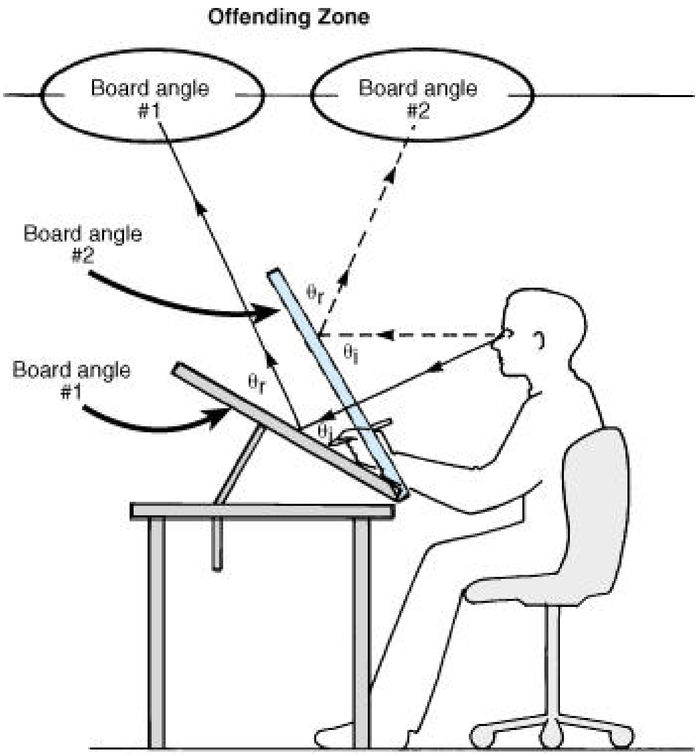


Figure 11-4. The offending zone moves with board angle changes and with eye movements relative to the task surface.

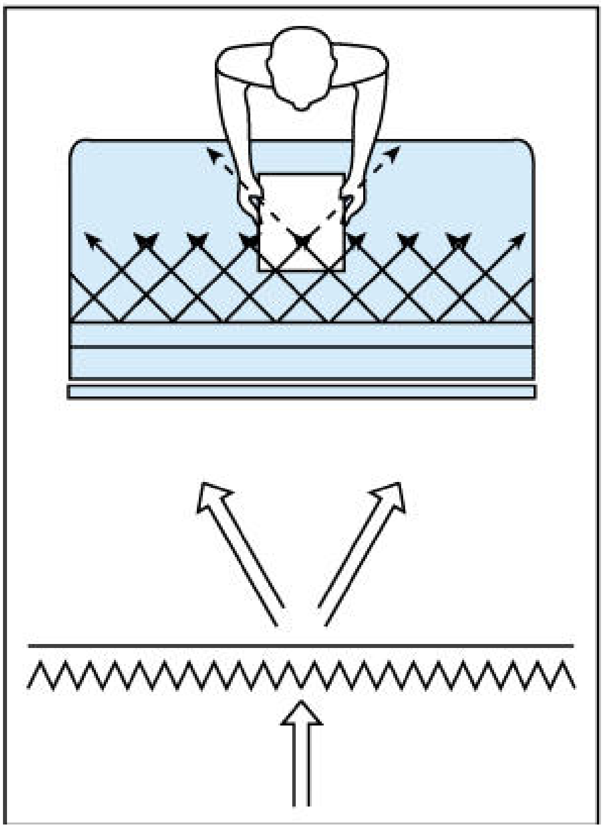


Figure 11-5. Task light with a batwing lens that directs light out to the sides.

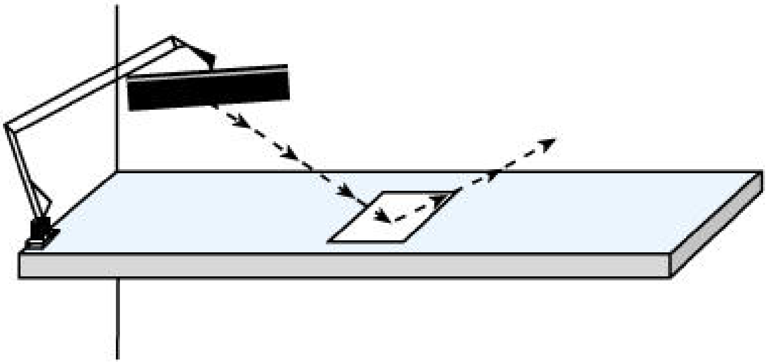


Figure 11-6. Portable task light. Arrows indicate the mirror angle.

The designer should always consider multiple working areas within the space. In open office areas, for example, one luminaire placed outside the offending zone for one worker may be in the offending zone for another. Luminaire light output should be limited at angles greater than 55° from vertical in order to prevent veiling reflections[8,9] and to reduce discomfort glare.

Reflected Glare. Reflected glare is usually caused by a mirror image of the light source in the offending zone reflected to the worker's eyes from VDTs or highly polished wood or glass-covered desk tops. It can be reduced by the use of matte surfaces and by carrying out the procedures for reducing veiling reflections on the task. Additionally, large-area low-luminance luminaires or indirect luminaires can be used when specular surfaces cannot be avoided.

Shadows. In most office work, shadows reduce visibility. Shadows reduce the illuminance on the task and, if sharply defined, can be distracting and cause excessively high luminance ratios on desk tops. Shadows are minimized if the light arrives at the task from many directions, helped by high-reflectance matte finishes on room surfaces. Large area luminaires can also reduce shadows.

Overall Room Brightness. Workplaces that have dark walls and ceilings may not be as well accepted by employees as spaces with bright room surfaces. White and light-colored paint finishes, combined with the washing of walls and ceilings with light, can brighten both the space and worker attitudes. This applies to furniture, too. Dark brown partitions and walnut grain work surfaces may not look as cheerful as lighter finishes, and they certainly do not use lighting energy as efficiently.

Patterns of Wall and Ceiling Brightnesses. Gradients of light on a wall, ceiling, or desk top affect brightness perceptions. Until there is a better understanding of this, it is a good idea to avoid harsh or striated patterns of luminance. Even more important, patterns of light must make sense; otherwise they are distracting. A scallop of light on a wall looks odd, for example, unless there is a piece of art centered in it or it is one of several rhythmical scallops that correspond to the spacing of wall panels.

Modeling of Faces. In spaces such as conference rooms, interview rooms, and video conference facilities, faces should be easily seen and pleasantly lighted. Strongly directional downlighting, for example, can cause harsh raccoon-like shadow patterns on the face. Diffuse lighting or light bounced off of surfaces can help soften shadows and make facial features more readable.

Color Appearance. People's preferences for warm or cool light sources are often cultural or climate related, so it is difficult to recommend color temperatures appropriate for office spaces. However, the color rendering ability of the lamp is important if food, faces, or fine architectural finishes are involved. In general, choose lamps of 70 CRI or greater, or 85 CRI or above if color critical tasks are being performed.

Flicker. Perceived flicker can cause headaches. Electronic ballasts can eliminate flicker for fluorescent lamps, and magnetically ballasted HID lamps can be wired to alternate phases of a three-phase system to reduce flicker.

Daylight and View. Access to windows provides many benefits for workers. It provides a view, allowing an individual to relax his or her eyes by focusing on distant objects. It provides a contact with time of day, weather conditions, and activities outdoors. If designed to introduce daylight without glare, windows and skylights can provide ambient light, reducing the need for electric light during daylight hours (see Chapter 8, Daylighting).

THE PSYCHOLOGICAL EFFECT OF LIGHTING IN OFFICES

Subjective Responses

Although office spaces are primarily task oriented, other less quantifiable effects of lighting on users' satisfaction and well-being should also be considered during the lighting design process. There is a body of literature that discusses the subjective responses to lighting.[10-14] Although this literature is not extensive, some guidelines can be suggested to the lighting designer. In general, the underlying belief is that light not only provides the physical stimulus necessary for visual performance, but also communicates or reinforces certain cues that influence people's subjective impressions of the environment surrounding them. These impressions can make a significant impact on long-term user satisfaction in the office.

Four characteristics of lighting systems have been shown to be important in influencing subjective impressions.[13] These characteristics are defined in general terms as overhead/peripheral, bright/dim, uniform/nonuniform, and visually warm/visually cool. By varying the emphasis of the lighting system in each of these lighting modes, the designer can influence the types of impressions he or she believes are desirable for the particular project being developed. By doing so, the designer has the opportunity to enhance desirable characteristics of the office workplace (e.g., selecting a high color rendering light source to reinforce aspects of visual clarity), while helping to overcome its inadequacies (e.g., perimeter wall lighting to evoke impressions of spaciousness in a small office or conference room).

Of course, people's impressions of architectural interior environments are influenced by many factors in addition to lighting, such as room size and proportions, type of space, furnishings and finishes used, and furniture layout. In many cases, these other factors provide a stronger influence on some subjective responses than will the lighting. Variations in the intensity, distribution, and color tone of the lighting exert some influence, intentional or not, on subjective impressions such as spaciousness, relaxation, visual clarity, and pleasantness. These influences must be carefully considered as an integral part of the office lighting design process.[15]

Admittedly, these guidelines are qualitative in nature, and the actual psychological effects of a particular lighting design solution are difficult to predict with confidence. However, ongoing research is taking place to develop methods for better predicting these effects during the design process. Efforts to define quantitative aspects of the lighted environment or to develop computer graphic models of lighted spaces show potential in providing design tools that assist the designer in predicting the subjective effects of lighting.[16,17]

Lighting Methods

General Lighting Versus Localized Lighting. There are basically two methods for lighting office tasks. One is to design the general lighting so that required illuminances are provided at all task locations. This is most appropriate for private offices or special situations where task lighting is inappropriate. The other is to supply localized lighting from task-lighting luminaires in conjunction with a low level of general illumination. In open-plan arrangements where vertical partitions or storage cabinets over work surfaces cause shadows, localized lighting becomes essential for adequate task illumination and shadow reduction (Figure 11-7). When localized lighting is used, the general illumination should be designed with a low illuminance appropriate for circulation, for casual viewing of tasks, and to provide the recommended luminance ratios between the task and other areas within the field of view. The design of the general illumination can also be better coordinated with the interior design and the architecture.

Direct, Indirect, and Direct-Indirect Lighting. Alternatives for general lighting are direct (downward), indirect (upward), or a combination of the two (Figure 11-8).

Indirect Lighting. Indirect lighting illuminates the ceiling, which in turn reflects light downwards. Thus, the ceiling becomes the brightest surface in the visual field (Figure 11-9). To avoid excessive luminance, the illumination on the ceiling should be evenly distributed. Two criteria that should be established in evaluating an indirect lighting approach are maximum ceiling brightness, typically directly above the luminaire, and uniformity ratios. The maximum allowable ceiling luminance should be determined by the task illuminance requirements.

If the primary task in a large office space is reading a VDT screen, the maximum allowable ceiling luminance should not exceed 850 cd/m^2. The uniformity ratio is the ratio of the brightest area of the ceiling, typically above the luminaire, to the darkest area of the ceiling, between luminaires, in other words, the ratio of the maximum to the minimum. In a VDT-intensive environment, better uniformity results in less noticeable glare on the screen. Ratios up to 8:1 are acceptable with light background screens; however, 4:1 creates a lower potential for glare and should be the target maximum for dark background VDTs. 2:1 ratios are achievable and more desirable. The designer should attempt to provide as smooth a gradient as possible between the high and the low luminance. If the maximum ceiling luminance is less than 425 cd/m^2, this low luminance is not reflected in VDT screens, and thus ceiling luminance uniformity is not important.

Figure 11-7. A workstation with built-in task lighting illuminating the desk top below. The low-brightness ceiling luminaire with parabolic louvers cuts down on reflections on the VDT screen.

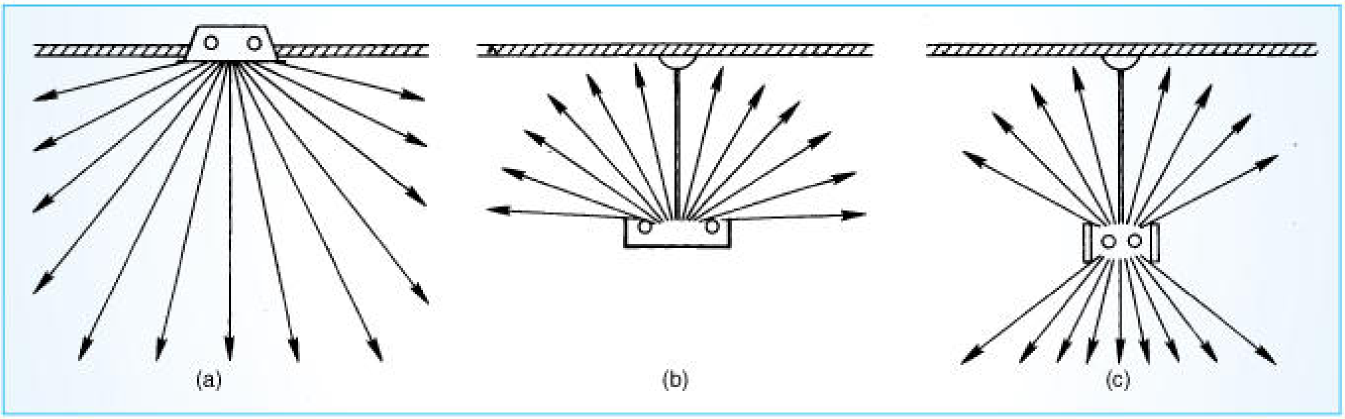


Figure 11-8. Luminaires for general lighting are classified in accordance with the percentage of total light output emitted above and below the horizontal. Three of the classifications are (a) direct lighting, (b) indirect lighting, and (c) direct-indirect lighting.

Figure 11-9. Pendant luminaires are commonly used to provide indirect illumination.

If VDTs are not present, higher ceiling luminance may be allowed. The ratio (R) of the maximum average ceiling luminance to the luminance of the task should not exceed 10:1. For example, a 75% reflectance task ($\rho = 0.75$) illuminated to 500 lx (E) would limit the ceiling luminance to approximately 1200 cd/m^2, according to the following equation:

$$L_{\text{cmax}} = \frac{\rho E R}{\pi}$$

$$L_{\text{cmax}} = \frac{0.75 \times 500 \times 10}{\pi} = 1194 \text{ cd/m}^2$$

Ceiling uniformity also should be assessed in terms of aesthetic considerations and of acceptable luminance ratios between the task and more remote surfaces. If extreme ceiling luminances are present, lower visual comfort can result.

Many indirect luminaires emit light below the horizontal plane. This can provide both an increased sense of perceived brightness and a recognizable source of light.[18] If a luminaire does emit light below the horizontal plane, the average intensity in the lengthwise, crosswise, and 45° horizontal planes, at angles between 55° and 90° from vertical, should be limited to avoid direct glare. Indirect lighting can provide a calm, diffuse light that is void of highlights and shadows, similar to the light of an overcast day. Indirect lighting can provide good visual task illumination, since it tends not to cause bright images in VDT screens nor appreciable veiling reflections on paper-based tasks. It may be especially good for drafting tasks because it does not create shadows from the tools used to perform the task. It may, however, reduce the sense of visual clarity, depth perception, or orientation. The lack of highlight and shadow minimizes visual cues. This problem can be addressed by using more color, adding accent lighting, or wall washing, all of which establish visual cues and make it easier to interpret the visual environment, as well as to contribute to the pleasantness of the space.

A major consideration in designing an indirect lighting scheme is the selection of lamps. The most common choices are metal halide and fluorescent. These sources differ greatly as to luminaire size and color. Luminaire size varies because of the inherent difference in the lamp sizes and, as a result, the luminaire shape and scale can determine luminaire location and the appropriateness of the design. Color consistency is an important consideration when lighting a flat, white plane, such as the ceiling. The color shift in metal halide lamps through life is more noticeable when illuminating a ceiling plane than downlighting the floor.

Direct Lighting. Direct lighting emphasizes horizontal planes, such as work surfaces and the floor (Figure 11-10). Floor colors are reflected and may actually tint the ceiling. With wide-distribution luminaires and perimeter placement, direct luminaires emphasize vertical surfaces.

There is a wide range of direct-type luminaires with a variety of distribution characteristics. These characteristics are dependent on lamp type, size, and reflector and shielding materials. Light distributions range from broad, using translucent diffusing shielding, to concentrated, using specular reflectors and louvers.

Figure 11-10. Direct lighting from a fluorescent system that provides good general illumination as well as adequate light for working at the drafting table.

Luminaire light distributions may be compared by reference to their intensity distribution curves and related values on a photometric report. Luminaire luminances can also be compared by referring to the luminance summary section of a photometric report. This information is typically given in two or three horizontal planes (lengthwise, crosswise, 45°) at angles of 0° (vertical), 45°, 55°, 65°, 75°, and 85°.

Diffusers. A diffuser scatters the light emitted by the lamps before it leaves the luminaire. Since the area of the diffuser is much larger than the area of the lamps, the total flux is more evenly distributed, and thus the average luminance is less than that of bare lamps. Nevertheless, the average luminance of a diffuser is still rather high and nearly constant for all viewing angles. In a large office, diffusers may have low VCP as well as producing unacceptable reflections in VDT screens. Diffusers are not recommended for open office environments, except when a special effect is desired, such as with a luminaire that mimics a skylight. In small private offices, they may be appropriate if they are not visible at viewing angles required for visual tasks. Their broad distribution does not create excessive brightness on the walls.

Lenses. A lens incorporates a series of small prisms that reduce the apparent brightness of the luminaire at the near-horizontal viewing angles of 45° to 90° from vertical. Depending on the specific optical characteristics of a lens, acceptable glare ratings may be obtained. However, most lenses do not reduce glare sufficiently to prevent luminaire reflections in VDT screens. The luminaire efficiency depends on the specific lens.

Polarizers. Polarized light can reduce veiling reflections and reflected glare under special conditions. Some commercially available luminaire lenses are designed to polarize the emitted illumination by transmitting light through multiple refractive layers (see Chapter 1, Light and Optics). The degree of polarization in the illumination depends on the number of layers through which the light is transmitted, as well as the angle of transmission. There is no polarization produced at the angle perpendicular to the transmission plane, that is, directly below the luminaire. As the angle of transmission increases, for a given number of layers, the degree of polarization increases up to Brewster's angle, approximately 60° for these lenses. At this angle, and depending on the number of transmission layers, the light can be polarized by between 30 and 50%.

The benefits of polarized light in reducing veiling reflections and reflected glare depend on the degree of polarization in the illumination, the luminaire-task-eye geometry, and the specular characteristics of the task surface.[19-22] Because the effectiveness of polarized light depends on all of these factors, it is difficult to provide a general statement on polarized light that is correct for every application. Guidance on the significance of polarized light for a specific application can be obtained from the literature.[23,24] The luminances of luminaires using polarizing materials should also comply with VCP recommendations for typical offices, and the luminance guideline for spaces with VDTs.[25]

Parabolic Louvers. Luminaires with a grid of parabolic louvers having a specular finish can control brightness precisely. The louver is an array of open cells, the walls of which form parabolic reflectors. The cells range in size from 12.5 cm × 12.5 cm (0.5 in. × 0.5 in.) to almost 30 cm × 30 cm (12 in. × 12 in.). The smaller cell types are usually injection-molded plastic, which is then vacuum metalized with aluminum. The larger cell types are usually fabricated from aluminum sheets, usually anodized prior to forming. When either type is made with a specular finish, the light output can be precisely controlled so that practically no light is emitted at angles above the cutoff angle. When this is the case, the louver can look darker than the ceiling. This precise light cutoff angle also darkens walls near the ceiling and places greater importance on illuminating vertical surfaces.

Parabolic louvers do not always have a sharp cutoff or a low luminance. Their optical performance depends on the degree of specularity of the louver surface and the optical cutoff of the louver. A semi-specular finish diffuses the light reflected from the louver surfaces and, at angles of view above the nominal cutoff angle, provides some luminance rather than the dark surface achieved with very specular surfaces. A semi-specular finish also tends to hide dust, fingerprints, and imperfections in the reflector surface. However, the semi-specular luminance may show up as a reflection on VDT screens. Aluminum finishes can provide a middle ground, as they often offer higher luminance then specular aluminum beyond the cutoff angle, but not as high as found with typical semi-specular material.

Parabolic louvers actually have two cutoff angles. The first is the physical cutoff angle, which is the angle from vertical that just occludes a view of the lamp. The second is the optical cutoff, which is the angle from vertical at which light reflected from the parabolic surfaces is just occluded. This angle depends on the precise shape of the reflector surfaces and is not always the same as the physical cutoff angle. For a precise cutoff, the two cutoff angles should be the same (Figure 11-11).

The degree of specularity and the louver cutoff angles are not usually included in luminaire specifications. The shielding angle sometimes given in photometric reports refers to the angle from the horizontal at which a direct view of the bare lamp first becomes visible. However, the performance of a luminaire resulting from the degree of louver specularity and from the louver cutoff characteristics can be determined from the luminaire photometric report. The luminance summary table in the report can be used to compare and select direct-lighting luminaires, especially for offices with VDTs. The luminance summary table shows the luminaire luminance at various angles measured from the vertical. The table typically shows these values in the lengthwise and crosswise horizontal planes. It is an advantage when the table also gives values for the 45° plane, as this may reveal a higher luminance at a given angle than for lengthwise and crosswise planes (Figure 11-12).

Direct-Indirect Lighting. A combination of direct and indirect approaches can produce excellent results (Figure 11-13). Luminaires that provide both upward and downward light are most commonly used for this application. The indirect portion should have characteristics so as to not create hot spots or excessive luminance on the ceiling. The direct portion should provide diffuse lighting and adequate shielding to provide good visual comfort and avoid glare.

The results of direct-indirect lighting can be quite satisfactory. Typically this design solution obscures the inadequacies of each individual approach and maximizes the advantages of each, creating both a pleasant and a functional environment.

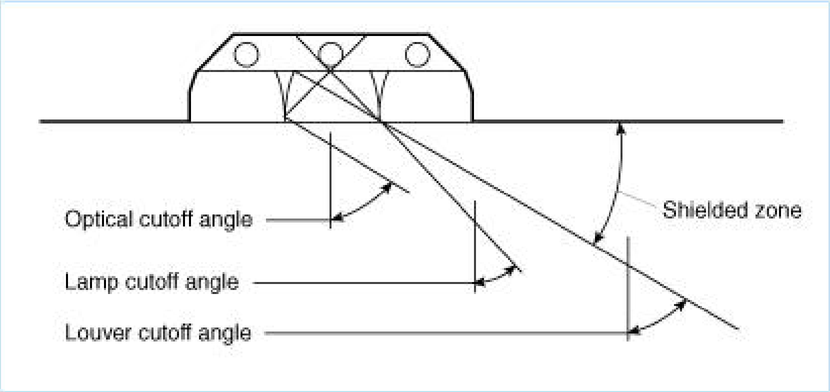
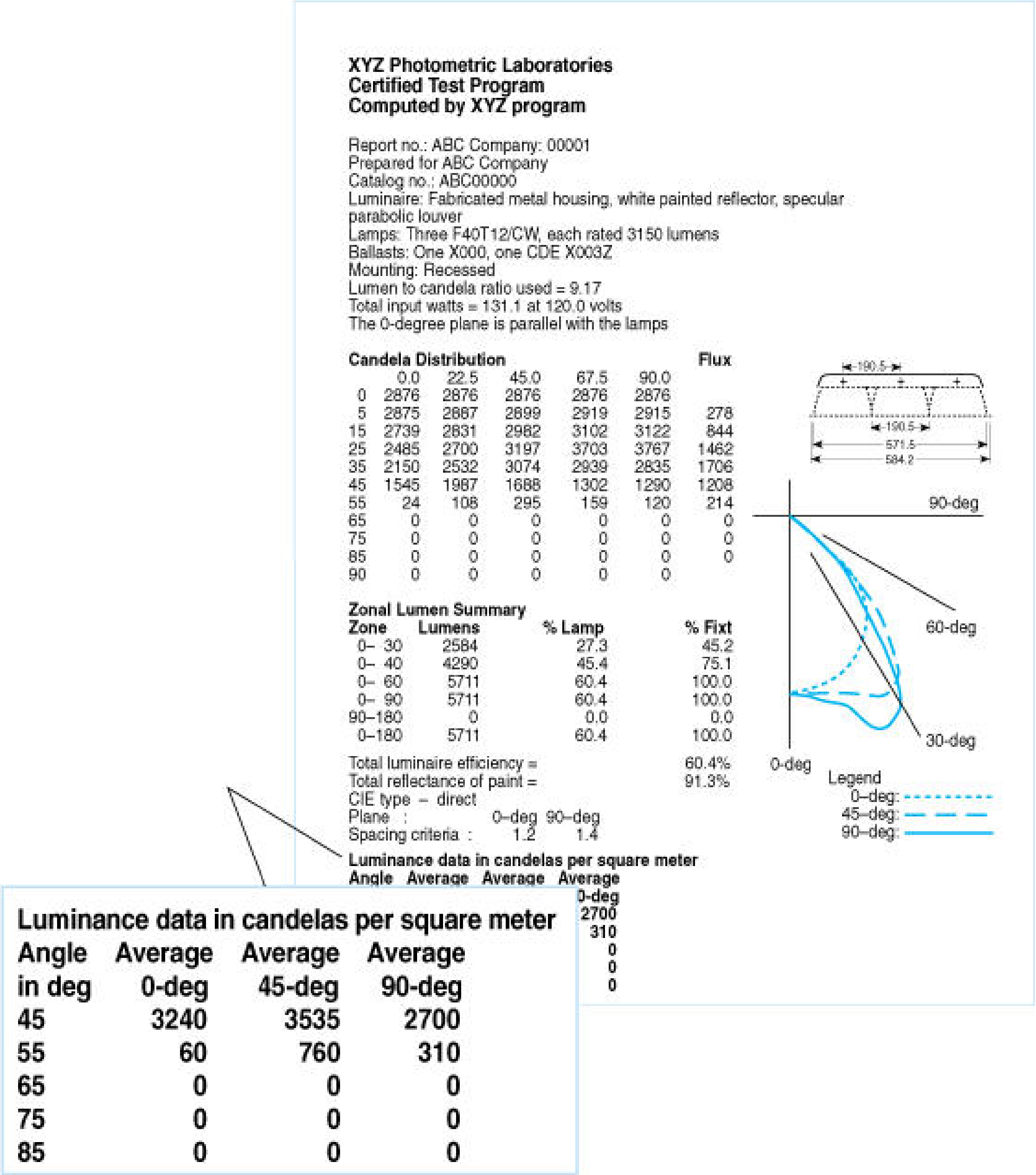


Figure 11-11. The blades of a parabolic louver provide a physical cutoff in the same way as an egg-crate louver; however, a parabolic louver with a specular finish reflects light from its curved blades at an angle equal to or less than the louver cutoff angle.



XYZ Photometric Laboratories
Certified Test Program
Computed by XYZ program

Report no.: ABC Company: 00001
Prepared for ABC Company
Catalog no.: ABC00000
Luminaire: Fabricated metal housing, white painted reflector, specular parabolic louver
Lamps: Three F40T12/CW, each rated 3150 lumens
Ballasts: One X000, one CDE X003Z
Mounting: Recessed
Lumen to candela ratio used = 9.17
Total input watts = 131.1 at 120.0 volts
The 0-degree plane is parallel with the lamps

Candela Distribution

	0.0	22.5	45.0	67.5	90.0	**Flux**
0	2876	2876	2876	2876	2876	
5	2875	2887	2899	2919	2915	278
15	2739	2831	2982	3102	3122	844
25	2485	2700	3197	3703	3767	1462
35	2150	2532	3074	2939	2835	1706
45	1545	1987	1688	1302	1290	1208
55	24	108	295	159	120	214
65	0	0	0	0	0	0
75	0	0	0	0	0	0
85	0	0	0	0	0	0
90	0	0	0	0	0	

Zonal Lumen Summary

Zone	**Lumens**	**% Lamp**	**% Fixt**
0– 30	2584	27.3	45.2
0– 40	4290	45.4	75.1
0– 60	5711	60.4	100.0
0– 90	5711	60.4	100.0
90–180	0	0.0	0.0
0–180	5711	60.4	100.0

Total luminaire efficiency = 60.4%
Total reflectance of paint = 91.3%
CIE type – direct
Plane : 0–deg 90–deg
Spacing criteria : 1.2 1.4

Luminance data in candelas per square meter

Angle in deg	**Average 0-deg**	**Average 45-deg**	**Average 90-deg**
45	**3240**	**3535**	**2700**
55	**60**	**760**	**310**
65	**0**	**0**	**0**
75	**0**	**0**	**0**
85	**0**	**0**	**0**

Figure 11-12. A typical photometric report showing the luminance summary table.

Figure 11-13. An open-plan office with direct-indirect fluorescent luminaires in a regular pattern, providing ambient light for the workstations beneath.

Photometric Data. An intensity distribution curve, which is a part of the luminaire photometric report, will show how light exits the luminaire. This curve helps to determine luminaire placement, layout, uniformity, and whether or not the luminaire can achieve the desired results for both illuminance and luminance criteria.

Along with the intensity distribution, a photometric report can also provide information on luminaire luminance. The luminance summary data provide information on the average luminance of the luminaire at a variety of angles in several planes. Along with the luminance summary, VCP data give further information on luminaire brightness for direct luminaires within the context of a given set of spatial dimensions. It should be noted that most VCP data are reported for task illuminance of 1000 lx (100 fc). For lower-illuminance applications, additional VCP data should be requested. Within open-plan offices, where large ceiling areas are within typical fields of view, and especially in VDT-task environments, where the tasks are typically performed in a heads-up position, the VCP should be at or above 80. In smaller private offices, VCP data are less significant because of partitions, unless full-height walls are brightly illuminated and the ceiling luminaires are visible.

Final Selection Process. Although much of a luminaire's performance can be evaluated through data analysis, the final selection process should include more than just reviewing printed information or photographs. Actual luminaire samples should be obtained and examined. Physical inspection of the luminaire can reveal aspects of both performance and quality not represented in printed information.

A mock-up is a further step to assure the quality of both the design and the luminaire selection. Mock-ups should duplicate the characteristics of the final space as closely as possible. Variations in finishes or ceiling heights, for example, may greatly influence perceptions. Also, mock-ups should contain a suitable number of luminaires so that appropriate judgments can be made concerning illuminance values under realistic conditions. If a mock-up is not feasible, visits to installations with the same luminaires give both designer and client the opportunity to see the luminaires function, even if the spatial conditions are different.

DESIGN ISSUES FOR SPECIFIC AREAS

Open-Plan Office Lighting

General Considerations. Open-plan or open offices are areas that accommodate workers in a common space with few, if any, floor-to-ceiling partitions or walls (Figure 11-14). There can be many different kinds of visual tasks and activities, and the furniture configurations may be specific to the activity. Individual work areas can consist of:

- Bullpen-like desk arrangements
- Desk-and-credenza combinations
- Floor-standing panels partially enclosing a space, often supporting work surfaces and storage components
- Freestanding screens or panels between desks

The office configurations have an effect on the light distri-bution and illuminance. Panels and storage shelves above work surfaces can create undesirable shadows on the visual task and on adjacent surfaces. Panel heights and workstation density and size change the distribution of the general illumination and affect luminance and illuminance uniformity at the work surface. As the number of vertical partitions increases, their reflectances become more significant; dark finishes absorb more light and lower the general impression of brightness as well as the actual illuminance on the task.

Figure 11-14. An open plan office with several types of lighting: decorative pendants and column luminaires provide indirect lighting; recessed downlights provide general illumination; and task lighting is provided by portable task lamps as well as by luminaires built into the workstations. Daylight also contributes to the pleasantness of the room, and is utilized through skylights as well as perimeter windows.

Calculating Illuminance. Accurately calculating illuminances in open-plan office areas can become complex. Often perceptions of brightness may depend more on vertical illuminances rather than horizontal illuminances. Additionally, when calculating illuminance for general illumination that is supplemented with task lighting, the general illumination calculation may not be critical because absolute ambient illuminances are less important than task illuminances to the success of the office environment. When calculating illuminance, the empty-room assumption is not a valid approximation of the environmental condition. Vertical obstructions such as partitions and filing cabinets play an important role in determining the lighting within and surrounding a workstation. For example, an average density of partitions 1.5 m (60 in.) high may decrease task surface illuminances by 10 to 50% (depending on reflectances and illuminance distribution characteristics). Since classical room zonal cavity computations cannot include these obstructions, their value is limited. A better estimation can be made through the coupled-cavities extension of the standard method[26-28] (see the section "The Lumen Method Applied to Partitioned Spaces" in Chapter 9, Lighting Calculations).

Since a partitioned work space takes on many of the visual aspects of a small room, the importance of surface reflectances, color, and height should be stressed. Point-by-point computer calculations may be required if an accurate prediction of illuminances is desired. An alternative might be a controlled mock-up in which illuminance readings can be taken.

It may be desirable to plan general illumination separately from task illumination, given the limits of calculation procedures and the expense of a mock-up. In this way, localized illuminance calculations can be performed from the photometric characteristics of the task luminaire and the reflectance characteristics of the workstation.

Luminance Considerations. The background luminance at the visual task can be considered from two perspectives. Luminances within the immediate task area should maintain a maximum bright-to-dark ratio of 3:1. Away from the immediate task area, but within the field of view, greater contrast may be desirable to enhance visual clarity, depth perception, and a sense of spatial orientation. In these areas a maximum ratio of 10:1 is recommended.

Consideration of task versus background luminance is different for VDT screens than for paper tasks, and different for partitioned workstations than for visually open spaces. In the open office the immediate surround is the work surface for horizontal paper tasks. For tasks with an elevated line of sight, such as VDT screens or vertical copy stands, the immediate surround is part of more remote room and furniture surfaces or the panel surface of a partitioned workstation.

Flexibility. In the design of the lighting for an open-plan office, the permanence of workstation location must be considered. A planned design or layout may be quite different from the actual furniture layout six months after initial occupancy. A lighting design tailored to a specific furniture orientation, such as rectilinear or diagonal, may create glare or low illuminances if furniture is moved.

Psychological and Design Issues. One of the most overlooked design aspects of open-plan office lighting is the consideration of the psychological effect of all the elements in the space. The spatial arrangement and the lighting distribution become integrated by the user, whether the interior and lighting designs were integrated or not, causing a psychological effect.

Large open spaces create an entirely different feeling from that of partitioned workstations. The lighting, the furniture layout, and the room and furniture finishes must work together to communicate to the occupant the sense of the design concept.

In open-plan offices, another major objective is the identification of circulation patterns and activity areas. Users need to have a sense of orientation with respect to their environment. This may involve the ability to quickly locate exits, reception areas, specific departments, individual offices, and locations of adjacent areas like the copy machine room and the conference room. The lighting system, in conjunction with the interior design, can provide the appropriate visual cues to communicate orientation and circulation. As open-plan offices become larger, the need for users to understand the limits of space and their relationship to the space becomes increasingly important.

Acoustical Aspects. The acoustical criteria for open-plan offices are often quite stringent. Of special concern is the acoustical privacy between workstations. In closed office spaces this is provided by permanent walls, but in their absence, the ceiling takes on increased importance along with the space dividers. Luminaires, either recessed or surface mounted, can have an adverse effect on acoustical absorption. Lensed luminaires can reflect sound to adjacent workstations, whereas louvered units break up the reflected sound. To ensure a completely satisfactory open-plan installation, the designer should work with an acoustical consultant.

Private Offices

A private office is generally a fairly small space (8 to 12 m^2) with floor-to-ceiling partitions and one occupant. Ceiling-mounted direct luminaires are typical. Usually luminaires outside the private office cannot be seen by the occupant, so the luminaire brightness may be less important than it is for larger spaces. However, if the partition walls are glazed or contain clerestory windows, overhead lighting within the private office may affect those outside and vice versa. In this case, the overhead lighting should be treated as in open-plan areas.

As in open-plan offices, task lighting, combined with low-level general illumination, can be used for private offices. Because the wall area of a private office is large relative to the room size, there is opportunity for wall lighting to provide all or part of the general lighting; the result is often more pleasing in appearance than lighting from ceiling sources alone. Wall washing with individual luminaires or continuous linear sources produces a more open, brighter appearance. Highlighting features such as artwork or creating patterns of brightness on the walls also lend variety and interest.

For the best lighting layout, the furniture arrangement should be determined before the lighting is planned. This allows for specific placement of luminaires so as not to cause veiling reflections. This is rarely possible in a private office, so alternatives should be considered. These include indirect lighting from wall-mounted or ceiling-suspended luminaires, a combination of indirect luminaires and direct lighting, wall coves to provide both wall luminance and task illumination, and direct-indirect illumination from suspended or wall-mounted luminaires.

Downlighting should not be used to provide task illumination. The point source nature of these types of luminaires is likely to cause harsh hand shadows on the task. Additionally, if these luminaires are placed in the offending zone, reflected glare or veiling reflections can occur. Downlighting may be appropriate for wall washing or accent lighting, however.

Conference Rooms

Visual tasks in conference rooms range from casual to difficult. Direct glare and modeling of faces or objects as well as design composition, style, and image are the key issues for the lighting design for meetings. See Chapter 10, Quality of the Visual Environment. Two or more lighting systems should be planned to provide flexibility for this range:

1. A general lighting system in which the control of illuminance is provided by switches or dimmers.

2. A supplementary lighting system consisting of downlighting with dimmer control for slide projection and other low-level illumination requirements. Due to improved technology and the reduced cost of electronic dimming systems for fluorescent lamps, it is sometimes effective to incorporate dimming into the general fluorescent system, thus eliminating the need for a second system.

3. A perimeter or wall-wash lighting system controlled with dimmers for better visual appeal and for wall-mounted presentations.

Video Conference Lighting

Video conference lighting serves two purposes: to illuminate people working and interacting with each other, as in any conference room, and to illuminate people interacting with other people at remote locations, via video displays. These two requirements do not always complement each other. Lighting that is designed for maximum visual comfort and minimal glare does not always lend itself well to the lighting requirements for high-quality camera images.

Lighting for video conferencing has its roots in photographic and television lighting, where most of the fundamental principles and techniques for camera lighting apply. Camera lighting consists of key light, back light, and fill light. Key light creates dimensionality and a modeling effect for the subjects of the scene. Back light helps to outline the subjects, creating depth of field and heightening the sense of drama. Fill light provides general illumination, reduces harshness, and softens shadows. Both key and back light are task-specific, focused light aimed at the main subjects of the scene, whereas fill light can be regarded as ambient and diffused light.

Since video conference room lighting should create a normal conferencing setting without having the feeling of being on stage or under the spotlight, it is desirable not to have dramatic lighting for video conferencing. Practical implementation can also be achieved with two different layers of lighting: one with totally indirect luminaires for fill light, and the other with totally direct luminaires to provide key and back light. One benefit of using two separate lighting systems is that dimming can be separately applied to each lighting layer, creating a flexible lighting design that is more accommodating to individual preferences and to the varying functions of the conference room.

Typically, illuminances of 500 lx (50 fc) are adequate for occupants and for most modern video cameras. For more information on meeting room lighting and television lighting, see Chapter 15, Theatre, Television, and Photographic Lighting.

Drafting and Graphic Production Rooms

Visual requirements for drafting demand high-quality illumination, since discrimination of fine detail is frequently required for extended periods of time. Significant graduation of shadows from drawing equipment and hands reduces visibility and productivity. Lighting systems that avoid reflected glare, veiling reflections, and task shadows are very important in providing maximum visibility. Indirect, semidirect, or other forms of overall ceiling lighting minimize shadows. When ceiling heights or energy constraints do not permit the use of these systems, direct lighting systems can be applied where the work surface is illuminated from both sides. In such a system, the absence of any luminaire in the offending zone also minimizes veiling reflections and reflected glare. Supplementary lighting equipment with user-adjustable support stems may be attached to the working surfaces, allowing the worker to position the light for critical task requirements or to overcome shadows and reflections. Some lighting systems are attached to drafting machines so that the light moves with the task. The requirements for computer-aided drafting (CAD) are very different. They are similar to but often more demanding than those for VDT tasks, because of the use of dark color monitors and very fine detailing and line weight (see the section "Offices with Video Display Terminals" in this chapter.)

Reception Areas

Reception areas are designed for people who are waiting for their appointments and, while waiting, reading or conversing with others. The lighting should be restful and yet provide enough illumination for reading.

One way to provide a restful atmosphere without direct glare is by illuminating one or more of the walls. Another way is to light the ceiling and part of the walls. Accent lighting for pictures or for a piece of sculpture enlivens the appearance of the room. If there is a receptionist located in the area, the ambient illumination may need to be augmented, depending on the visual tasks involved. Care should also be taken to illuminate the receptionist's face, so as to make this person look approachable, and also to eliminate harsh shadows caused by the downlights directly overhead. Task lighting can be provided for people waiting in the reception area.

Files

Files are primarily vertical work surfaces. In active filing areas, the work is likely to be long and visually difficult. Illumination should be directed onto the opened file drawers to minimize shadowing within the drawer. Where files are located in a general office environment and vertical illumination may also cause glare, consideration should be given to local illumination at the files, with individual manual or automatic switching located nearby.

Restrooms

Uniform illumination is not required in restrooms. Luminaires should provide light in the vicinity of the mirrors to illuminate the face. Other luminaires should illuminate bathroom fixtures and stalls and should be located so that partitions do not cast shadows on the plumbing or floors of the stalls. High illuminances in these areas also have a tendency to encourage cleanliness.

Public Areas

Public areas in a building include entrance and elevator or escalator lobbies, corridors, and stairways. Since many people move through these areas, the appearance of the space is very important, but so are safety requirements and the brightness balance with respect to adjacent areas. Public areas must remain illuminated for long periods, if not continuously. Therefore, serious consideration should be given to low-power lighting systems. Since many public areas are egress areas, an auxiliary lighting system is required to cope with power outages and system failures. These auxiliary systems can also serve as security lighting.

Entrance Lobbies

First impressions of office buildings are often perceived in entrance lobbies (Figure 11-15). The lighting should complement the architecture and provide for safe transition from the exterior to the interior. Consideration must be given to adaptation by the visual system from bright daylight conditions to darker interiors, or vice versa.

Perhaps the most important element in a lobby is the walls. Some may be of glass and some of opaque materials. Walls, if they are of high reflectance, can be illuminated, and the reflected light can provide all of the illumination for the lobby to provide orientation for people moving through it. If specular materials are used, unwanted reflections from luminaires must be considered. Grazing light from luminaires close to specular surfaces will minimize visible reflections.

Figure 11-15. The main lobby of a building should provide a good impression. Materials in lobbies are often of high reflectance. The lighting should enhance the beauty of the building materials and at the same time minimize visible reflections.

If the lobby is enclosed with glass, the interior walls need to be at a higher brightness during the day in order to be seen from outside against the high daylight brightness. At night, a much lower brightness is required. The variable brightness also makes it easier for eyes to adapt to the ambient conditions when entering or leaving a building. For these reasons, the lobby lighting should incorporate dimming or switching controls. Since surfaces have a profound effect on the interaction of light and the space, the designer should work with the architect to choose building materials and lighting systems that work together to achieve the desired appearance from different perspectives and at different times.

Corridors

Corridor illumination on the floor should be at least one-fifth the illuminance of the floor in adjacent areas. This illuminance is both safe and energy efficient and does not require major visual adaptation upon entering and leaving the corridor.

Wall finish reflectances should equal or exceed those in adjacent areas. Linear luminaires oriented crosswise to the corridor generally make the narrow space appear wider. Continuous linear luminaires located adjacent to the side walls provide high wall brightness and can give a feeling of spaciousness. Corridors, which are paths of egress, must be provided with emergency lighting.

Elevator Lobbies

These are classified as casual seeing areas, so high-luminance differences are acceptable. Relatively high illuminance should be provided at the elevator threshold to call attention to possible differences in elevation between the elevator cab and the floor.

Elevators

Brightnesses approximately equal to those provided in the building corridors should be provided in elevators. Elevators are small confined spaces often shared by strangers, so the lighting should help people feel comfortable. Bright ceilings and walls can give a feeling of increased size and will also indirectly light people's faces. The lighting in an elevator should always be connected to the building's emergency power supply to help alleviate distress in the event of an elevator power failure or malfunction.

Stairways

The stair treads should be well illuminated, and the luminaires should be located to avoid glare and shadows cast by occupants onto the stairs. Luminaires should be easy to maintain because ladders are difficult to use in stairways. Emergency lighting should be provided in all public stairways. Although the lighting requirements are the same for all stairways, the lighting design solutions may be different.

OFFICES WITH VIDEO DISPLAY TERMINALS

The VDT is a major element in today's office and presents the design team with special problems. In creating a successful lighting design, direct and reflected glare must be controlled, as must the luminances in the field of view.

The VDT screen tilt is important; angles range from vertical to a tilt of 45° from vertical away from the operator. Many terminals offer vertical adjustment, so the angles may not be fixed. Ergonomic recommendations typically suggest a tilt angle of 5° to 15° from vertical, and this value seems to be quite common. The tilt angle, along with eye height and screen height, determines the geometry and location of the area from which brightness can cause reflected glare.

The location of the VDT screen is important, and the design of the entire work area affects the success of the lighting design. In open-plan offices, it should be assumed that the VDT can be located anywhere within the space and that the lighting conditions outside the defined workstation affect VDT screen visibility. Panels and partitions can mitigate screen reflections. Partitions in front of the screen can limit direct glare from luminaires and windows. Windows are the most difficult problem to address. Curtains or blinds are always required, and orientation of the screen perpendicular to the window can limit both reflected glare and veiling reflections. In private offices the ceiling luminaires are usually directly overhead and are less likely to cause direct and reflected glare at normal viewing angles.

The VDT screen characteristics are also important. Screens can display either positive-contrast characters (light letters on a dark background) or negative-contrast characters (dark letters on light background). The latter is better for minimizing veiling reflections. Screen surfaces can be specular or diffuse. The latter is much better for reducing reflected glare, and in fact, most modern screens employ a diffusely reflecting screen. The surfaces can also have different shapes. Wide-angle, convex screen shapes are more likely to reflect windows and luminaires that create reflected glare.[29]

In offices containing VDT screens, particularly in open-plan environments, it is appropriate for the general illumination to be kept relatively low. A low illumination level produces low brightness reflections and therefore has less effect on screen contrast. Average maintained illuminance levels should not exceed 500 lx (50 fc) on the horizontal workplane. Although the illuminance should never exceed this value where VDT tasks predominate, it may be appropriate to provide an even lower level if reflected image brightness remains high. Windows can be a particular problem with regard to bright reflections. Although not often recognized, direct sunlight reflecting off even a low-reflectance carpet can be a problem. If paper tasks are being performed that require higher illuminances, particular attention should be paid to the quality of the task lighting. Other luminances in the field of view should not exceed the recommendations for luminance ratios established for any office environment (Figure 11-16).

VDT visual tasks differ from conventional paper tasks in another significant manner. Whereas paper tasks are typically performed looking down on the horizontal task, a typical VDT visual task is performed in a heads-up position. Because of this, in large open-plan offices a significant portion of the ceiling may be in the field of view. For this reason, it is important to limit ceiling plane brightness. The ceiling brightness from indirect lighting may also cause problems. The maximum ceiling luminance should not exceed ten times that of the VDT screen if the luminance ratio standards are to be maintained (Figure 11-17). Windows, again, can be a particular problem. Visual comfort probability (VCP) calculations for direct luminaires can provide useful information, but actual luminaire average luminance values at specific angles are more useful.

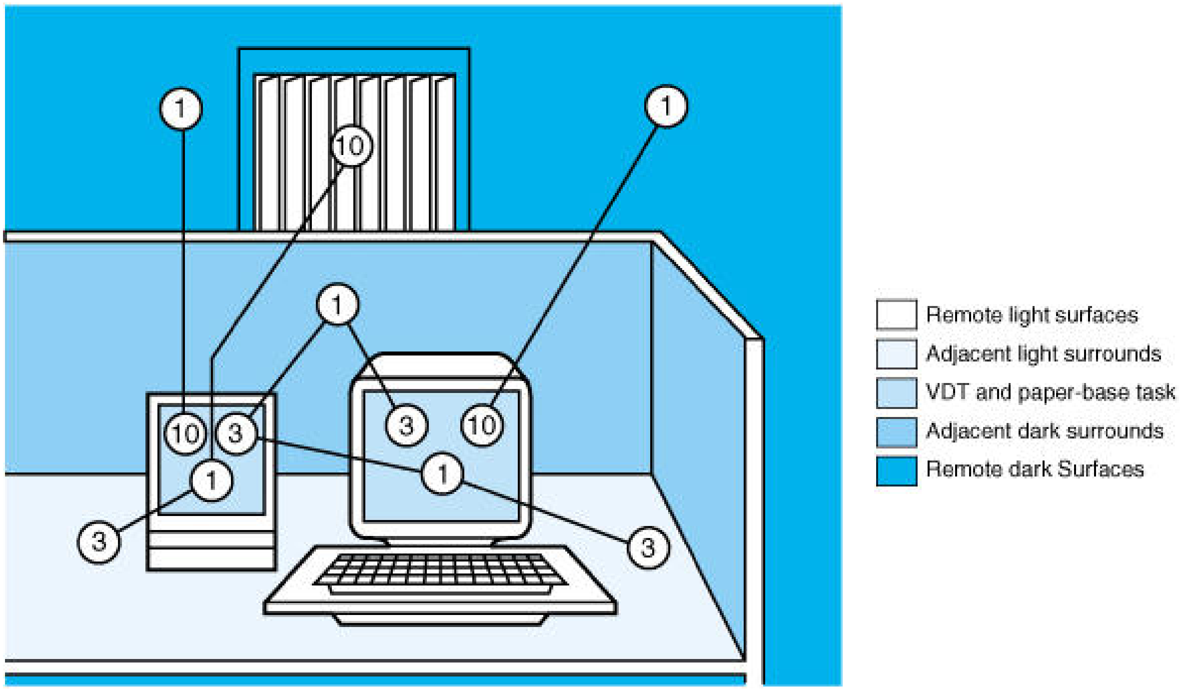


Figure 11-16. Maximum luminance ratios recommended for a VDT workstation. The values joined by lines illustrate the maximum recommended luminance ratios between various surfaces.

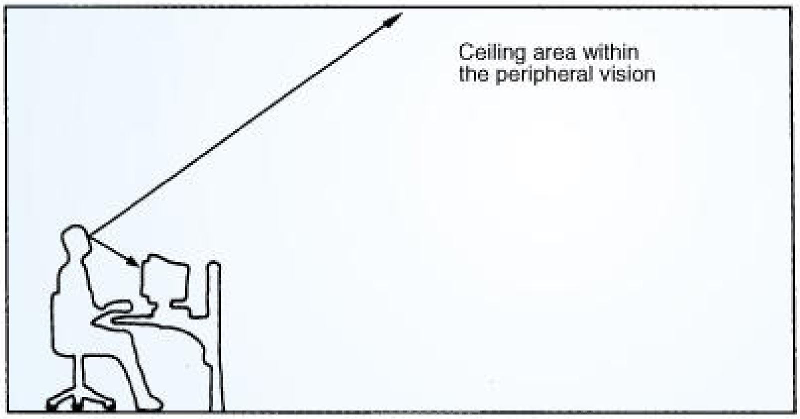


Figure 11-17. Viewing a VDT usually requires a nearly horizontal line of sight; thus, a large area of the ceiling will be within the peripheral vision.

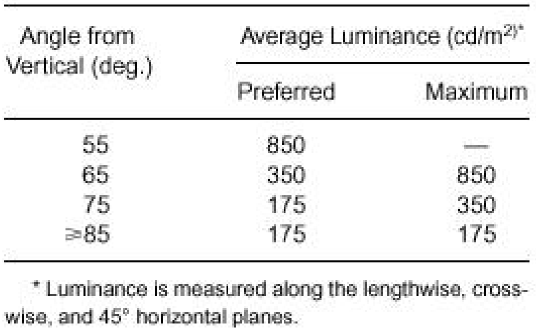
Paper Tasks

Paper tasks adjacent to VDT screens can cause a conflict between illuminance and luminance ratio recommendations. An 80%-reflectance white background paper illuminated to 750 lx results in a luminance level of roughly 200 cd/m^2. If the VDT screen's average luminance is 50 cd/m^2, the paper task is four times brighter. This exceeds the recommended 3:1 luminance ratio between the paper task and adjacent VDT screens. The recommended luminance ratio can be exceeded in favor of a higher illuminance level if the paper task includes small print or low contrast. Conversely, the illuminance level should be reduced if high brightness reflections in the screen cannot be avoided.

Direct Lighting

Specific luminance-value limitations are important for designs using direct luminaires. The geometry shown in Figure 11-18 illustrates the offending zone for VDT lighting. Since some screens provide a wide-angle reflection of the space, many luminaires can be in the offending zone in an open-plan environment. When a luminaire is viewed lengthwise, crosswise, or from 45°, the average luminances should be constrained. The current method for describing the luminance of a luminaire at specific angles is a calculated value. It is called average luminance and is typically provided in five- or ten-degree increments. It is determined by photometric laboratories by factoring the intensity at a given angle and the projected surface area of the luminaire at that angle. As a result, luminance values for luminaires of different sizes vary, even if the actual intensity at a specific angle is the same. Thus, Figure 11-19 shows preferred and maximum luminance values at specific angles. The preferred levels offer the lowest potential for veiling reflections or reflected glare and should be used in offices where the primary task is viewing VDTs. The maximum levels provide a higher potential for veiling reflections or reflected glare on the VDT screen, but may be suitable for offices where the VDT task is performed only on an occasional basis and is not the primary visual task.

Figure 11-18. Depending on the eye-screen geometry, the offending zone may be located on the ceiling plane, a wall, or a partition. Screen curvature may enlarge or change the location of the offending zone.



Angle from Vertical (deg.)	Average Luminance (cd/m^2)*	
	Preferred	Maximum
55	850	—
65	350	850
75	175	350
≥85	175	175

* Luminance is measured along the lengthwise, crosswise, and 45° horizontal planes.

Figure 11-19. Recommended Preferred and Maximum Average Luminance for Luminaires Used in the Direct Lighting of a VDT Environment

The average luminance of a luminaire is shown on its associated photometric report in the luminance summary table (Figure 11-12). Some reports may show values in footlamberts (1 fL = 3.43 cd/m^2), whereas the recommendations above are made in the preferred units of candelas per square meter (cd/m^2). Although average luminaire luminance values are a critical part of lighting guidelines, it may actually be the maximum luminaire luminance that is most meaningful in determining the potential for reflected glare. However, since there is currently no acceptable method for measuring maximum luminance, further research is required.

Using low-brightness luminaires may solve the technical problems associated with VDT glare, but eliminating glare does not in itself result in a pleasant environment. Additional design efforts are needed to create an appropriate perceived brightness and a sense of well-being.

Indirect Lighting

With indirect lighting, luminaire distribution characteristics, luminaire spacing, and the distance between the luminaires and ceiling become critical (Figure 11-20). This is especially true if, while viewing a VDT screen, the offending zone is the ceiling plane, and indirect luminaires light this plane. The maximum ceiling luminance should not exceed 850 cd/m^2. Also to be considered is the relationship between the ceiling luminance and the task luminance. Since the VDT task is typically a heads-up task, the ceiling may be visible in the peripheral view while looking at the screen. To meet current recommendations, the ceiling luminance should not exceed 10 times the average screen luminance. Thus, if the screen luminance is only 70 cd/m^2, the maximum ceiling luminance should not exceed 700 cd/m^2.

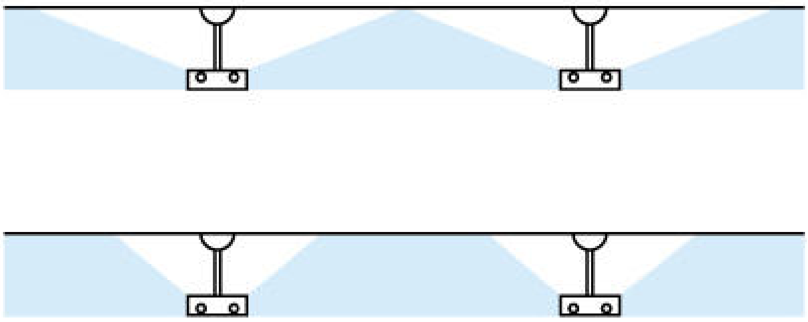


Figure 11-20. Indirect luminaires should have a widespread light distribution as shown in the upper sketch. A narrow light distribution as shown in the lower sketch may cause patches of brightness.

Additionally, since it is an area of the ceiling and not a single point that is reflected in the screen, that area should have uniform brightness in order to prevent a distracting reflection in the VDT screen. An 8:1 uniformity ratio between the brightest area, typically directly above the luminaire, and the least bright area, typically between luminaires, should be the maximum allowed. A 4:1 ratio is a more desirable goal, and 2:1 should be achievable with the appropriate equipment and layout. (As stated above, control of overhead brightness in a private office is far less important than it is in large spaces. Therefore, these guidelines are primarily for large spaces.) If the maximum ceiling luminance is less than 425 cd/m^2, veiling reflections typically are not visible, and ceiling uniformity is not an important factor.

In addition to ceiling luminance, the luminaire itself must also be considered. The luminaire creates contrast when seen against an illuminated ceiling. When reflected in the VDT screen, the image of the luminaire can be distracting and can alter the task contrast when compared to other areas of the screen. To avoid this problem, the luminaire itself should have a high reflectivity, and the reflectivity of the surfaces below the luminaire should be considered as well. Some luminaire luminance may be useful in enhancing the perceived brightness of the space, however. This luminance should be evaluated to assure that it is not excessive and is not reflected as glare on the VDT screen. Because this brightness is viewed against the background of a luminous ceiling, it does not have to meet the full guidelines for direct luminaires.

Direct-Indirect Lighting

A direct-indirect lighting system can combine the positive attributes of both direct and indirect lighting and often eliminate the shortcomings of both. With this approach, either one luminaire produces both direct and indirect illumination or different luminaires are used to create different distributions.

FINANCIAL FACILITIES

The various functions, tasks, and spatial arrangements that are found in financial facilities are on the whole similar to those that occur in offices: conference areas, accounting spaces, and general and private offices, including bookkeeping and VDT use. However, there are several areas specific to banking functions where the lighting needs are different from those in office spaces. Design recommendations, including illuminance values, are provided in Chapter 10, Quality of the Visual Environment. Special areas are described below.

Lobby Spaces

Very high ceilings were prominent in the design of early banking institutions. Today, because of increased building and operating costs, they are usually no more than 3.5 to 4.5 meters (12 to 15 feet) high (Figure 11-21). Where high ceilings exist, luminaire placement and lamp selection should be considered to help lower operation and maintenance costs while providing the recommended illuminance level.

Special attention should be given to adequate illumination in writing areas. This can be accomplished with additional ceiling-mounted luminaires or local counter-mounted task lights. When promotional incentives such as merchandise are located in the lobby, there should be provisions for highlighting to create a focal point (see Chapter 17, Retail Lighting).

Figure 11-21. A modern banking facility with general illumination provided by fluorescent lighting.

Network Control

The bank's network control area is usually a continuously occupied space in a major banking facility. Because of the large numbers of VDT data screens and electronic displays present in these areas, it is advisable to treat these spaces in the same way as a VDT space (see the section "Offices with Video Display Terminals" in this chapter).

Tellers' Stations

The most active areas in a bank are the tellers' stations. Here the lighting should provide for fast, accurate transactions. Reflections from ceiling-mounted lights on the deal plate can be problematic. One way to reduce reflections is to use large-area, low-brightness luminaires at the tellers' stations. Luminaires mounted on either side of the deal plate directing light onto the plate can also be effective. Recessed downlight luminaires directly over the deal plates should be avoided because they tend to cause shadows and reflected glare. Stations are also equipped with VDT screens to access account information. This also requires special attention in luminaire selection and location to assure good screen visibility.

The interior lighting at a drive-up window should be similar to other tellers' stations; however, because of the sloping window glass in many of these areas, luminaires behind the drive-up teller should be of low brightness to minimize reflections from the glass itself.

Possibly the most neglected area of bank lighting is the outdoor drive-up area. The illuminance outside this area should be about the same as that in the interior to avoid a mirror effect on the glass looking into or out from the drive-up tellers' position. The luminaires should be located to illuminate the area between the car driver's window and the teller drawer, not the top of the car. In addition to the visual drive-up teller facilities, where the teller sees the client or customer directly, there are special luminaires to provide lighting for cameras.

ATMs[30]

The automatic transaction machine (ATM) environment requires adequate illuminance so users can perform reading and writing tasks, as well as enjoy safe passage to and from the ATM location. The customer's unrestricted access to ATMs means that proper lighting is a primary requirement during all hours of daylight and darkness. Proper illuminance is required at all ATM locations for the safe, accurate, and rapid use of the facility (Figure 11-22).

Figure 11-22. ATM illuminated with a side-mounted HID light source that provides proper lighting to the user of the machine with no veiling glare. In addition, the light source is properly directed to highlight such potential obstructions as the desk and the planter.

Almost every building design variable impacts an ATM lighting system. The building's architecture and use of space can control the style and placement of luminaires. For indoor installations, lighting plays a major role in leading the customer from the outside zone to the interior space or from one exterior zone to another.

Whether an ATM is located in a vestibule or lobby or next to a parking lot, there are three specific task locations within the ATM unit that must be illuminated: the keyboard, a vertical work surface; the video terminal screen, a vertical visual task; and a writing surface, a horizontal work surface. A single unit is contained in a wall area about 0.76 m (2.5 ft) wide and 1.22 m (4 ft) high; multiple units are often installed, and larger areas are needed.

It is best to provide task lighting from both ends of each transaction area, not directly overhead or in front of the ATM unit. Such two-source directional lighting allows sufficient illumination while reducing both the shadowing effect that can occur during the actual transactions, and the potential for veiling reflections on the video screen. The area surrounding an outdoor ATM within a 3 m (10 ft) radius should have additional illumination at pavement level for safety, and at approximately 1 m (3 ft) above pavement level to ease the viewing tasks of searching for items in purses, briefcases, or wallets.

Vertical illuminance at all ATM locations is a critical criterion for visual surveillance of the surrounds and for potential perpetrator identification. Additionally, vertical illuminance must be specifically required for video cameras so they can properly monitor and record all activity within 3 m (10 ft) ATM area radius. Most ATM video equipment can operate with a minimum of 50 lx (5 fc) vertical, allowing the camera to be set for the entire area without the need for continual aperture adjustments.

In the United States there are no federal mandates regarding the lighting of the ATM machines; however, several states and municipalities have enacted (or are in the process of enacting) such laws. One regulation that may influence ATM lighting design in the United States is the American Disabilities Act (ADA), which prohibits wall objects such as luminaires from projecting more than 10 cm (4 in) into walks, corridors, hallways, or aisles when these objects are mounted between 67 and 200 cm (27 and 80 in) above a finished floor.

Security Lighting

Security lighting should be incorporated in accordance with the latest bank security regulation specified by the 1968 Bank Protection Act,[31] whereby adequate night lighting, exit lighting, and lighting on the vault are required to be on at all times. Also, there must be adequate interior lighting for any camera system. Lighting requirements for cameras should be obtained from the manufacturer. Lighting should also be provided for night deposit areas. Dark corners and shadows should be eliminated in the surrounding area.

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12

Educational Facility Lighting

EDUCATIONAL FACILITY DESIGN ISSUES

Classrooms
- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Direct Glare
- Light Distribution on Task Plane (Uniformity)
- Luminances of Room Surfaces
- Reflected Glare
- Source/Task/Eye Geometry

Corridors
- Daylighting Integration and Control
- Direct Glare
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Modeling of Faces or Objects
- Point(s) of Interest

Gymnasiums
- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Light Distribution on Task Plane (Uniformity)
- Reflected Glare
- Shadows

Lecture Halls
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Task Plane (Uniformity)

Libraries
- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Light Distribution on Task Plane (Uniformity)
- Reflected Glare
- Color Appearance (and Color Contrast)
- Source/Task/Eye Geometry

Science Laboratories
- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Task Plane (Uniformity)
- Reflected Glare
- Shadows
- Source/Task/Eye Geometry

There are continuing challenges and opportunities for the lighting designer of educational facilities. New educational buildings reflect new philosophies of education and new technologies for instruction. Many existing educational buildings need retrofitting to improve the new visual environment and to reduce energy usage. In general, it is not sufficient simply to replace old lighting equipment. Innovative lighting designs are often required to meet new visual needs and to reduce energy consumption.

THE GOAL OF EDUCATIONAL FACILITY LIGHTING

The overarching goal of educational facility lighting is to provide a visual environment for both students and instructors that is supportive of the learning processes. This can be achieved only if the occupants can see their visual tasks accurately, quickly, and comfortably. Uniform horizontal illuminance throughout an educational facility does not necessarily ensure high levels of visual performance because of the great variety of visual tasks, including visual display terminal (VDT) tasks, found in a school. The visual tasks become more varied as the student moves from the elementary school through high school to college.

Lighting also must be responsive to the psychological and emotional needs of learners. Lighting can make a school pleasant and attractive, reinforce feelings of spaciousness, delineate areas of different functions, stimulate learning, and improve behavior.

VISUAL TASKS

Visual tasks in educational facilities vary in size, contrast, viewing direction, and distance.[1] The primary critical tasks are reading and writing, commonly requiring prolonged and close attention. There are both near and far visual tasks, of small and large size, on matte and glossy surfaces. Students are often required to rapidly adjust from reading at a desk to reading from a chalkboard, and from looking almost straight down to looking along or above the horizontal.

Educators can play an important part in providing a good visual environment. They should:

1. Select writing instruments that do not produce specular or shiny lines on writing paper. Good examples are felt-tipped pens and No.2 grade pencils.

2. Avoid small type size on printed material. Ten-point type should be the minimum size. Also, printed materials should have liberal spacing between printed lines.

3. Select opaque matte paper for textbooks and workbooks, tablets and notebooks, tests, and other reproduced materials.

4. Purchase high-grade white chalk for black chalkboards. Chalkboards should be kept clean and periodically restored or resurfaced. Teachers should use large letters and figures when writing on chalkboards. Whiteboards are highly encouraged because of their high reflectance. In combination with dark marking pens, high contrast can be achieved.

These measures have a significant positive impact on improving the illuminated environment and reducing the lighting energy bill.

ENERGY MANAGEMENT AND MAINTENANCE

Efficient light sources and luminaires should be carefully selected to work in combination with daylight, in order to provide the proper quantity of high-quality, comfortable lighting (see Chapter 26, Energy Management). Daylight, if it is to be effectively used, must be carefully controlled (see Chapter 8, Daylighting). Consideration should be given to lighting control methods such as multi-level switching, photosensors and motion sensors, and whole building controls (see Chapter 27, Lighting Controls).

The designer should prepare written instructions for the maintenance of the lighting system, covering such major items as: (1) listing of specific lighting equipment used, (2) the cleaning schedule for lamps and luminaires, (3) the relamping schedule, and (4) the room surface maintenance schedule, including repainting (see Chapter 28, Lighting Maintenance).[2] If such information is not made available, the resulting neglect contributes to decreased illumination for the same amount of energy.

QUALITY AND QUANTITY OF ILLUMINATION

Quality and quantity of illumination are interdependent. A lighting system may provide the appropriate illuminance level for the task, but reflected glare, veiling reflections, and excessive luminance in the field of view can compromise visibility and therefore encourage the perception that the system provides low lighting quality. The most important lighting design factors to be considered in educational facilities are: daylighting integration and control; direct glare; horizontal and vertical illuminance; light distribution on surfaces; and light distribution on the task plane (uniformity).

Illuminance

Because it is uncommon for learning spaces to contain a single visual task, the determination of the optimum illuminance must begin by evaluating each visual task in terms of such variables as size, contrast, and time. Then the illuminance can be selected in relation to the most demanding visual task that occupies a significant part of the time spent in the space. Illuminance recommendations for a few of the tasks found in educational facilities are listed in Chapter 10, Quality of the Visual Environment.

The usual approach is to select the most difficult commonly occurring task and to provide an appropriate level for that task. Reading pencil writing is most often the task selected. Where reading printed materials of high contrast is the most commonly occurring difficult task, lower levels are adequate.

In some cases, selection of the most difficult commonly occurring task in a classroom or other teaching station can result in uneconomically high illuminances. In such cases it is preferable to provide a level that is adequate for the less demanding tasks and to provide increased illuminance at each specific task location where a high illuminance is required. Drafting tables and chalkboards, for example, need high often vertical levels, but the remainder of the space does not need to be lighted to the same level. School shops, sewing rooms, art classrooms, areas for those who are partially sighted, and many other educational spaces can and should be lighted with a combination of task and ambient lighting. Computer rooms may need lower ambient levels to reduce veiling reflections. In each of these cases, careful attention should be given to the vertical component of illuminance.

Reflectances

Walls, including tackboards and large cabinets or cupboards mounted on the wall, should have nonspecular surfaces with 40 to 60% reflectance (Figure 12-1). Blinds or drapes, like walls, should be light colored, with similar reflectances. Walls adjacent to windows should also have very high nonspecular reflectances to avoid excessive luminance ratios between the windows and the wall surface. The portion of the wall above the level of the luminaires should have a minimum reflectance of 80%. The ceiling should be even more highly reflective (white) and nonspecular, because the ceiling is most important in reflecting light downward toward tasks on desk tops when using direct-indirect or indirect luminaires. It is also necessary to avoid obvious brightness differences between the ceiling and the luminaires. Ideally, the ceiling should have a luminance greater than or equal to that of the side walls. It is desirable to have the luminance of the side walls at least one-half that of the upper walls and ceilings.

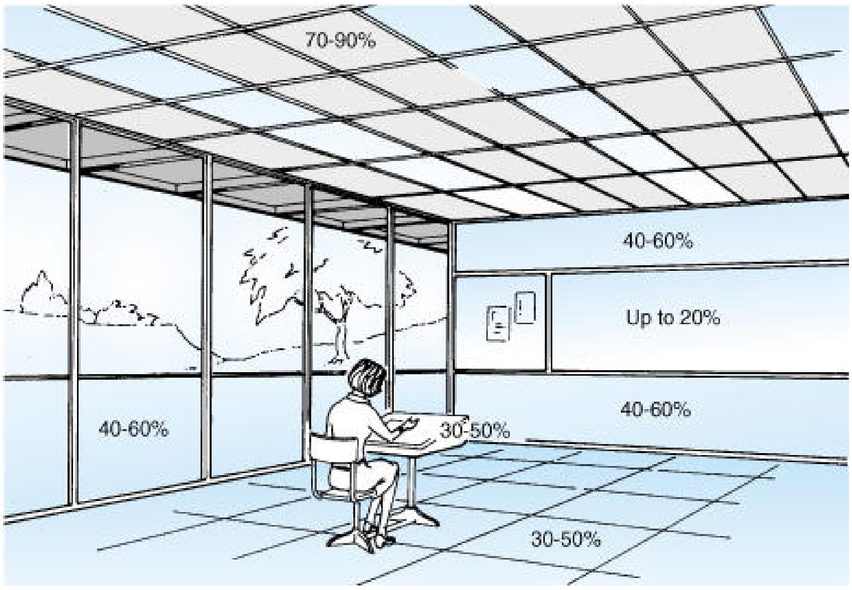

Figure 12-1. Recommended reflectances for surfaces and furnishings in the classroom.

Floors provide the secondary background for desk-top tasks. Floors should, as with all other surfaces, be nonspecular. The reflectance should be as high as practicable using readily available materials for floor covering with the objective of having a reflectance approaching 25%. The floor reflectance is not as critical as other room surfaces, but it does contribute to the ambiance of the space and should not be overlooked.

Luminance Ratios

The brightnesses of the various surfaces in the normal field of view must be kept within accepted limits. When the eye fixates on a task, an adaptation level is established. As the eye shifts from one luminance, such as for a book, to another luminance, such as for the chalkboard, it must adapt to the new level. If there is much difference between the two levels, a period of time is required for the eye to adjust itself to the new situation, which can slow visual performance. Further, if the difference is great, discomfort and fatigue can be experienced.

For good visual performance and comfort, the luminance of any surface normally viewed directly should not be greater than five times the luminance of the task (Figure 12-2). No large area, regardless of its position in the room, should have less than one-third the luminance of the task. The luminance of surfaces immediately adjacent to the visual task is more critical in terms of visual comfort and performance than that of more remote surfaces in the visual surround. Surfaces such as desk tops that are immediately adjacent to the visual task should not exceed the luminance of the task, but should have at least one-third the luminance of the task. The difference in luminance between adjacent surfaces in the visual surround should be kept as low as possible.

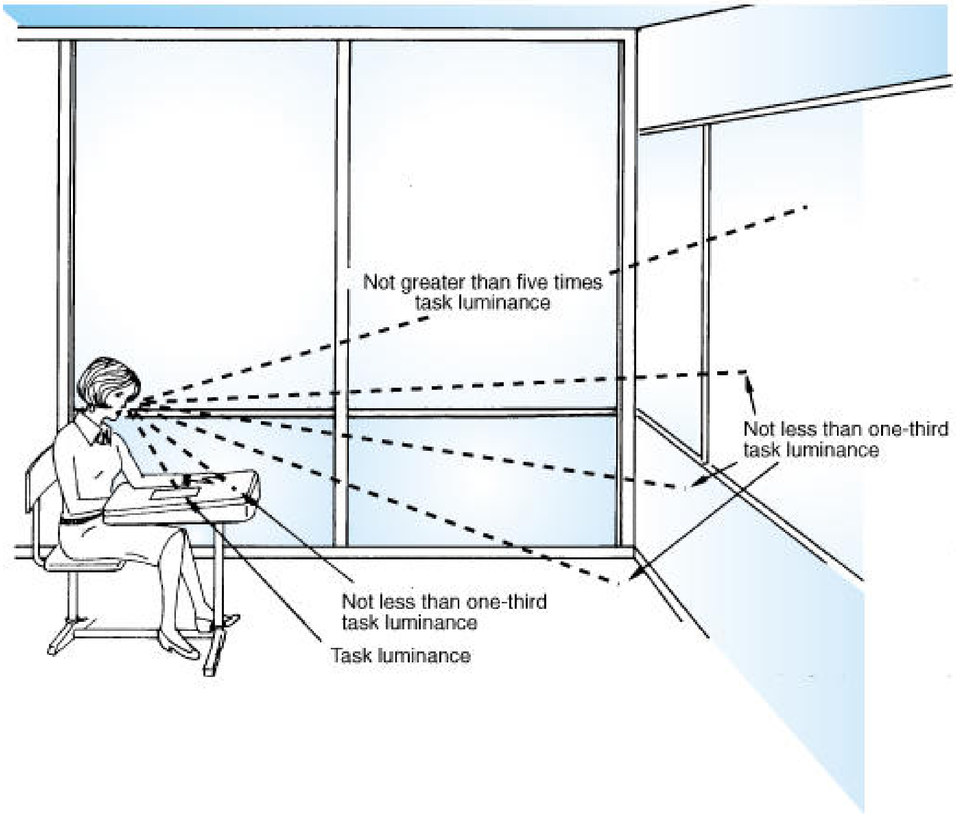

Figure 12-2. In a classroom the luminances of significant surfaces should not differ greatly from that of the visual task. The luminance of the surface immediately surrounding the task should be less than the task luminance but not less than one-third the task luminance. The lowest luminance of any significant surface should not be less than one-third the task luminance. The highest luminance should not be greater than five times the task luminance.

The general approach to providing low luminance ratios over the entire visual field is to limit the luminance of luminaires and of fenestration and to increase the luminance of all interior surfaces. Two ways to augment surface luminance are to increase the reflectance of the surface and to increase the quantity of light onto the surface.

Glare

An educational space must minimize glare. Electric or natural light sources that are too bright can produce discomfort and impair vision. Visual comfort probability (VCP) is a measure of discomfort glare from a lighting system and is used to evaluate lighting systems in many educational facility spaces. Strictly speaking, VCP has limited application but can still be used as an indicator of potential problems. The system takes into account the size and shape of the space, surface reflectances, illuminances, luminaire type (including size and light distribution), luminance of luminaires in the field of view, observer location, and line of sight (see Chapter 3, Vision and Perception, and Chapter 9, Lighting Calculations).

To minimize glare, fenestration controls should prevent direct sunlight from entering classrooms. Shades, blinds, louvers, baffle systems, and roof overhangs can be used (see Chapter 8, Daylighting). Optical control devices, such as louvers, or prismatic lenses should be incorporated into the luminaires as well to minimize glare.

Reflections of light sources from specular surfaces in the field of view are referred to as reflected glare. Reflected glare can be reduced by using matte finishes on furniture, equipment, and room surfaces, and by using low-brightness sources.

Losses in task contrast can result when light is reflected to the eyes from the task at a minimum angle. These reflections can act as a luminous veil superimposed on the task. The veiling reflections are quite apparent for glossy magazines and more subtle for written material on matte paper. People are quick to move the task or their posture to overcome deleterious veiling reflections; however, such changes may not be easy to achieve in a structured classroom, so special care must be given to limit veiling reflections by paying careful attention to the geometry between the light sources, task, and observer.

Shadows cast on visual tasks impair effective seeing. Sharply defined shadows and ones close to the visual task are particularly annoying. This does not mean that shadows must be completely eliminated, but the shading should not be excessively dense. Sufficient uniformity on the task plane should be provided. Shadows and modeling of faces and objects can be important in rooms, such as gymnasiums and art classrooms, where visibility of three-dimensional surfaces is important.

Color is also an important consideration. High reflectances and light colors should predominate to provide uniform high levels of illuminance and brightness. If the recommended reflectances and luminance ratios are met, wall, floor, and furniture colors have high reflectances. Light colors carried to an extreme, however, may lead to bland and uninteresting results. Touches of accent color or limited areas of relatively bright color, not conforming to the general recommendations given above, can give vitality and dramatic interest to a space.

Where exceptionally good color rendering is important, as in art education rooms, it is advisable that light sources be selected with a high color rendering index (CRI > 75). Where good color rendering is less important, as in workshops, light sources having a more limited spectrum can be satisfactory.

LIGHTING SYSTEMS FOR EDUCATIONAL FACILITIES

Daylighting

There are numerous aspects of daylight that make it desirable as a light source. Well-designed fenestration systems can provide light for the performance of visual tasks; a distant focus for the eye, allowing the eye muscles to relax; and psychological benefit from viewing the exterior world. Even so, daylight is a variable source, and it must be controlled and supplemented by an electric lighting system.

Means of controlling potential glare and maximizing daylight include exterior architectural appendages such as screens, overhangs, and awnings, and interior devices such as shades, blinds, drapes, and solar-reflecting or -reducing glazing materials. Blinds and drapes can be managed by the occupants to compensate for daily and seasonal changes in sunlight. Both manual and automatic control systems for the electric lights can be used to compensate for inadequate daylight and reduce energy costs when daylight provides sufficient illumination.

Electric Lighting

Light Source Selection. At the heart of any electric lighting system is the light source itself. Of the three main categories of light sources (fluorescent, high-intensity discharge, and incandescent), fluorescent is the most frequently used in classrooms. For more information on the characteristics of each type of light source see Chapter 6, Light Sources.

Fluorescent lamps of high efficacy and high CRI have become the most frequently specified light source. These lamps are well suited for general illumination, particularly where color rendering is important. Modern fluorescent lamps are also easy to dim by electronic ballasts.

High-intensity discharge (HID) lamps have long been used in school gymnasiums and for outdoor applications. Their high lumen package, high efficacy, compact size, and long life make them economical and practical lamps for use in high-ceilinged interior spaces and for almost all exterior applications. Care should be taken in the selection of HID sources with regard to color rendering, correlated color temperature, and stroboscopic effect. In multiphase wiring systems, the serving adjacent lamps from different electrical phases reduce the stroboscopic effect. Most HID lamps require start-up times that can range from 2 to 6 minutes. For quiet areas, such as libraries and study halls, HID lamp ballasts should be located remotely in order to minimize their inherent hum or buzzing.

Tungsten-halogen lamps can provide supplemental lighting for the classroom but should not be used for general lighting. The optical compactness of tungsten-halogen lamps allows for a high degree of light control, making them excellent choices for highlighting, art room display lighting, and featured instructional aids in the classroom. They can be switched on and off instantly and are inexpensively dimmed.

Luminaire Selection. Luminaires serve many purposes; they can maximize visibility, attract attention, establish a mood, create interest, and unify or separate spaces. Factors to be considered in selecting luminaires can be found in reference 2 and in Chapter 7, Luminaires.

SPECIFIC APPLICATIONS

The modern educational facility, whether an elementary school, a high school, or a university building, has a variety of lighting needs. A few specific applications are reviewed here to emphasize different lighting requirements for educational facilities. See reference 1 for further information.

Lighting the Classroom

The academic classroom is the most commonly considered space in educational facilities. Regular classroom floor areas range from 61 to 83 m^2 (660 to 900 ft^2) or more. Daylight is often a primary consideration. Windows range from a "vision strip," the length of one wall but only one meter (a few feet) high, to a full floor-to-ceiling window wall. Some classrooms are windowless or have a small window in one corner. More typically, classroom windows reach almost to the ceiling above a solid spandrel usually 760 to 910 mm (30 to 36 in.) high. Windows are almost always perpendicular to the usual line of sight between teacher and students; nevertheless, good control of sunlight and daylight are essential.

The recommended classroom illuminance depends on the tasks to be performed. The tasks in most regular classrooms that occupy most of a pupil's time include writing, reading good-quality printed material, and reading from overheads, chalkboards, and whiteboards.

Windows play such an important role in classrooms that there is invariably excellent energy-saving potential from dimming and switching electric lights. However, since classrooms are often used at night or when direct sunlight requires pulling of shades and blinds, it is necessary to design the lighting as if daylight were not available. Therefore, illuminance levels and luminance distribution must be specified as if daylight does not exist (see Chapter 10, Quality of the Visual Environment).

Type and Placement of Luminaires. Once the desired illuminance has been determined, other factors, such as direct and reflected glare, shadows, and color, should be considered in the luminaire and lamp selection.

The type of luminaire selected also depends on the ceiling height and type. In high-ceilinged spaces, suspended direct-indirect luminaires provide downlighting and reflected light from the ceiling. Well-designed indirect lighting systems provide low-brightness, shadow-free illumination (Figure 12-3). Many school classrooms, however, have low ceilings that necessitate ceiling-mounted or recessed luminaires.

Figure 12-3. Uplighting is used to light a vaulted-ceiling classroom. A suspended uplight luminaire is

positioned in the center of the vault at the same height as the uplights mounted on the perimeter walls.

Classroom luminaires should be selected and arranged with regard to the following factors:

- Position and orientation of desks (this may not be predictable)
- Location of chalkboard or whiteboard
- Location and proximity of windows
- Ceiling height
- Photometric characteristic of luminaires
- Flexibility of the space for other functions

Lighting for Audiovisual Presentations. Television, video, overheads, and slides are used extensively in classrooms.[3] For effective viewing it is necessary to reduce or to extinguish the electric lighting; drapes or blinds can usually provide adequate daylight control. The room should not be completely darkened, however, since students may be expected to take notes during audiovisual presentations. With proper controls and lighting circuitry, some luminaires, particularly those near the visual display, can be extinguished or dimmed separately from those that provide ambient illumination.

Task/Ambient Lighting

Lighting design criteria for classrooms are not necessarily important for all spaces in schools. Greater emphasis may be given to discrimination of color, three-dimensional modeling, or variations in brightness. It is sometimes practical, in the interest of wise energy use, to reduce illuminance in general activity spaces and then to provide supplementary lighting in a few locations.

Sewing Rooms. Sewing is one of the most difficult visual tasks because the thread matches the cloth. Task lighting can provide the high illuminances for this low-contrast task, and the directional nature of local lighting can reveal the differences in specularity between cloth and thread.

Shops. School shop lighting should follow industrial lighting practice for the types of activities provided in the shop (see Chapter 19, Industrial Lighting). Stroboscopic effect from HID lamps should be minimized by three-phase circuiting. Task lighting should illuminate work benches and machines.

Art Rooms. The appearance of colors in an art room is important, so lamps with high color rendering capability are required (see Chapter 4, Color, and Chapter 6, Light Sources). This is true of both ambient and task lighting. Supplementary lighting from adjustable concentrating directional sources can be useful with displays and models because it provides high illuminances and creates desired highlights and shadows needed for modeling.

Classrooms for the Handicapped

Certain classrooms may be specifically designed for handicapped students.[4] In most cases partially sighted individuals benefit from higher-than-normal illuminance levels as long as direct and reflected glare are carefully controlled. There are some exceptions, however, and special provisions should be made for those who need lower levels.

Students having impaired hearing often depend on speech reading (lip reading) for much of their understanding. It is necessary that the speaker's face be well lighted. The illumination should provide sufficient modeling for the movements of the lips and other facial features to be readily perceived. Glare control of daylighting in these spaces is very important, as is uniformity of lighting on visual tasks.

Spaces with Visual Display Terminals

Most schools have classrooms with VDTs. Low general illuminance levels and supplementary task lighting are usually recommended. Excessive vertical illuminances should be avoided to maximize visibility of VDTs. For more information see Chapter 11, Office Lighting.

Science Laboratories

Most laboratories are equipped with computer-based measurement tools, which make extensive use of VDTs. The principles of lighting for VDTs should apply to the laboratory (see Chapter 11, Office Lighting). Active laboratories are cluttered spaces with many students using various electrical and mechanical devices or studying biological specimens, so the location of the VDT with respect to the lighting is largely unpredictable. The devices and specimens under study by the students often require high illuminances for good visibility (Figure 12-4). These high illuminances can also reduce VDT screen visibility. Emphasis should therefore be placed on selecting suitable VDT screens.[5] Special consideration should also be given to electrical safety where computer-based measurement tools and local lighting are used.

Figure 12-4. Fluorescent lighting is used to provide high illuminance in a chemistry laboratory. The parabolic louvers help control glare from equipment used in a laboratory including bench tops, glassware, and VDT screens.

The laboratory is also often used by the instructor for lectures and audiovisual presentations (see the section "Conference and Seminar Rooms" below). Consequently, the lighting designer should advocate the use of lighting controls (dimming/switching for electric lighting, and drapes/blinds for fenestration) and local lighting in the science laboratory. Flexible local lighting can provide high illuminances and directional lighting to improve the visibility of specular materials under study as well as the VDT screen. Another advantage of local lighting is the minimization of shadows in the task area. If task illumination rests solely with windows and overhead illumination, shadows from shelving, people, and equipment at laboratory stations are particularly troublesome. One liability of completely flexible local lighting is the impact it may have on adjacent workspaces. Local luminaires that can be positioned to assist one workstation can provide direct or reflected glare to another. Instructions to the students to use cooperative behavior in the laboratory can eliminate this problem if it is understood and valued by the instructor.

Learning Resources Centers and Libraries[6]

Libraries in schools range from very simple rooms with a reading area surrounded by book stacks to very complex learning resources with a circulation desk and card catalogues, conference and seminar rooms, display and exhibition areas, microfiche viewing areas, audiovisual rooms, technical processing areas, and offices. Some may have word-processing equipment rooms for the students' use. Each of these areas presents different lighting problems.

Seeing Tasks in Libraries.

Reading is the visual task performed most often in a library, although computer viewing is becoming more prevalent. Reading materials vary widely, including children's books printed in 10- to 14-point type on matte paper; newspapers printed in 7-point type on low-contrast, off-white pulp paper; law books with long paragraphs in condensed type; and rare books with unusual type faces printed on old paper. There are also handwriting tasks, involving pencils and pens, and computer tasks. Many of the details about the general principles that must be considered to provide the quantity and quality of illumination needed for these tasks are in Chapter 10, Quality of the Visual Environment, and Chapter 11, Office Lighting.

A task that is fairly specific to the library is that of browsing among and searching book stacks or other forms of storage space. In public spaces some material may be on low shelves, on tables, on racks, or in bins that are very accessible. However, the vast majority of books, magazines, and reference materials are stored in shelving that is tightly spaced and up to 2.5 m (8 feet) high, or in compact shelving with limited aisles. The task involves reading a title or author's name, assisted perhaps by an index number applied to the material. The books or other printed materials are often worn or old, causing the title or other means of identification to be of very poor contrast. Vertical illuminance is important for such tasks.

When a library is associated with an educational institution, it contains areas used for studying or, more specifically, reading, writing, and computer tasks. Such areas may contain several workstations or constitute an individual workstation such as a study carrel. Task lighting is often provided at these locations, and it is imperative that veiling reflections be minimized. Computer stations have very specific requirements (see Chapter 11, Office Lighting).

Lighting Systems. Many libraries make use of daylight through windows or skylights. In all cases the luminance ratio and glare recommendations should be the same for offices.

The designer should aim to provide sufficient illumination for the most common visual task performed in an area. If a more difficult visual task is performed in a small portion of that area, additional illumination should be specified in the form of extra overhead luminaires or supplementary task lighting equipment located close to the task. Higher illuminance should also be provided in areas that are used by persons with impaired vision. When relighting existing traditional library reading rooms, supplementary lighting equipment consistent with the decorative treatment of the room is sometimes required. It is especially important to avoid direct and reflected glare and to avoid veiling reflections when using supplementary lighting.

Reading Areas. Reading usually occurs on either side of long tables, in lounge chairs, in study carrels, or at the circulation desk. Care should be taken to locate the luminaires to avoid veiling reflections on the visual tasks and to use luminaires that reduce the luminance in the direct glare zones.

Individual Study Areas. Individual study areas, or carrels, may be found in almost any public area of the library building (Figure 12-5). Shadows produced by the dividing walls of the carrel can be a serious lighting problem.

Figure 12-5. Study carrels outfitted with individual task lights. An indirect lighting system provides general illumination.

When designing individual task lighting located on carrels, serious consideration should be given to the luminaires flanking a position directly in front of the work surface in order to minimize veiling reflectance. Due to the close proximity of the luminaire to the user, optical shielding is required to prevent direct glare for the user. Thermal protection is also important.

Shelving and Stack Areas. The visual tasks in book stacks can be very difficult, including identification of a book by number and author on the lowest shelf. Projecting light downward to the lowest shelf is hard to achieve. One recommended solution is to use a continuous row of fluorescent lamp luminaires centered on the stack aisle and located just above the top of the book stack (Figure 12-6). To project the lights downward along the shelves to the floor requires a highly reflective, properly shaped reflector or a prismatic lens. High-reflectance floor coverings are beneficial in reflecting the light upward to the lower shelf books. Where it is impractical to position the luminaires on the stacks or use ceiling-mounted lighting, fluorescent lamp luminaires should be installed in continuous rows running perpendicular to the stack rows considered. This allows for the stack to be moved without relocating the luminaires. Luminaires controlled by occupancy sensors for energy conservation should be considered for these stack areas.

Catalogs. Computer catalog systems require the same considerations in lighting as VDT workstations (see Chapter 11, Office Lighting).

Circulation Desks. Often the general overhead lighting system is sufficient to illuminate the desk (Figure 12-7). Supplementary lighting, such as task lighting, is often beneficial. Architectural element lighting can help identify the circulation desk as well as provide aesthetic appeal.

Conference and Seminar Rooms. Sources and controls should be selected to modulate illuminance levels and provide for multiple uses. In addition to general overhead lighting, provision should be made to illuminate speakers and their materials. For more information, see Chapter 11, Office Lighting.

Figure 12-6. Open-access stacks are lighted with rows of fluorescent luminaires parallel to the stacks.

Figure 12-7. Direct lighting in a library using fluorescent luminaires for general illumination and for highlighting the circulation desk.

Display and Exhibition Areas. Display may be in glass-covered horizontal cases or mounted on vertical walls or dividers. See the section "Museums and Art Galleries" in Chapter 14, Lighting for Public Places and Institutions, for display lighting techniques.

Audiovisual and Audio Listening Areas. To allow effective viewing of visual presentations or provide a pleasant setting for listening, it is necessary to dim or switch general overhead lighting (see Chapter 27, Lighting Controls). Ambient illumination can be provided by the overhead luminaires if those located near the screen or listening station can be switched off, while other luminaires are operated at a low level.

Lighting for VDT and Microfiche Viewing Areas. Microfiche materials include rolls and cartridges of microfilms on strips, aperture cards containing single frames, or microfilm and microfiche cards or sheets containing a series of microimages. When notes must be taken, task illumination should be provided optically with controlled luminaires that reduce reflections on the screen. See the section "Offices with Video Display Terminals" in Chapter 11, Office Lighting.

High illuminances are needed for reading printed labels on microfiche files. Where viewers must be placed in reading areas or work areas with higher illuminances and switching or dimming is available, machines should have hoods and screens treated to reduce reflections.

Offices. Office areas in libraries should be illuminated in accordance with the recommendations in Chapter 11, Office Lighting.

Rare-Book Rooms. Higher illuminances are recommended for rare-book rooms because of the poor quality of printing often found in rare books; however, lighting techniques such as those used in museums and art galleries should be used for books displayed in glass cases. These include means to reduce the amount of radiation that leads to photodegradation.

Archives. Archives include storage of legal documents, minutes of meetings, legislative actions, and other historical papers. Pencil writing, small letters, and condensed type are used in many of these documents, so high illuminances are required.

Map Rooms. The wide aisles in map rooms should make it easily possible to illuminate maps when drawers are open for access. Vertical surface lighting should be provided on map hanging areas.

Fine Arts, Picture, and Print Rooms. See the section "Museums and Art Galleries" in Chapter 14, Lighting for Public Places and Institutions, for the proper lighting of displays, paintings, and art objects.

Group Study Rooms. These are small isolated rooms for up to six people. Techniques used for classroom lighting are recommended, as discussed throughout this chapter.

Overnight Study Halls. Libraries may provide areas for this purpose. Lighting for these areas is similar to that required for reading areas, individual study areas, or VDT spaces (see the section on Offices with Video Display Terminals in Chapter 11, Office Lighting).

Entrance Vestibules and Lobbies. Lighting in entrance vestibules and lobbies should create an atmosphere suitable for the particular type of library. The lighting may emphasize the architectural features and provide a transition to the functional areas (see Chapter 10, Quality of the Visual Environment).

Physical Education and Multipurpose Spaces

Physical education facilities in schools are usually the largest spaces in the building. For sports events such as basketball, uniformity and minimization of shadows are important considerations. For this reason they are sometimes used as multipurpose spaces to accommodate large groups for many activities not related to physical education and athletics.

The elementary multipurpose room is often planned to provide for physical education classes, after-school recreation, dining, and auditorium activities, such as musical and dramatic rehearsals and presentations. Community activities can also be accommodated. The lighting should be appropriate for the uses planned and should be adaptable to levels suited to assemblies and other activities. When appropriate, lighting can contribute to a perception of "sparkle" in these spaces for certain events. If there is a stage, either built-in or portable, suitable stage lighting of an appropriate type should be provided.[7] For more information on stage lighting, see Chapter 15, Theatre, Television, and Photographic Lighting.

The high school gymnasium or college field house is normally a multipurpose space. Besides physical education and athletics, it is used for graduations, assemblies, dances, concerts, and community meetings. The range of visual tasks and lighting requirements dictates a choice of illuminances. Flexible circuitry can provide the highest illuminance and reduce it when appropriate. Supplementary low-level lighting often is necessary.

HID and fluorescent light sources are suitable for high-ceiling gymnasiums because of their high lumen packages (Figure 12-8). In some schools the gymnasium also serves as the auditorium, theatre, and lecture hall. Due to the inherent high ballast noise, HID systems can be unacceptable for many functions, and so other forms of lighting are required. Incandescent and fluorescent lighting systems can be successful as secondary or alternate light sources. They are particularly useful if immediate start and restart or dimming are required.

Figure 12-8. A gymnasium lighted with surface-mounted HID luminaires.

Lecture Halls

Lecture halls as commonly found in universities and colleges have capacities that range from 50 or fewer occupants or to several hundred. Floors may be flat, slightly sloping, or steeply ramped. The problems of lighting lecture halls become more complex with an increase in floor area and the demand for good observation during demonstrations. A lecture hall should have a general lighting system that is flexible enough to provide at least two illuminances, the higher level for note-taking and a subdued one for demonstrations and film projections.

If a demonstration table or ceremonial dais is used, directional downlights should be located at a 40 to 60° angle above horizontal in relation to the location of the lecturer or speaker. This minimizes glare and provides good lighting for the speaker's face. Lighting can be arranged for audiovisual presentations (Figure 12-9) at the same time that the lecturer is speaking.

Figure 12-9. A lecture hall/interactive classroom outfitted with equipment for audiovisual presentations and student computers. Uplighting provides ambient lighting, while track lighting puts light on desk tops.

Dormitory Rooms

Dormitory rooms are commonly provided at colleges and universities with task-ambient lighting for study purposes. Direct-indirect table or floor luminaires are suited to reading and study. If study carrels are used, the luminaires should flank the task location.[8] Illuminances on desk tops should be adequate for pencil tasks. For information on lighting other residential tasks, see Chapter 18, Residential Lighting.

Corridors

Corridors should be adequately lighted to promote safety and discipline. Direct glare from overhead luminaires should be avoided. Corridors lined with lockers require higher levels than those used simply for passage. Supplementary lighting may be required at the positions where monitors or security personnel are stationed. If appropriate, control of daylight must also be provided.

Corridor lighting also provides an opportunity to add visual interest to school environments and emphasize displays, bulletin boards, and posters. Special attention to the lighting of architectural elements adds to the pleasantness and vitality of corridors. Modeling of faces is another key design element for school corridors.

The lighting of stairwells requires significant attention because during class changes they are full of students moving rapidly in opposite directions. Significantly higher illuminances are required for stairs than for corridors. Automatically programmed stair and corridor lights can be coordinated with the class changes. Emergency alarms also must coordinated with stair lighting to provide proper illuminances (see below).

Cafeterias

In school cafeterias, color appearance is important in the dining area, since color contributes to the enjoyment of food. In the food preparation area, where many specular surfaces can be present, attention must be paid to reflected glare, as well as to the appropriate illuminances needed for performing kitchen tasks. Modeling of objects is also an important design issue for cafeterias.

Emergency Lighting

The illumination provided by the emergency lighting system should be adequate to permit an orderly, accident-free exit from anywhere in the building. In schools, emergency lighting luminaires should be protected where mischievous students may be attracted to the unit or its test switch.

Outdoor Lighting and Security Lighting

Many educational buildings are used after dark. Building facades, approaches, and outdoor activity areas should be illuminated for nighttime activities, for general safety, and as a deterrent to vandalism and theft (see Chapter 21, Exterior Lighting). Outdoor lighting areas such as parking lots, roadways, and athletic fields are discussed in Chapter 20, Sports and Recreational Facility Lighting, and Chapter 22, Roadway Lighting.

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13

Hospitality Facilities and Entertainment Lighting

HOSPITALITY DESIGN ISSUES

Hotels

Guest Rooms

- Appearance of Space and Luminaires
- Color Appearance (and Color Contrast)
- Luminances of Room Surfaces
- Modeling of Faces or Objects

Lobby

- Appearance of Space and Luminaires
- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Direct Glare
- Light Distribution on Surfaces
- Luminances of Room Surfaces
- Point(s) of Interest
- Reflected Glare

Food Service Facilities

Kitchen

- Color Appearance (and Color Contrast)
- Illuminance (Horizontal)
- Modeling of Faces or Objects
- Reflected Glare
- Shadows
- Source/Task/Eye Geometry

Food Courts

- Appearance of Space and Luminaires
- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Direct Glare
- Flicker (and Strobe)
- Light Distribution on Surfaces
- Shadows

Casino and Gaming Facilities

General Gaming Area

- Color Appearance (and Color Contrast)
- Direct Glare
- Illuminance (Horizontal)
- Modeling of Faces or Objects
- Reflected Glare

Game Surface

- Color Appearance (and Color Contrast)
- Direct Glare
- Illuminance (Horizontal)
- Light Distribution on Task Plane (Uniformity)
- Modeling of Faces or Objects
- Reflected Glare
- Shadows

Sport and Race Books

- Direct Glare
- Illuminance (Vertical)
- Reflected Glare
- Surface Characteristics
- System Control and Flexibility

Video and Slots

- Color Appearance (and Color Contrast)
- Direct Glare
- Flicker (and Strobe)
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Reflected Glare

In designing lighting for hospitality facilities,[1] which include hotels, motels, and food service facilities, the first task is to identify those items that the staff and users want or need to see. Both groups must be able to see and comprehend their environment in order to move about and work within it. In addition, they should enjoy the environment. In facilities such as hotels and restaurants, the psychological effects of lighting are particularly important. By creating an attractive, comfortable, and functional environment, the lighting design becomes a marketing tool. Moreover, the lighting design must be integrated with the overall architectural design.

Lighting that is inappropriate in quality or quantity can ruin an otherwise successful installation. By using an appropriate combination of daylight and electric lighting, the designer can develop and reinforce almost any visual mood and satisfy the visual needs in any space by day and by night. The lighting system must be compatible with acoustic, thermal, spatial, and aesthetic requirements and objectives for each area. A successful total environment requires a cooperative effort by the owner, facility manager, architect, engineer, interior designer, and consultants to integrate all concepts into a harmonious design solution. In hospitality facilities, where architectural treatment is critical, the lighting designer must strike an appropriate balance between efficiency and aesthetics while considering energy management (see Figure 13-1 and Chapter 26, Energy Management).

Figure 13-1. Elevators become moving illuminated sculptures against the neutral background of the building's architecture. Festoons of tivoli lights add sparkle to the balconies. A lighted fountain column and trees reinforce the festive atmosphere of this hotel courtyard.

The following general objectives should be addressed:

- Achieve harmony with the architectural and decorative character of the facility
- Provide high-quality illumination for visual tasks
- Control glare and luminance ratios
- Provide an adequate illuminance
- Optimize costs to maximize net revenues, including first costs, operating costs, and maintenance costs
- Use energy efficiently

Consideration must be given to the desired appearance of each space and to the visual tasks to be performed. The factors that affect task visibility and performance are discussed in Chapter 3, Vision and Perception. All potential hazards such as changes in floor level should be well lighted for the safety of guests and staff. If thought out in advance, such highlighting of potential hazards can be made part of any decorative scheme.

Hospitality spaces often have different visual tasks at different times. Function rooms, for example, are used for banquets, meetings, lectures, conferences, classroom applications, exhibitions, and entertainment. To accommodate all these different uses with their various illuminances and distribution patterns, several lighting systems may be required with multiple switching and dimming.

GENERAL DESIGN CONSIDERATIONS

Selection of Architectural Finishes

The factors that influence how well people perceive a task or space include the brightness distribution, the task contrast and the size, color, form, texture, familiarity, and length of time for viewing. Some specific recommendations can be made with regard to hotels and motels, food service facilities, and casinos.

Because these facilities typically include adjacent areas with very different illuminances, readaptation in moving from one space to another can be a problem for both staff and patrons. The designer must therefore provide appropriately lighted transition spaces. For example, a patron who has been registering at the front desk adapts to a relatively high luminance. Turning back into the lobby, the person may be momentarily unable to distinguish the location of steps or to recognize faces if the difference in luminance varies greatly between the two areas. As the potential hazard or task difficulty increases, it is important to keep luminance ratios within recommended limits.

Room surfaces exert an important influence on luminance ratios between luminaires and their surroundings and between tasks and their backgrounds. On large surfaces, matte finishes with recommended reflectances help to prevent excessive luminance ratios and undesirable specular reflections. Light-colored matte surfaces serve as effective secondary light sources that can reduce shadows. Soft shadows generally accentuate the form and depth of objects, supporting rather than hindering the process of perception.

Selection of Light Sources

Both daylight and electric lighting systems are used in hospitality facilities. Each has its own characteristics. The lighting systems should integrate the two.

Most hospitality facility spaces have windows. The opportunity to look through windows can be psychologically satisfying. It permits relaxation when the eyes can shift focus occasionally from nearby to distant objects. However, windows can bring large areas of high luminance into the field of view, causing discomfort and problems of readaptation. The designer should not locate very brightly lighted areas next to dimly lighted interior spaces without allowing adequate transition spaces between them. Proper daylight control with blinds, curtains, or architectural overhangs is preferable to increasing the illuminance level produced by the electric lighting.

Enhancement of public spaces and provision of proper task lighting are the two principal considerations in the design of lighting systems for hospitality facilities. Three families of electric light sources are used: incandescent, fluorescent, and high-intensity discharge (HID). Choice of source depends on the particular requirements of each space, the economics, energy considerations, maintenance, and the personal preferences of the system designer and the facility operator. See Chapter 6, Light Sources, for more information on light sources. Generally, for public spaces, incandescent or rare-earth fluorescent lamps are recommended.

In these facilities, the chief advantages of incandescent lighting are low initial cost, good color rendering properties, and excellent optical control inherent in such a small source. Because they are easily dimmed, it is recommended that all incandescent luminaires in public areas be dimmer controlled. Drawbacks of incandescent lamps are their short life and low efficacy.

In support areas, where optical control and good color rendering may be less critical, the designer should consider the more efficient, longer-life fluorescent and HID sources. When using these sources, the designer should always be aware of ballast hum, temperature effects, restrike times, and color rendering. Ballasts can generally be mounted remotely from critical areas if ballast noise is objectionable. When using fluorescent sources outdoors and in unheated spaces such as garages, only lamps and ballasts rated for low ambient temperature should be used. HID lamps may take 15 min to restrike and come to full output following a power interruption. The designer should verify the consistency of the correlated color temperature and the color rendering properties of every source selected.

Color of Surfaces and Light

In any hospitality facility space, the color of the finishes affects both patrons and workers. While no rigorous rules exist, it is generally accepted that strong colors are more stimulating, whereas less intense colors are more restful and tend to expand the perceived size of a space. Whatever the colors selected, it is imperative that they be evaluated under the light source or mix of sources that will be used in the finished space, since light sources vary significantly in their color rendering qualities.

The use of colored light is often overlooked as a design tool. Strong colors of light can create interesting effects when surfaces are illuminated for decorative purposes, but they should not be used to light food or people because of the resulting color distortion.

Emergency Lighting

In public areas of hospitality facilities, the designer must provide lighting for public safety during emergency conditions without either disorienting the users or causing them to panic. Emergency systems for public facilities should be designed to provide lighting for short durations during evacuation of guests and staff. For security purposes and to assure continuity of critical operations, emergency lighting of longer duration may be required at hazardous locations. A common error is the installation of "permanently on" emergency luminaires in restaurants. Since these luminaires cannot be switched off or dimmed at night, they are sure to disrupt an intimate dining atmosphere.

While it may be possible in a small facility to meet emergency lighting needs with independent battery-powered units, a central emergency generator or battery installation may be required in a hospitality facility. Options of which the designer should be aware include double-circuiting of luminaires and the use of transfer relays to provide power to emergency-only sources during power failures.

DESIGN CONSIDERATIONS FOR SPECIFIC LOCATIONS

Selection

The design criteria for specific spaces and activities selected from Chapter 10, Quality of the Visual Environment, should be based on an assessment of the needs of the staff and guests with input from management.

Exterior and Site

The exterior lighting system should draw attention to the facility at night and create a favorable visual impression (Figure 13-2). Building facade lighting and marquee, walkway, and parking lighting should be coordinated with signage to produce an effective and coherent overall impression. Buildings grounds should be lighted to:

Figure 13-2. Illuminated turrets atop a Las Vegas theme hotel beckon visitors to a world of chivalry and magic.

- Merchandise the property (when warranted)
- Provide for the safety of guests and property, especially in parking areas and along pedestrian paths, steps, walkways, and entries
- Minimize vandalism or security problems
- Make all areas accessible to handicapped guests

All entryways should be well lighted to make them "landmarks" that may be used safely by guests. Lighting should be used to provide orientation and to reinforce intended traffic patterns. Marquees, taxi stands, drive-ups, registration areas, and unloading areas should be lighted so that they are clearly distinguishable from surrounding areas.

Parking area lighting should provide for traffic and pedestrian safety, visual security, and protection from assault, theft, and vandalism. Luminaire placement and elevation should be coordinated with buildings and plantings to minimize shadows. Light sources should provide adequate color rendering for easy vehicle identification.

Outdoor Hospitality Lighting

The primary focus of exterior areas around hotels, motels, and restaurants is either for pedestrian walkways or for sit-down enjoyment. A combination of the techniques described in Chapter 21, Exterior Lighting, for softscape/landscape, hardscape, and walkways can be used here to create inviting and comfortable settings (Figure 13-3).

Figure 13-3. Illuminated food and wine bars on the grounds of a California winery provide an inviting setting for dining and sampling wines. The ambiance of the site is enhanced by the lighted gazebo and trees that are uplighted with MR-16 lamps.

Many times, outdoor recreational facilities are provided for the guests. Open swimming pools should be internally illuminated with approved luminaires. Special luminaires are also required for the area around the pool edges and for other wet surfaces. Low-illuminance ambient lighting from sconces, lanterns, facade lighting, or landscape lighting can be used to softly illuminate areas surrounding the pool pavilion.

The outdoor lighting for hotels and motels should not disturb guests during the night. Conservatively planned walkway and landscape lighting can safely guide interested guests to outdoor areas and buildings without disturbing others.

Public Spaces

The lobby typically establishes the main design themes for the facility and houses a number of areas that can be differentiated and enhanced with appropriate lighting techniques. These include the elevator lobby, reception desk, lounge areas, and bell captain's desk. The entrance foyer is a transition space between the outdoors and the interior space, so foyer lighting should promote a sense of security and welcome while allowing adaptation between high and low illuminances. In the lounge area both casual and prolonged reading tasks must be anticipated, although these can usually be accommodated with fairly low illuminances. A residential treatment may be appropriate to create an inviting ambiance (Figure 13-4). Where information television monitors are located in public spaces, care should be taken to avoid reflected glare on the screen from windows, doors, luminaires, or other high-brightness surfaces.

Many visual tasks are performed at the registration desk. To make this area easy to locate and to use (Figure 13-5), the designer should designate a high general lighting level to accommodate all tasks; however, a lower overall level with a system of local task lighting should be considered, especially where visual display terminals (VDTs) are used. Care should be taken so that the lighting is compatible with surrounding areas.

Areas for storage of luggage should be lighted so that labels and other means of identification can be quickly and easily seen. In enclosed storage areas the color rendering qualities of the light should be adequate to permit correct identification of stored items. If not separated from the main lobby, storage areas should have somewhat higher illuminance than the ambient level.

Figure 13-4. This hotel lobby combines elegance with a feeling of home by employing graceful table lamps and traditional chandeliers as well as wall-wash luminaires. The comfortable seating areas are ideal for conversation, reading, or relaxation.

Figure 13-5. A custom stained-glass chandelier set inside a neon-illuminated cove is the dominant feature in this hotel lobby. The reception desk provides another focal point with its lighted wall sculpture.

The lighting for elevator lobby areas should be designed to orient people to the elevators, enable them to read directional signage and instructions, and select the proper controls to signal the elevator. Internally illuminated signage and controls should be considered so that they are clearly visible without high ambient illuminances.

Corridor lighting should illuminate room numbers, room name identification signs, and the locks in doors. Lighting should be designed to make the passage through hallways, on stairs, and to elevators a pleasant and safe experience. It should make guests feel secure. It should call attention to circulation modes such as elevators and vending areas. The tunnel effect associated with long corridors should be minimized by creating areas of varying luminance. See Figure 13-6.

Suitable lighting for shops, newsstands, and other specialized services (including cleaning and maintenance) may require sophisticated equipment and controls. Such merchandise lighting should be considered as part of the overall interior lighting scheme (Figure 13-7) and should be balanced with adjacent public areas. It may be possible to use display lighting that remains on continuously to light adjacent corridors, eliminating corridor luminaires.

In most cases, the lighting of ballrooms,[2] function and meeting rooms, and conference areas should be related to the overall design themes for the hotel. These rooms are used for meetings, exhibits, dancing, dining, and other functions, which makes it important to provide a variety of lighting levels and effects. If decorative luminaires such as chandeliers are used, at least one or two supplementary lighting systems are usually required. Dimming and multiple switching should be provided and organized and clearly labeled for easy operation by banquet and function personnel. Lighting must be adequate for critical tasks such as reading and note-taking. Adjustable accent lighting should be provided at speaker's areas, head-table locations, and likely locations for displays. Outlets for local lighting should be provided in exhibit areas. Highest illuminances are required for setup and cleaning purposes.

Figure 13-6. Corridor lighting should be designed to make hotel guests feel safe on their way to and from their rooms. Uplighting and spotlights on the carpet create visual interest, and at the same time provide adequate general light for passage and identifying room numbers and locks.

Figure 13-7. An elaborate illuminated sign marks the beginning of the merchandise area in a Las Vegas hotel lobby.

In public toilets, visual tasks include grooming, which requires shadowless illumination on both sides of the face. Color rendering is important. Lounge areas in restrooms require only low levels of light.

Guest Rooms

The guest room is one of the major commodities of a hospitality facility. Since it is frequently used for small business conferences, flexibility is needed in the lighting plan. General illumination from ceiling- or wall-mounted luminaires provides a background for task lighting, aids housekeeping, gives a feeling of cheer, and allows for needed flexibility for nonresidential uses. To establish an inviting, homelike atmosphere, a variety of lighting equipment, some decorative in appearance, is usually needed. Visual tasks in the guest room include reading in a chair or in bed, desk work, television viewing, and grooming at the mirror both in the bathroom and at the dresser (see Chapter 18, Residential Lighting).

The small entry foyer, which typically is part of the guest room, should have its own source of general illumination that reflects light from the ceiling or walls. Recessed incandescent luminaires are not usually suitable because the distribution of light is too narrow. Often the foyer lighting can be designed to illuminate closets, luggage storage, and grooming areas as well. Self-luminous switches with lighted handles are a convenience for guests in unfamiliar surroundings. Low-wattage switch-controlled night lights should be installed in each guest room, usually in the bathroom, so that guests do not leave other lights on all night long.

Mirror lighting generally provides adequate illumination in bathrooms. However, if there are separate compartments for toilet, tub, or dressing, each space should have a separately switched source of general illumination adequate for safety when the door or curtain is closed.

Entertainment and Food Service Spaces[3]

Entertainment and food service spaces within the hospitality facility are complex and energy-intensive areas in which lighting plays a key role in establishing the mood or atmosphere. The success of the lighting effect depends on the appropriateness of the illuminance level, the correlated color temperature of the light source, luminaire type and location in relation to the architecture, and control of glare. In addition to creating an intimate feeling, well-shielded downlights, for example, can produce a pleasing sparkle in reflective objects such as glassware (Figure 13-8). On the other hand, indirect lighting or large-area diffuse sources, such as fluorescent luminaires, typically define a brighter-looking space and call more attention to the whole room.

The decorative features in the dining area may require special lighting, which can range from highlighting a picture or sculpture to lighting an entire wall. The effects can range from dramatic and sophisticated to cozy and cheerful.

The luminaires themselves may, if used decoratively, become distinctive features in their own right (Figure 13-9). Many suspended decorative luminaires, regardless of shape, size, or style, have a general diffuse distribution that can produce dull, uniformly lighted spaces when used as the sole source of illumination. Unless low-wattage lamps are used, permitting these luminaires to be more than luminous decorative elements and providing no supplementary lighting can make the luminance of such suspended luminaires seem uncomfortably high.

In a general food service facility, supplemental systems, switching, and the use of dimmers may be required to make the same space comfortable for breakfast, lunch, and dinner. Variation in the quantity and quality of light may be needed, both to change the environment at different times of the day and to permit a higher illuminance for cleanup than would be desirable for dining. Automatic preset, programmable dimming control is preferable to switching, since a smooth transition between levels is desirable.

Figure 13-8. A stained-glass widow provides a colorful backdrop for a hotel bar. MR-16 lamps add sparkle to the glassware.

Figure 13-9. These distinctive luminaires add a stylish and contemporary aspect to a trendy wine and coffee bar.

Food displays should be lighted so that they draw customers' attention and allow them to clearly see the details of the food being offered. Color rendering is more important for fresh foods than for packaged foods. A good rule of thumb is that the illuminance level used in food displays should be at least twice as high as surrounding areas. However, heat from luminaires should be a major consideration over fresh, cooled, or frozen foods.

The mood established by lighting can vary from subdued and relaxing to bright and lively, depending on the type of facility and the intended clientele. Dining spaces are usually grouped into three categories: intimate, leisure, and quick service.

Intimate types of dining spaces, which include cocktail lounges, nightclubs, and some restaurants (Figure 13-10), are those places where people congregate as much to visit, be entertained, and be seen as to eat and drink. These spaces characteristically have a subdued atmosphere with low luminances throughout, accented with subtly lighted feature elements. The lighting must be well controlled in level and distribution.

Leisure types of dining spaces include many restaurants and dining places where eating is the most important activity. A restful atmosphere with interesting decor is appropriate. Lighting should be generally unobtrusive, except where decorative luminaires or highlighted features are used as part of the theme decor. Moderate illuminance levels (50 to 100 lx [5 to 10 fc]) are typical. Good control of glare is required (See Figure 13-11`).

Quick service types of dining spaces include lunchrooms, cafeterias, snack bars, coffee shops, and franchise menu restaurants, where the diner and management are intent on both fast service and quick customer turnover. High illuminances (500 to 1000 lx [50 to 100 fc]) and uniform distribution can be used to suggest a feeling of economy and efficiency.

Figure 13-10. A circular design element is used in a number of ways in this intimate restaurant: in the

concentric circles in the ceiling, in the circular cove lighting, and in the circular waiting area that can be set off from the dining area by draperies. Downlights are aimed to illuminate table tops and provide general lighting.

Figure 13-11. This hotel restaurant has a a cheerful interior with a moderate illuminance level. Pendant luminaires delineate the section of booths.

Food Courts

Food courts are designed to keep shoppers in the mall. If food is available in an inviting setting, there is less likelihood of people going home or off-site during peak meal hours.

Proper color rendering is critical, to complement the appearance of the food and the patrons. Although walk-up fast food counters may present a less sophisticated image than fine restaurants, the lighting should still make a positive contribution to the experience of being seen in a public space.

If lamp life and accessibility are not critical issues and directional light sources are required, incandescent and tungsten halogen reflector lamps are often considered. However, a variety of luminaires utilizing compact metal halide and color-improved high-pressure sodium lamps can also provide directional light distributions and good color rendition, along with longer lamp life and lower energy use.

For more diffuse lighting effects, compact fluorescent, linear fluorescent, and metal halide lamps are usually considered. These long-life light sources provide good to high color rendering capabilities, and they are available in a variety of correlated color temperatures. Typical applications include both direct and indirect lighting.

Recognizing that tables, chairs, trash receptacles, and other floor furniture can complicate maintenance accessibility in a food court, open luminaires with screw-based lamps can simplify relamping procedures. Although line-voltage incandescent and tungsten-halogen traditionally fulfilled this need, metal halide screw-based lamps are now available in a variety of versions for "open" luminaires.

In addition to line-voltage sources, low-voltage incandescent and tungsten halogen lamps are frequently used to highlight planters, fountains, and other special features. However, luminaires designed for compact metal halide lamps, reflector-style metal halide lamps, and color-improved high-pressure sodium lamps can also provide precise directional beam control, with longer life and lower energy use.

Depending on the demographics of the mall's patrons and the quality of the food vendors, the illuminance levels might range from relatively high values that stimulate fast turnover and frequent cleanup (100 lx [10 fc] or higher) to fairly subdued levels that encourage shoppers to linger and relax (50 to 100 lx [5 to 10 fc]). Selected illuminance levels should also account for the potential congestion that can occur in circulation aisles as peak-hour patrons negotiate their way past tables and chairs, while balancing loaded trays.

With the food vendors' signs, lighted graphics, and front-counter lighting, it is common for the tenant areas to contribute to the illumination at the adjacent food court walkways. However, as in the concourse, the designer of the food court rarely has direct control over the tenant lighting and its resultant contribution to the public space. Therefore, while it is important to consider anticipated conditions at the service counters, the food court lighting should be capable of providing appropriate illuminance levels independently of those same conditions (Figure 13-12).

Figure 13-12. Whimsical signage delineates the food court of an upscale mall. A variety of light sources contributes to the cheerfulness of the place, including neon, fluorescent, and metal halide. Daylighting is incorporated through a skylight and window walls.

Just as the selected illuminance levels and resulting luminance ratios in the concourse must strike an appropriate balance with the retail shop windows, the lighting of the food court must achieve a similar balance with the counter areas of the food vendors. A certain level of contrast is desirable to focus attention on the visual excitement of each tenant's graphics. However, an atmosphere of high contrast that might be appropriate in a bustling regional mall may be inappropriate in a more sophisticated fashion center.

Cleanup lighting is always an issue, even if the composition of the food court leans more towards fine dining than towards fast food. Typical recommended illuminance levels for cleaning are 100 to 200 lx (10 to 20 fc) averages maintained.

During normal hours the main lighting system must facilitate the level of clean-up activity that is appropriate for the given atmosphere, time of day, and service methods. After business hours, it is possible to rely on a secondary system of cleanup lights or a control system that allows a portion of the main lighting system to provide the necessary illumination. If dedicated cleanup lights are used, color rendering is not important.

Kitchen and Food Preparation Areas

Well-designed lighting helps to create a bright, hygienic atmosphere in a kitchen and, by revealing dirt and the presence of debris, can stimulate good housekeeping (Figure 13-13). Food preparation involves peeling, slicing, dicing, and cutting operations, both by machine and by hand. These are obviously hazardous, and lighting for safety must be a strong consideration.

Figure 13-13. This university food service kitchen has a bright, hygienic appearance with light levels high enough to accomplish the variety of food preparation and clean-up tasks that are performed in a kitchen.

Good lighting can reduce accidents, reveal spills that make floors slippery, and emphasize hazardous areas. In kitchen and associated support areas there is a need to eliminate shadows and to provide illumination on both vertical and horizontal surfaces. While kitchens contain difficult and demanding tasks that may require relatively high illuminances, luminaires should be placed and shielded so as not to create glare into adjacent intimate dining areas when kitchen doors are opened. This is particularly important when the adjacent dining area has lower light levels. Color rendering is important in food preparation and inspection areas.

Visibility can be reduced by large brightness variations in the visual field. Direct and reflected glare can be significant obstacles to employee comfort, productivity, and safety; therefore, exposed lamps in direct luminaires should not be used. In most food preparation areas, gasketed, damp-labeled luminaires are preferred. This allows for easy cleaning and prevents dirt and grease from entering the luminaires. Although glare can be controlled in direct luminaires by effective shielding of the lamps, indirect or direct-indirect lighting is preferable because it turns the entire ceiling into a large, low-brightness area source.

Light-colored walls further diffuse the general lighting, reducing shadows. Because vertical surfaces of equipment and furnishings typically occupy a significant portion of the visual field, especially in kitchens, light finishes are recommended for these surfaces.

Horizontal surfaces, such as table tops in restaurants and equipment tops in kitchens, are important because they serve as backgrounds for critical tasks. Whenever possible, matte finishes are preferable because they minimize reflected glare, which can produce discomfort and fatigue. Stainless steel kitchen equipment is a common offender in this respect. Matte or brushed finishes combined with careful placement of luminaires and good glare control can minimize these problems. The same principles apply elsewhere. Lighting near specular surfaces, such as mirrored ceilings or glazed walls, must be very carefully planned if one is to avoid unintended reflections of sources.

In areas such as bakeries and dishwashing areas that have inherent dust or moisture conditions, the use of enclosed dustproof or vapor-tight luminaires is recommended. Where open-type fluorescent luminaires are located directly over food storage, preparation, service, or display areas, plastic sleeve protectors should be used to prevent glass from falling into the food in case of breakage.

In receiving and storage areas, lights should be installed in the aisles rather than near the walls. In this way, stacked shelves do not block the illumination.

Support Areas

Support areas include such spaces as key shops, plant facilities, and paint shops. The visual tasks in such areas are often demanding and sometimes dangerous. Where flammable materials are stored or used, explosion-proof luminaires should be used. Task lighting using localized luminaires should be considered as an alternative to general high-illuminance, ambient lighting.

Refuse Areas

The maintenance of safe and sanitary conditions in refuse areas is extremely important. Illumination should permit all hazardous or unsanitary conditions such as slippery spots, foul waste, and evidence of insects, rodents, or mold to be seen. Corners and other out-of-the-way places should be well lighted.

Merchandising Areas, Offices, Laundry Areas, and Indoor and Outdoor Recreation Areas

For lighting recommendations for these spaces see Chapters 17, Retail Lighting, Chapter 11, Office Lighting, Chapter 18, Residential Lighting, and Chapter 20, Sports and Recreational Facility Lighting, respectively.

LIGHTING FOR CASINO AND GAMING FACILITIES[4]

The gaming entertainment industry is rapidly expanding worldwide. This section helps define the role illumination plays in gaming while considering the needs of customers, owners, manufacturers, and regulators.

Objectives of Casino and Gaming Lighting

General. The objectives of lighting for casino gaming areas are to:

- Attract the customer. Bright signage, well-lighted entrances, focal accents, and patterns of light that create a visual rhythm can be used to attract the customer to the gaming area.
- Provide for customer comfort. The lighting should create a pleasant atmosphere. High general illuminance creates impressions of perceptual clarity and spaciousness, and nonuniform luminance creates a more friendly, sociable, pleasant, and interesting space; direct and reflected glare should be low.
- Provide for seeing tasks. High illuminance, light sources with good color rendering, and low direct and reflected glare provide appropriate lighting for players and operators at task and game locations.
- Enhance safety and surveillance. High illuminance can be used to ensure adequate surveillance.

Lighting Design Considerations

General. Numerous factors must be considered in lighting casino and gaming facilities to achieve the desired luminous environment. In general, these fall within three categories:

- Appearance of the space and the occupants. Spaces appear clearer, brighter, larger, and more spacious at high illuminances; spaces are considered more public when the lighting scheme clearly shows facial expressions and gestures.
- Appearance of the activities and physical accoutrements. Sparkle can create certain points of visual interest; color can improve task visibility and help create a more pleasant and attractive visual environment.
- Economic and maintenance aspects of the space. Efficient equipment and the organization of spaces help to achieve the most energy-efficient lighting solutions.

Surveillance Lighting Considerations. The role of surveillance in casinos is to protect the assets of the company, provide a secure environment for the customers, and allow regulated games to be properly officiated by all parties concerned, such as the guest, the company, and regulatory agencies. Assets include tangible items such as chips, coins, currency, and inventory, and intangible items such as safe surroundings in the physical space (to prevent injury, theft, and assault, and to avoid litigious situations).

One objective of casino lighting is to support adequate surveillance. Cameras are used most often to provide adequate surveillance. Manufacturers of surveillance camera equipment usually specify a minimum illuminance needed for a clear picture. If moving objects are to be easily seen, illuminances above the minimum suggested are required.

Certain areas require surveillance cameras. These are described in guidelines provided by gaming regulators and include:

Pit Games. Identities of players must be easily distinguished. The chip rack must be viewed so that the value of the wager can be determined. The cards and dice must be viewed in order to determine their value. All payoffs must be clearly visible.

Count Rooms. Count rooms are areas used to count cash and coins. Visual tasks include operating automated coin and bill counting machines as well as handling, identifying, and sorting coins and bills. All areas and tasks must be clearly visible.

Casino Cage and Coin Room. All areas of the cage and count room must be visible, and all transactions must be clearly verifiable. All patrons and employees must be identifiable.

Slot Areas. Lighting for machines offering substantial payoffs should show all reels or video screen depictions and patrons clearly, in order to comply with regulatory requirements, prevent machine tampering, and ensure player security.

All Floor Cash Handling Areas. All areas such as change booths and keno cashiers must be viewed so that all transactions are clearly visible.

Lighting Methods

General. Once the type of casino and the class of clientele to be attracted have been determined, the lighting should be designed in keeping with their character. The lighting design should consider all surfaces in the customers' fields of view.

The gaming lighting system should permit easy, accurate viewing of gaming activities. Lighting is important because the game must be adequately illuminated so players can comfortably see the action and make wagers. The following should be considered:

- Players' faces should be softly lighted with light sources that flatter skin tones and from a direction that minimizes direct glare.
- Overhead lighting directed toward tables should be provided at multiple angles to eliminate shadows when wagerers lean over the table.
- The table should be adequately lighted over its entirety. Controlled downlighting can also be used effectively for table lighting.
- Reflectance, color, and illumination of the background are important.
- The use of multiple luminaires ensures that gaming action is not interrupted if a lamp burns out during the course of a game.

The lighting system should help create a pleasant, attractive atmosphere that emphasizes the gaming activity and makes the area a desirable place in which to play. Well-designed lighting can also improve seeing comfort by minimizing harsh luminance differences.

There are three basic approaches to the lighting of gaming areas in casinos: the general pattern system, the specific system, and the flexible system. Each system should have supplemental lighting to attract attention to featured activities or displays, to influence traffic circulation, and to create added interest.[3]

General Pattern System. The general pattern system uses a pattern of luminaires to provide general lighting, with and without display lighting, throughout the casino area, and without regard to the location of the games. The system should include switching and dimming controls for flexibility in the use of spaces and efficient energy use.

Specific System. The specific system uses a layout of luminaires determined by the location of gaming activities and displays (e.g., slot machines, table games, keno boards, and give-away prizes). It is tailored to emphasize the games and delineate gaming areas. See Figure 13-14.

Figure 13-14. A stained-glass luminaire is used to delineate the slot machine area.

Flexible System. The flexible system employs a pattern of electric outlets of the continuous or individual type for nonpermanent installation of luminaires. These may be wired for multiple circuit application and control.

Roulette Lighting. Roulette is a table game in which players place wagers on a specially marked table adjacent to a roulette wheel. The placement of chips or cash on a certain area of the table denotes the outcome under which the player's wager shall be rewarded or lost. The roulette wheel is spun and a small ball is released on the rotating wheel. The outcome of the game is determined by which slot in the rotating wheel the ball comes to rest.

The table, roulette wheel, and ball must be illuminated so players can comfortably view the action and make wagers. Lighting for the table surface should eliminate shadows when players lean over the table to place bets. Placement of luminaires should minimize direct glare in the eyes of players.

Lighting that highlights the roulette wheel draws players to the gaming activity. The location of the ball on the roulette wheel should be clearly visible to players and surveillance cameras. Care should be taken to avoid reflected glare from the wheel or table surface (Figure 13-15).

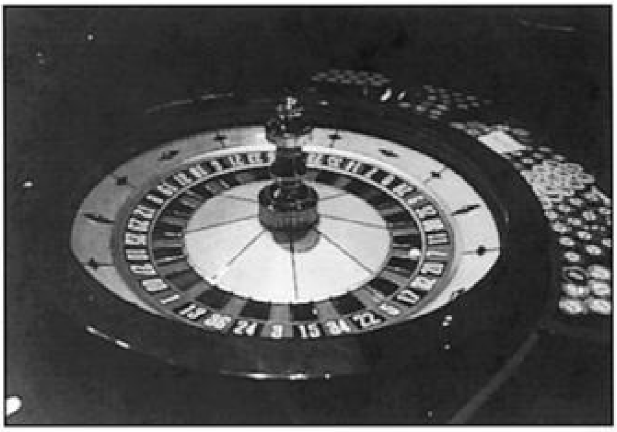

Figure 13-15. Size comparison between a ball and a roulette wheel. The lighting needs to be planned

so that both are easily seen.

Keno Lighting. Keno is a numbers game in which players choose up to ten numbers between 1 and 80. The players mark the chosen numbers on the keno card, and twenty numbered keno balls are drawn and shown in the display.

Lighting can promote the gaming action and focus attention on the game. The principal task is to highlight the keno balls and selection apparatus. The lighting should also provide for easy surveillance of the game and transactions going on in the player area. The keno balls must be clearly visible to the customers and security cameras. Reflected glare from the keno balls should be minimized. Shiny work surfaces should be avoided to reduce reflected glare problems. Lighting for keno should provide adequate illumination to read and mark keno cards efficiently and comfortably, while drawing attention to display, menu, and advertising boards. Design concepts in surrounding spaces can be used to enhance the aesthetic composition of the keno area.

Teller Line. Teller line operators verify keno cards and handle cash transactions. They may also perform computer operations by typing in data and reading input and output data at computer work stations. They read pencil writing and fine print. Indicator lights and lighted push buttons need to be sufficiently bright to be visible under general illumination.

Circulation and Queuing Areas. The lighting in circulation and queuing areas should provide orientation and direction for customers to make a wager on the next keno game or to collect on winning tickets. High illuminance levels at the teller counter highlight the destination for the customer as well as providing task lighting at the counter. Lighting can also be used to delineate the queue line.

Display Boards. Most keno boards are backlighted. They should be brighter than their surroundings to draw attention to the table game. Different levels of contrast may be effectively used to reflect different stages of the game. The locations of keno boards should be planned to avoid reflected images of luminaires, windows, and veiling reflections.

Managers' Area and Office Tasks. Task lighting is required for reading, typing, filing, accounting, clerical work, performing data processing, and conducting meetings (see Chapter 11, Office Lighting). Lighting in the keno managers' area should not distract people in the players' area.

Bingo Lighting. Bingo is usually played by large groups of people. Players are often over 50 years of age and thus generally have reduced visual capabilities. The visual task requires a player to identify numbers and letters on a vertically mounted board or screen from across the room, then to focus on bingo cards, a matrix of letters and numbers. They attempt to match the number on the screen with letter-number combinations on their cards. When a player finds a match, the player marks his or her card(s) with a disc or other type of marker.

Players can play using multiple plastic cards in various positions on a table. The speed of play is a critical component to winning the game, so lighting design should provide for adequate illuminance to see bingo cards and enable easy visual transitions (uniform brightness) from a player's bingo cards to the bingo board. Direct and reflected glare, either on a player's bingo cards or on the board, can seriously hinder play.

Lighting for Race and Sports Books. Race and sports books are areas where patrons view and wager on and view sports activities. It is important that good reading lighting be available in the sports book area. Patrons tend to be over 50 years of age and thus have reduced visual capabilities. They often need to read sports and race forms, which can be in fine news print. See Figure 13-16.

Figure 13-16. Task lighting in a race and sports book area provides adequate light levels to complete race forms.

Video Games and Machines. Video games and slots consist of games of chance played on machines with video screens. Poker, blackjack, and electronic slots are just a few of the games played on video terminals. Players typically need to see the location of the coin slot, casino slot club card, credit buttons, player option buttons, and game activation buttons or levers. The current trend in machine design is to highlight these items with lighting integral to the machine, transmitted through translucent materials and parts. Excessive lighting displays on a row of slot machines can result in visual clutter distracting the player's attention from gaming action. To reduce visual confusion, banks of similar-looking machines with identical games are often installed in rows or islands. This arrangement offers the potential for lighting small areas containing machines of a specific design or game.

Care must be taken to light the machines for visual attractiveness. At the same time, the lighting should be designed for the seeing tasks in this area. See Figure 13-17.

Figure 13-17. Lighting has been integrated with the ceiling design to focus interest on the video machines.

Card Games. Card games, such as poker and blackjack, are pit games played while sitting down at a table. There is one dealer with possibly eight or nine players. The dealer shuffles the cards and must deal cards to each player. Players pick the cards up off the table surface and hold the cards in a vertical position to determine their play. Players lay cards down on the table. Each player must see cards lying up on the table as well as cards held vertically. Players must be able to distinguish their own cards from those of other players when the cards are lying face down on the table. It is important for players to clearly see the facial expressions and body positions of other players. Directional light and any resulting glare must not have a detrimental effect on the players as they participate in the game. See Figure 13-18.

Craps. Casino craps is a pit game played on a felt-covered, large table with high rails around the side. The table surface should be lighted to attract attention to the game. Wagers and dice rolls should be clearly visible. Lighting should minimize shadows cast by people leaning over the table. Contrast between the table surface and dealers' or players' faces should not be so high that surveillance cameras cannot identify them while monitoring action on the table. Ideally the cameras should detect the brightness transition from the table surface to areas just beyond the outer perimeter of the table without difficult brightness adjustments.

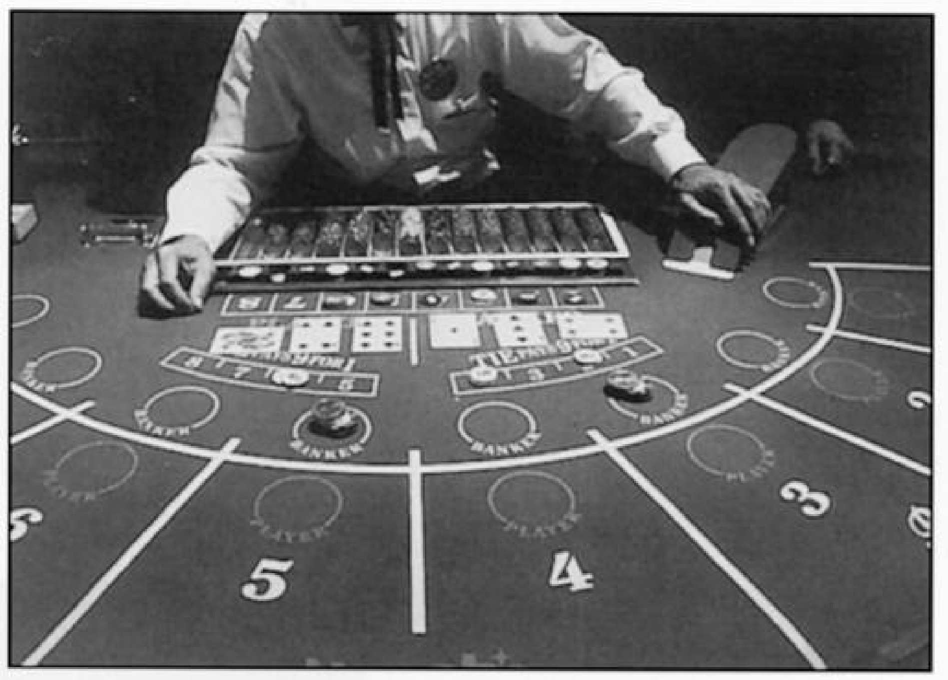

Figure 13-18. Players must be able to see wagers, cards, and dice clearly to determine subsequent plays.

Players and dealers must be able to see dice across the length of the table. They must be able to distinguish the color and type of chips and who placed bets. Coins and chips often have shiny surfaces, so minimizing glare from these items placed on the table should be considered in the lighting design.

Stock Rooms. Storage shelves, bins, and racks should be lighted so that labels and other means of identification can be quickly and easily seen. In enclosed storage areas, the color rendering qualities of lamps should be adequate (greater than 75 CRI) to permit correct identification of stored items. Storage areas should have somewhat higher illuminance than general ambient levels (300 to 500 lx [30 to 50 fc]).

Locker Rooms and Restrooms. Lighting in these areas is for sanitary maintenance, use of lounge facilities, and lockers. Locker room and dressing room lighting is principally a matter of arranging the luminaires so that the interior of the lockers is illuminated, and general lighting is provided for safe movement about the room.

Uniform illumination is not required in restrooms. Luminaires should be located to provide enough light in the vicinity of the mirrors for adequate illumination of the face. Visual tasks include grooming, which requires shadowless illumination on both sides of the face. Color rendering is an important consideration. Other luminaires should be located so that their maximum light output is concentrated on the urinals and toilet stalls. Concentration of light in these areas tends to encourage more effective hygiene. Lounge areas in restrooms require only low illuminances (50 to 100 lx [5 to 10 fc]).

Escalators, Elevators, and Stairways. First impressions of a gaming area or casino are often made in entrance lobbies. The lighted environment should be aesthetically pleasing, should complement the architecture and the gaming, and should fulfill simple visual requirements. The illumination should provide a safe and attractive transition from the exterior to the interior. Illuminances should facilitate readaptation as patrons move from inside to outside and vice versa.

To aid circulation and draw attention to functional areas, nonuniform lighting is often desirable in entrance lobbies. Supplementary adjustable lighting equipment can be used for displays or graphics.

Classified as a casual seeing area, elevator lobbies are areas in which high brightness differences are acceptable. Contrasting luminous areas and geometric patterns of light may be designed to add interest. Higher levels of safety should be provided at the elevator threshold to call attention to possible differences in elevation between the elevator cab and floor level.

Illuminances equal to those provided in the building corridors should be provided in elevators. The light in an elevator should always be connected to the building's emergency power supply in the event of elevator power failure or malfunction. Elevator car interior finishes should have high reflectances.

Good lighting should be provided on escalator treads. The illuminance where a person steps on and off the moving treads should be higher than the ambient level. The luminaires in these critical areas should be arranged so that the person getting on or off the escalator does not cast a shadow on the treads. In some instances it may be necessary to provide shielded supplementary luminaires in the balustrade. A colored luminous strip at the edge of the stair tread is commonly used, which helps a person see the moving tread quickly. Escalator finishes should have high, but not specular reflectances.

Stair treads should be well illuminated, and the luminaires should be located to minimize both glare and shadows on the stairs. The luminaires should be located for ease of maintenance because ladders are difficult to use in stairways. Emergency lighting should be provided in all public stairways (see Chapter 29, Emergency, Safety, and Security Lighting).

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14

Lighting for Public Places and Institutions

LIGHTING FOR PUBLIC PLACES AND INSTITUTIONS

Museums

Flat Displays on Vertical Surfaces

- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Illuminance (Vertical)
- Light Distribution on Task Plane (Uniformity)
- Reflected Glare
- Shadows
- Source/Task/Eye Geometry

Exhibit Cases, Three-Dimensional Objects, and Realistic Environments

- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Task Plane (Uniformity)
- Modeling of Faces or Objects
- Reflected Glare
- Shadows
- Source/Task/Eye Geometry

Houses of Worship

Congregational Areas

- Color Appearance (and Color Contrast)
- Direct Glare
- Flicker (and Strobe)

Leadership Areas

- Appearance of Space and Luminaires
- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Direct Glare
- Flicker (and Strobe)
- Illuminance (Vertical)
- Modeling of Faces or Objects
- Shadows
- Source/Task/Eye Geometry
- Sparkle/Desirable Reflected Highlights
- Surface Characteristics
- System Control and Flexibility

Highlighted Items

- Illuminance (Vertical)

Courtrooms

- Appearance of Space and Luminaires
- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Modeling of Faces or Objects
- Source/Task/Eye Geometry
- System Control and Flexibility

Correctional Facilities

- Daylighting Integration and Control
- Flicker (and Strobe)
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Task Plane (Uniformity)
- Modeling of Faces or Objects
- System Control and Flexibility

MUSEUM AND ART GALLERY LIGHTING

Museums and art galleries collect, preserve, analyze, and display natural artifacts and examples of human achievement and their impact on us. Effective exhibit lighting must balance exhibition and conservation needs and enrich the museum experience.

This section touches upon issues that are key to successful museum lighting, including illuminance, color, glare, shadows, modeling of objects, safety/security, and system control and flexibility. See the section "Museums" in the Lighting Design Guide in Chapter 10, Quality of the Visual Environment, for a ranking of these and other design issues. See also the IESNA Recommended Practice for lighting in museums and art galleries for further information regarding each of the areas discussed in this chapter.[1]

Exhibit lighting impacts several important groups, including museum curatorial, educational, and conservation staff; designers; and visitors. Effective museum lighting must balance the concerns of each group.

Systems Approach Solution

Artifact conservation and display requirements should be determined based on the following:

- Low illuminance can compromise the visual enjoyment of an artifact but can still cause some damage. There is no point in causing any damage if the artifact cannot be seen well.
- The institution should decide how much illuminance and how much exposure time is acceptable, that is, what artifact lifetime is desirable.
- The institution should determine the sensitivity to light of each artifact or group of artifacts as accurately as possible.[2]

Design Guidelines

Museum and art gallery lighting design differs in some important respects from many other types of lighting design. Museum objects are often unique in size, shape, texture, and color, and many are extremely sensitive to light damage. Lighting design becomes a selective visibility process that governs what we see, how we see it, and when we see it (Figure 14-1).

The Design Concept. Concept development begins by analyzing the reasons for the exhibition and identifying the dominant elements. The designer should then put these ideas into a simple, declarative sentence expressing the lighting concept. This statement becomes the "channel" through which the design flows. Concept development facilitates implementation.

Color. Using color in museums is different from using color in other places because the color of the light source should not change the look of an artifact, that is, affect its "original appearance." Thus enhancement of certain colors with selective colored light is usually inappropriate when lighting museum artifacts.

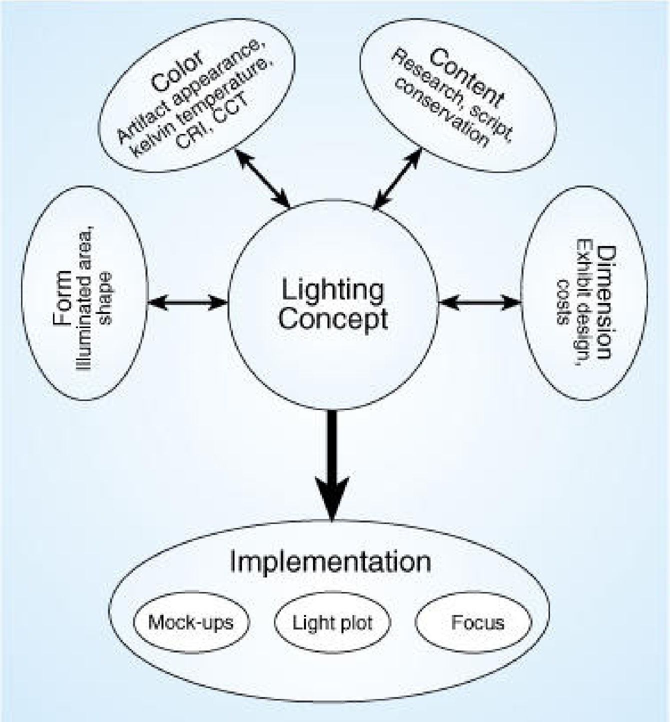


Figure 14-1. This lighting design model illustrates how focused creative effort including the four basic artistic elements (form, color, content, and dimension) can lead to the implementation of a visually interesting and informative exhibition.

The color rendering index (CRI) of the lamp and its correlated color temperature (CCT) affect the color appearance of artifacts. Typically, the higher the CRI the better the light source for maintaining "true" color, although this is not always the case. As a guide, lamps with CRI values of 80 or greater should be used, but it is important to visually inspect the artifact under the proposed light source.

The CCT of a light source will determine whether the display takes on a cool or a warm appearance. Higher CCT values are "cool," or more blue-white; lower temperatures are "warm," or more yellow-white. Noontime daylight is cool and has a CCT of about 5000 K. Triphosphor fluorescent lamps exhibit CCTs from 2800 K to 6500 K, tungsten-halogen lamps have a CCT of about 3000 K, and an incandescent lamp is warm and has a CCT of about 2800 K (see Chapter 6, Light Sources, and IESNA DG-1-1990).[3]

Implementation. The designer's obligation in the museum is to present a visually interesting and informative exhibition while preserving artifact life as long as possible. The process involves understanding the exhibition layout, the appropriate appearance and irradiance limitations of the artifacts, and communicating the luminaire type and placement to others.

Lighting designs must be communicated to other designers, museum management, technicians, and contractors. This communication can occur on many levels by using renderings, light plots, luminaire schedules, and focusing charts. The luminaire schedule should list the type of luminaire, symbol used, manufacturer, wattage, voltage, lamp, and number of units required.

It is important to understand the location of graphic panels and artifacts in the exhibition so that the luminaires can be positioned appropriately. Light track should be located parallel to the vertical surfaces. For further discussion, see the section "Four Typical Lighting Situations" below.

Focusing the Luminaires. Perhaps the most rewarding part of the design is focusing (aiming) the luminaires. The lighting designer should look at the end result from the viewpoint of the visitor, not from the top of the ladder. The lighting designer should walk around the exhibit, looking at it from many different viewpoints, as the focusing progresses. As the designer Robert Edmond Jones states, "Does this mean that we are to carry images of poetry and vision and high passion in our minds while we are shouting out orders to electricians on ladders in light rehearsals? Yes. This is what it means."[4]

Accessibility Laws. The Architectural Barriers Act of 1968, the Rehabilitation Act of 1973, and the Americans with Disabilities Act (ADA) of 1990 require museum and art gallery access for people with disabilities.[5] While the laws' accessibility standards do not specify lighting requirements, the spirit of the law and the programmatic requirements of the Rehabilitation Act in particular require visual access to museum objects and label text. This area is currently under research by various museum and design organizations. The basics of accessibility lighting include the following:

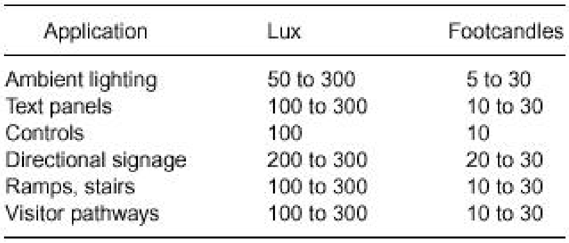
- Visitor's safety must be given equal consideration with exhibit design and conservation issues. This is especially important for those with low vision.
- Light and color must combine to produce a clearly delineated circulation route into, through, and out of every exhibition space. This is a particularly important requirement whenever there are changes in floor level or unexpected turns or obstacles in the route.
- There must be sufficient illuminance on objects to make them visible to all visitors unless the irradiance would do substantial damage to the objects.
- Labels should be illuminated in order to be readable by all visitors.
- The elimination of glare from cases and on labels must be considered for those visitors who are seated as well as for those who are standing.
- Sufficient illuminance to accommodate speech reading and sign language conversation must be provided in locations throughout the exhibition space (Figure 14-2).

DAMAGE TO MUSEUM OBJECTS

Effects of Exposure to Light

Light is radiant energy, and exposure to light gradually causes permanent damage to many museum objects. When radiant energy is incident on the surface of a material, whether opaque or transparent, some portion of that energy is absorbed. This can promote two distinctly different processes that can cause degradation of museum objects: radiant heating and photochemical action.

Radiant heating produces a temperature rise at the surface of the material exposed to the source of energy. The surface expands relative to the body of the object, and moisture is driven from the surface material. The symptoms are surface cracking, lifting of surface layers, and loss of color.



Application	Lux	Footcandles
Ambient lighting	50 to 300	5 to 30
Text panels	100 to 300	10 to 30
Controls	100	10
Directional signage	200 to 300	20 to 30
Ramps, stairs	100 to 300	10 to 30
Visitor pathways	100 to 300	10 to 30

Figure 14-2. Accessibility Lighting Levels

The symptoms of photochemical action can be similar, but the process is quite different and often more serious. A chemical change occurs when a molecule irreversibly changes its structure. Photochemical action may include fading or darkening of colors, yellowing, brittling, loss of strength, fraying of fabrics, and even dramatic color changes of some pigments.

It can be difficult for lighting designers to come to terms with the idea that their art is damaging the artifact. To illuminate many museum artifacts is to expose them to potentially damaging radiant energy. Conservators are likely to approach lighting designers with reserve, and so the lighting designer needs to demonstrate understanding of conservation issues if cooperation is to be achieved.

Assessment of Exposure

Illumination of museum artifacts involves exposing them to radiant energy. The lighting should provide satisfactory viewing conditions with minimum irradiance of the objects. Techniques such as elimination of glare and control of surrounding brightness can serve to reduce the need for light on the artifacts.

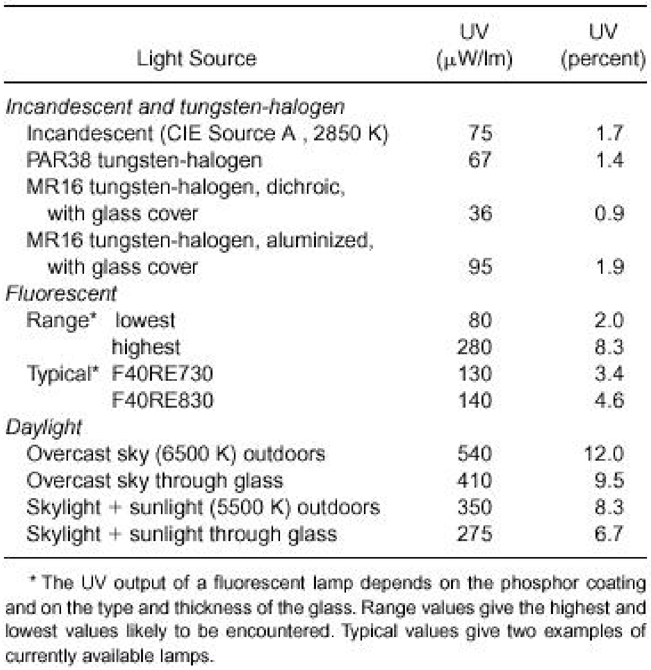
The annual extent of exposure is governed by two factors: the reciprocity principle and the spectral power distribution of the incident energy. The reciprocity principle may sound complicated, but it is quite simple. For a given source, exposure is the product of intensity and time. To expose an object at 10 W/m^2 for 10 hours is equivalent to exposing it for 5 W/m^2 for 20 hours or 20 W/m^2 for 5 hours: in all three cases the exposure is 100 watt-hours/m^2.

The use of the term "watt" might seem surprising in this context. The watt is the unit of power, or rate of energy flow, and irradiance can be measured in watts per square meter regardless of its spectral composition. However, the spectral composition is important. Visible light contributes to both vision and damage; infrared (IR) and ultraviolet (UV) energy, which are not visible, contribute only to damage. Unless all artifacts in a display area are totally insensitive to exposure, UV and IR should be controlled, usually with filters.

Some light sources, notably incandescent (including tungsten-halogen), emit more IR energy than light. For this type of source the radiant heating effect is relatively high for a given illuminance unless corrective measures are taken. There are no standards for acceptable IR irradiance levels, nor are there convenient meters for checking such levels.

Most other light sources, including fluorescent lamps, mercury and metal halide lamps, and daylight, emit significant quantities of UV energy, as shown in Figure 14-3. Although the UV energy is usually small compared with the energy in the visible portion of the spectrum, high photon energies in this region of the spectrum make UV energy particularly potent for photochemical action.

There are two measures for rating the UV output of light sources. Microwatts of UV per lumen (µW/lm) expresses UV energy emission relative to the luminous output of a lamp, and UV percent expresses total energy between 300 and 400 nm as a proportion of that between 300 and 700 nm (Figure 14-3).



Light Source	UV (μW/lm)	UV (percent)
Incandescent and tungsten-halogen		
Incandescent (CIE Source A , 2850 K)	75	1.7
PAR38 tungsten-halogen	67	1.4
MR16 tungsten-halogen, dichroic, with glass cover	36	0.9
MR16 tungsten-halogen, aluminized, with glass cover	95	1.9
Fluorescent		
Range* lowest	80	2.0
highest	280	8.3
Typical* F40RE730	130	3.4
F40RE830	140	4.6
Daylight		
Overcast sky (6500 K) outdoors	540	12.0
Overcast sky through glass	410	9.5
Skylight + sunlight (5500 K) outdoors	350	8.3
Skylight + sunlight through glass	275	6.7

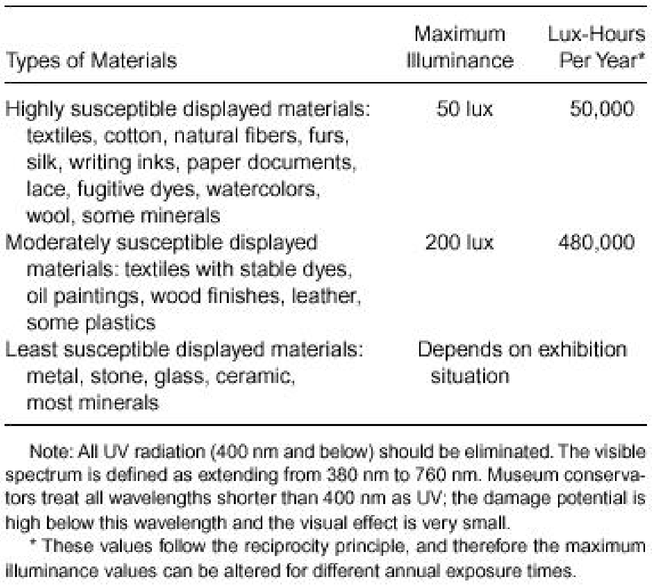
* The UV output of a fluorescent lamp depends on the phosphor coating and on the type and thickness of the glass. Range values give the highest and lowest values likely to be encountered. Typical values give two examples of currently available lamps.

Figure 14-3. Absolute and Relative Amounts of Ultraviolet (UV) Radiation from Electric and Natural Light Sources Useful to Museum Applications

Visible Energy: Limiting Illuminance. Visible energy is the region of the electromagnetic spectrum by which the artifacts are seen, and, almost invariably, the overriding concern of the lighting designer is to provide enough visible energy for discrimination of detail and color.

Classification of museum objects for susceptibility is the responsibility of the conservator. Figure 14-4 gives guidance on three categories of susceptibility that are widely accepted in the museum community.[6]

For general guidance it is recommended that illuminances for highly susceptible artifacts (Figure 14-4) not exceed 50 lux (5 fc). However, for particularly susceptible or precious materials, illuminance can be reduced to 35 lux (3.5 fc) and still provide for satisfactory viewing, provided the viewer is fully adapted to low brightness levels.



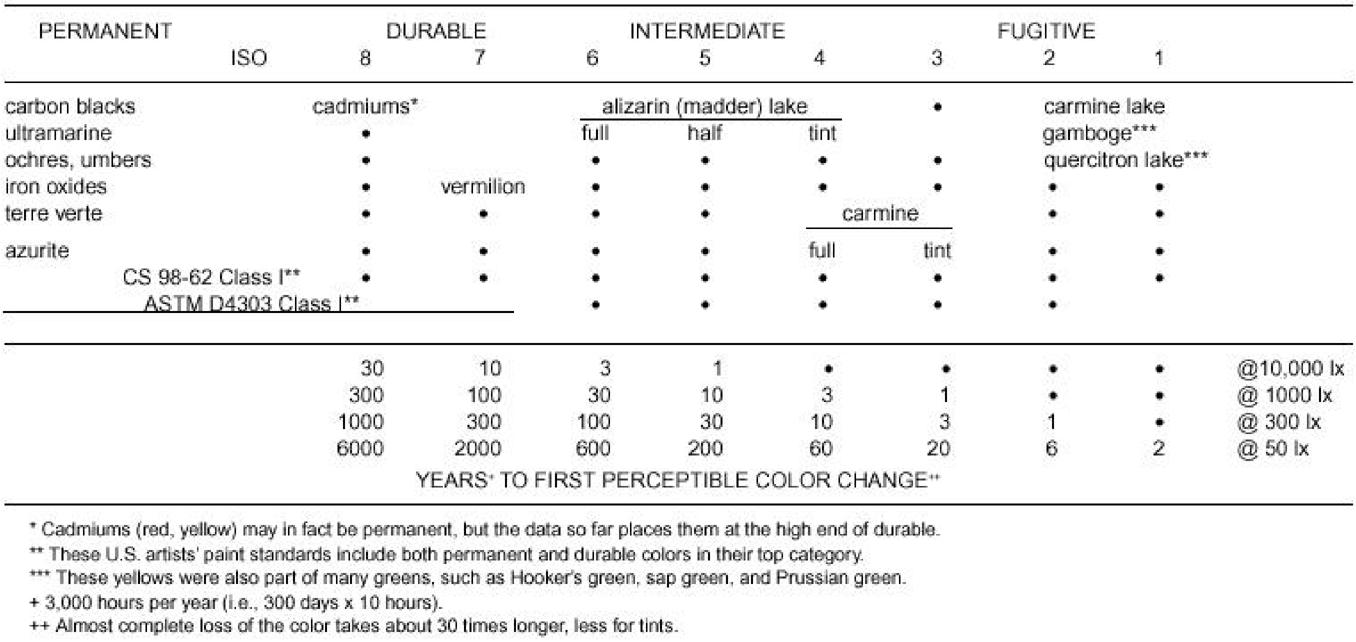
Types of Materials	Maximum Illuminance	Lux-Hours Per Year*
Highly susceptible displayed materials: textiles, cotton, natural fibers, furs, silk, writing inks, paper documents, lace, fugitive dyes, watercolors, wool, some minerals	50 lux	50,000
Moderately susceptible displayed materials: textiles with stable dyes, oil paintings, wood finishes, leather, some plastics	200 lux	480,000
Least susceptible displayed materials: metal, stone, glass, ceramic, most minerals	Depends on exhibition situation	

Note: All UV radiation (400 nm and below) should be eliminated. The visible spectrum is defined as extending from 380 nm to 760 nm. Museum conservators treat all wavelengths shorter than 400 nm as UV; the damage potential is high below this wavelength and the visual effect is very small.

* These values follow the reciprocity principle, and therefore the maximum illuminance values can be altered for different annual exposure times.

Figure 14-4. Recommended Total Exposure Limits in Terms of Illuminance Hours per Year

Figure 14-5 shows some historic pigments, their lifetimes when exposed to various illuminances, and how reducing the illuminance on the artifact helps increase its permanence. For many art works, the first effect of light exposure to become noticeable is fading or some other pigment color change. The light-fastness of artists' pigments can be assessed in terms of ISO ratings based on the "blue wool" test procedure.[7] A sample of the pigment is exposed to broadband radiation in a test cabinet alongside a card that carries eight standard blue-dyed strands of wool. The wool samples have progressively increasing light-fastness, so that, for example, wool sample 4 fades at approximately half the rate of sample 3 and twice the rate of sample 5. ISO ratings are determined by comparing the color change of the pigment sample with those of the wool samples. Figure 14-5 shows the ISO ratings related to four categories of light-fastness: ratings 1 to 3 are termed "fugitive," 4 to 6 are "intermediate," 7 and 8 are "durable," and the "permanent" category is for pigments that are unaffected by light exposure.[8]



PERMANENT	DURABLE		INTERMEDIATE			FUGITIVE			
ISO	8	7	6	5	4	3	2	1	
carbon blacks	cadmiums*		alizarin (madder) lake			•	carmine lake		
ultramarine	•		full	half	tint		gamboge***		
ochres, umbers	•		•	•	•	•	quercitron lake***		
iron oxides	•	vermilion	•	•	•	•	•	•	
terre verte	•	•	•	•	carmine		•	•	
azurite	•	•	•	•	full	tint	•	•	
CS 98-62 Class I**	•	•	•	•	•	•	•	•	
ASTM D4303 Class I**			•	•	•	•	•		
	30	10	3	1	•	•	•	•	@10,000 lx
	300	100	30	10	3	1	•	•	@ 1000 lx
	1000	300	100	30	10	3	1	•	@ 300 lx
	6000	2000	600	200	60	20	6	2	@ 50 lx

YEARS+ TO FIRST PERCEPTIBLE COLOR CHANGE++

* Cadmiums (red, yellow) may in fact be permanent, but the data so far places them at the high end of durable.
** These U.S. artists' paint standards include both permanent and durable colors in their top category.
*** These yellows were also part of many greens, such as Hooker's green, sap green, and Prussian green.
\+ 3,000 hours per year (i.e., 300 days x 10 hours).
\++ Almost complete loss of the color takes about 30 times longer, less for tints.

Figure 14-5. Some Historic Pigments and Their Lifetimes (Permanence) for Various Illuminances[8]

The light-fastness of a pigment can be substantially affected by how it is applied by the artist. Carmine when undiluted is rated ISO 4, when applied as a tint is rated ISO 3, and when applied as a lake (as in watercolors) is rated ISO 2 or 1. The identification of pigments and their applications requires the expertise of a conservator; when there is doubt, it must be assumed that the least light-fast pigment likely to have been used by the artist is present. Modern pigments offer artists a full palette of colors that have been developed to have high resistance to the effects of light exposure. ASTM D4303 Class 1 pigments are all in the permanent or durable categories.

The importance of relating illuminance to the light-fastness of the most susceptible pigment present is indicated in the lower portion of Figure 14-5 by the "years to first perceptible color change" values. These values are based on UV-free illumination that is in use for 3000 hours per year at one of the four listed illuminances. Shown are the number of years of display that induce a just-perceptible color change; in other words, after this period of display, the object would be likely to appear noticeably faded in a side-by-side comparison with an unexposed sample of same material. It can be seen in Figure 14-5 that durable pigments, such as those in ASTM D4303 Class 1, can withstand a century of display at 1000 lux before a perceptible color change occurs, while carmine lake may undergo a perceptible change after only two years of display at 50 lux. Before placing an artwork on permanent display at even a moderately high illuminance, the curator must be confident that there are no fugitive (ISO = 1, 2, or 3) or intermediate (ISO = 4, 5, or 6) category pigments present.

Exposure when the artifact is not on display also needs to be taken into account for assessing annual exposure. The lighting for nondisplay hours should be designed with the same care as the lighting for display hours, since it can have a substantial effect on conservation due to its greater duration.

FOUR TYPICAL LIGHTING SITUATIONS

Most museum exhibit displays can be categorized into one of four groups: flat displays on vertical surfaces, display cases, three-dimensional objects, and realistic environments. Within each group, the lighting designer must deal with unique challenges and creative opportunities.

Flat Displays on Vertical Surfaces

Uniform illumination of large vertical displays presents a common lighting problem in museums. Paintings, prints, documents, and explanatory labels are included in this important category. Lighting becomes difficult when acrylic or glass is used to protect the artifact. The combination of the specular surface and improperly placed luminaires can cause reflected glare and obscure the artifact. Preferences for alternative lighting distributions have been studied by Loe et al.[9] In general, the lighting should provide uniform illumination over the entire surface. Luminaires positioned so that the beam center axis is 30° from the vertical usually produce minimal shadows and glare-free viewing while allowing the visitor to approach the artifact closely without casting his or her own shadow on the artifact.

Wall Wash. A good method of achieving uniform illumination over a large vertical surface is to employ wall-wash luminaires. Most manufacturers can provide charts that show the luminaire's distribution on the wall.

Spotlights. For small- and medium-size pictures or label panels mounted on a wall, the designer usually selects spotlights. The mounting position can be determined by following the diagram in Figure 14-6. Increase or decrease "X" as required to avoid shadows from oversize frames on paintings. Compute the angle of incidence/reflection to avoid glare to viewer. Optical projectors can be used to "frame" the object, but this can cause an artificial appearance. If projectors are used, additional soft lighting in the display space may be necessary to prevent a painting from looking like a transparency. It is also practical to allow some spill light onto the surrounding area for a softening effect. If a picture label is separate, it should be located in the spill-light area, away from the frame shadow.

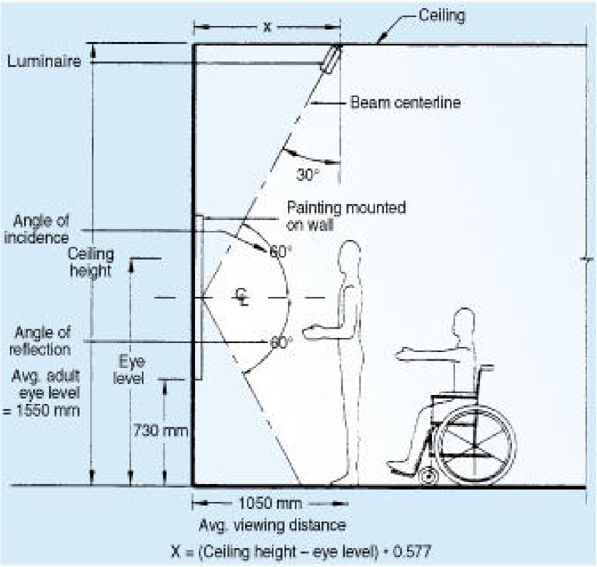


Figure 14-6. Guidelines for luminaire mounting position for flat displays on vertical surface. Use the formula as a guide. Increase or decrease "X" as required to avoid shadows from oversize frames on paintings. Compute the angle of incidence/reflection to avoid glare to viewer.

Exhibit Cases

Museum exhibit cases allow visitors to approach rare and delicate artifacts closely while maintaining a barrier against degradation, vandalism, or theft. Cases usually contain small, delicate, and valuable artifacts. Display cases (vitrines) can range from a 50-mm (2-in.) acrylic cube holding a jewel to a 3-m (10-ft) cube holding rare clothing. The case can have either mullions at the corners or clear acrylic or tempered glass panels glued at the edges.

These cases can have internal or external lighting. Lamp types may vary from low-voltage incandescent to fluorescent to high-intensity discharge.

Problems with display case lighting include reflections in the glazing, shadows produced by visitors or displayed artifacts, and heat buildup. A transparent or translucent barrier should always be put between the luminaire and the artifact, to mitigate the unwanted heat (Figures 14-7 and 14-8).

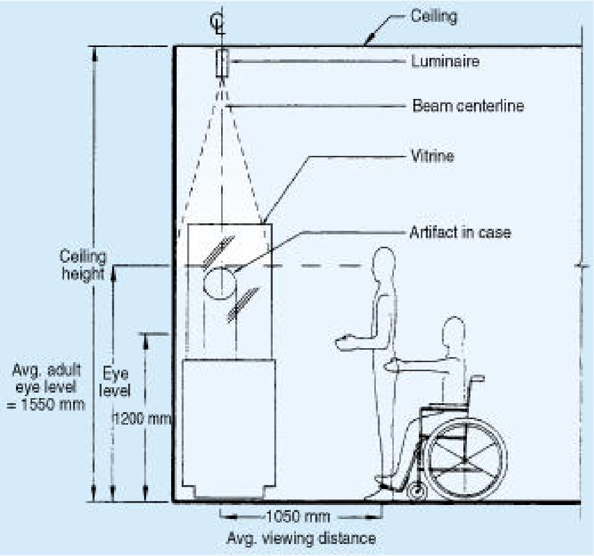


Figure 14-7. Guidelines for luminaire mounting position for a display case, with the luminaire outside the case.

Minimizing Reflections. Reflections are most troubling in display cases that have dark interiors. In these instances, it may be necessary to have the cases face a black wall and to minimize outward light spill so that the visitor's image is not reflected in the glazing. Other possible light solutions include:

- Using glass that is angled toward the viewer, so that the principal reflections of the gallery are directed to the floor, which must be kept dark
- Using specially curved viewing glass that reflects a dark surface
- Eliminating the glass in favor of some other kind of barrier (e.g., railings, taut wires, and alarmed motion sensors)
- Creating a high luminance ratio (10:1) between the interior and exterior of the case

In most instances a small reflection persists, but this is acceptable when the displayed artifact is brighter than the reflection. In fact, some reflection may be desirable, because otherwise the viewer may reach out and discover that the display is protected.

External Lighting. When display cases are lighted from an external source, the lights should be above the front of the case and focused straight down. Other luminaire positions produce shadows within the case from the case edges or corners, even if there are no opaque supporting structures. Diffusing material such as milk-white diffusing acrylic placed across the top of the case reduces harsh shadows and produces a self-lighted effect; however, the diffusion material may produce a reflection from the case top onto the ceiling. External light sources produce some heat within the case because of the greenhouse effect. Using dichroic reflector lamps and heat filters reduces this problem.

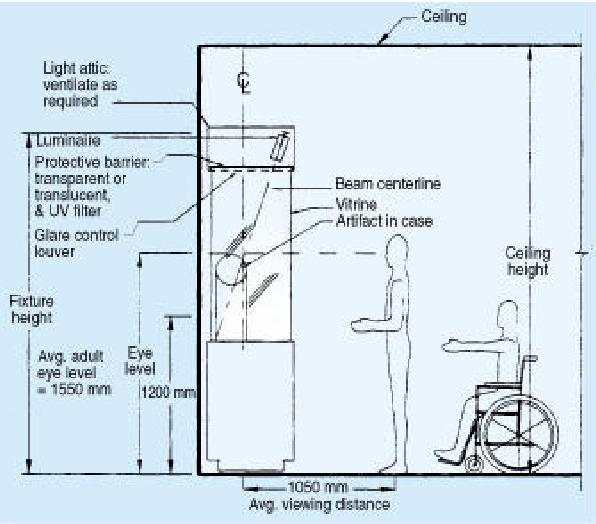


Figure 14-8. Guidelines for luminaire mounting position for a display case, with the luminaire inside a full

light attic.

Externally lighted display cases usually employ reflector lamps in one of various beam patterns. Caution should be exercised when mounting heavy lamps (such as the PAR38) directly above a glass case. If the lamp is dropped during servicing, it can cause severe damage. This hazard can be reduced by placing a clear "safety" barrier between the lamp and the case, or by using less massive lamps.

Internal Lighting. Freestanding or built-in display cases frequently have light attics or light boxes overhead. They offer light source concealment and customized illumination for the case and its contents.

Partial Light Attic. Display cases that are always observed from one direction can have a partial light attic just above the viewing window with a sloping light-attic glazing. This light attic can contain fluorescent lamps for soft illumination, fixed or adjustable incandescent lamps for controlled and directional illumination, or a lighting track that can accommodate both. Luminaires for a light attic should be simple, functional, and easily maintained. Swivel lamp holders provide the greatest flexibility. Luminaire appearance is the least important aspect of light attic design (Figure 14-9).

Full Light Attic. Display cases that are seen from all sides require a light attic that is the same size as the case top. Soft, uniform illumination from fluorescent lamps works well. If spotlights are required, the light attic should be deep (300 to 600 mm [1 to 2 ft]), with the spots directed through small apertures in opaque material or in a louver. The light source should be shielded from the viewer to eliminate glare through the use of parabolic wedge louvers or lenses. Spotlights should be positioned carefully to avoid projecting the pattern of the apertures or louvers (Figure 14-10).

Supplementary lighting from the side, back, or bottom of the cases is practical and can reveal the texture and the shape of three-dimensional objects. Such lighting can greatly enhance the appearance of ceramic, glass, and polished-metal pieces.

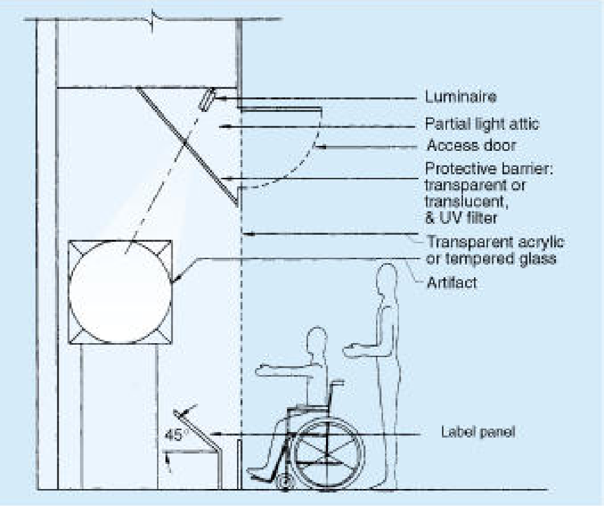


Figure 14-9. Guidelines for luminaire mounting position for a display case, with the luminaire inside a partial light attic.

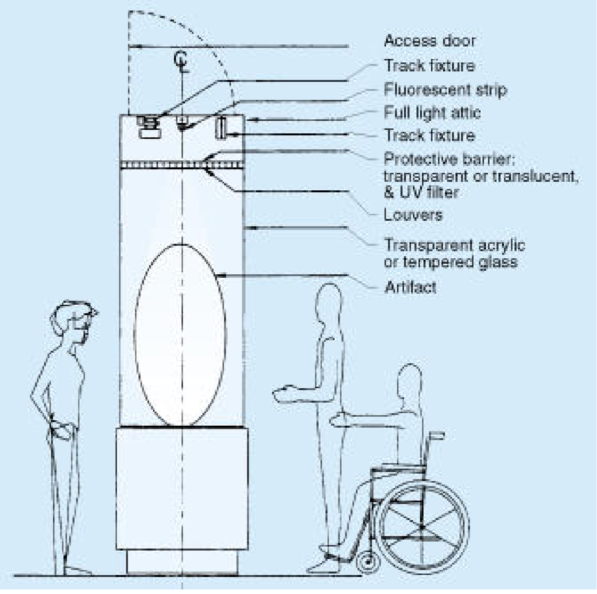


Figure 14-10. Guidelines for luminaire mounting position for a display case, with the luminaire inside a full light attic.

Maintenance. Luminaires built into a display case should be serviceable through a separate access door. Lamp changing should not jeopardize the display through accident, error, or theft. The lamp chamber should be separated from the display case contents by a secured glazing material.

Cooling. Light chambers require ventilation to prevent heat buildup and should have air vents for air exchange and convection cooling.[9] In extreme situations, these chambers may require conditioned air or electric fans to improve air flow. All chamber openings should be filtered to reduce dirt deposit on the luminaires and on the glazing.

Ultraviolet Reduction. The light glazing should be constructed from UV filtering material. UV filtering lenses can also be installed on the luminaires.

Light Gradients. A display case with a glass front door reflects light into the lower area of the case, and the top-to-bottom illuminance uniformity should be satisfactory. If this does not happen, either the case finish is too dark, the case is too tall, or the case is too shallow for top lighting only. In these instances consider side lighting, repainting, or internal or external spotlights. There may be no perfect single solution, but a combination of these techniques should correct most problems.

Luminous-element signs or transparency boxes. The transparency box is an internally illuminated case and requires careful attention by the designer. The basic premise of a transparency box is to provide even illumination over an area. Fluorescent lamps do this best while keeping heat generation to a minimum, particularly when the lamps are electronically ballasted.

The box should be constructed of 16-gauge metal and designed to accept standard fluorescent lamps, preferably in 900- or 1200-mm (3- or 4-ft) lengths. The same length lamp should be used throughout the entire box. These lamps should have a color temperature between 4000 and 5000 K. The lamps should be evenly spaced, 1 to 1.5 times the distance from the lamp to the transparency. The box must accommodate the luminaire plus this distance. The inside of the box should be painted white, and there should be a layer of milk-white diffusion acrylic (not just diffusion acrylic) between the lamp and the transparency (Figure 14-11). Some transparencies are manufactured with milk-white diffusion in the transparency.

Black-and-white transparencies require less light than multicolored transparencies. Filters to the inside of the transparency can be used to reduce brightness. Lamps should not be removed because the evenness of illumination is compromised, and removal can cause harm to the remaining lamps and ballasts.

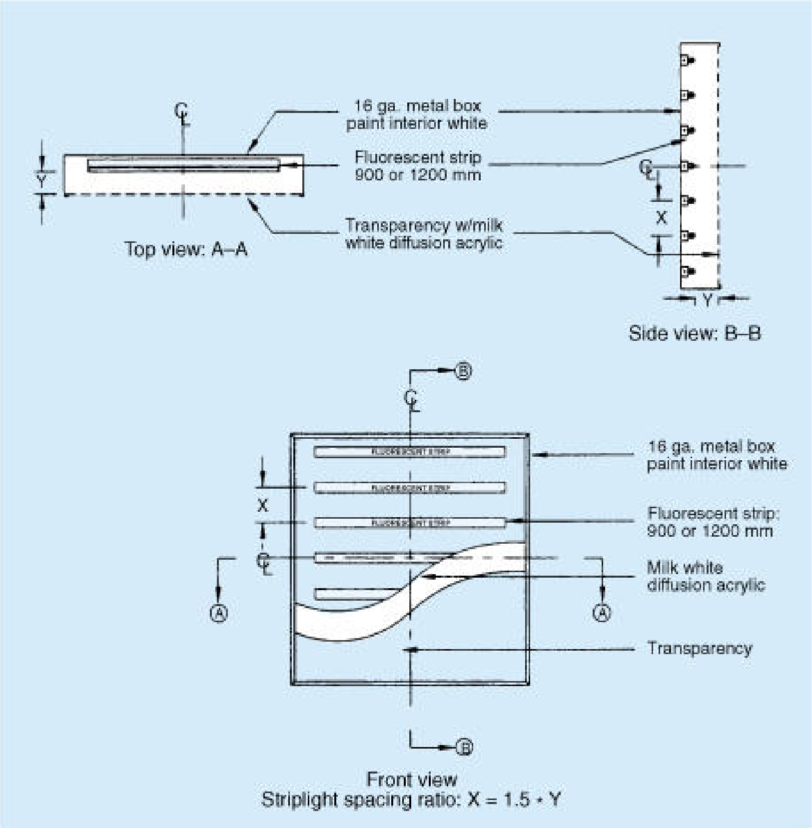


Figure 14-11. Guidelines for constructing a transparency box. Note that the distance between the fluorescent strips should be 1.5 times the distance from the lamp to the transparency.

Fiber Optic Options. Fiber optics provide distinct advantages for internally lighted display cases. Low-level light can be "piped" directly into a case and focused at a specific object while the case remains sealed. The illuminator can be remotely located outside the display case thus mitigating heat buildup. Virtually no UV radiation is transmitted through the fiber. Multiple direct runs of fiber optics can emanate from one illuminator. The one disadvantage of fiber optics is the finite fiber length at which noticeable light attenuation occurs, approximately 10 to 15 m (30 to 45 ft). For more information see Chapter 7, Luminaires.

Three-Dimensional Objects

Irrespective of size, a three-dimensional artifact must be illuminated from several different directions. Light from multiple directions models a sculpture, expressing depth by highlighting some areas while allowing others to fall into shadow. Consider, for example, a bronze figure with a patina of light blue, green, and gray coloring. Light sources from different angles render these hues with lesser or greater emphasis.

Highlight and Shadow. Highlights give a good visual clue about surfaces, but care must be used so that highlights do not become dazzling or hypnotically repetitive. Shadow is a good indicator of surface forms and textures, provided it is not so strong as to conceal relevant detail.

Minimizing Glare. There are few problems for the viewer when an object at eye level or lower is lighted from all sides where the center beam axis of the luminaire is 30° or less from the vertical. For a small, low object, the luminaires should be steeply angled, limiting the risk of glare for the observer on the opposite side. When an object is tall, some light may go past the display and cause glare for viewers on the far side looking upward at it. Solutions to this problem include:

- Angling the luminaires sharply down and relieving shadows with a high-reflectance pedestal
- Keeping light beams entirely within the mass of the display
- Illuminating objects from below as long as appearances are not distorted
- Using overall soft lighting (fill light) in the display space so that all objects can be readily seen, while focusing a narrow beam (key light) on the important parts of each object
- Lighting the background behind the artifact

(The above methods are detailed in Figure 14-12a through f.) In situations where an object is placed in a niche but not directly against a wall, treat the niche as a display case and be guided by the procedures discussed in the section "Exhibit Cases" above.

Outdoor monuments and sculptures require the same lighting principles outlined above, but they require different lighting equipment due to monument size, placement, weather conditions, and the potential for vandalism. Care should be taken to minimize light pollution or light trespass. See Chapter 21, Exterior Lighting, for further details.

Figure 14-12. Sculpture lighting: Alan Houser's Apache Warrior. Los Angeles County Museum of Natural History, 1982. (a) Key, fill and back light. (b) Key light only. (c) Fill light only. (d) Back light only.

Realistic Environments

Museums sometimes create realistic environments, where the space itself becomes the message. Examples include period rooms, outdoor scenes, or historic houses. Lighting in character with the original purpose of the space is desirable, within reason. The Museum of Science and Industry in Chicago has a simulated "coal mine." Real miners with helmet lamps require very little light because they are familiar with the environment. Thus a true coal mine's underground lighting would be too dark for visitor safety, much less transmit the exhibit's intended message.

Clearly, realistic exhibit spaces require compromises. The lighting designer can employ at least two techniques to achieve realistic lighting: concealed lighting positions and dual lighting systems.

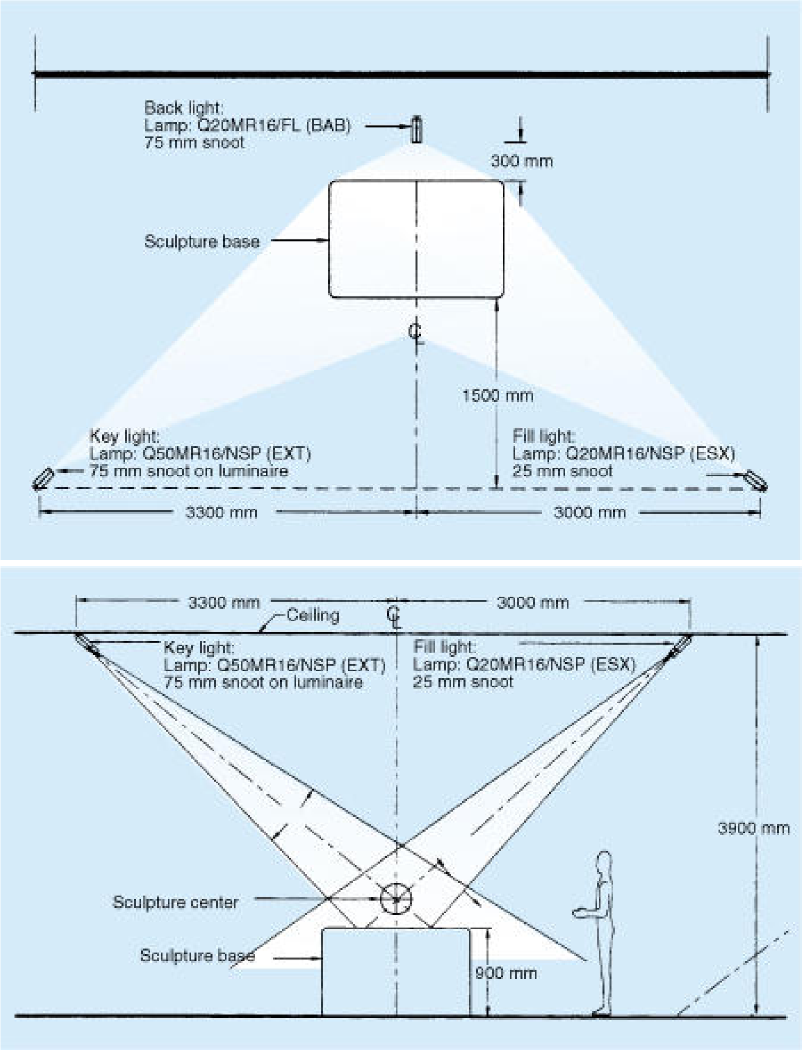


Figure 14-12. Sculpture lighting, *continued*. (e) Plan view. (f) Front elevation.

Concealed Lighting. Concealed lighting locations require definitive viewing positions, highlighted prominent display features, and adequate light for visitor safety.

Dual Lighting. A dual lighting system uses control equipment that alternates, either automatically or manually, between realistic lighting and good display lighting. The display lighting should complement the realistic lighting in both style and color. Electric lighting must substitute for original flame source lighting (candles, mantles, gas jets) for safety and conservation reasons. (Any real flame would emit unwanted soot and water vapor into the display area.) Electric light that very slowly alternates between the glow emitted by a gas jet and the intensity required for easy viewing can be very effective. Reproducing realistic lighting requires extensive research and observation by the designer, as has been described by Robinson.[10]

ARCHITECTURAL ASPECTS AND DAYLIGHT

Architectural forms and daylight affecting lighting in museums and art galleries should be analyzed in terms of their impact on adaptation, orientation, and artifact preservation. Six factors affect the final luminance produced by architectural surfaces and daylight:

- The area of operative glazing in relation to the floor area
- The room dimensions, especially the ceiling height and room depth
- The placing and spacing of available glazings
- Site location in terms of longitude and latitude and direction
- Obstructions, external and internal
- The reflecting characteristics of interior surfaces

Adaptation, Orientation, and Artifact Preservation

The human visual system can comfortably perceive only a narrow range of brightness at one time (see Chapter 3, Vision and Perception). In general, the exhibit illuminance should be no more than five times the illuminance of the surrounding area (5:1).

Transitional Spaces. The exact time required to adapt to a change in retinal illumination depends on the magnitude of the change, the extent to which it involves different photoreceptors, the direction of the change, the transition time, and the visitor's age. Usually, adaptation occurs within 1 second if the change in luminance is in the range of 100:1. When changes in retinal illuminance are large (luminance range greater than 1000:1), photochemical adaptation is required. The direction of the change is an important consideration if photochemical adaptation is involved because changes to a higher retinal illuminance occur faster than changes to a lower retinal illuminance. When only cone photoreceptors are involved, a few minutes is sufficient for adaptation to occur, while changes from cone photoreceptor operation to rod photoreceptor operation may take tens of minutes. The visitor's age is important. Relative to young people, older people may take longer to adapt and achieve a less complete adaptation. See Chapter 3, Vision and Perception, for more information.

Preservation. Window walls should face north (in the northern hemisphere) and transmit only the visible portions of the spectrum. Such glazing should eliminate all wavelengths below 400 nm. The illuminance within the room should remain within the guidelines outlined in Figure 14-4. This could result in glazing transmittance of less than five percent of the visible and solar energy. Galleries illuminated by daylight should incorporate a method for completely restricting daylight when the galleries are closed to the public. Finally, in no case should direct sunlight strike a sensitive artifact.

Sample of Architectural Features

Light Wells. Skylights with light wells can bring the outside into a gallery without contributing to artifact degradation. All light wells should be splayed, with the side walls tilted at, preferably, 30° to the vertical. The walls should be finished in matte white.

Electrically Controlled Glazings. Glazings have been introduced that have electrically charged particles embedded in the glass. Applying voltage to these windows causes the particles to align and the glass to become translucent. Removing the electric charge allows the particles to form random patterns and the glass to become transparent. This is a new product, but its potential for museum use is far reaching (see Chapter 8, Daylighting).

Low-Emissivity Glazings. Low-transmittance or low-emissivity glasses and plastics offer a measure of brightness reduction that increases as their transmittance decreases. Low-emissivity glazings reflect most of the sun's UV rays, the wavelengths chiefly responsible for fabric fading. Most low-emissivity windows have a clear outer pane, a space, and a low-emissivity coating on the airgap side of the inner pane.

ELECTRIC LIGHT SOURCES

Light sources used for museum applications fall into three main categories; incandescent, fluorescent, and high-intensity discharge (HID). Incandescent includes halogen light sources, both line voltage (120 volts) and low voltage (usually 12 volts). Incandescent and fluorescent lamps are generally the best sources for interior display applications. See Chapter 6, Light Sources, and manufacturers' literature for information on lamps.

LUMINAIRES AND ACCESSORIES

Typical museum and art gallery interior lighting applications include:

- General lighting
- Accent lighting
- Indirect lighting
- Case or cabinet lighting
- Flood lighting
- Special effects lighting
- Safety lighting

Track lighting systems serve a dual purpose: connecting a light source to the power source and supporting the luminaire. Care should be taken not to overload the track, both electrically and physically, with too many luminaires. Underwriters Laboratories and American National Standard Institute (UL/ANSI) 1574, Second Edition (1995), delineates twenty different parts of a typical track lighting system. Track lighting has become prominent in museums, mainly because of its versatility. Track luminaires can include many different light sources and beam patterns.

Track accessories include equipment such as lenses, filters, louvers, hoods, "barn doors," and shutters (Figure 14-13a to f) that allow the luminaires to conform to exact requirements of the display.

Lenses. Lenses change light direction and distribution (Figure 14-13a).

Filters. Filters change the spectral composition of the incident flux (Figure 14-13b). For example, a red filter in a luminaire produces red light because it absorbs or "subtracts" wavelengths in certain parts of the spectrum and transmits the remaining wavelengths, in this case long wavelengths. Subtractive filters can be combined to limit radiation to regions of spectral overlap. The process is explained by Bouguer's Law, which can be found in Chapter 1, Light and Optics. If a red filter is in one luminaire and a blue filter is in another, and both are focused at the same spot, the resulting color adds to produce magenta. Some filters simply eliminate unwanted radiation. Neutral filters reduce radiation at all wavelengths equally. UV filters eliminate radiation below 400 nm.

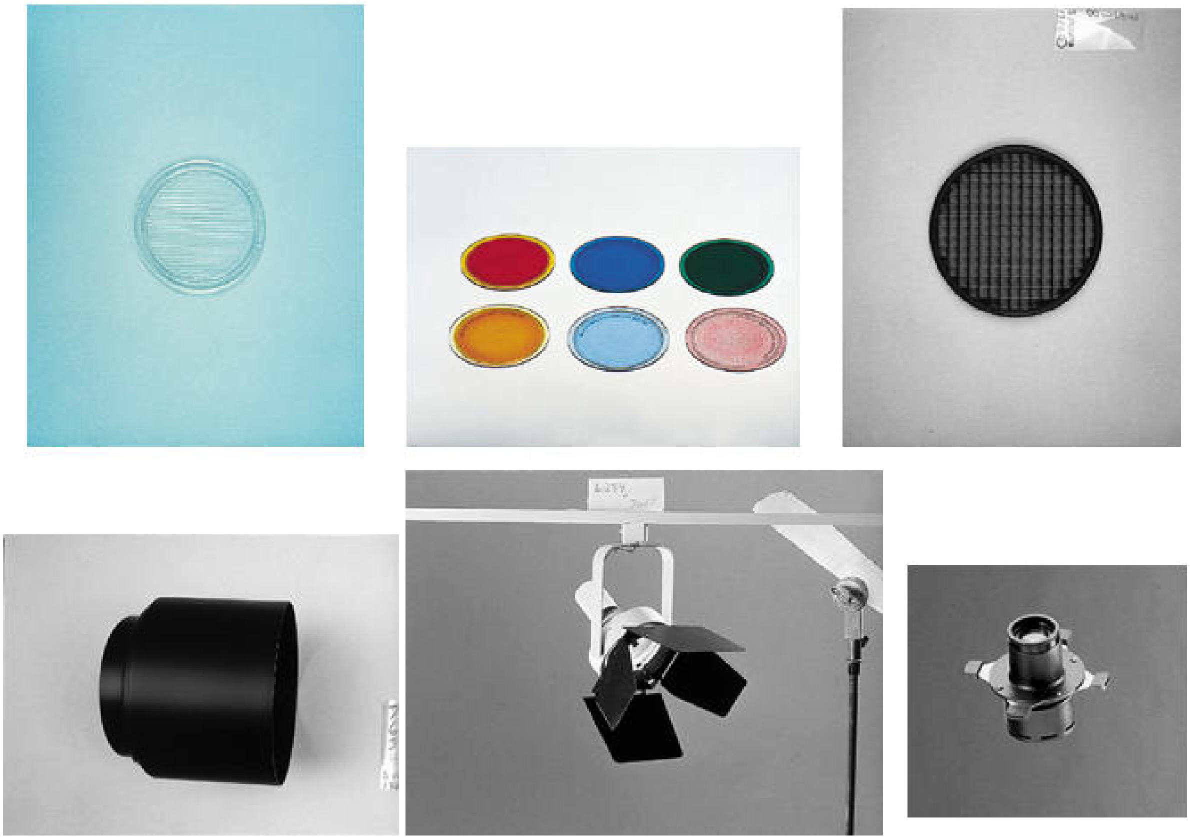


Figure 14-13. Examples of accessories that make track lighting fixtures perform to exact needs: (a) spread lenses, (b) color filters, (c) "egg-crate" louvers, (d) hoods, (e) "barn doors," and (f) and shutters.

Screening. Common metal window screening found in most hardware stores can help reduce illuminance. Screened luminaires deliver between 30 and 50% of the illuminance relative to an unscreened luminaire. Screens can be cut with scissors to fit any luminaire aperture, and screens are virtually indestructible. Screens for television, film, and theater use are made with a metal frame. The screen should always be metal, and stainless steel is the best screen material.

LIGHTING CONTROLS

Lighting controls for museums and art galleries historically have been limited to dimmers for reducing light levels and possibly adjusting source color. Today, the application of modern controls must also limit (or remove) UV radiation, shield sensitive objects from sunlight, create visual drama within displays, and limit the time artifacts are exposed to all visible light.

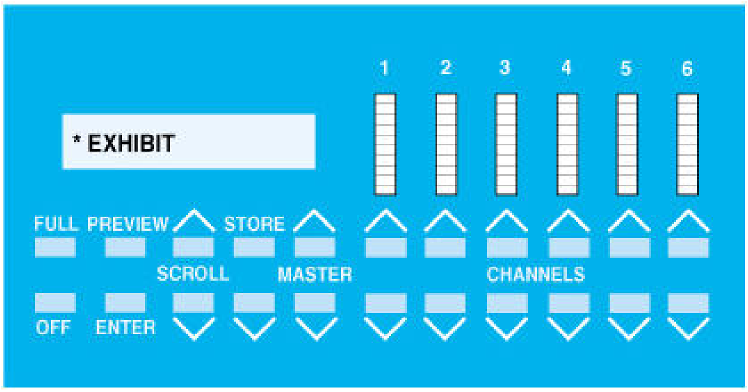


Figure 14-14. Preset dimming control systems allow programming each exhibit for a specific light level and can be combined with automatic sensors that let the exhibit lighting remain low until a person approaches.

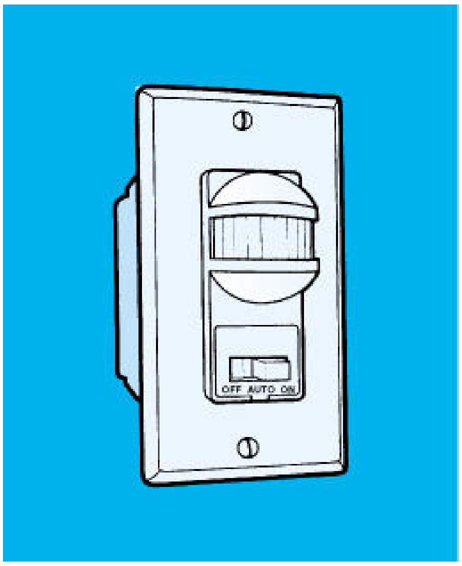


Figure 14-15. Wall-mounted motion sensors use ultrasonic or infrared technology to determine movement within a space.

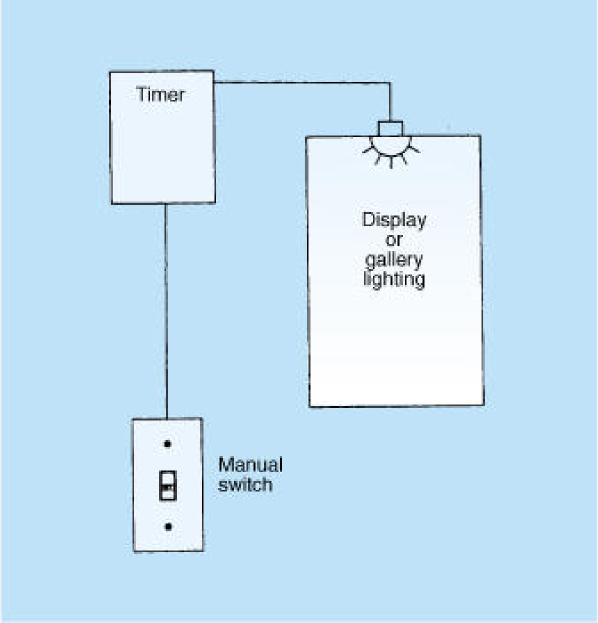


Figure 14-16. Manual switching systems are a familiar and inexpensive way to activate display lighting. The timer automatically limits artifact exposure.

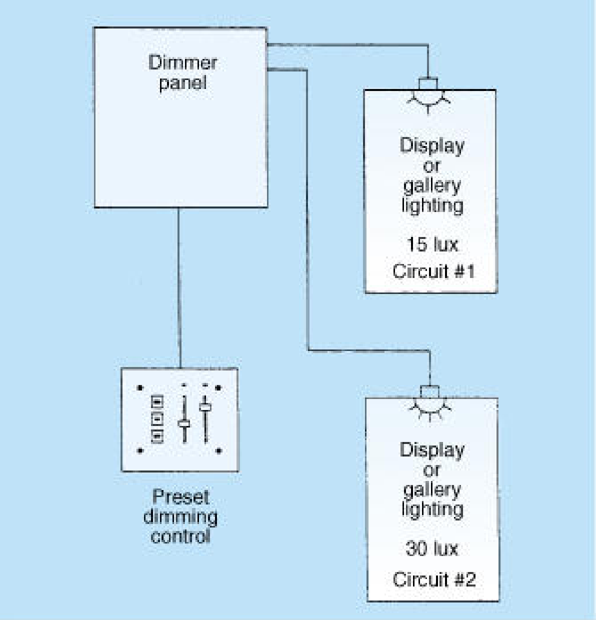


Figure 14-17. Preset dimmer systems can be turned on each day to provide the same light level every time. Lockout protection can keep the settings from being changed by anyone except authorized personnel.

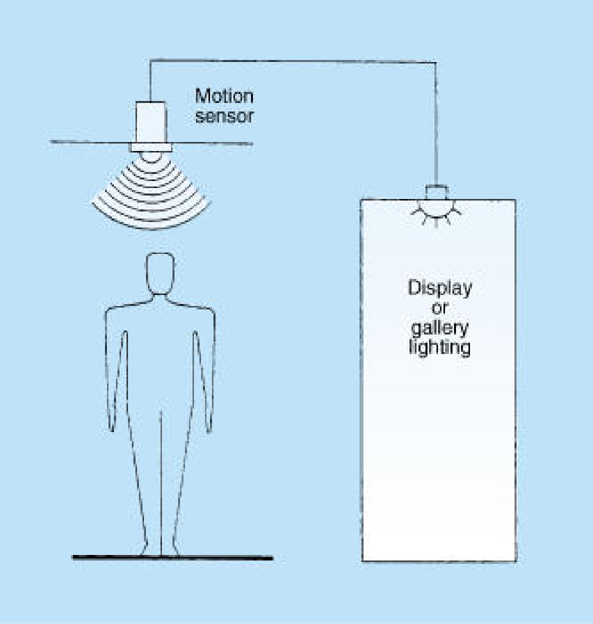


Figure 14-18. Motion sensor systems detect the approach of a person and then illuminate the displays. The lights remain low (or off) until actually needed.

Figure 14-19. Synagogue lighting. Accent lighting highlights the holy ark and bema. Downlights mounted on a triangulated space frame illuminate the congregational area.

There are six major types of lighting controls: manual switching, manual dimming, preset dimming, program control, motion sensor, and filters (Figures 14-14 to 14-18). Additional information can be found in Chapter 27, Lighting Controls, and in other sources.

The future holds new options for the lighting designer, including electrically tinted window glass maintainable at any tint grade from clear to fully darkened. When coupled with a dimming system for electric light, this window shading allows for very subtle shifts between daylight and electric light.

HOUSES OF WORSHIP[11]

One of the most important aspects of a successful design for a worship facility is the method employed to provide illumination. Skillfully used lighting makes services at houses of worship (such as synagogues, mosques, and churches) more meaningful and enhances the architectural design (Figure 14-19). An important consideration is the strategic and feasible use of daylight. In conceiving the design elements for a house of worship, the designer should consider the electric light as an augmentation to daylight.

There is no aspect of the space for which daylighting cannot be considered. Daylight can be used for task lighting, accent lighting, and architectural and celebration lighting. Consideration of daylighting must be related to the time of day. Daylighting can be used for task or general lighting in the nave area, as well as accent lighting in the leadership areas (sanctuary, chancel, or bema). Sources of daylighting are the roof (skylights or dormer windows) and the walls (windows or full walls). Such lighting may be direct or indirect. It should be used with care so that glare and view do not create visual competition during the religious service.

Controls are required for every lighting system, the simplest controls being blinds for daylight and on-off switches for electric light. Consideration of more sophisticated control methods is strongly suggested. The ultimate success of the lighting system is enhanced by a more sophisticated control system (see Chapter 27, Lighting Controls).

The owner, architect, and lighting designer should work closely to achieve a good solution. Since there is a wide range of equipment and lamps available, mockups at the site are recommended for existing facilities.

There are state, provincial, and local energy codes governing lighting installations. These regulations do not necessarily preclude tungsten-halogen sources when they are used with highly efficient luminaires. Refer to Chapter 26, Energy Management, for more information.

Main Worship Area

The interior lighting system consists of four components (Figures 14-20 and 14-21):

- *Task lighting for reading*: Congregational and leadership function lighting
- *Accent lighting*: Lighting for focus on the speaker, leader, and religious objects (vertical surfaces)
- *General ambient lighting*: The illumination that lights the ceiling (indirect) and washes the walls to reveal the religious interior, and highlights the architectural features such as arches and trusses
- *Celebration lighting*: The festive and joyous light from candles, reflections in polished metal and sometimes chandeliers and lanterns at a relatively low brightness

Seventy-five to one hundred years ago, all four components came from one source, first, single gas luminaires and, later on, electrified pendant church lanterns. Today, with new technology light sources and systems, it is appropriate to design for flexible lighting.

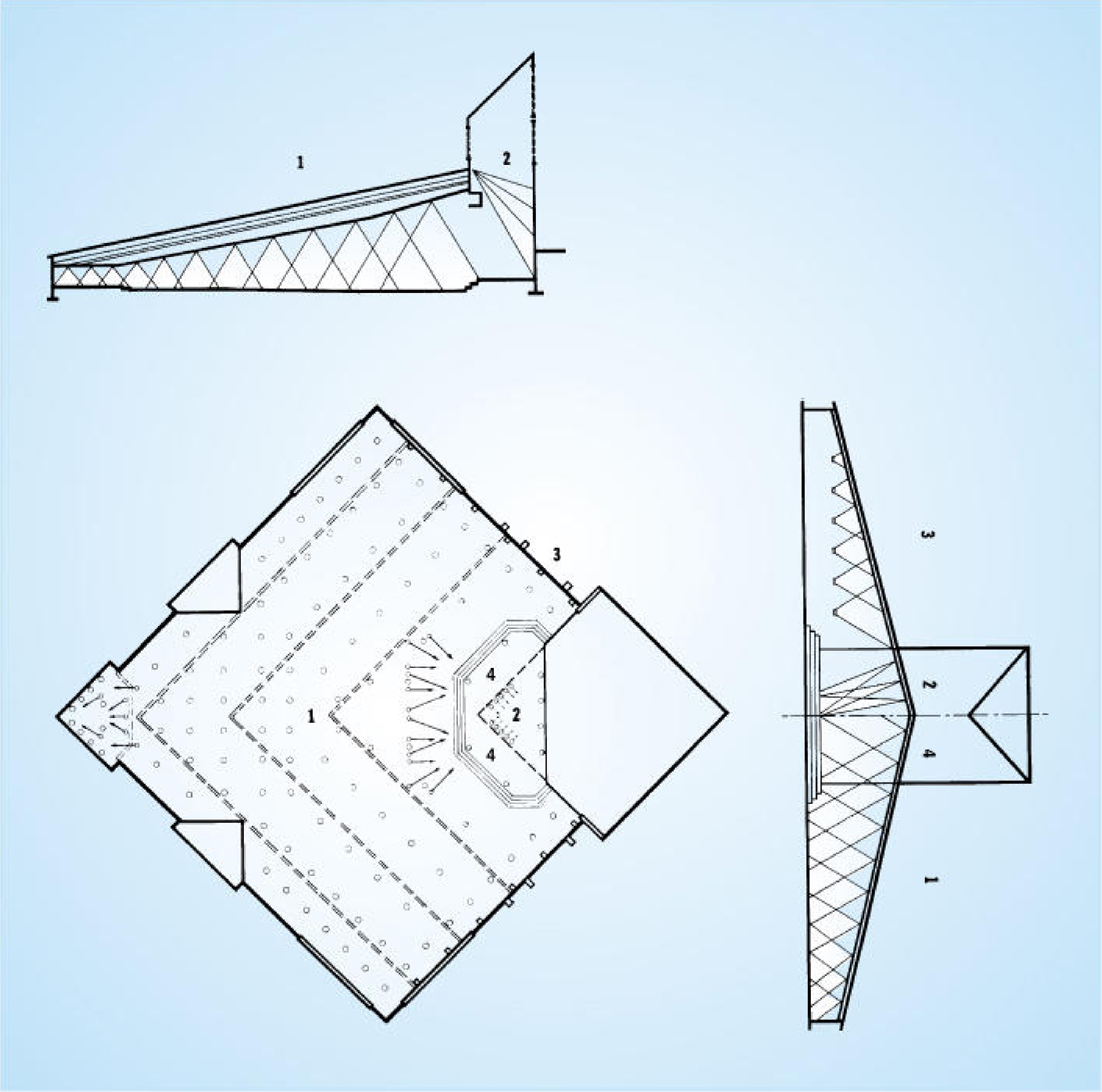


Figure 14-20. A possible system of lighting for a modern fan-shaped church: (1) Task reading light from recessed downlights. (2) Accent light from recessed adjustable spotlights. (3) Architectural light from wall-mounted urns. (4) Celebration light utilizing candles with polished brass to add sparkle.

Relative brightnesses in main worship areas are more important than absolute illuminance levels. A survey showed that the illuminance levels of previously lighted (1920 to 1980) houses of worship vary from 30 to 1000 lx (3 to 100 fc) in the seating area. Lower light levels were found in older architecturally rich houses of worship, and higher light levels were found in more modern facilities and in those associated with less liturgical groups.[11]

The base horizontal illuminance for reading (task lighting) is 100 to 200 lx (10 to 20 fc). This is the illuminance value to which accent and architectural lighting levels are compared. For accent lighting, the vertical illuminance should be approximately three times higher than the horizontal illuminance for reading in the seating area. For general ambient lighting, the vertical illuminance should be approximately one-fourth (or less) of the illuminance for the reading task in the seating area. For other recommended illuminance levels, refer to Chapter 10, Quality of the Visual Environment.

Television Lighting

Supplementary accent lighting used for video cameras and television broadcasting can be part of the original design; thus, it can be integrated into the architecture so that it does not create glare for those in attendance. Luminaire positions must be reviewed to provide adequate vertical surface illuminance. This component of the lighting system should be separately controlled, as it may be used only occasionally.

Lighting Controls

Lighting control systems can entirely change the appearance of the worship space. There are various types of equipment that can be part of a lighting control system: (1) simple switches to turn lights on and off; (2) time clocks to control interior and exterior lights automatically; (3) sensors that respond to occupant motion; (4) wall-box dimmers, motorized louvers and shades for daylighting; or (5) a modern dimming control system that combines all of the above controls. See Chapter 27, Lighting Controls, for more information.

A modern dimming control system allows all the lighting to be grouped into control channels, and scenes can be created so that one preset button allows for easy settings of all the light levels. At the installation stage, the designer sets the relative levels for each control channel (groups of lights) so the lighting system best supports the different functions. Suggested preset functions (or moods) are:

- *Visiting hours*. When the building is open to the public, there is a low level of general ambient lighting with accent lighting on the devotional shrines.
- *Before and after service*. Lighting at low level is provided for movement of the congregation.
- *Service*. Accent lighting is used in the leadership area, reading lighting is increased, and lighting on devotional areas is diminished.
- *Sermon*. The speaker is lighted with accent lighting, and all other lighting is at a low level.
- *Service at focal point*. Downlights and accents are combined on processional and focal areas.
- *Weddings and funerals*. Celebration and general ambient lighting is provided with selected accent lights for the specific ceremony.
- *Major feasts and concerts*. Higher levels of downlighting and accent lighting are used in the performance area, with lower levels in the congregational area.
- *Manual*. The ability to override presets and allow direct control of the lighting is an important feature.

These are only a few of the possible choices for preset functions.

Not all interiors need the full capabilities of a dimming control system. A small church may use only a set of master controls that provide direct control over groups of luminaires. Larger churches may need a preset system with remote activator buttons at door entry, pulpit, organ, and other locations. For special events, houses of worship need to continuously vary illuminance from very low to full output during the course of the event. Naturally, all lighting hardware should be integrated to account for this variation.

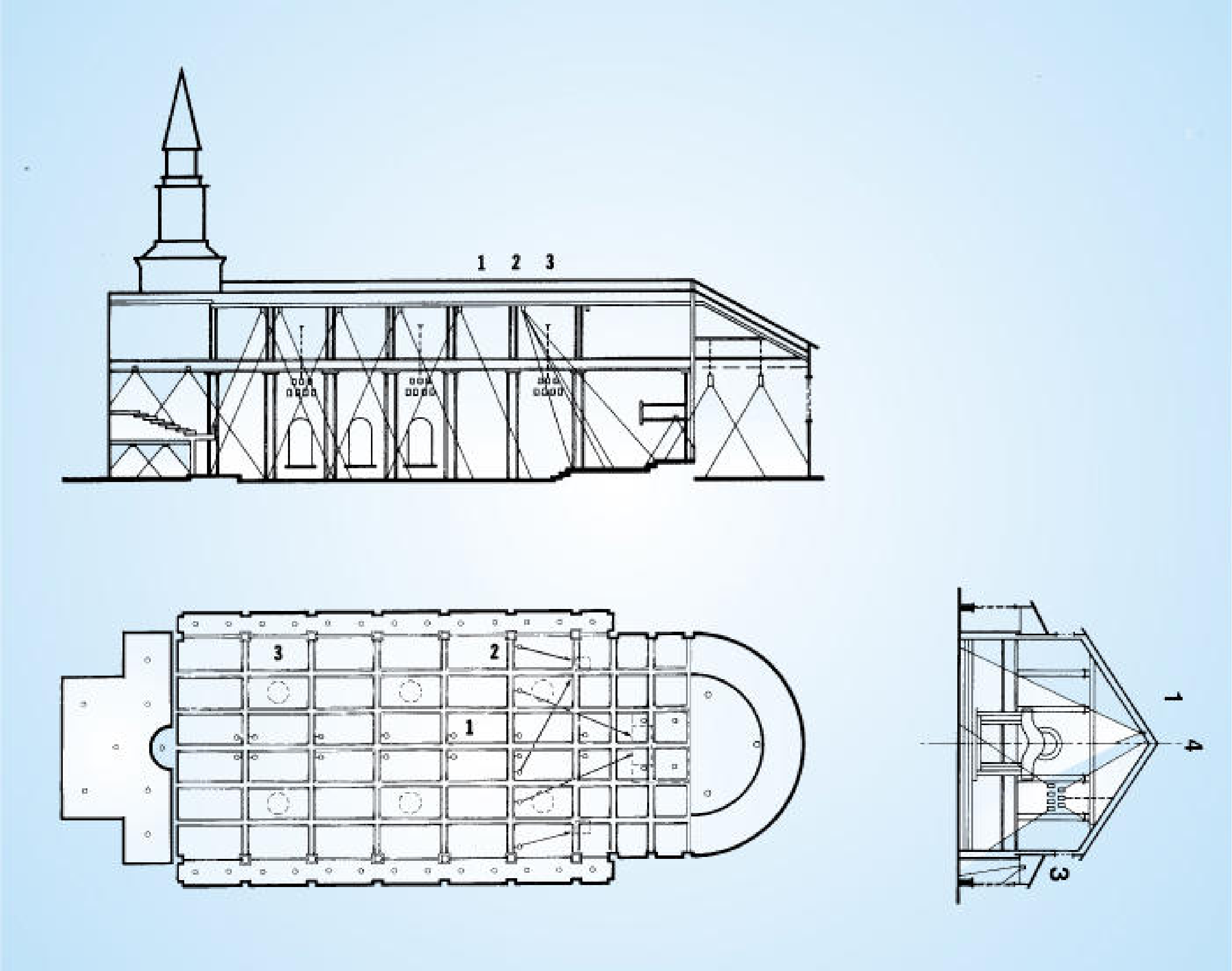


Figure 14-21. A possible lighting system for a modified traditional church: (1) Task reading light from bracketed downlights. (2) Accent lighting with bracketed spotlights. (3) Architectural light with uplighting in a chandelier and side-aisle wall washers. (4) Celebration light with controlled adjustable chandeliers.

In all cases, when dimming controls are used, energy is saved, since modern dimmers reduce wattage throughout the dimming range. Further, dimming can prolong lamp life and reduce maintenance.

Exterior Lighting

A house of worship is one of the main focal points in the urban or country landscape. It can be a point of reference for the community, and its exterior projected image is of great importance. The exterior lighting should be attractive and inviting. When designing lighting for the exterior of a house of worship, the following issues should be considered:

- The directions in which the building is viewed
- The effects that seasonal change will have upon the lighting system
- Other existent visual competitions
- The energy codes applicable to exterior lighting
- The precautions required to avoid unwanted spill light

In addition to understanding the issues discussed above, the designer should also consider factors such as brightness relationships, glare, shadows, surface texture and color, light source color, energy utilization, and maintenance. During the design process, specific design objectives should be established for the following:

Facade illumination. When lighting the facade for identification or enhancement, considerations should be given to the viewing angles, visual competition, luminaire locations, color rendition, brightness relationships, and maintenance. Generally, direct lighting is used, and control of the spill light should be addressed.

Spire and Steeple Illumination. Lighting is generally provided so that the community can identify the building as a place of worship. Brightness relationships, surface reflectances, and maintenance should be considered. Generally, spire and steeple lighting is nearly always directional (narrow-beam floodlights), although installation of an internal illuminator has been successful where the surface materials are translucent (see Figure 14-22 and Chapter 21, Exterior Lighting).

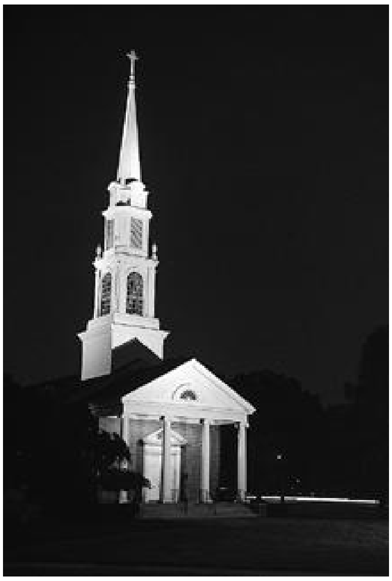


Figure 14-22. Steeple uplighted with narrow-beam floodlights.

Art Glass Window Illumination. Lighting specialists should work closely with the art glass window designer to determine its desired appearance. In all stained art glass windows the density, diffusion, and refractive qualities of the glass determine the light source intensity and size to be used. The selection of the source type also should be based on the predominant colors of the glass. Different source types affect the glass colors differently, so a visual comparison of the effects should be performed. A combination of sources usually gives the best results. It is not necessary or desirable to achieve perfectly flat or uniform lighting effects. It is recommended that a mockup of the lighting system be built to determine how the glass will respond.

Generally, the lighting of art glass windows serves two purposes: general viewing from inside during nighttime services, and viewing from outside for passing traffic at night.

Viewing from inside. The window can be lighted with outside floodlighting if the glass has sufficient diffusion qualities (from irregularities on the surface of the glass and within the glass). If the glass is not diffuse, the luminaires should be located so that they are not seen through the glass and do not produce visual "hot spots." Clear stained glass needs a luminous background, such as a closed light box around the outside of the window, or a diffuse protective layer, such as frosted or opalescent protective glass; however, these solutions eliminate the view of the window from the exterior.

Viewing from outside. The floodlighting approach discussed above also can be used, with equipment carefully located inside the building. The luminaires' positions are often limited. The most convenient location often is on the ceiling, but the viewer is usually below the window, making bright spots a potential problem. A larger number of low-intensity floodlights can make the spots less apparent. For transparent stained glass, a scrim, movable screen, or drape can be placed inside and lighted to form a luminous background. This element can be moved away when the window is to be viewed from the inside.

Sign Illumination. Sign illumination is used to identify the function of the location within the building. The signs should be lighted to provide legibility and highlighted to contrast with the general surrounding. If only the name of the facility appears on the facade, spot lighting or wall-wash lighting can be used.

Driveway and Parking Illumination. When lighting driveways and parking areas, glare, light trespass, security, general view, and maintenance should be given consideration. Uniform illumination of the parking lot is desirable, with highlights for the entrances, exits, and congested areas.

Entrance and Walkways. When lighting an entrance and adjacent walkways, spill light on the facade, on stain-glass window lighting, or on nearby buildings should be avoided. Glare should be minimized. The entrance should be highlighted, and walkway lighting can be part of the roadway or parking area lighting systems.

Security Lighting. In some interior areas it may be desirable to provide motion sensors to energize selected interior luminaires that will alarm an intruder and give notice to passersby that someone is inside the space. A path of light also can be provided automatically to authorized occupants entering the facility. This can obviate night lighting. With regard to exterior security lighting, the use of a site lighting system, building-mounted luminaires, or interior lighting that illuminates the exterior through the windows should be considered.

Maintenance Concerns. Light sources, luminaires, and controls should be selected so that maintenance is easy. Lighting devices should be placed where access is convenient.

Lighting for Special Functions. An exterior devotional grotto, facility, or shrine should be lighted in a manner that does not subject the visitor or worshiper to glare and provides the proper reverent atmosphere. Low-profile landscape and walkway lighting can be incorporated into most designs for general area lighting, with the grotto or shrine lighted from within. See the section "Landscape Lighting" in Chapter 21, Exterior Lighting.

Additional circuits can be supplied to parking area lighting or driveway poles to connect temporary lighting for church festivals and seasonal outdoor events. See Chapter 22, Roadway Lighting, for parking and walkway lighting.

COURTROOMS

Courtrooms are associated with a variety of visual tasks including reading, audiovisual presentations, camera monitoring, and recording. Special lighting considerations for courtrooms include low-glare luminaires, dimming with preset levels for typical functions, and luminaires that enhance the dignity of the courtroom. Color rendering is important because color can be an important aspect of the evidence introduced in the courtroom. Recommended horizontal illuminance levels are described in Chapter 10, Quality of the Visual Environment.

Flexibility of the lighting system is extremely important in the modern courtroom. Audiovisual equipment is used for video arraignment, giving evidence, recording court proceedings, and providing public access through news organizations. With the use of audiovisual demonstrations in the courtroom, the illuminance on the wall must be less than 5 lx (0.5 fc). At the same time, the judge, jury, and attorneys must be able to take notes. Lighting must minimize glare for courtroom participants (Figure 14-23) and for video technologies and should be in keeping with the dignity of the legal process. Lighting control, often managed by those with limited technical skills, must be flexible to accommodate diverse visual tasks.

Figure 14-23. The 15 courtrooms in the Mark O. Hatfield U.S. Courthouse are lighted with a combination of 32-watt T-8 fluorescent lamps with electronic ballasts plus 50-, 60- and 100-watt halogen lamps. The lighting is controlled by a system on the judge's bench.

CORRECTIONAL FACILITIES

The challenges of lighting correctional facilities include the analysis of various visual tasks, emergency lighting, lighting control, fixture durability, and security. Different visual environments should be provided for central security personnel, jailers, inmates in various categories of incarceration, dispatch personnel, inmate visitors, attorneys, judges, juries, and witnesses. To understand the basic principles involved, refer to Chapter 3, Vision and Perception; Chapter 4, Color; and Chapter 10, Quality of the Visual Environment.

Many operations are not unique to correctional facilities but are similar to those in many other facilities, such as offices, laundries, kitchens, and exercise areas. Lighting for these functions and their related tasks is not discussed in this chapter; the reader is referred to the respective chapters of interest in this Handbook. In some cases, there is an overlap of recommendations. As an example, the lighting of dormitory sleeping rooms is similar to that in a minimum security unit, yet the latter is differentiated from the former by security risks associated with incarcerated individuals, by the penal character of the institutions, and by monitoring tasks assigned to central security operations.

Lighting Objectives

The approach to the lighting needs of correctional facilities has been undergoing rapid change with the development of new sources and equipment, new computer modeling programs for evaluating applications, and new energy codes.

The selection and application of lighting sources and equipment should consider the behavioral aspects of the incarcerated individuals. For the morale and self-image of inmates and visitors, the color rendering of skin, eyes, hair, and clothing also should be considered. Daylighting may soothe rather than agitate the incarcerated individuals, as well as support the visual needs of personnel and other participants in the correctional system. Light sources that flicker should be avoided, particularly in situations where inmate self-control is important. Energy conservation and management are also of great public concern (see Chapter 28, Energy Management).

Illuminance recommendations for correctional facilities are given in Chapter 10, Quality of the Visual Environment. To ensure comfortable lighting environments it is desirable to limit the luminance ratios between the task and other areas in the field of view. The luminance ratio between the task and the adjacent surrounding should be no greater than 3:1; between the task and remote darker surfaces, no greater than 5:1 and between the task and remote brighter surfaces, no greater than 1:5. To help achieve these ratios, the reflectances of the ceilings should be 80%; the walls, between 40 and 60%, the furniture and equipment, between 25 and 45%, and the floors, between 20 and 40%.

Types of Facilities

Prisons. Prisons are those facilities that incarcerate adults whose criminal offenses are serious in nature with sentences exceeding more than one year. These facilities are typically managed by national and state (or provincial) governments, although in some cases they are managed by local government agencies. Some prisons may house only minimum-security or medium-security inmates, only female inmates, or only maximum-security inmates.

Due to the long sentences for some inmates in these facilities, educational opportunities are often offered. Medical and dental facilities are provided to serve the inmates of these facilities so as to avoid risk of transportation to public places.

Residential Inmate Facilities. Halfway-house services have been added to some correctional facilities. In these areas the lighting may include design features and controls similar to those in residential facilities. Daylighting helps soften the facility and may assist the inmate in adjusting to greater freedom.

Work Release Program. Work-release facilities vary in the types of inmates incarcerated and the philosophies of the program administrators. Facilities vary from minimum security to residential facilities. Since the inmates leave the facility every day, many of the security features are relaxed, and lighting design features and controls may be similar to residential facilities.

Juvenile Detention Facilities. The philosophy of juvenile detention facilities is evolving. For many years, juvenile facilities had a residential character; however, with the recent teen-gang violence many new facilities are much like facilities for adult populations.

Jails. Jails generally house individuals whose offenses are locally prosecuted and less serious in nature, and whose sentences are less than a year. Jail facilities are often combined with court facilities to reduce the difficulty and expense of transporting prisoners for judicial proceedings. With the use of video arraignment, juxtapositioning facilities is becoming less important.

Forensic Facilities. At forensic facilities incarcerated individuals are analyzed for judicial purposes and correctional purposes. The inmates of forensic facilities pose a greater risk to themselves and are usually more unpredictable than those found in prison facilities for general populations. Forensic facilities may be part of a prison or mental health campus. The lighting presents challenges on several fronts: aesthetics, health issues, security, and local control.

Lighting Design Considerations

Cells. For American Correctional Association (ACA) accreditation, an average of 200 lx (20 fc) must be provided in a cell. For reading, 300 lx (30 fc) should be provided at the head of the bed. Luminaire construction needs to be rugged to withstand tampering and physical abuse. Special luminaire mountings often must be used, which can accommodate recessed lighting in security plaster ceilings or in concrete, or surface mounting to concrete. Considerations should be given to security screws in luminaire construction that preclude the hiding of contraband by inmates. Lighting control varies for different security levels and may be based on local preference. Lighting for medium- and maximum-security cells is typically controlled from the security operations center. Minimum-security cell lighting may be controlled locally with a central override or from the security operations center.

Dayroom. Dayrooms involve a variety of visual tasks including television viewing, conversation, reading, and eating. These tasks range from 150 to 300 lx (15 to 30 fc), although other levels can be used depending on the age of the occupants or other factors. Typically, glare is difficult to control with security style luminaires, but it can be reduced with architectural features such as valances. Lighting control from security operations can reduce glare for television viewing and save energy.

Perimeter Fence. Perimeter fences are usually comprised of two fences with a roadway in between for vehicle patrols. Lighting is typically located beyond the secure perimeter of the outside fence. A minimum vertical illuminance at the fence of 50 lx (5 fc) is recommended. Pole locations should be coordinated with the locations of security cameras. See the section "Emergency, Safety, and Security" in Chapter 10, Quality of the Visual Environment.

Prison Yard. Prison yard lighting is required for visual identification of potential security breaches by inmates. Luminaire placement must consider the locations of personnel in guard towers and in vehicles patrolling the perimeter fence as well as security cameras. In addition, the poles need to be located far enough from the fence to prevent inmates from using them for escape. Fences should be illuminated and not in shadow from the viewing angles of the guard personnel and cameras. Lighting controls may include a combination of photocells, motion sensors, and manual controls. Consideration should be given to energy conservation and light trespass (Figure 14-24).

Figure 14-24. High-mast lighting for a prison yard.

Security Operations. Security operations involve control panels with pushbutton or rotary switches, touch screens, and monitors. Glare from the luminaires must be minimized in the security operations rooms, as well as from adjacent areas such as corridors. This must be accomplished by architectural shielding because typical correctional luminaires do not include louvers, and indirect lighting is difficult to apply unless ceiling heights are high enough to prevent damage to luminaires by inmates. Dimming is used for night operations.

Dispatch. Dispatch includes a variety of office tasks. The dispatch center is usually located in a hardened (secure) facility, often with no windows to the outside. The job is highly automated with an electronic control panel and one or more VDTs; however, there can still be paper-based tasks.

In many cases, the lighting system utilizes dimming to provide different illuminances for different operators. The area for emergency (911) operations can be separated from other areas. Many dispatch centers are highly dynamic with inmate moves, adds, and changes occurring regularly. Most modern dispatch center control consoles are designed into modular furniture. The optimum configuration is a combination of low-level general lighting with local task lighting controlled at every station. This allows every dispatcher the opportunity to customize the station.

Crime Laboratories. Crime laboratories can be very simple or complex, depending on the resources of the agency. Simple labs require typical office lighting. The more advanced laboratories can have electronic equipment, a shooting range, a darkroom facility, and other areas that require lighting.

Some crime laboratories use sensitive electronic equipment. As with special treatment areas in hospitals, special power line filters and radio frequency interference (RFI) filtering may be required.

The visual work in a crime laboratory can be very detailed and performed for a very long time. See the section "Illuminance" in Chapter 10, Quality of the Visual Environment, to specify the appropriate illuminances.

Corridors. Corridors in correctional facilities consist of both public (nonsecure) and detention (secure) areas. Lighting for the public areas is covered elsewhere in this chapter.

Corridors in detention areas are used for inmate traffic (both escorted and unescorted) and temporary holding. They can also serve as a buffer between the secure and public areas. Corridor lighting must be adequate for both visual and electronic observations. Luminaires must be selected and placed so that adjacent spaces are not negatively affected, especially control centers equipped with large expanses of security glass.

Visitation Area. Visitation areas in correctional facilities consist of public (nonsecure) and detention (secure) areas. Lighting for public areas is covered elsewhere in this chapter. Lighting should provide for visual and electronic surveillance.

Finally, space functions can change with the needs of the facility. What was once a minimum-security area can become a maximum-security area. The initial lighting design should provide for changes for future uses.

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15

Theatre, Television, and Photographic Lighting

For theatre, television, and film, the lighting system design and luminaire choices are based on production plans. The size and complexity of the system are based on production needs, from elementary training facilities to professional facilities. In all facilities, however, the budget usually determines the degree of complexity.

Theatre design requires information concerning the types of programs (opera, orchestra, choral, dance, drama, variety) that are produced by resident groups or touring companies. Television design requires information concerning types of productions (variety shows, dramas, news, soap operas, panel shows) that will be produced for network or local broadcasting or for closed-circuit or syndication release. The actual illuminance levels for television vary from under 1000 lx (100 fc) to several thousand lx (several hundred fc), depending on the type of camera used.

In lighting for film, both still and motion picture, the function of the lighting is to produce the photochemical changes on the film required to produce the image. Thus, the illuminance required is determined largely by the sensitivity of the film. Additional material on motion picture lighting and projection lighting can be obtained from the Society of Motion Picture and Television Engineers (SMPTE) at <http://www.smpte.org>.

LUMINAIRES, LAMPS, AND CONTROL SYSTEMS

Luminaires for Theatre, Television, and Photographic Lighting

In theatre, television, and photographic (film) lighting, different types of luminaires are used to produce qualities of light that fall within three basic categories:

1. Key light is illumination with defined margins. Its output produces defined but soft-edged shadows and highlights. (A typical luminaire is the Fresnel spotlight.)

2. Soft-edged light, sometimes referred to as "fill light," is diffuse illumination with indefinite margins. Its output produces poorly defined shadows, and it softens and fills the shadows produced by key light. (A typical luminaire is the soft light.)

3. Hard-edged light is illumination that produces sharply defined, geometrically precise shadows. (A typical luminaire is the ellipsoidal spotlight.)

The basic types of luminaires used in theatre, television, and film production have a variety of optical characteristics (Figure 15-1).[1] Most luminaires contain provisions for color filters or diffusion materials. Some special luminaires, or accessory devices, have the ability to remotely control aiming, focus, or color.

Nonlens Luminaires. The nonlens luminaire (primarily used in film location applications) embodies a lamp, a reflector, and frequently a focus mechanism to change the field and beam angles, corresponding to 10% and 50% of maximum intensity, respectively. The spectral quality of the illumination produced by a nonlens luminaire can vary depending on lamp type, reflector finish, heat filters, daylight correction filters, and color frames.

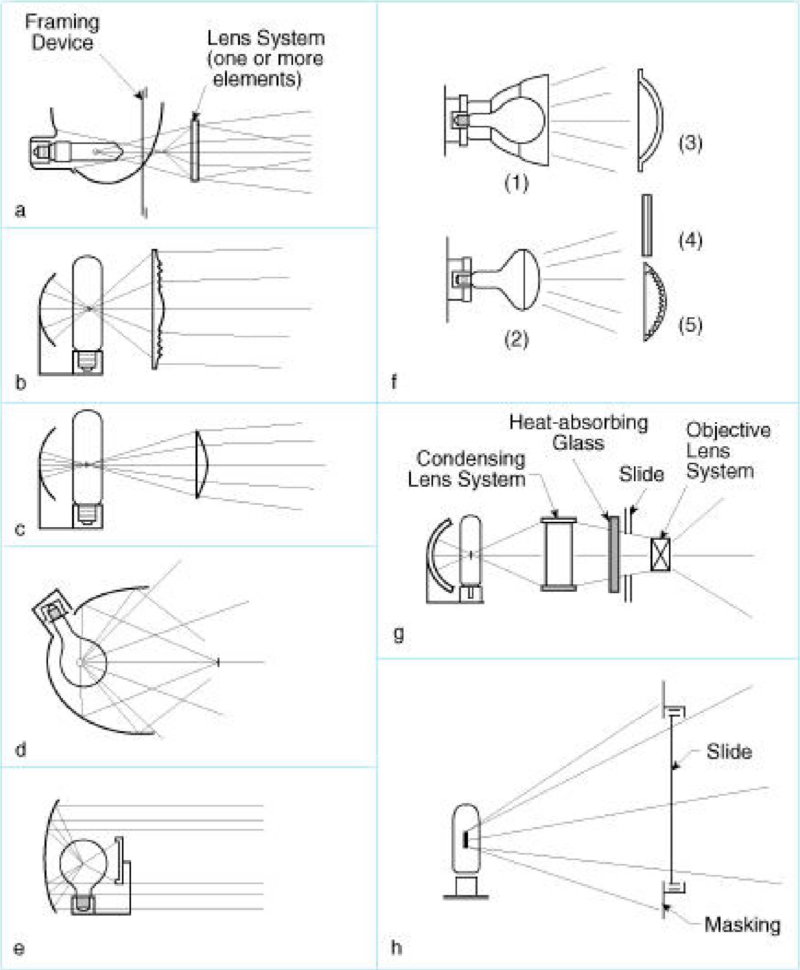


Figure 15-1. Optical characteristics of stage lighting equipment. (a) Ellipsoidal reflector spotlight. (b) Fresnel-lens spotlight. (c) Plano-convex lens spotlight. (d) Scoop-type floodlight. (e) Parabolic-reflector floodlight. (f) Striplight: (1) reflector with general service lamp; (2) reflector lamp; (3) glass roundel; (4) sheet color medium; (5) spread lens roundel, plain or colored. (g) Lens-type scenic slide projector. (h) Nonlens-type scenic slide project (Linnebach type). The luminaires shown in c and e are used primarily in Europe.

There are many different types of nonlens luminaires that can be considered as spotlights or floodlights. They utilize tungsten-halogen lamps from 100 to 2000 W, and discharge sources from 200 to 4000 W. Nonlens luminaires include a variety of light distributions.

Barn doors are swinging flaps attached to the front of a luminaire to control the shape and spread of light; however, the degree of control afforded with barn doors is limited.

Scoops are floodlights consisting of a lampholder, lamp, and reflector with a matte or brushed finish. The lamp and reflector can have a fixed or variable relationship. Scoops are equipped with front clips to hold a color frame containing either color media or diffusion material. The scoop produces illumination having a field angle of 90 to 180°. The quality of the illumination is considered soft, and the shadow sharpness depends primarily on the texture of the reflector. Scoops are available from 250 to 450 mm (10 to 18 in.) in diameter and are usually equipped with incandescent pear-shaped (PS) or tungsten-halogen lamps from 400 to 2000 W. The lamps are usually frosted for further softening of illumination. In general, the larger the diameter of the scoop, the softer the light output. There are variable-focus scoops.

Parabolic (reflector) spotlights consist of a lamp and a parabolic specular reflector. Some luminaires have a reflector in front of the lamp to redirect light into the main reflector. Other luminaires are equipped with spill rings to minimize spill light and glare. In most types of parabolic spotlights, the lamp and reflector are adjustable to produce a wide or a narrow beam of light; the closer the lamp is to the reflector, the wider the beam. This luminaire produces a hard-edged beam that cannot be easily controlled, except, in part, by spill rings. A parabolic spotlight is also known as a sun spot or beam projector. Parabolic spotlights have not enjoyed great interest in North America, but they are becoming more popular.

Soft light luminaires are well-diffused, almost shadow-free, light sources used in special applications. All of the light in these units is reflected off a matte-finish reflector before reaching the subject, and due to this design, they are not efficient sources of illumination.

The soft light is the most common fill light chosen for television studio applications. Soft lights are available from 500 to 8000 W and are used where either shadows or reflections must be minimized.

Broads are small, rectangular floodlights used primarily in television for a very wide, soft lighting effect and fill light. Broads are available in ratings up to 1500 W and are generally designed to use double-ended tungsten-halogen lamps. They commonly have different distributions in the horizontal and vertical directions. Horizontal spreads of over 100° and vertical distributions of near 90° are common.

Cyclorama, or cyc, lights provide an overall wash of illumination over the cyclorama curtain for background. There are two types of cyc lights: strip cyc lights, which are compartmentalized luminaires with lamps on 200 to 300 mm (8 to 12 in.) centers, and cluster lights, mounted on 1.8 to 2.4 m (6 to 8 ft) centers.

Strip cyc lights, when mounted either from above or on the floor, can generally light a cyclorama which is 3.6 to 6.0 m (12 to 20 ft) high. If lights are used on both top and bottom, or if they have an asymmetrical reflector to improve the beam distribution, even higher surfaces can be suitably illuminated. Normally a single group, either suspended from above or floor mounted, has an illuminance falloff greater than 50% from the top of the space to the bottom. Lamps for these luminaires are available from 300 to 2000 W. Striplights have the advantage of much closer mounting to the cyclorama than the cluster lights. This can be critical in those theatres where stage space is limited.

Cluster lights can light a cyclorama up to 9 m (30 ft) high by lighting from the top only, and the illuminance falloff is less than 5%. Since these lights are mounted on 1.8 to 2.4 m (6 to 8 ft) centers, rather than the 300 mm (12 in.) centers for striplights, the power savings is substantial. This type of cyc light usually requires greater stage depth than striplights. Striplights for two-color luminaires use 3300 W/m (1000 W/ft), whereas cluster lights use 820 W/m (250 W/ft) for the same two-color coverage.

Lens Luminaires. The lens luminaire used in theatre, film, and television embodies a lamp, a reflector, a system of one or more lenses, and, frequently, a focus mechanism to change the light output by varying the field and beam angles. The quality of the illumination produced by a lens luminaire can vary from soft to hard, depending on lamp type and reflector finish. External beam control is possible with barn doors, gobos (devices that allow patterns to be projected onto the stage or curtain, usually cut into a flat metal sheet), irises, shutters, color frames, and in some cases adjustable-focal-length arrangements to permit zoom control.

There are many different types of lens luminaires that can be considered as spotlights or floodlights. They utilize tungsten-halogen lamps in the range of 100 to 6000 W. Among those luminaires considered "lens" are Fresnel and ellipsoidal spotlights, parabolic aluminized reflector (PAR) luminaires, striplights, and follow spots. Plano-convex spotlights also fall into this category; however, while they are popular in other parts of the world, they get little use in North America, and for that reason they are not discussed here.

Fresnel Spotlight. The Fresnel spotlight is a luminaire that embodies a lamp, a Fresnel lens, and generally a spherical reflector behind the lamp. The field and beam angles can be varied by changing the distance between the lamp and the lens. The distance between the lamp and the reflector is defined by the optical design and cannot be changed.

The quality of illumination produced by a Fresnel spotlight tends to be intermediate or hard, and the beam angle is soft-edged. The illumination varies considerably depending on the optics of the luminaire. Typical luminaires of this type have a beam angle of 10 to 50°, depending on the relative position of the lamp and lens.

Fresnel spotlights are generally equipped with tungsten-halogen lamps with C-13 or C-13D planar filaments. Many Fresnel spotlights are now available using a compact-source metal halide lamp as well. In order to shape the light beam, barn doors are used, as well as snoots. Snoots are metal tubes mounted on the front of spotlights to control stray light. They are also called funnels, top hats, or high hats. The light beam may also be colored or diffused by means of materials placed in its color frame.

Fresnel spotlights are manufactured in lens diameters from 75 to 610 mm (3 to 24 in.) and in wattages from 75 to 12,000 W. Remote operation (pan, tilt, focusing, on/off) is available on some luminaires. Remote operation of these units can be achieved manually by using a pole, or electrically by use of servomotor-equipped units.

These units are generally designed to be operated within approximately 45° of horizontal, particularly in the higher wattages in the range of 1 to 2 kW. Operating Fresnel luminaires in this wattage range for long periods of time in a vertical position can cause damage to the luminaire and reduce lamp life (which is fairly short anyway), because the fixture cannot dissipate heat well in that position.

Ellipsoidal Spotlight. The ellipsoidal spotlight, or pattern light, consists of a lamp and ellipsoidal reflector mounted in a fixed relationship. The light is focused through the gate of the unit, where the beam can be shaped with the use of shutters, a gobo, or an iris. The shaped beam is then focused by the lens system.

The output of the ellipsoidal spotlight is a hard-edged light with precise beam control. By defocusing the lens system, the hard edge can be softened somewhat. Units are also available with variable beam angles. The lens diameter and focal length determine the throw and coverage of the unit.

Ellipsoidal spotlights are available in sizes from 90 mm (3.5 in.) and 400 W to 300 mm (12 in.) and 2000 W. Units employing metal halide lamps as the light source are also available. The effective throw of the larger units is about 30 m (100 ft).

PAR Luminaires. PAR luminaires embody a PAR lamp, lampholder, and housing. The performance of the luminaire depends on the type of lamp selected. The beam pattern of most PAR lamps is oval, so the luminaire is designed to rotate to cover the desired area. Glare can be reduced by barn doors, and the intensity can be modestly increased by applying a top hat.

PAR luminaires using 650-, 1000- or 1200-W lamps are designed to accommodate either single lamps or groups of lamps in clusters of 3, 6, 9, 12, or more. For special effects, low-voltage, narrow-beam aircraft landing lights are commonly used.

The PAR-64 luminaire is used in many theatres because it can do many jobs and is fairly inexpensive. It is popular with traveling road shows because it can withstand physical abuse.

Striplights or Borderlights. Striplights are compartmentalized luminaires. Every compartment contains a reflector lamp, or a lamp and reflector, and a color frame. The compartments are arranged in line and wired on two, three, or four alternate circuits, with each circuit producing a different color.

Striplights provide an overall wash of illumination on a stage. They can also be located at the front of a stage as footlights to provide an overall low illuminance.

Although striplights have been replaced in many applications by more versatile individual units such as Fresnel and ellipsoidal spotlights, they are still used in applications where cost is a major consideration. Striplights and borderlights are less expensive than Fresnel and ellipsoidal lights. They are also used in applications where labor costs are high and the use of more flexible units would increase the labor required to set up a show.

Luminaires using PAR-38, PAR-46, and PAR-56 lamps can be arranged in linear strips functioning as borderlights or striplights. There are striplights available that use 12-V multifaceted reflector (MR)-16 lamps wired in series. These units are useful in applications where space is at a premium, but they are generally not considered a suitable substitute for full-size striplights. In addition, cost and required maintenance are relatively high for these units.

Follow Spot. A follow spot is a special type of spotlight, stand mounted, with a shutter (commonly a douser), an iris, and a color frame or "boomerang" to hold color media. Most follow spots utilize a tungsten-halogen lamp, a metal halide lamp, or an arc source and a lens system. For high-intensity follow spots, the carbon arc has been almost totally replaced by compact metal halide or xenon lamps.[2] All of these arc units produce more output, watt for watt, than the tungsten-halogen units. Follow spots are selected to provide the throws required for the application.

Arc Light Luminaire. There are still some arc units in use today, although they are not popular in new installations. An arc light luminaire uses a carbon electrode arc as the source of illumination. These produce carbon monoxide as a by-product. In some concentrations this is a deadly gas. In addition, the operators required for these luminaires can be expensive, particularly for the small theatre or school auditorium.

Lamps for Theatre, Television, and Photographic Lighting

The most prevalent light source for the theatre stage is the tungsten-halogen lamp that has been designed especially for this type of service. For television and film lighting, tungsten-halogen and hot-restrike mercury arc discharge lamps are the two most common sources. Conventional incandescent spotlight lamps have been supplanted by tungsten-halogen lamps designed to retrofit into existing luminaires. Ballasts for hot-restrike mercury arc discharge lamps that produce no noticeable flicker have been developed for use in television and film lighting.

Carbon arc lamps are still used occasionally, principally for motion picture production, but they have been supplanted to a great extent by multiple lamp arrays of 650- or 1000-W tungsten-halogen or PAR lamps, often with integral daylight filters, and more commonly by compact metal halide lamps.

Virtually all types of light sources find occasional use in theatre, television, and film production. For example, metal halide high-intensity discharge (HID) lamps are used to light such areas as stadiums and arenas, providing illuminances and color quality suitable for televising performances. They also have the capability of providing "daylight fill" for movie and television productions. Fluorescent lamps with a variety of spectral power distributions, often on special dimming systems, may light cycloramas in television studios or theatre stages, or backings of motion picture sets. Fluorescent lamps are also used as television and motion picture base lights. Both fluorescent and HID lamps for use in television and film work require high-frequency ballasts to overcome the flicker effect inherent in these lamps when operated on 60-Hz power.

Xenon flash tubes, similar to those for photo studios, may be used in a repetitive-flash mode for theatrical effects. Lasers and light-emitting diodes may also be used for spectacular effects. Standard PAR and reflector (R) lamps, as well as sign, decorative, and indicator lamps, have a variety of common theatrical applications. Fiber optics are employed in many stage settings for special effects such as star curtains or irregular linear shapes. In still photography, tungsten-halogen and variable-output xenon strobe lights are the most common lamps.

Tungsten-Halogen and Incandescent Lamps.[3-6] General information about the lamps most frequently used in lighting for theatre stages, television and motion picture production, and professional still photography are found in Chapter 6, Light Sources. In many cases lamps may appear to be mechanically interchangeable with each other, that is, they have the same base and light source location. However, caution should be exercised. For example, in luminaires designed specifically for tungsten-halogen lamps, the bulbs of some incandescent lamps may be too large to fit within the luminaire. Furthermore, there may be differences in filament configuration that could affect the luminaire's optical performance. The designer should consult manufacturer information before making a lamp type substitution.

In addition, some luminaires may not provide adequate heat dissipation for higher-wattage lamps. Lighting equipment manufacturers should be consulted for the maximum allowable wattage.

The drive to conserve energy and reduce heat from theatrical lighting equipment has led to the introduction and acceptance of lower-wattage tungsten-halogen lamps with efficient reflector systems. For example, ellipsoidal spotlights are now available with dichroic reflectors that use 575-W tungsten-halogen lamps. Previously a 1000-W tungsten-halogen ellipsoidal spotlight would have been required to accomplish the same effect.

High-Intensity Discharge Lamps. A wide variety of metal halide lamps are used for general interior and exterior lighting systems. These compact arc lamps are also used to provide supplementary light to approximate daylight for television and film production and have been adapted into such specialized equipment as scenic projectors and follow spots. Xenon short arc lamps of the types commonly used for motion picture projection are also used in some scenic projectors and follow spots.

Special types of metal halide lamps have been developed with characteristics that are often better suited to the requirements of lighting for film and television production outside of the studios and for scenic projectors and follow spots.[7-9] These lamps are ac-operated discharge lamps in which the luminous arc burns in a dense vapor atmosphere comprising mercury and the halides of rare earths. They are of single- and double-ended construction, and they have short arc gaps, which means that their arc brightness is several times that of typical incandescent spotlight lamps. This feature makes them useful in follow spots and effects projectors. These lamps are available in a range of sizes, from 200 to 18,000 W. They are also available in PAR configurations and have a broad spectrum with a very high color rendering index (CRI), making them well suited as sources for "daylight fill" in movie and television shooting. Effective service lives range from 300 to 2000 h. After ignition, they require a minute or so to warm up. Most ballast and ignitor equipment can restrike the lamp immediately after it has been turned off. The flicker produced by these ac-operated lamps is not generally a problem for television, but for motion pictures careful coordination of frame and flicker is needed to prevent stroboscopic effects. Ballasts are available that provide waveform and frequency modifications that minimize or eliminate stroboscopic motion in movies. Refer to Chapter 6, Light Sources, for information on lamp correlated color temperature, color rendering, and life.

Low-Noise Construction. Most tungsten-halogen and incandescent lamps for theatre have special low-noise construction to minimize audible noise generation when operated on ac circuits. The lamp manufacturer should be consulted for information on which lamps have low-noise construction. Lamps, sockets, and wiring often generate noise when used with solid-state dimmers because they distort the normal sine-wave and such noise is minimal with autotransformer and resistance dimmers. Recent developments in dimmer choke design and firing techniques reduced the noise generated by lamps operating on dimmers that distort the waveform. Generally noise is not generated on dc circuits.

Caution Notices. Caution notices are generally provided with most lamps for stage and studio service. Virtually all tungsten-halogen lamps operate with internal pressure higher than 1.0 atmospheres; therefore, protection from lamp abrasion and avoidance of overvoltage operation is advised. The use of screening is advised where appropriate to protect people and surroundings in case a lamp shatters.

Control Systems for Theatre and Television Lighting

The design of a lighting control system is based on the artistic and technical needs of projected productions.[10-14] It is related to the building architecture, luminaire rigging system, and density of electrical outlet distribution. Design parameters are expressed in terms of power capability, number of lighting outlets, dimmer bank capacity, interconnection system, and lighting control facilities.

A lighting control system must provide the designers with total flexibility of control over all of the luminaires lighting the set. There must, therefore, be adequate dimmers, circuits, and control equipment to establish the number of lighting channels required, to assemble those channels into cues, and to switch and fade from one cue to another, thus achieving the desired lighting changes.

Lighting control systems for the theatre and for television differ slightly. Theatre lighting control systems make extensive use of memory, require accurately timed faders, and must be capable of complex simultaneous operations, whereas television lighting control systems generally require less memory and fewer operational features and benefit from automated dimmer channels.

Dimmers. Almost all of the lighting control devices used in theatre and television lighting use silicon-controlled-rectifier (SCR) dimmers, which are manufactured in a range of 1 to 12 kW. Triac dimmers, manufactured in a nominal capacity of 2 kW, are used occasionally in inexpensive portable dimming equipment. Dimmers are rated by Underwriters Laboratory (UL) for continuous operation at 100% of their rating. Dimmers are assembled into portable packs of 6 to 24 or into racks that can contain several hundred dimmers custom built to suit the installation.

European countries have much more stringent harmonic requirements than North America, and companies wishing to do business on both continents have to comply with European requirements. This likely requires a change from the current SCR-based dimmer circuits, which produce significant harmonics during dimming operation, to sinusoidal dimming circuits, which create no harmonics and also have the advantage of not producing high neutral currents.

It is highly desirable for electronic dimmers to have stable output, cause no interference to audio and video circuits or to other dimmers, be insensitive to load, and have high efficiency. The relation of the dimmer line voltage output on the control input voltage is usually fixed,[15,16] but some systems allow other dimming curves to be selected from software options in the dimmer rack or at the control console.

All electronic dimmers require ventilation to maintain components within specified operating temperature ranges. The amount of ventilation required depends on the dimmer's efficiency and the individual manufacturer's recommendations. A 97% efficient dimmer produces approximately 100 to 120 Btu/h for each kilowatt of connected load.

Distributed dimming systems, those in which individual dimming modules are located at the lighting instrument rather than in a centralized dimmer enclosure, are becoming more common. They are particularly cost effective in older theatres where existing wiring is to be reused and capacity is limited. The controls can follow a common protocol that can be easily "daisy-chained" to reduce the cost of installation and maintenance.

Properly sized dimmers can be connected directly to the various lighting outlets. This is termed the dimmer-per-circuit control method and is contrasted with power programming systems that employ a cord-and-jack or slider-and-bus system to switch individual outlets to larger-capacity dimmers. While the dimmer-per-circuit method leads to a large number of small dimmers, the improvement in wiring efficiency and the elimination of enclosures and power interconnect panels, when considered in conjunction with the added flexibility of these systems, usually amount to a cost savings and significant operating advantages. The control console, whether computerized or manual, generally contains an electronic soft patch that connects the control channels to the dimmers, performing much the same function as the power interconnect panels formerly did.

Manual Preset Lighting Control System. The basic form of lighting control is the manual preset system, which employs groups of manual controllers for each dimmer or control channel. These controllers are arranged in horizontal rows termed presets. Presets are connected to submaster faders that are, in turn, switched to paired master faders for proportional, dipless (smooth dimming curve) cross fades between presets. Illuminances are set as required on individual controllers in each preset, and lighting cues are achieved through submaster and master controllers.

Memory Lighting Control Systems. Memory lighting control systems are generally programmed software-based systems. In such a system, the operational program is permanently stored in a read-only-memory (ROM) section, which may be updated by the manufacturer to provide additional operational facilities as they are developed. These systems may incorporate video monitors for displaying cue information and have a floppy disk or cassette for storage of program information. Peripheral equipment used with memory lighting control consoles may include hand-held remote controllers used with remote receptacles at lighting positions to assist in focusing lights, designer's remote consoles (used in conjunction with the console in the operator's booth), printers, and remote monitors.

Communications between control positions and the dimmers can be accomplished by discrete analog signals, by multiplexed control signals, by digital and analog multiplexed protocols, and by discrete analog methods. These standard protocols provide for interchangeable hardware, and may reduce the complexity and cost of wiring.

There has been an industry shift toward standardizing on the Digital Multiplexing (DMX512) protocol. This control signal can now drive a whole range of peripheral equipment such as fog machines, moving lights, color scrollers, and more. The signal can be distributed to a number of control and equipment locations throughout the facility including back stage, orchestra pit, and equipment and lighting positions for total flexibility. This is relatively economical and allows the lighting console to drive all of these devices.

Electrical Installation. A major expenditure in any lighting system, whether theatrical or architectural, is the cost of the electrical distribution. To minimize this cost, care should be taken to locate the dimmer racks so as to achieve the most economical balance between the cost of the electrical feeders to the dimmer racks and the cost of the distribution wiring from there to the individual lighting positions or outlet boxes. For SCR-type solid-state dimming systems it is required to install a "hot" wire and a neutral from each dimmer module to its outlet. Therefore, the distribution wiring required for an electronically dimmed lighting system requires more wires than for a typical room lighting system. The cost of installing these additional wires must be included when determining the best location for major system components.

The designer should consult the applicable codes when determining the size of power distribution feeders for electronic dimming systems (i.e., the wiring from the building electrical system to the dimming rack). Recent code changes have given more flexibility to the designer in determining the actual dimmer lighting load and required feeder size. Caution should be exercised in sizing the neutral conductor because SCR dimmer circuits can cause harmonic distortion that may result in neutral currents that are substantially higher than the line currents. Neutral wire sizing for current capacities in the range of 1.5 to 2.0 times the line conductors is common. In portable installations, many municipalities have mandated two parallel neutral conductors, each sized the same as the individual feeder conductors, to provide adequate capacity for the neutral current.

In addition to the cost and number of wires required, there are noise consideration in locating and installing the dimming equipment and the wiring. It is important that noise generated by the dimming equipment is considered when locating the equipment. Although there may be no perceptible noise from modern dimming units, there may be a cumulative effect if a large number of dimming units are installed in the equipment racks. In addition, there is a significant amount of heat generated by the dimming equipment that must be removed from the equipment cabinets to keep operation within the temperature limits of the solid state in the dimmers. Fans are traditionally installed in the dimmer racks to force air through the rack. As the number of dimmers in a rack is increased by more effective miniaturization of the dimmers, the heat as well as the noise generated by the cooling fans increases. It is important that the dimmer racks be located far enough away from the audience, or in a sound-conditioned location, to control the level of noise that can be heard in the theatre.

Another potential source of noise is the alternating magnetic field generated between the "hot" and "neutral" wires of the individual dimmer circuits when the wiring is installed in the raceway system. If several individual circuits are installed in a common raceway, the additive effects of the wiring noise could be audible. Therefore, it is wise to consider banding the individual hot and neutral wires of each circuit together to minimize some of this noise. It may also be appropriate to consider "tie-wrapping" all of the circuit wires in an individual raceway to reduce the generated noise. Caution must be exercised in doing this to ensure that there is not a significant heat buildup as a result of reducing the air flow around the individual conductors. The services of a qualified electrical engineer should be sought to help with these questions.

Emergency Power. A system of emergency lighting is required for spaces suitable for occupancy by 100 or more people. The lighting required to be supplied by the emergency system includes, as a minimum, house lights necessary to meet the minimum egress lighting illuminance requirements, exit signs, aisle lights if provided, step lights, and back stage lighting to allow safe egress. It is very difficult to provide the required emergency lighting throughout large spaces with self-contained units with adjustable heads.

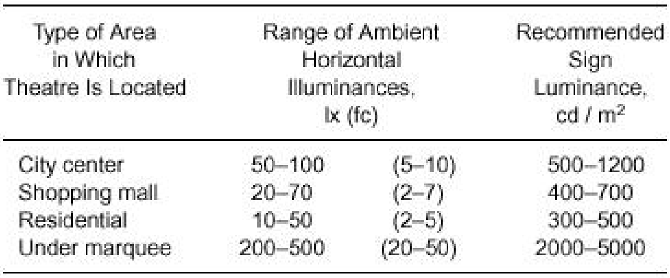
Lighting other than that legally required may be added within the capacity of the emergency power system if it is judged to enhance the safety of the facility. Regulations now require dimmer-controlled lighting circuits used as part of the emergency lighting to be transferred by an automatic transfer switch that meets the requirements of UL 1008.[17] Optional lighting deemed desirable for emergency lighting must be installed in accordance with the requirements of NFPA 70, Article 702.[18] Requirements for the emergency lighting system can be found in the applicable regulatory documents.[17-21]

LIGHTING FOR THEATRES

There are two basic types of theatres, for live productions and for film (motion picture). The former can be further classified as legitimate, community, and school theatre. The term "live production" refers to the presence of live actors on stage. In the case of motion picture theatres, there is only one classification to consider, and that is the indoor auditorium. Drive-in theatres, which were popular several years ago, have all but disappeared.

Lighting requirements for the marquee, lobby, and foyer are similar for live and for film auditorium theatres. An important goal common to both types of theatre is to provide transitional illuminances to accommodate readaption as patrons proceed from the brightly lighted marquee and street area to the lobby, the foyer, and eventually the auditorium. The lighting requirements for the various types of spaces within the two types of theatres are quite different, however.

Marquee. Attracting attention is one of the motives in the design of theatre exteriors. Much of the selling for current and coming attractions can be done here. Flashing signs, running borders, color-changing effects, floodlighting, and architectural elements are but a few of the many techniques employed (see the section "Lighting for Advertising" in Chapter 17, Retail Lighting). As styles and tastes change, it is necessary to design the exterior elements of a theatre to convey the feeling of the neighborhood. Many marquee "current attraction" panels are lighted with incandescent filament lamps, fluorescent sign tubing, or fluorescent lamps behind diffusing glass or plastic. Opaque or colored letters on a lighted field are generally more effective than luminous letters on a dark field. The principal requirement is uniformity of luminance, because variations in luminance across the face of the sign that exceed a ratio of 3:1 from the brightest to the darkest area are noticeable and detract from the message being presented (Figure 15-2). Luminaires designed to emit infrared radiation for heating and snow melting can be used in cold climates.



Type of Area in Which Theatre Is Located	Range of Ambient Horizontal Illuminances, lx (fc)		Recommended Sign Luminance, cd / m^2
City center	50–100	(5–10)	500–1200
Shopping mall	20–70	(2–7)	400–700
Residential	10–50	(2–5)	300–500
Under marquee	200–500	(20–50)	2000–5000

Figure 15-2. Recommended Illuminances and Theatre Advertising Sign Luminances in Various Locations

Lobby. An illuminance of 200 lx (20 fc) is desirable in theatre lobbies. The ceiling luminaires are often integrated with the marquee soffit. Many lighting treatments are applicable here; some considerations are easy maintenance, designs that retain architectural elements, and brightness patterns that attract attention as well as influence the flow of traffic. (People tend to move toward brighter areas over darker areas; this is known as phototropism.) Poster panels often contain their own lighting system, including fluorescent lamps, spotlighting, or transillumination. Poster luminances should range from 70 to 350 cd/m^2, depending on surroundings brightnesses. An important consideration is to allow sufficient depth behind the illuminated panel so fairly uniform brightness may be obtained. (See the section "Lighting for Advertising" in Chapter 17, Retail Lighting, for further information on sign construction.)

Foyer. Usually a restful, subdued atmosphere is desirable in the foyer. Illumination from large, low-brightness elements, such as coves, is often employed. Wall lighting and accents on statuary, paintings, posters, and plants are important in developing atmosphere. Obviously, light must not spill into the auditorium. Before and after performances, general illuminance levels of 50 lx (5 fc) for motion picture theatres and 150 lx (15 fc) for live production theatres are recommended.

Lobbies and foyers can also be used as public gathering places and as places of assembly for civic and business events. The likelihood of these events occurring should be considered in planning the lighting system as well.

Live Production Theatres

Although there are many varieties of indoor and outdoor live production theatres, such as amphitheater, music tent, arena, and open stage, the most common are the traditional proscenium and the open stage or thrust type (Figure 15-3).

Figure 15-3. Two views of the Ford Centre for the Performing Arts in Vancouver, British Columbia. The theatre has a traditional proscenium stage, shown here set for a chamber music performance with a large spotlight on the piano. An orchestra pit is located in front of the stage and would be used for musicals, opera, and ballet performances. The interior lighting design features evenly spaced downlights, mounted on the building's structural supports. The lighting provides adequate general illumination and contributes to the pleasantness of the space.

The proscenium-type theatre is composed, typically, of a seating area and a stage area. It may serve not only as a theatre, but as an assembly and lecture hall, a study room, and a concert area. Considerable attention is being given to the development of speech and theatre arts programs not only in schools but also as a community activity among adult groups. The many uses of the theatre require well-planned lighting.

It is important to provide a large number of power outlets at various locations, as well as the proper luminaires and control equipment, so that the stage lighting designer can create lighting for all stage performances. The necessary structural provisions must be made to allow placement of the lighting equipment and access for their installation, operation, and maintenance.

Seating Area. The seating area should have diffuse, comfortable illumination. Because the seating area often accommodates a variety of activities, different illuminances are necessary. A minimum illuminance of 100 to 200 lx (10 to 20 fc) should be provided in the seating area when performances are not taking place. This general lighting should be under dimmer control, preferably from several stations, such as the stage lighting control board, the projection booth, and a staff entrance. There should be transfer capabilities, however, so that the lighting is not accidentally turned on during performances. Lighting equipment for the seating area may include general downlight luminaires, coves, sidewall urns, and curtain and mural lights. Higher illuminances of at least 300 lx (30 fc) are required to perform visual tasks, such as reading or the taking of examinations. Selected lighting system circuits can be used for cleaning and rehearsals. "Panic" switches independent of dimmers and switches should be provided to allow an operator to bring on selected lights in the house in case of emergency. In accordance with local and national codes, an alternate electrical supply for emergency lighting must be provided. This system may include emergency house lights, exit lights, shielded aisle and step lights, and other required lighting (see Chapter 29, Emergency, Safety and Security Lighting).

Stage Lighting.[22-25]

Basic Lighting Functions.

An appreciation of the dramatic potential of lighting begins with an understanding of its four basic functions:

- Visibility. This is the most basic function of lighting in the theatre. For the audience to hear and understand in the theatre, they must be able to see.
- Motivation. Motivation or naturalism is the term given to the expression of time and place.
- Composition. Composition is revealed artistically through light and shadow. Warm and cool light give plasticity and composition to the visual effect. The concept of the production as indicated by the playwright and implemented by the director determines the approach of the designer.
- Mood. Mood, or atmosphere, as created by the total visual effect, brings the stage into focus with the meaning of the play. The final visual effect is provided by equipment that has been chosen by the designer because it supplies the desired output of light in terms of intensity, form, color, and movement.

Properties of Light

The controllable properties of light as they apply to the theatre include intensity, form, color, and movement. The control exercised by the designer over these properties has a direct bearing on the success of the performers in achieving the intended response from the audience.

Intensity. Intensity control is achieved with various types of luminaires, lamps, mounting positions, and color media and, of course, with dimmers. Precise, consistent dimmer control is essential for establishing and maintaining various intensity levels. Vertical illuminances of 2000 lx or higher are required to highlight selected performances.

Form. Form, meaning the distribution of the light, calls for a wide variety of luminaire types and mounting positions. The angle of the light relative to the object and the viewer creates dimensionality, which in turn is a function of the fixture type, location, focus, and dimmer balance. Luminance ratios on the stage should not exceed 100:1.

Color. Color in lighting design is used to accent, enhance, distort, and motivate the scene. Color is controlled by means of lamp selection, dimmers, and filters that can be placed in front of each source. Incandescent lamps, in particular, become much yellower as they are dimmed. A tonal quality can be obtained by the additive mixture of two or more sources. The color rendering index (CRI) of light sources used in theatre should not be less than 80.

Movement. Movement consists of a change in one or all light properties. Movement is usually accomplished by dimming individual luminaires rather than by luminaire movement. However, manually operated follow spots are commonly used.

Lighting Locations.[26]

There are two basic locations for lighting equipment (Figure 15-4): (1) in front of the proscenium opening, including the auditorium ceiling, side walls of auditorium and proscenium, balcony front, follow-spot booth, and edge of the stage apron; and (2) behind the proscenium opening, including pipes for attaching tormentor (side) lights, overhead cyclorama or top lights, and stage electrics (see below) above the stage. Also employed are cyclorama pit or base lights as well as special locations in free spaces at the side or rear of the stage, including ones that are floor mounted, hanging, or set beneath the stage area.

Though the positions may be fixed, virtually every luminaire is portable and gets shifted around for each production. The focus, direction, intensity, and color generally are different for each production. To determine the required lighting positions, the stage is divided into lighting areas. Although every project has its own unique requirements, the following example is typical.

A typical multipurpose stage can be divided into smaller lighting areas 3 to 4 m (10 to 12 ft) in diameter. Therefore, a stage 12 m (40 ft) wide by 9 m (30 ft) deep would each have three rows of four lighting areas, for a total of 12 lighting areas. Each lighting area should have four sets of luminaires (Figure 15-4):

> 1. Two luminaires, 35 to 45° above horizontal and 45° to both sides of the lighting area should be located on a "front-of-house" ceiling bridge, box boom, stage electric, or tormentor position. Ellipsoidal and possibly Fresnel spotlights can be used at these locations.
>
> 2. One luminaire, 35 to 45° above horizontal, should be mounted directly in front of the lighting area on the same supports as those in number 1 above. These luminaires are also of the same type as in number 1 above, with the possible addition of PAR-type luminaires for the upstage positions.
>
> 3. One luminaire should be mounted from the stage electrics directly above the lighting area. An ellipsoidal spotlight, a PAR, a striplight or borderlight, or, possibly, a scoop can be used.
>
> 4. One luminaire 45 to 75° above the horizontal should be mounted from the stage electrics directly behind the lighting area as a back light. An ellipsoidal spotlight or a PAR can be used for this purpose. If low cost is a consideration, striplights (borderlights) can be used in this position.

In addition to the positions listed above, a row of cyc lights located at the top and ideally about 2.5 m (8 ft) in front of the cyclorama can be used to illuminate the background. Many times this space is not available for luminaires and compromises have to be made. In the case of high cycloramas, the cyc lights can be placed at the bottom of the cyclorama.

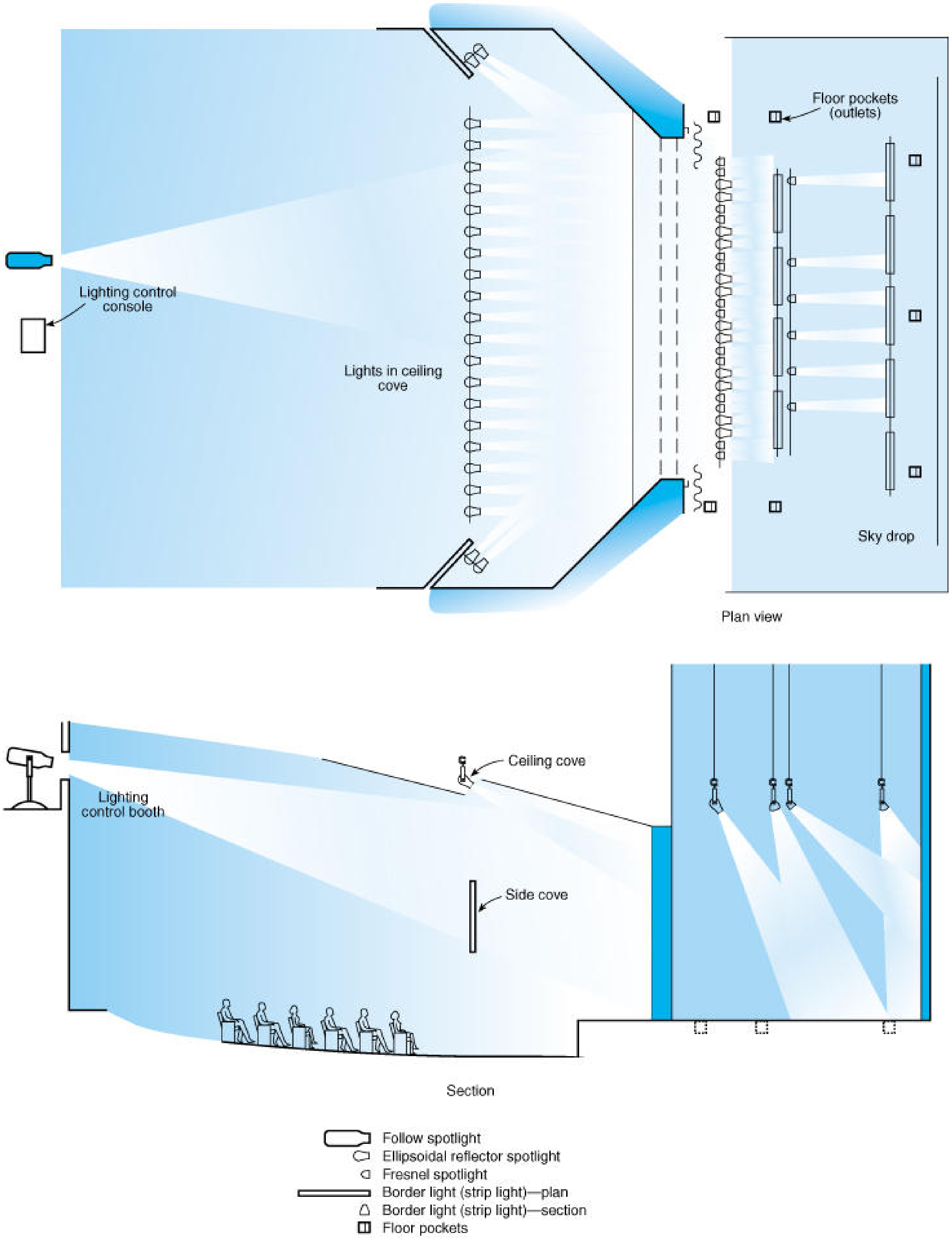


Figure 15-4. Typical plan and section of an average size theatre.

There are many other possible luminaire positions. For example, a luminaire mounted 25 to 35° above the horizontal at the front of a balcony can be effective in reducing shadows, particularly for television work. Further, the side-wall slots and tormentor positions are effective for modeling and for dance productions. In general, the lighting systems should permit the stage lighting designer enough flexibility to be as creative as necessary to provide the lighting required for the full range of activities envisioned for the stage.

Luminaires in Front of the Proscenium Opening

Luminaires in the Auditorium Ceiling. Stage-lighting luminaires in the auditorium ceiling are generally used for lighting downstage and apron acting areas. Each luminaire should produce a well-defined light beam that can provide an average illuminance of 500 to 1000 lx (50 to 100 fc) of white light on a vertical plane, with adjustable means for a controlled cutoff, so that the beam can be varied in shape to cover a desired area with little or no spill onto adjacent areas (Figure 15-1). These spotlights are best located behind slots, or coves, in the ceiling and are ideally mounted in a continuous slot stretching across the ceiling from side wall to side wall.

Luminaires in Auditorium and Proscenium Side Walls. Luminaires located on or in the side walls are recommended, although not absolutely required. They are used mainly as a supplement to the ceiling spotlights and are of a similar type. Preferably, these luminaires should be recessed into wall slots. They provide lower illumination angles than the ceiling luminaires as well as a variety of side lighting angles.

Luminaires on the Balcony Front. There are occasions when the balcony position affords desirable low lighting angles or a soft wash of directional front lighting. Attention must be paid to shadows, however. There is a danger that shadows from low-angle front spots may fall on the scenery and move as the actor moves. This causes an unacceptable distraction. Easy access must be provided to these spaces so that the luminaires can be readily put in place, focused, and lamped.

Follow Spot Booth. Follow spots are used to highlight selected performers. A follow spot should be capable of providing a level of at least 2000 lx (200 fc) in an area of 2.5 m (8 ft) in diameter and should have available beam size and shape so that it can be reduced to only cover the head of a person or widened to flood a considerable portion of the stage. In addition to the usual accessories, such as an iris, spread lens, or horizontal paired shutters, follow spot equipment often includes a color wheel or boomerang (a device for inserting individual filters of several different colors into the follow spot) that can be operated from either the side or the rear of the spotlight. Follow spot positions should be near the center of the house at the rear. It should be possible for the beam of light to reach all areas of the stage and the orchestra pit in front of the stage, particularly because a portable stage can be used to fit over the orchestra pit.

Footlights. Footlights are a set of striplights, sometimes multicolored, at the front edge of the stage platform, used to soften face shadows cast by overhead luminaires and to add general tone-lighting from below. Footlights may be used to light large flat scenery, for special effects, for mood, or to duplicate period scenes.

Luminaires Behind the Proscenium Opening

Overhead Locations. The greatest number of luminaires in any one location upstage of the proscenium is mounted on the first pipe, or bridge, immediately upstage. The luminaires for this position may include spotlights, borderlights, and scenic projectors. The majority of the spotlights have variable focus to produce a soft-edged beam. A number of ellipsoidal reflector spotlights or PARs are usually mounted in this row. There should be provisions for mounting additional rows of lights on pipes parallel with the proscenium opening every 2 to 2.5 m (6 to 8 ft) of stage depth.

Stage Electric. The stage electric is a pipe, or bridge, with an electrical connector strip mounted to it and running the width of the stage proscenium opening. The basic purpose of the connector strip is to provide a simple and quick method of electrically connecting a number of luminaires above the stage. Outlets on the connector strip should not be spaced closer than 300 mm (12 in) apart, and every outlet should be on an individual circuit with a separate neutral.

A more flexible alternative to connector strips incorporates a number of multiconductor cables and electrical boxes. Every cable should be long enough to locate the outlet box at any position on the stage electric and at any height above the stage.

Border Lights and Scoops for Stage Light Pipes. Although Fresnel and ellipsoidal luminaires are most commonly used on stage light pipes, other luminaires can also be used. A borderlight or series of scoops provides general stage lighting and illumination on hanging curtains and scenery. They contribute tonal quality to the overall lighting effect. Separate control of the borderlight or scoops enables parts of the stage to be variously accented in brightness and color. These luminaires should illuminate the whole width of the curtain or flat scenic drop but should be wired on three or four separate circuits to enable changes in the color of illumination. They should be mounted at least 1.2 m (4 ft) upstage of the conventional borderlight equipment. The illuminance provided by borderlights or scoops in the center of the vertical surface should not be less than 250 lx (25 fc) of white light when measured at a point 1.8 m (6 ft) from the stage floor.

Cyclorama Top Lighting. Cyclorama borderlights must illuminate the visible width of the background, independent of illumination from cyclorama bottom lighting. Cyclorama lighting requires at least twice the illuminance provided by other borderlights. When the cyclorama is an important feature and deep color filters are used, then the wattage of the associated borderlight equipment can be from two to four times that of a regular borderlight, depending on the density of the filter. The required illuminance may necessitate two parallel rows of borderlights, using, for example, 250-W PAR-38 lamps on 150 mm (6 in.) centers or 500-W PAR-56 lamps on 200 mm (8 in.) centers in each strip. An alternative is striplights using series-wired MR-16 lamps.

Backlighting From an Upstage Pipe. It is desirable to provide a row of high-intensity, narrow-beam luminaires, such as Fresnel spotlights, parabolic spotlights, or PAR luminaires, suspended on an upstage pipe and directed downstage to provide backlighting of artists in the main acting area. There may be one 500- to 750-W luminaire for every 1.2 to 1.8 m (4 to 6 ft) of effective stage width.

Mounting for Stage Side Lights. There are two methods of providing side stage lighting; suspended three- or four-rung ladders or floor-mounted boomerangs or tormentor pipes. Side and modeling light are essential to a stage production.

Special Theatrical Effects. Fluorescent paints, fabrics, or other materials responding to ultraviolet (UV) radiation are often used for special theatrical effects. Sources for exciting the fluorescent materials include mercury lamps with filters for absorbing visible radiation; fluorescent "black light" lamps, which also require a filter; and integral-filtered fluorescent "black light" lamps. Carbon arc follow spots are sometimes filtered for "black light" effects. Strobe lights and lasers are used in today's theatre. Great care must be exercised where using UV and lasers to comply with all government and municipal regulations and to avoid operations that could cause permanent eye damage to the audience, performers, or operators. See Chapter 5, Nonvisual Effects of Radiant Energy, and the section "Museum Lighting" in Chapter 14, Lighting for Public Places and Institutions.

Automated Luminaires and Accessories. Many theatrical and television productions use luminaires that can be remotely moved or steered, or whose color, pattern and beam edge, and focus can be changed to achieve the effect of moving light. These luminaires generally are mounted in the same way as fixed luminaires but require additional power and control wiring.

Lens accessories are available for remote color selection. These require additional power and control wiring.

Scenic Projectors. An increased understanding of the techniques of slide projection by theatre personnel has led to an improvement of the basic optical design for projection in the live theatre. Some of the principal improvements include: increased projector lamp wattages up to 10 kW; the introduction of new compact metal halide lamps to provide additional scene illumination and coverage; improved methods for slidemaking; remote, programmed slide changing; wide-angle projection to screen widths of 1.5 times the projection distance; standardization of units to permit easy interchangeability; and the availability of relatively simple and inexpensive remote-control 35-mm projectors.[27]

Motion Picture Theatre Auditoriums

The objectives of auditorium lighting in the motion picture theatre may be outlined as follows:

- To create a pleasing, distinctive environment
- To retain brightness and color contrasts inherent in the motion picture
- To create adequate visibility for safe circulation at all times
- To provide comfortable viewing conditions

For general lighting during intermission, 50 lx (5 fc) is considered the minimum. During the picture, illumination is necessary for safe and convenient circulation of patrons. Illuminances between 1 and 2 lx (0.1 and 0.2 fc) represent good practice. The screen luminance with the picture running is between 3 and 20 cd/m^2. The need to eliminate stray light on the screen dictates controlled lighting for at least the front section of the auditorium. Downlighting is one of the most effective methods for this purpose. In general, diffusing elements, such as coves, allow too much light to fall on the screen if they provide adequate illumination in the seating area. Diffusing wall brackets, semidirect luminaires, and luminous elements are generally too bright to be used for supplying illumination during the picture presentation.

The luminous contrast between the screen and its black border is sometimes more than 1000:1, creating uncomfortable viewing conditions. The luminances of areas around the screen can be raised; however, they should not have decorations that are distracting. Light for this purpose may be reflected from the screen under special conditions, or it may be supplied by supplementary projectors or by elements behind the screen.

Curtains may be lighted in color with a projector border during intermissions. Adequate spotlighting on the stage is desirable for announcements and special occasions.

Aisle luminaires should have low brightness and be spaced to give a uniform illuminance of 10:1 in the aisle. House lights should be dimmer controlled.

Meetings, Conventions, and Industrial Show Facilities[28-30]

Meetings and conventions require comfortable ambient illumination as well as accent lighting. Where open discussion takes place between speakers and audience, the lighting should be free of glare to support dialog. Lighting for industrial shows and new-product presentations may require some form of theatre lighting.

Stage locations may vary considerably from meeting to meeting. A show that uses rear projection may move the stage area 4.5 to 6 m (15 to 20 ft) forward. Another meeting may require a simple platform with maximum space for an audience seated in classroom or conference style. Many meetings use a center area or theatre-in-the-round arrangement. Other producers find a projected stage along a wall more satisfactory for their presentation.

Many meetings are conducted in multipurpose spaces that are used for food service, fashion shows, motion pictures, social events, and meetings. The ease and speed with which these areas can be changed from one arrangement to another are important economic factors.

Lighting must be coordinated with many other elements. These include wall surface brightness, projection screen location, and communications and sound systems. Projection from audiovisual equipment and follow spots requires unobstructed views of the screens, stages, and acting areas. Chandeliers must not be placed in locations that interfere with the projection or "stage" lighting. A sufficient number of dimmers, as well as a flexible distribution of wiring and luminaire mounting locations, should be provided. For the required flexibility, no fewer than twenty-four dimmers should be available for spaces intended for complex presentations.

Theatre-Restaurants, Lounges, and Discos

Stage lighting design criteria for theatres and auditoriums are generally applicable to theatre restaurants, night clubs, and lounges. However, theatrical lighting in a small area, such as a lounge, utilizes more compact luminaires. For low ceilings, a basic luminaire is an "inky" with a 76-mm (3-in.) Fresnel lens or an adapter accessory having individually adjustable framing shutters and lamps up to 375 W. In larger spaces with longer throws, a Fresnel spotlight or a floodlight for 250- to 400-W lamps and a beamshaper accessory can be used. An alternative is a small ellipsoidal framing spot of 650 W or less, available with wide-, medium- and narrow-beam lens systems.

Discos employ many stage lighting techniques and a variety of theatrical equipment. Typically, flicker, flash, and movement in light patterns are introduced through the use of mirror shower balls, spinners, rotators, and police emergency lights. Control systems include presets, chasers, and programmers.

Luminaire Locations. Luminaires can be positioned closer to vertical than would be acceptable for legitimate theatre, the limit being closer to 30° than to the 45° prevailing in theatrical work. Downlights are used to produce pools of light on dancers and set pieces. Uplights, recessed in the stage floor, can also be used. Side-mounted luminaires, located from 45° in front of to 45° behind the performer, are essential for three-dimensional effects, particularly in dance and production numbers. Floor-mounted linear strips can be used for horizon effects on cycloramas. These may be of the disappearing type or recessed with expanded metal covers to permit performers to walk over them.

Follow Spots. Locations for several follow spots should be provided to light the performers from all viewing directions. One or more follow spots should be able to cover audience areas. Some performers enter from the audience, and runways are frequently used to bring the chorus closer to the viewers. Side stages on each side of the main stage are frequently used for bands and stage action, and provision should be made for adequate lighting of these areas.

Transparencies. Scrims are frequently used to hide the band when playing for a show. On the other hand, the band and performers are frequently revealed by bringing up lighting behind the scrim and keeping light off the front of the scrim. These changes may occur on the side or on the principal (center) stage.

Special Effects. Mounting devices and switching circuits and receptacles are required for "black lights," projectors, electronic flash, motor-driven color wheels, and for dissolves, fog and smoke machines, mirror balls, and similar equipment. Color organs are used to pulsate lights with music. Plastic-covered floors for dancing and entertainment should provide selectable color and pattern effects. In small spaces, fluorescent lamps and dimming ballasts are used. If ventilation can be provided, incandescent lamps can be used for special effects.

Controls. Single lights are frequently used. Receptacles should be on individual dimmer circuits. Permanent grouping should be avoided. Nondimmed controls should be integrated with the dimmer controls, that is, they should be switched with voltage-sensitive relays controlled by potentiometers of the same type as those used for the dimmer controls.

LIGHTING FOR TELEVISION

Television broadcast lighting requires extensive planning and flexibility due to continuous dramatic action on the set. Several scenes are arranged for several cameras and continuous switching from one camera to the next. Consequently, the lighting for each scene is preset for cameras positioned at different angles, and the lighting in one set should not interfere with adjoining sets. The quantity and quality of the lighting needed for television production depend on the absolute spectral sensitivity of the camera and the properties of the objects in the scenes. A limiting factor for any camera is the contrast range that the camera will accommodate.

Studio Lighting for Color Television

The spectral response characteristics of cameras are critical to color reproduction. Experience has shown that the light sources used for television should have very broad spectral power distributions. The gains of the red, blue, and green channels of a camera can be adjusted to operate with almost any broad spectrum light source, but the wide variation in the spectral characteristics of the light sources used to illuminate a scene can cause unpredictable changes in color reproduction.

Incandescent filament lamps have long been used for color studio lighting because of their continuous spectra, their low cost, and their availability in a wide range of sizes with approximately the same correlated color temperature. Incandescent filament lamps having correlated color temperatures between 2900 and 3200 K are currently used. These lamps are favored because their housing equipment is generally less bulky and lighter in weight, and the smaller filament allows for better optical control of the light beam. Furthermore, color filters are easy to use with these luminaires. Where filament lamps are used, current practice indicates the correlated color temperature of all lamps used in a scene should be within a 300-K range for consistent camera colors.

New developments in fluorescent and HID light sources are now providing greater flexibility for mixing sources. In particular, discharge lamps are now being manufactured with much better, and in some cases continuous, spectral power distributions. Some sports arenas have successfully mixed 75% HID and 25% incandescent sources.

For televising color pictures, illuminances between 350 and 3500 lx (35 and 350 fc) are satisfactory. Many studios, especially those producing color spectaculars, have found it desirable to provide up to 5000 lx (500 fc). This is done to compensate for older-model color cameras or to provide greater depth of field. In scenes employing a very low light level, the problems of focus may be complicated by the very narrow depth of field afforded by wide-open lenses.

Television Film Production

The significant element in lighting for television film production is the control of the contrast range. Most television film reproduction systems require that a picture luminance range not exceed 25:1. This differs from the current theatre projection range of about 100:1, and video recording should have contrast ratios less than 20:1. Contrast control can be obtained by the introduction of fill light to raise the luminances in shadowed areas. This does not mean that flat lighting is desirable, but rather that the lighting ratios used for modeling should be lower than is normally used when making films for theatrical projection.

Unlike the human visual system, color contrast is not enough to ensure an acceptable signal for television film. Brightness contrasts are required for a monochrome receiver tuned to a color broadcast. A poor monochrome picture is particularly conspicuous when scenery is painted in several pastel shades, all having similar reflectances.

Projected Backgrounds

A scene may be projected onto a translucent screen from behind. This technique is used to simulate background scenery, which may take the form of stationary objects as produced by a slide, moving effects such as clouds and water, or continuous motion simulating moving trains or motion from an automobile as produced by a motion picture film.

For realism, projected highlight levels should be within a 2:1 ratio of live highlight levels. As a rule, it is desirable to have a projected highlight luminance of 250 cd/m^2 when the acting area is illuminated to 1000 lx (100 fc).

Chroma Key

The production technique known as chroma key is a special effect that enables any background material to be matted into a scene. In the studio, a color camera views the subject against a backdrop of a primary color that has sufficient saturation to produce a full output level in the corresponding channel of the camera. This signal output is used to key a special effect generator so that all information except the wanted subject is matted out of the original studio scene. Information from any other source, such as a film chain or video tape recorder, can then be inserted in the matted portions of the signal.

The primary color used in the backdrop is chosen on the basis that it is not present in the color of the wanted subject. When human subjects are used, blue is usually the best background color because it is absent in flesh tones. Additional precaution must be taken to avoid the use of the background color in costumes or stage props.

The illuminance on the backdrop must be high enough to produce a full output signal from the camera without excessive noise. Light should not be reflected from the background onto the subject, because it will create spurious keying signals.

Types of Illumination

A graphic representation of the following types of lighting is shown in Figure 15-5.

Base Light or Fill Light. Base light or fill light is usually supplied by floodlights that supply broad, soft illumination. It is desirable to aim base lights at a 12 to 15° angle below horizontal.

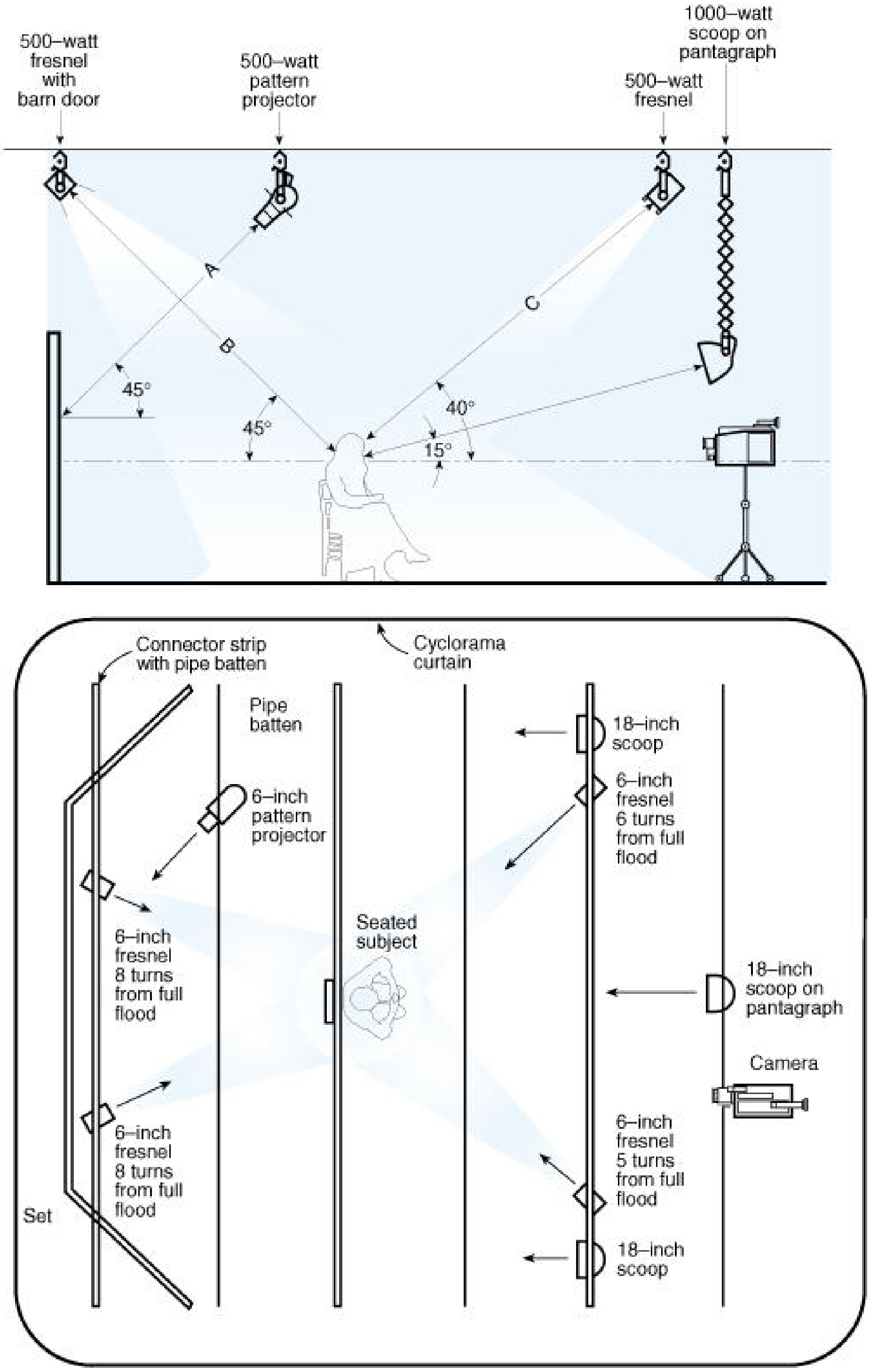


Figure 15-5. Diagrams showing good practice in luminaire location and aiming angles. In the top diagram *A* = 3 m (10 ft), *B* = 3.7 m (12 ft), and *C* = 4 m (13 ft). The 1000-W scoop on the pantagraph provides base light; the 6-inch fresnels in front of the subject provide key light; the 6-inch fresnels behind the subject provide back light; and the pattern projector provides set light.

Key or Modeling Light. Key or modeling light is usually supplied by Fresnel lens spotlights ranging in lamp size from 500 to 10,000 W. Fresnel luminaires are equipped to hold supplementary masking devices, such as barn doors, snoots, and color frames. The barn door fits in front of the lens and is used to limit the bottom, top, or sides of the light beam. These units can either be hung or used on floor stands and are generally aimed at a 20 to 40° angle below horizontal. Back light is used for separation. Back lights are hung behind a subject and are aimed at approximately a 45° angle to light the back of the head and shoulders, and to separate the subject from the background. Back light illuminances should be from one-half to the same as that of the front light, depending on the reflectance of the hair and the costume.

Set Light. Set light is used to decorate or help give dimension to scenery. The amount of light necessary is totally dependent on the reflectance of the scenery. Light skin reflects 40 to 45% of the illuminance. Therefore, the major part of the background must be kept below the luminance of the face. A gray-scale reflectance of 30% is a good average value for the background.

There are many other luminaires that can be used to help dramatize a show, such as sun spots, ellipsoidal spots, follow spots, pattern projectors, and striplights. These luminaires are described above in the section "Lighting for Theatres."

Balancing for Correct Contrast. It is important to have the proper balance among the different types of lighting discussed above. For instance, if the set is painted in a color value that reflects more light than the flesh of the actor, skin tones may appear darker than desired in the picture. This means that the set light should be reduced. A quick way to do this is to cover the set-lighting luminaires with diffusing material. Spun-glass diffuser material is available in 1 by 4 m (3 by 12 ft) rolls and can be cut to fit the luminaire. One 0.38 mm (0.015 in.) thickness cuts about 20% of the light. Additional thicknesses can be used until the correct contrast is obtained. The problem in using spun glass is that the character of the light has been altered from somewhat firm image-forming to soft, diffuse, flood, and less directional ambient light.

Another medium that is sometimes used to balance the lighting is one or more layers of ordinary house window screening. Black window screening material has the virtue of minimizing changes to the optical characteristics of the light.

If the installation includes dimmers and a cross-connecting system, the different luminaires can be grouped and then dimmed until the desired contrast is obtained. There is no apparent color effect due to dimming in black-and-white television. In the case of color television, the correlated color temperature decreases 10 K per volt for lamps operated at 120 V. As stated before, differences of 300 K contained in one scene are perceptible. A very low correlated color temperature contains little short-wave energy and may make blue hues dark and as a result introduce unwanted noise into the picture.

Lighting Equipment Installation

The method of supporting the luminaires depends to a great extent on the ceiling height and the intended use of the studio. Where the height is low, in the range of 3.5 to 5 m (12 to 16 ft), a permanent pipe or track grid is usually installed from which the luminaires are hung directly or through pantographs, which permit individual vertical positions (Figure 15-6). The luminaires are capable of complete rotation and tilting. In high-ceiling studios and in television theatres, the luminaires are supported either from fixed pipe or track grids or on counterweighted pipe or track battens (Figure 15-6).

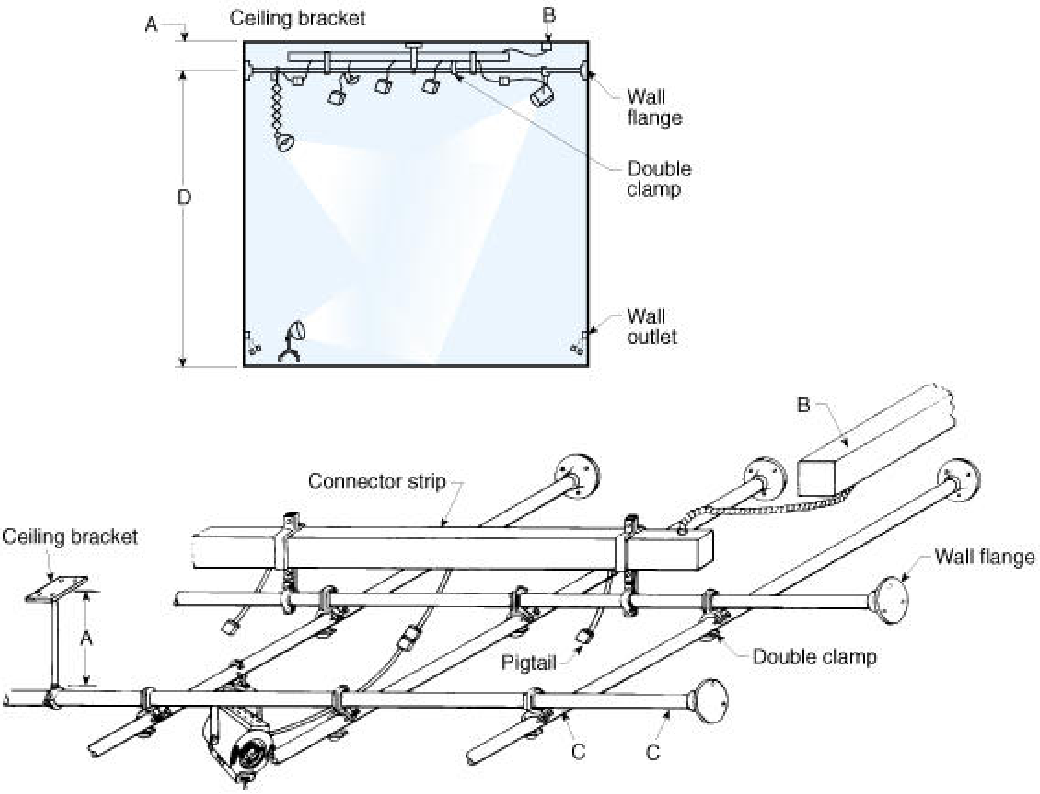


Figure 15-6. Diagram showing a typical overhead grid system for mounting lighting equipment in a small low-ceiling studio. Typical systems for larger studios with higher ceilings can be raised and lowered. In the drawings A = 300 mm (12 in.), B = 100 × 100 mm (4 × 4 in.) duct, C = 32 mm (1.5 in.) ID pipe, and D = 3 to 3.7 m (10 to 12 ft).

Television Control-Room Lighting

The lighting system for use during control-room operating periods should meet the following requirements:

1. General illumination. A diffuse, evenly distributed illuminance of 50 lx (5 fc) should be provided by low-intensity sources located so as to avoid any specular reflections in picture monitors, clock faces, windows, control panels, console desks, or similar surfaces, as seen from normal positions occupied by operation personnel.

2. Work illumination. Localized higher illuminances of approximately 250 lx (25 fc) should be provided on the production consoles, control consoles, switching consoles, and announcer's desk.

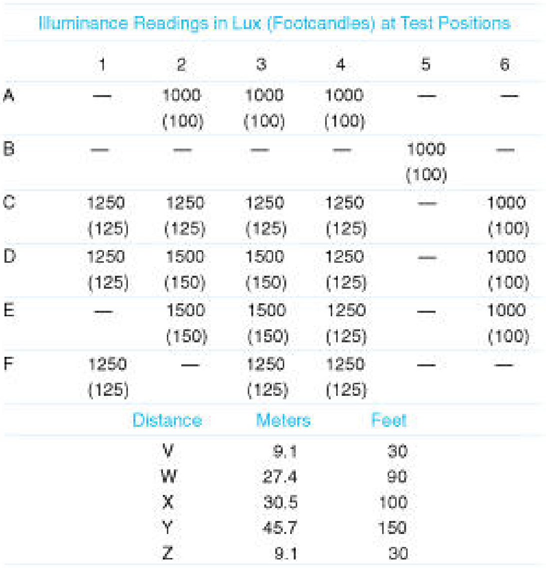
3. Correlated color temperature. The correlated color temperature of control-room operating lights should be nearly constant.

4. Emergency lighting. Emergency power from a separate source should be provided.

The lighting system used during maintenance of the area should have an illuminance of approximately 250 lx (25 fc). This system should be independent of the production lighting outlined above and used only for installing, repairing, and moving equipment or for cleaning.

Field Pickups of Sporting Events

Lighting recommendations for sports are largely based on the visual requirements of players and spectators (see Chapter 20, Sports and Recreational Area Lighting). When filming or telecasting is involved, the lighting requirements are often more stringent. Light sources should have a CRI of 80 or above. Horizontal and vertical illuminances should be no less than 750 lx at any point on the playing surface. Illuminance distribution is especially important for modeling players, and special calculation and measurement procedures are required to ensure satisfactory performance by the camera systems. See Figure 15-7.



Illuminance Readings in Lux (Footcandles) at Test Positions

	1	2	3	4	5	6
A	—	1000 (100)	1000 (100)	1000 (100)	—	—
B	—	—	—	—	1000 (100)	—
C	1250 (125)	1250 (125)	1250 (125)	1250 (125)	—	1000 (100)
D	1250 (125)	1500 (150)	1500 (150)	1250 (125)	—	1000 (100)
E	—	1500 (150)	1500 (150)	1250 (125)	—	1000 (100)
F	1250 (125)	—	1250 (125)	1250 (125)	—	—

Distance	Meters	Feet
V	9.1	30
W	27.4	90
X	30.5	100
Y	45.7	150
Z	9.1	30

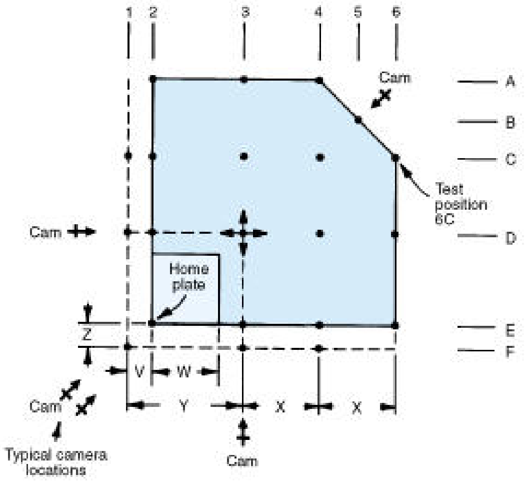


Figure 15-7. Recommended minimum illuminance levels and survey test position for television pickup of baseball.

Modeling. The vertical illuminances should be recorded along and perpendicular to the camera's viewing direction. Measurements of horizontal and vertical illuminances in four directions should be made at a height of 900 mm (36 in.) above the playing surface. The visibility for players and spectators depends on the values of horizontal- and vertical-plane illuminance, since modeling of an object is related to the proportion of horizontal to vertical illuminance reaching an object from different directions. As the number of vertical planes at any one point is infinite, it is convenient to consider only faces of two vertical planes at right angles (Figure 15-8).

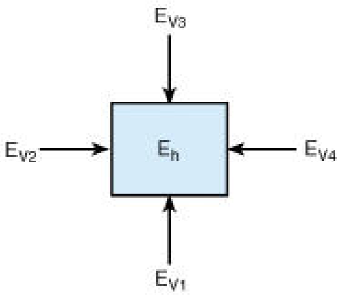


Figure 15-8. Five illuminance measurements used to determine acceptable modeling for sports lighting.

If E_h (the horizontal illuminance at the point under study) and E_{v1}, E_{v2}, E_{v3}, and E_{v4} (the four vertical-plane illuminances at that point separated by 90°) are approximately the same, the modeling (or revealing power of the lighting) is poor, that is, it is difficult to see objects in three dimensions. On the other hand, extreme differences in these five values cause harsh modeling that can distort the appearance of the object. For the purpose of sports lighting, since viewing is from all directions, it is usual to take the average of the values at a number of points over the area. See Chapter 20, Sports and Recreational Area Lighting, for the distribution of calculation measurement points on the various playing surfaces. Acceptable modeling will generally be achieved if E_{hav} (the average horizontal illuminance over the area) is no greater than twice the average value in any one of the four vertical planes.

It is also important to provide illumination in the spectator area adjacent to the playing field for crowd shots and for wide-angle shots of the playing field. This is best accomplished from behind the spectators, to limit glare for both the spectators and camera positions in the spectator seating area.

PHOTOGRAPHIC LIGHTING

Photographic lighting is used by amateur photographers, portrait and commercial photographers, industrial photographers, and cinematographers. The needs of these photographers vary considerably, as do the film materials and lighting systems. A portrait photographer may use flashlights to minimize discomfort for the subject. Strobes and flashbulbs stop the motion of moving objects. Color photography requires compatibility between the film spectral sensitivity and the light source spectral output. In motion picture photography, the stroboscopic effect of fluorescent and HID light sources must be minimized with special ballasts or synchronized with the film speed and shutter angle. The lighting requirements are therefore many and varied.

Photosensitive Materials[31]

Commonly used photosensitive films and plates include the following (spectral sensitivity curves are given in Figure 15-9):

- Panchromatic (sensitive to all colors, produces a black-and-white image)
- Orthochromatic (sensitive to all colors except orange and red, produces a black-and-white image)
- Color (sensitive to all colors, produces a color image)
- Infrared (sensitive to red and infrared, produces a black-and-white image)

For photography, light sources must emit energy in the spectral region in which the photographic material is sensitive. Even with black-and-white photography, color delineation in the form of faithful gray values is required. In black-and-white photography, photographers endeavor to secure a scale of grays in their negatives corresponding to the various brightnesses of the subject; thus, it is necessary that the film and the light source complement each other. Where this is not possible, it is general practice to employ a filter at the camera lens.

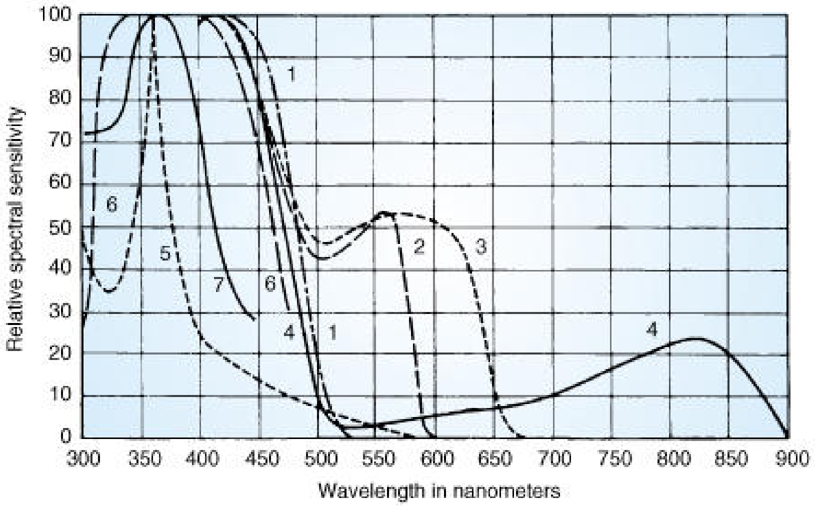


Figure 15-9. Spectral sensitivity curves for common types of photographic and photoprocess materials. (1) blue sensitives; (2) orthochromatic; (3) panchromatic; (4) infrared sensitive; (5) bichromate coating; (6) diazotype paper; (7) blueprint paper.

For color photography, the spectral quality of the illumination is even more critical. Color emulsions are "balanced" for use with a particular quality of light. Because most color photography materials are based on three emulsion layers, each sensitive to a narrow spectral band, adjustment by filtering to a light source other than the one for which the material was originally intended calls for precise filter selection.

Photographic Lighting Equipment

Still camera lenses ordinarily cover an angle of about 45°; therefore, for lighting equipment placed at or near the camera, reflector beam patterns for complete light utilization should fill an angle of about 45°. However, difficulties caused by inaccurate aiming of the reflector and other variables are minimized by filling a 60° cone with reasonably uniform illuminance. A luminaire with a 60° beam angle usually provides lower illuminances toward the edges of the scene, but this is seldom objectionable, since the point of interest in a picture is generally in the middle.

The shadows and contrasts that help to light a person as normally seen are usually "soft," such as those produced by a light source of appreciable angular size. Large reflectors 400 to 600 mm (16 to 24 in.) in diameter produce more natural modeling and are used in portrait studios or other applications where their size is not a handicap. Flashlamp equipment used with smaller-format cameras necessarily have smaller reflectors, which produce somewhat sharper and less natural shadows.

Photographic Lighting Techniques

The lighting required depends on the final effect desired from a photograph. If good rendering of shadow detail is desired, a rather narrow range of illuminances is required so that both the brightest parts (highlights) and the darkest parts (shadows) of the scene are fully rendered in the final print or transparency. The brightness range reproduced on film is much narrower than brightnesses perceptible by the human eye, particularly in the case of color photography. With typical subject reflectance ranges, the recommended maximum illuminance range within the scene is 10:1 for black-and-white and 4:1 for color film.

In color photography the correlated color temperature of all of the light sources used must be the same. The eye readily accepts illumination of mixed correlated color temperature, but photographic film does not.

The monocular vision of the camera tends to render subjects flat; that is, they tend not to have a three-dimensional look. To compensate for the lack of stereo depth, the best lighting on photographic subjects emphasizes their roundness, form, and spatial relationship. This is largely a matter of lighting direction, such as lighting from the side or the back.

In photography, both general and modeling illumination are needed to produce a natural-appearing likeness of a subject. General illumination, if used alone, produces a negative that is flat and without modeling. Such illumination does not produce prominent shadows. Density differences in the negative are created by differences in the reflectance of various portions of the subject. This general illumination goes by several names, among which are front light, broad light, flat light, camera light, and basic light. Modeling light, if used alone, produces a negative in which the highlights can be well exposed, but the shadows show no detail at all. Modeling light is usually highly directional and is used for the express purpose of creating shadows and highlights.

For ordinary subjects, the background should not be very dark, very light, or too close behind the subject. Neither should it be of exactly the same luminance as important parts of the subject, because such a condition would have the effect of merging the subject with the background. Better photographs result where less detail and fewer distracting spots are in the background.

Photography of Lighting Installations

The photography of installations by "existing light" does not require special photographic materials or equipment. Attention to focus, proper exposure, and composition is necessary, and the use of a tripod is recommended.

The finished picture should represent the actual installation as closely as possible.[32,33] Because most installations have a luminance range that exceeds the range of the film, various techniques in photographing and photographic finishing are used to compensate and so produce a more natural-appearing photograph.

In taking the picture, exposures can be split (meaning a separate exposure is used on the same film frame for each different source of light), fill light may be introduced, lampshades may be lined, and bulbs may be substituted to reduce brightness. When fill light is used, great care must be taken to avoid unnatural shadows. This may mean bouncing light off of walls or the ceiling. In black-and-white photography, a 10:1 ratio of scene illuminance is desirable. In color photography, the ratio should not exceed 4:1.

The rule of exposing for shadows and developing for highlights is still valid for black-and-white photography. Through experience and testing, the photographer finds the best combination of lighting technique, film, and processing that yields an easily printed negative. The printer can also use various methods of compensation, such as dodging, flashing, and burning in, to overcome the deficiencies of a poorly executed negative.

When using color film, exposure should be for the highlight areas where detail is desired. It is also imperative that all the light sources be similar in color. Fluorescent lamps generally should not be combined with incandescent fill light, since this usually produces a noticeable color mismatch in the final photograph.

Installations of discharge lamps photographed with color-positive material present color balancing problems. Because all films are designed to respond to a continuous spectrum, and HID lamps generally do not have continuous spectra, filtration in some form is required to produce an acceptable color balance. Lamps and film manufacturers can generally furnish recommendations for suitable filters to balance the various color-positive films to specific discharge lamps, both fluorescent and HID.

Another much simpler method of color photography is to photograph the installation on unfiltered color-negative material and to work with a professional color laboratory to produce prints or slides with the correct color, with the necessary filtration being done in the photofinishing laboratory.

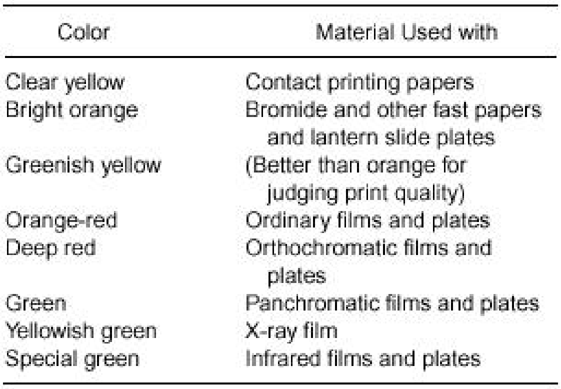
Darkroom Lighting

In general, any type of darkroom safelight filter must transmit light that has the least effect on the photographic material and yet provides the most illumination for the eye. Any photographic material fogs if left long enough under even the best safelight illumination.

The placement, size, and type of safelight lamp depend on the purpose that the light serves. The two types of darkroom illumination are general, to supply subdued illumination over the whole room without concentration at any one point, and local, to supply higher illumination on some particular point or object. These are combined, depending on the size of the room and the type of work.

Because of the varying sensitivities of the different classes of photographic materials, several safelight filters are available, differing in both color and intensity. These have been produced by the manufacturers of the luminaires, and it is never safe to use substitutes. Other materials may appear to the eye to have the same color as a tested safelight filter, but they frequently have a much greater effect on the exposed, unprocessed film. The use of makeshift safelight substitutes is not recommended.

Figure 15-10 indicates available types of safelight filters. Film manufacturers should be consulted for more complete information.



Color	Material Used with
Clear yellow	Contact printing papers
Bright orange	Bromide and other fast papers and lantern slide plates
Greenish yellow	(Better than orange for judging print quality)
Orange-red	Ordinary films and plates
Deep red	Orthochromatic films and plates
Green	Panchromatic films and plates
Yellowish green	X-ray film
Special green	Infrared films and plates

Figure 15-10. Types of Safelight Filters

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16

Health Care Facility Lighting

HEALTH CARE FACILITIES DESIGN ISSUES

Critical Care Areas

- Color Appearance (and Color Contrast)
- Direct Glare
- Flicker (and Strobe)
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Task Plane (Uniformity)
- Modeling of Faces or Objects
- Reflected Glare

Emergency Outpatient

- Color Appearance (and Color Contrast)
- Direct Glare
- Flicker (and Strobe)
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Modeling of Faces or Objects
- Reflected Glare

Nurseries

- Color Appearance (and Color Contrast)
- Direct Glare
- Flicker (and Strobe)
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Modeling of Faces or Objects
- Reflected Glare

Nursing Stations

- Color Appearance (and Color Contrast)
- Flicker (and Strobe)
- Illuminance (Horizontal)
- Light Distribution on Surfaces
- Light Distribution on Task Plane (Uniformity)
- Luminances of Room Surfaces
- Modeling of Faces or Objects

Patient Rooms

- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Flicker (and Strobe)
- Light Distribution on Surfaces
- Luminances of Room Surfaces
- Modeling of Faces or Objects

Postanesthetic Recovery Room

- Color Appearance (and Color Contrast)
- Direct Glare
- Flicker (and Strobe)
- Illuminance (Horizontal)
- Illuminance (Vertical)

Surgical Suite

- Color Appearance (and Color Contrast)
- Direct Glare
- Flicker (and Strobe)
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Modeling of Faces or Objects
- Reflected Glare

Health care facilities include a variety of seeing conditions and present many concerns and challenges for the lighting designer. Excellent visual conditions should be provided for doctors, nurses, technicians, maintenance workers, and patients. For a better appreciation of the principles involved, a review should be made of Chapter 3, Vision and Perception; Chapter 4, Color; and Chapter 10, Quality of the Visual Environment.

Lighting for hospital and health care support areas that are not directly related to patient health care are not discussed here. Refer to other sections in this handbook for lighting of libraries, kitchens, laundries, and offices.

Design issues, including illuminance recommendations for health care, are given in Chapter 10, Quality of the Visual Environment. Primary considerations for lighting quality in health care include (but are not limited to) color appearance, daylighting integration and control, flicker, horizontal and vertical illuminance, luminances of room surfaces, and modeling of faces or objects. In addition, special considerations appropriate to the very specific requirements of each space are detailed in this chapter. Higher illuminances from localized lighting are required for good visibility in surgery, obstetrics, dentistry, emergency treatment, trauma, and autopsy rooms. The lighting should also be comfortable. To this end, luminance differences between the task and other areas in the field of view must be limited. The luminance of adjacent surroundings should be no less than 33% of that on the task, for remote darker surfaces no less than 25% of that on the task, and for remote lighter surfaces, no less than 20% of that on the task. To achieve these relationships, room surface reflectances should be within the following percentage ranges: ceiling, 80 to 90%; walls, 40 to 60%, furniture and equipment, 25 to 45%; and floors, 20 to 40%.

TYPES OF FACILITIES

Health care facilities include acute care hospitals, chronic care hospitals, and extended care facilities for the physically and mentally ill, as well as other facilities that offer professional care for ambulatory patients. In lighting these institutions, the designer should consider current as well as future health care services that might be provided. For example, a facility designated as an extended care unit may become recertified as an acute care unit. Where it can be determined that such future flexibility is needed, provisions for wiring capacity and raceways should be installed to minimize future alterations.

The Acute Care Hospital

Although some acute care hospitals are faced with all of the diverse lighting design considerations of a complete multidisciplinary hospital, there are others that are not. For example, obstetric and pediatric departments are being allocated to certain hospitals and abandoned in others. This trend toward specialization places greater demand upon specialized support facilities but reduces the need for flexibility.

The Chronic Care Hospital

The chronic care hospital is largely disappearing. Psychiatric and contagion institutions are being replaced by comparable units within general acute care hospitals.

Outpatient services are expanding, including some that heretofore have been considered as in-hospital functions. Many outpatient procedures require the same lighting as that found in hospital operating rooms. Some operations are now being carried out in special ambulatory operating rooms located in free-standing clinics or office buildings designed for physicians and dentists.

The Extended Care Facility

Extended care facilities, specifically nursing homes, are proliferating. Most of these are inhabited by the elderly whose visual difficulties include cataracts, presbyopia, glaucoma, retinitis pigmentosa, and macular degeneration. These difficulties pose special problems for the lighting designer. In general, for these patients contrast should be maximized (e.g., seeing door frames, food on plates, toilet facilities). Significantly higher task illuminances and much lower glare are needed for these patients than for the normally sighted. For further information on the aging eye, see Chapter 3, Vision and Perception, and Recommended Practice (RP) 28-98, Lighting and the Visual Environment for Senior Living.[1]

Single- or double-occupancy rooms are the most prevalent patient accommodations in any health care facility. By American Institute of Architects/U.S. Department of Health and Human Services (AIA/DHHS) guidelines, these spaces must be located close to windows to provide the patient access to daylight. Exception is made for intensive care areas, where typically there are either semienclosures with glass observation windows or cubicles acting as bed bays opening onto a central hall or workspace. Night and task illumination for these spaces presents some challenges to the lighting designer. See RP-29-95, Lighting for Health Care Facilities,[2] for a more extensive discussion.

Other Facilities

Self-contained ambulatory surgical centers, emergency centers, medical office buildings, and clinics warrant special attention because they form an appreciable and growing part of the health care network. Every doctor's office should contain lighting equipment that enables the physician to perform all tasks with ease.

LIGHTING DESIGN CONSIDERATIONS

In designing the lighting system for a new or renovated space, consideration should be given to the needs of the occupant of that space, the visual tasks to be performed, and the desired appearance of that space. Energy and economic constraints also should be considered.

Personal computers with visual display terminals (VDTs) are used in virtually every administration and functional support space. In addition, monitoring equipment (with associated VDTs) is used extensively in modern hospitals and requires the same lighting design considerations. For lighting areas where VDTs are used, see Chapter 11, Office Lighting.

Personnel working in diagnostic and therapeutic facilities come in all ages, as do patients. Consequently, lighting should be planned to be adequate for all. In particular, the need for good color rendering is clear in most task-related areas of the hospital.[3]

Seeing is a dynamic activity. The eyes do not remain fixed upon a single point, but move to all parts of the task area. For this reason, consideration should be given to three zones of lighting, particularly for the operating room: the highest level should be in the operative field; a second level should surround the table; and a third level should light the peripheral areas.

Hospitals contain areas designated for specific activities. Both quantitative and qualitative lighting recommendations are provided in Chapter 10, Quality of the Visual Environment.

Adult Patient Rooms

For patient rooms, the designer must provide different types of lighting for various people and still provide simple and economical selections. Nurses, physicians, and housekeeping staff require different lighting in any given room to perform their various services. The lighting should be acceptable to all patients occupying the room and satisfactory for the lighting needs of the hospital personnel as well.

Nursing Services. Lighting for nursing services and critical examinations is common to all hospitals. Patient comfort during convalescence can vary greatly, depending on the health and mobility of the patient, the quality of services supplied by the hospital, whether the hospital is public or private, and perhaps most important, on whether a room is for single or multiple occupancy. Modeling of faces and objects, luminances of and light distribution on room surfaces, flicker, and color appearance are important design criteria for nursing areas.

Routine Nursing. General lighting should be comfortable for the patient. Variable-control dimmers or multiple switching, located at the door of the room, provide flexibility. The nurse should never have to search for light to read charts and thermometers. Should more lighting be needed, the patient's reading light may be used. The luminance of luminaires and nearby surroundings should be less than 310 cd/m^2 (30 cd/ft^2) as seen from the patient's bed or any normal reading position to avoid discomfort glare. Bare fluorescent lamps, for example, have thirty or forty times this luminance (see Chapter 6, Light Sources).

Luminaires to meet these conditions should have low luminance. One or more such luminaires in a single- or multiple-occupancy room may be needed to provide general lighting for normal use. To prevent excessive spottiness of general lighting, the installation should limit the lighting level ratio to not more than 1:5 on a horizontal plane.

Patient Observation. Provision should be made for local illumination of good color rendering to allow for proper diagnosis of the patient's appearance. There should be lighting at each bed and its surrounding area so that the nurse can observe the patient and the medical equipment, such as drainage tubes and containers, with minimal disturbance to patients. The ambient lighting should be switched at the door and may sometimes be controlled by a dimmer. When the local or ambient lighting must remain on all night, or when higher levels are needed, portable curtains can be used to provide temporary screening from other patients.

For continuous use at night, a low-brightness flush-wall type luminaire with louvered or refractive cover should be installed approximately 360 mm (14 in.) above the floor. This luminaire provides enough light for movement throughout the space. It is very important to limit the luminance of this luminaire to less than 70 cd/m^2 (6.5 cd/ft^2) at any observation point.

Examination Lighting. The lighting for examining patients in their rooms should be of a color quality that does not distort skin or tissue color, of a directionality to permit careful inspection of surfaces and cavities, and shadowless (Figure 16-1). When curtains are used to isolate a patient, others in the room are protected from the examining lamp; however, whether fixed or portable, the examination lighting should be confined to the bed area and provide adequate lighting over a circular area 0.6 m (2 ft) in diameter.

Figure 16-1. Patient room lighting. Left, examination light, which can be controlled with a wall switch by hospital staff, utilizes compact fluorescent lamps for excellent color rendition. Right, reading lighting, which positions light directly onto the patient's reading material with no reflected glare.

Examination lights are defined as those luminaires used for minor medical procedures outside the operating room. Examples of these procedures are tissue examination and suture removal. Examination lights range from a simple gooseneck lamp to a luminaire similar to an operating room unit.

Local Lighting. Patients should be able to control a luminaire for reading, visiting, self-care, or viewing television. Control must be limited to prevent annoyance to other patients.

A patient reading light should provide illumination at the normal reading position, assumed to be 1140 mm (45 in.) above the floor. To allow the patient freedom to turn in bed without moving out of the reading light zone, the area of the reading plane (lighted by an adjustable unit) should be approximately 0.3 m^2 (3 ft^2), and for a nonadjustable unit the area should be approximately 0.7 m^2 (6 ft^2). To provide a reasonable degree of uniformity of light over the recommended areas, the illuminance at the outer edge of each area should be no less than two-thirds that at the center. To provide comfortable lighting conditions for reading, the luminance of the ceiling, provided by some means of general lighting, should be at least equal to the illuminance of the reading matter.

The luminance of the reading lamp and of any surface illuminated by it, as seen from the patient's bed or any normal reading position, should be 310 cd/m^2 or less. This condition is admittedly difficult to achieve and entails a careful choice of luminaire and limitations to its movement to prevent glare to other patients.

Housekeeping. A very important consideration is the lighting for housekeeping functions. Housekeepers need to see dust or dirt to remove it, including that beneath the furniture.

Nursing Stations

In most hospitals a nursing unit is coordinated around a nursing station (Figure 16-2). Here charts are stored, read, and written. A desk or shelf is invariably provided, usually against some type of counter or below a hung cabinet. Luminaires mounted beneath this counter or cabinet should provide task illumination. The task lighting should be arranged so that it supplements the general illumination of the station. Computer and monitoring VDTs should be positioned or screened to eliminate glare at normal viewing angles. Because the nurse must make frequent trips from the station to the patients' rooms and to service locations, the corridors should have transition lighting, providing a higher level during the day than at night.

Figure 16-2. Lighting at a nurses' station is multilevel, to allow for a higher illumination during the day and a lower level at night. The lighting is designed for the critical task of reading patient information from the computer screen. Undercounter task lights also function as night lights.

Some of the task lighting is in continuous use, night and day, and this should be considered in the lighting plan for the station. Luminaires used at night should not be visible to patients trying to sleep. Usually, when the nursing station is not visible from any of the patient accommodations, general ceiling luminaires can remain lighted during the night hours. Also the luminaires beneath counters should be shielded from patient view or turned off.

Critical Care Areas

The term "critical care" is replacing the formerly used expression "intensive care." Lighting for critical care areas can be highly specialized. These facilities accommodate postsurgical patients, including patients with coronary disease, respiratory disease, burns, or acute childhood and neonatal problems. All of these areas require patient and instrument monitoring and house equipment used for resuscitation, control of hemorrhage, or other emergency measures. Therefore some flexibility in the lighting is required to cover a variety of emergency and critical care scenarios (Figure 16-3).

The illumination should enable the observer to note changes in tissue contour and color, including the prominence of veins on the neck and the presence of a yellow tint in a patient's eyes. Good color rendering is important so that a patient's complexion can be assessed. Elimination of direct and reflected glare is also important.

Figure 16-3. Critical care room. Dimmable fluorescent lighting provides general illumination. Surgical

task lights are positioned over the patient beds for emergency procedures.

While the visual task demands for medical personnel in these units may be great, the well-being of the patient must also be considered. The general lighting should be dimmable. It should be located so that neither a supine patient nor one sitting with an elevated backrest is subjected to glare. In addition to general lighting, there should be lighting for examination by the physician. Also, some type of surgical task light should be readily available to provide higher illuminances for emergency procedures. Most of these facilities contain a handwashing area that requires good illumination. Hospital building codes typically require windows in patient rooms to enable each patient to be cognizant of the outdoor environment, though the provision of illumination by this means is not important.

The nursing station is usually visible to the patient, so task lighting in this area should be shielded, especially at night. Monitoring devices with VDTs should be considered in terms of luminaire placement so that glare or reflections will be minimized at normal viewing angles.

Children's Section (Pediatric)

A child admitted to the hospital for the first time may feel overwhelmed by its huge size and depressed from seeing so many sick people. Strange equipment may frighten and alarm patients or intensify anxiety. For this reason the pediatric section or department should provide ample space for play and educational projects. The lighting should be planned with this in mind, and should have continuity with adult areas.

A bright and cheerful atmosphere is essential. Corridors should incorporate warm surface colors and diffuse lighting. Spots of light and decorative patterns shorten the apparent waiting times and travel distances down hospital corridors. Arrangements for varying the lighting by multiple switching or dimming are often desirable. Windows and skylights can be used effectively where glare does not cause discomfort for visual activities. Children play and sit on the floor so the lighting should support reading, looking at pictures, drawing, and other visual activities at the floor level.

Nurseries

Nursery lighting should be designed so that infants in cribs and in incubators can be observed easily (Figure 16-4). Lighting is often needed for careful observation in both horizontal and vertical planes, but it should not be kept at high levels too long because infants do not have the ability to employ adult protective mechanisms to avoid retinal exposure. This must be taken into account when planning the illumination. The general lighting should be flicker free and of such a type so that the luminance of any luminaire, ceiling, wall, or specular surface, as seen from a working or normal bassinet position, is not excessive.

Figure 16-4. Fabric incubator covers have been used successfully to reduce high light exposures from electric lighting and from windows, while still allowing health-care providers a view of the infants inside.

In order to see minor changes in the color of the skin or sclera, light sources should have good color rendering capabilities and provide adequate modeling of skin and objects. For information on the treatment of infantile jaundice with fluorescent light, particularly the precautions that are recommended for such therapy,[4,5] and on the use of ultraviolet (UV) bactericidal barriers in pediatric sections,[6] consult the recommended publications as well as Chapter 5, Nonvisual Effects of Optical Radiation.

Senior Living Facilities

Seniors, whether they live in their own homes or in assisted living facilities, have special lighting needs. Most often seniors require higher illuminances, freedom from glare, and enhanced luminance or chromatic contrasts. Because their eyes require increased adaptation time, abrupt changes in luminance between contiguous spaces should be limited. Hazardous areas, such as stairways, platforms, and doorways, must receive special attention so that changes in elevation and obstructions are easily recognized and navigated. Seniors may require special task lighting in order to continue performing those visual tasks that are essential to their well-being, productivity, and pleasure (Figure 16-5).

Figure 16-5. The kitchen of an apartment for a disabled senior, which features countertops and appliances at wheelchair height. General illumination is provided by energy-efficient fluorescent luminaires. Undercabinet striplights and a range hood light illuminate the kitchen work area. A decorative pendant luminaire lights the dining area.

Fluorescent lighting is a good choice for producing a uniform brightness in interior spaces and for bringing high light levels into a room. Triphosphor (rare-earth) fluorescent lamps allow spectral choices with good color rendition and are energy efficient and cost effective. Depending on the application, a spectral choice in the 3000 K to 4100 K range should be considered, with 3500-K fluorescent lamps combining well with incandescent sources.

Since many elderly persons do not want an "institutional look" in their residences, luminaire selection is important. Fluorescent luminaires built into architectural elements (coves, domes, valances, soffits, shelves, etc.) or cabinets provide a high level of general illumination with consistent and even light distribution. Decorative luminaires selected and located to avoid glare may then be used for task and specific lighting without diminishing the quality of the overall plan.

In senior residences, tasks need to be defined in relation to where they take place. The elderly often write letters in bed, watch television in the kitchen, and perform tasks in different rooms and under different conditions than when they were younger. The visual tasks associated with the activities of daily living all need special consideration, and the designer should perform a complete analysis so that any unique lighting problems can be resolved before installation. For further information on senior lighting spaces such as living rooms, dining areas, kitchens, bedrooms, and bathrooms, see RP-28-98[1] or Chapter 18, Residential Lighting.

Corridors and Common Areas.

Older eyes adapt less quickly to differences in light level, and an even light distribution within a space makes rooms and hallways easier to navigate. Scalloped lighting effects on corridor walls, or alternating high and low illumination levels within the space, produce visual confusion that can make these areas more difficult to negotiate. Overhead lighting reflected by a polished floor often produces discomfort or disability glare. Highly reflective floors should be avoided. Glossy surfaces, especially near large-area windows, can also create severe glare problems. Floor surfaces should not contain strong or highly contrasting patterns, which could be misinterpreted as shadows, changes in height, or as objects on the floor.

Stairs and Elevators. Stair treads, landings, and handrails must be illuminated for regular use and during emergencies. Light levels for emergency egress should remain the same as for regular use. Current codes regarding emergency egress do not address stairway lighting separately from corridor lighting, yet the minimum emergency egress light promulgated for corridors is inadequate for safe use of stairs by older adults. Designers should select and locate luminaires to evenly light the treads and landing, while excluding luminaires with strong surface brightness in the viewing field, which can be perceived as glare. Shadows that obscure the definition of step edges must be avoided. Strongly patterned carpet is not appropriate on stairs since the design may obscure step edges. Stairs should have clearly marked edge strips, staircase borders, and handrails.

Lighting in elevators should be the same as in the adjacent lobbies and corridors. High-intensity downlights are discouraged because of the glare and strong facial shadows they create. Elevator call buttons should be clearly labeled and illuminated. Inside the elevator, the button display should have high-contrast lettering, and the emergency control buttons should be easily distinguished from all other buttons. Tactile buttons should be provided for those persons with severe visual impairment. To assure full compliance, refer to the Americans with Disabilities Act.

At each floor, outside the elevator, there should be clearly visible identification numbers, as well as signs that identify the floor levels. Arrival at each floor should be announced by an auditory signal that identifies the floor number.

Activity Areas. Seniors-only housing developments often include activities and amenities found in a nonrestricted community (e.g., a convenience store, coffee shop, arts and crafts studio, swimming pool, and exercise center). When designing for these activities, apply the general principles of providing adequate ambient illumination with additional task lighting that avoids glare. Each visual task must be defined, and appropriate lighting be supplied, to meet the spatial, speed, and accuracy requirements of the task at hand.

Mental Health Facilities

Facilities for mentally or emotionally disturbed patients are either "open," in which the patients are unrestricted, or "closed," where access is controlled. Either type may house patients who are considered to be under maximum security. The lighting should be designed to be inaccessible to these patients, in order to protect them from injuring themselves or others, and yet designed to avoid a prison-like effect. Lighting should be provided by nonadjustable luminaires recessed in the ceiling, not only out of reach of the patient but also protected from impact by thrown objects. These luminaires should be controlled by key switches, preferably mounted in hallways outside of the detention areas.

Most mental health facilities today handle patients who are not severely disturbed. Regardless of the type of patient, proper lighting depends on knowledgeable selection of patterns and areas of illumination to calm rather than disturb them. A general basic guideline is that the lighting of these facilities should provide interest, warmth, definition of spaces, and illumination for tasks and safety. It is particularly important that the color rendering of the illumination be good, both to ensure that objects are seen in their normal coloration and to provide a pleasant, colorful surround. Windows are also important in these facilities because they provide visual access to the outside world. Flickering fluorescent lamps should be replaced immediately.

Surgical Holding Areas

These areas (Figure 16-6) are designed primarily for the temporary retention of patients, who are nearly always supine on wheeled stretchers (gurneys). They are kept in these areas out of the traffic stream for periods ranging from a few minutes to as long as 30 minutes. Most of the time a subdued illumination for slumber is advisable; it should be designed to be out of the recumbent patient's line of sight. A higher illuminance is needed for supervision and observation, so switching or dimming is required. Both horizontal and vertical illuminances are important because patients can be positioned in a number of ways.

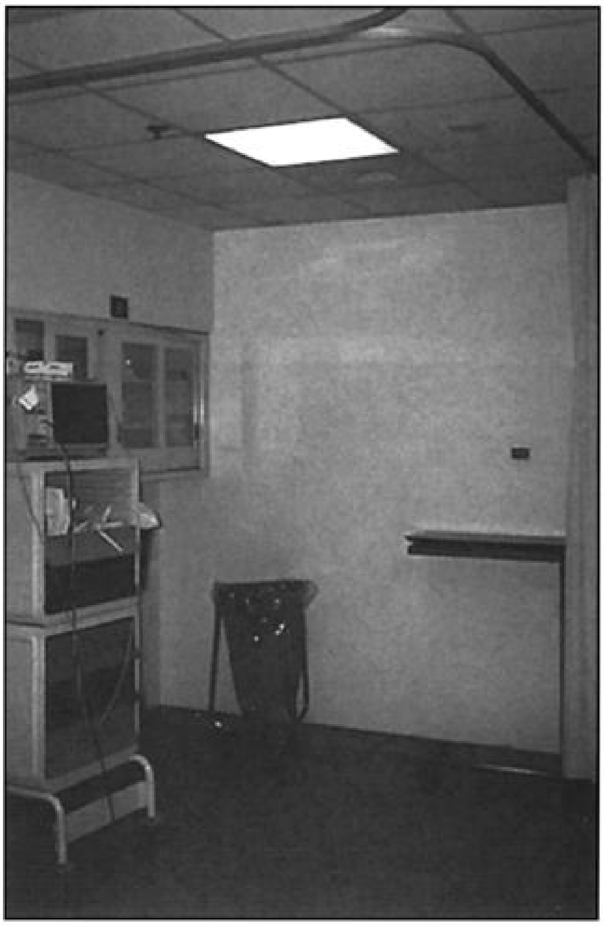

Figure 16-6. A surgical holding area, where patients are kept prior to surgery, requires low levels of illumination.

The holding area is not usually designed for surgical induction; however, some hospitals do use it for that purpose, and the planner must give such an arrangement additional consideration. Some type of lighting is useful for starting intravenous lines and for other preanesthetic activities such as shaving. This purpose might well be served by a flexible wall-hung bracket luminaire, which allows one patient to be prepared without disturbing another. Bright, cheerful, colorful surroundings with flicker-free illumination of good color rendering is important.

Surgical Suite

Operating Room. For the designer, lighting the operating room presents a challenge not only because of the number of people to be satisfied, but also because of the importance of the work performed there. Many design criteria must be considered because of the critical nature of the task (surgery).

There should be no dense shadows to prevent the surgeons from seeing past their own hands and instruments or to prevent them from adequately seeing the patient's tissue, organs, and blood with correct coloration and modeling. Sometimes the surgeon must see deep into body cavities. To enhance physical comfort for the surgical team, heat reaching the back of the surgeon's head and neck from the overhead surgical light must be minimized. The surgeon must be able to see without visual discomfort and without direct and reflected glare for hours, if necessary, and must be able to glance to and from the work areas without having to take time for the eyes to adjust to large brightness differences. Flicker should also be avoided.

The radiant energy produced by surgical lights must be limited for the protection of surgically exposed tissues and for the comfort and efficiency of the surgeon and assistants. For most operations the radiant energy in the spectral region of 800 to 1000 nm should be kept at a minimum. This is the band of infrared absorption by flesh and water; hence it heats the surgeon noticeably and, more importantly, may cause drying of exposed tissues. Current research suggests that in certain neurosurgical or intestinal procedures on delicate, thin, dry, or otherwise abnormal tissue, the light pattern's total irradiance should not exceed 0.1 W/cm^2. Manufacturers of surgical lighting should provide information on conditions under which their equipment can exceed this irradiance. Precautions should be taken to avoid a total lamp failure, for example, by having multiple lamps in a single lighthead unit or a multiple lighthead unit.

The following guidelines should be used for colors and reflectances of operating and delivery room interior surfaces, draping, and gown fabrics. Ceilings should have a near-white color with 90% or more reflectance. Walls should be painted matte or semi-matte of any light color with 60% reflectance. Floor reflectances should range from 20 to 30%, but may be as low as 8%, depending on the selection of flooring materials available. Fabrics for gowns and surgical drapes can be colored, usually in a dull shade of blue-green, turquoise, or pearl gray, with 30% or less reflectance. Surgical instruments should have a nonreflecting matte finish to minimize reflected glare in the area of the operative cavity. Any plastic materials used in draping should also have a matte finish.

Equipment for x-rays, anesthesia, microscopes, and ventilation competes with the lighting system for the limited ceiling space available. Therefore, to achieve the desired illuminance, the location and arrangement of the lighting system should be carefully planned. Because of the variety of surgical procedures, the general illumination in the operating room should provide a uniformly distributed illuminance with provisions for changing the level (Figure 16-7). Luminaires should be equipped with optical elements to diffuse the light and to prevent glare.

Figure 16-7. An operating room, showing state-of-the-art surgical lights.

Occasionally the surgeon uses equipment with self-contained light sources such as a microscope or a flexible fiber endoscope. Low lighting levels should be made available for procedures employing such equipment.

The patient's tissues should appear the same under the surgical light and the general room illumination. This can be achieved by matching the correlated color temperature and color rendering properties of the two lamp types.

The surgical task lighting system (Figure 16-8) should provide a minimum of 27 klx (2500 fc) averaged over a 20-cm (8-in.) diameter circle on the surgical table. For ceiling-suspended surgical lighting systems, the illuminance and patterns are measured 1000 mm (40 in.) from the face of the lamp cover glass, if a cover glass is used, or from the lower edge of the outer reflectors in a multiple-reflector unit with an individual cover over each lighting source. Luminance differences between areas within view of the surgeon and the surgical team should be no more than 33% between the wound and the surgical field and no more than 20% between the surgical field and the instrument table. The luminance difference between the surgical field and the room's lighter surfaces also should be no more than 20%. Visual comfort is probably greatest when there are no excessively bright reflections in the field.

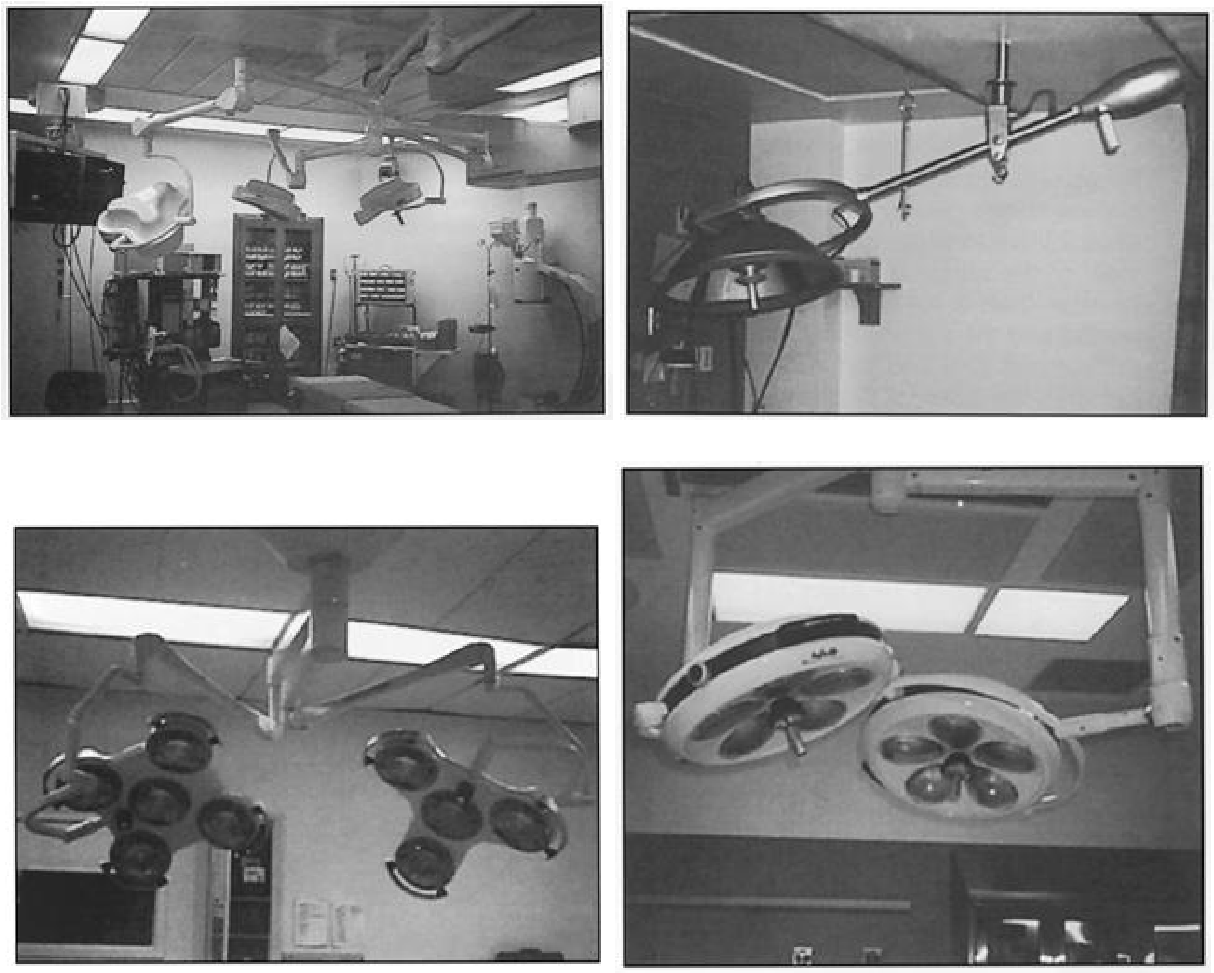

Figure 16-8. (a) View of ceiling-mounted lighting equipment in a modern operating room. The surgical lights are mounted on a stem, rather than on brackets, and have a wide extension. (b) A single-head luminaire used for outpatient surgery. (c) and (d) Typical multihead operating room lights.

The above is intended as minimum for general surgical procedures. In many specialized instances higher illuminances and various pattern sizes and shapes are desirable, as well as control of the illuminance level. Variable pattern sizes are provided by moving the light closer to or farther from the patient. Some lights provide, in addition, a focusing control that varies the pattern size. Users should determine the depth of field required for their work and evaluate the luminaires available that give a suitable pattern.

Flexibility in the surgical lighting unit can be accomplished by mechanical positioning of luminaires suspended from the ceiling or by electrical switching of stationary luminaires. Luminaire positioning is sometimes achieved by the scrubbed surgeon adjusting a sterile handle, but the asepsis of this technique has been questioned. If handles are used, they must be removable for sterilization or covered with disposable sterile sheaths. Handles should also have a guard to prevent contact with a nonsterile area and should be smooth to avoid glove puncture.

The requirements for directional flexibility in the main task lighting system vary with the surgeons and the type of surgical procedures to be performed. Requirements for orthopedic operations differ greatly from those for cardiovascular and neurosurgical operations, which in turn differ from those for gynecological procedures. Thus, the selection of the lighting system cannot be simply prescribed, and the lighting specifier must be aware of the limitations of equipment.

Supplemental surgical task luminaires are of two main types: those with a beam encompassing the entire field and those that operate by directing light through a glass or plastic fiber-optic bundle. Both types, when used where flammable anesthetic gases are employed, must be explosion proof or positioned higher than 1.5 m (5 ft) above the floor. The electrical system must be in accordance with the Standard for Health Care Facilities (NFPA 99).[7]

Free-standing lights must conform with safety standards to avoid tipping and must have a reasonable ability to retain their position. No part of a portable wide-beam lamp housing should project below 1.5 m (5 ft) from the floor. The entire unit must be grounded through a third wire in the flexible cable.[7]

A fiber-optic unit for use in a sterile field must be capable of sterilization or be encased in a waterproof and sterile static-free barrier. At the exit face of the fiber-optic device, the irradiance should be no more than 0.025 W/cm^2 if actually intended for insertion in the wound.

Low-voltage lighting equipment (less than 8 V) may be used in accordance with NFPA 99,[7] if supplied by an individual isolating transformer "connected by an anesthetizing location cord and plug" or from dry cell batteries or a transformer above the 1.5 m (5 ft) level. Isolating transformers should have a grounded case and core.

Two-team surgery is now frequently practiced for many procedures. For example, one team may remove a vein from the thigh while another implants it into the heart. For this purpose, additional lightheads or satellite units may extend from the primary luminaire mounting. On the other hand, the use of two or more luminaires on one surgical field requires special care; see the discussion above relating to the heating of tissues.

The anesthesiologist usually sits behind a tent of surgical drapes that prevents an accurate assessment of the patient's face color. Cover glasses of both digital and analog instruments tend to be reflective and may produce veiling reflections or glare, which should be prevented by either shielding or careful positioning. Furthermore, the anesthesiologist should be shielded from the operating task light. Shielding of the general illumination system and other special lighting considerations also may be needed.

Scrub Area. Scrub areas and corridors adjacent to the operating room should have illuminance levels and lamp color rendering properties similar to those they encounter in the operating room. This not only ensures a good job of scrubbing, but it also allows the surgical team members to enter the operating room with their eyes fully adapted.

Special Lighting

Photography and television. Operating room television and film camera systems can be grouped into three categories:

- Systems built into the lighthead. This type always coordinates the light and camera fields.
- Systems attached to a separate arm mechanism, but part of the surgical light system. This type allows more control of the viewing angle but requires more operator skill.
- Systems separated from the lighting system on booms, dollies, or platforms. This type allows higher-quality imaging but requires more space and good camera-operator skills.

For a given installation, the photographic needs can range from basic before-and-after documentation to sophisticated teaching films (the latter requiring the most versatile equipment). Upright image orientation is important for a television system. See Chapter 15, Theater, Television, and Photographic Lighting, for further information on lighting for photographic requirements.

Headlights. Headlights are often used by surgeons to supplement the illumination from overhead surgical lights, or to provide light from angles that overhead lights cannot achieve, such as upward from a low position. Typical headlight-to-task distances range from 300 to 600 mm (12 to 24 in.). Headlights are especially useful for seeing in small, narrow, or deep cavities where the beam of light must be parallel to the surgeon's line of sight (coaxial). A typical surgical headlight system consists of a headlight mounted on a headband, a cable, and a power or light source. There are two common styles of headlights: a coaxial type that projects a beam forward or downward from a location directly between the surgeon's eyes, and a direct type that projects a beam generally downward from a location on the forehead.

Headlights are usually illuminated through a flexible fiber-optic cable that plugs into an illuminator or light source box. A few headlights use low-voltage lamps and wires from a battery or small transformer. Factors to consider in evaluating headlights include:

- Spot size at anticipated working distance
- Spot size adjustability
- Illuminance at anticipated working distance
- Ability to pivot and aim the light beam in various directions

- Weight of both headlight and cable
- Comfort and adjustments of the headband
- Cable size, durability, and ease of maintenance (some cables have clips to transfer the cable's weight to the surgical gown)
- Ease of aiming by a scrubbed surgeon using a sterile handle

Factors to consider in evaluating fiber-optic illuminators to power headlights include:

- Size, weight, and mobility
- Ease of lamp replacement
- Light intensity and color
- Intensity adjustment
- Number of fiber-optic cables that the light source can power at the same time

Specialized Operating Rooms

Eye Surgery. Rooms for eye surgery contain some type of fixed pedestal or columns connected with an operating microscope. This equipment may contain its own luminaires and frequently contains beam-splitting devices to permit viewing by more than one person. There may be film or television camera equipment attached. Various lasers may be present, as well as an electromagnet for removing ferrous foreign material from the eye.

The general room illumination is planned to give the same level as in the general operating room in the horizontal and vertical directions. The surgeon, however, sometimes requires less general illumination and may prefer almost complete darkness to reduce reflections from the curved surface of the eye; therefore, a method for reducing the illumination becomes mandatory in the eye room. Separate lighting may be necessary for the anesthesiologist so that equipment may be observed. Pendant ceiling-mounted surgical lights are also used in eye surgery for work on muscles, tissue, and lachrymal glands surrounding the eye itself. These should be selected by adapting the criteria for surgical suite lighting to the requirements of the ophthalmologist. The heat production from microscope lighting needs to be limited. All lighting for the eye surgery area should be free from flicker.

Ear, Nose, and Throat Surgery. The requirements for this specialty are identical to those for eye surgery. Microscopic surgery is used for operations on the inner ear.

Neurosurgery. For opening and closing portions of a procedure, a neurosurgical operating room is no different in its visual requirements from general surgical operating rooms. For the major portion of the procedure, most neurosurgeons use surgical microscopes, which can be either portable or mounted on the floor, ceiling, or wall. Operating room microscopes contain their own illumination; surround lights should be controlled and task lights focused on instrument tables to allow scrub nurses to select instruments quickly and accurately. Many neurosurgeons prefer a triple or quadruple task light, which can be brought close to the surgical field and at the same time illuminate other surgical fields. For some procedures, neurosurgeons use headlamps.

Orthopedic Surgery. In general, the visual needs of an orthopedic operating room are no different from those of general surgery, but better facilities for x-ray equipment may be necessary. The type of x-ray equipment and its mounting should be coordinated with the lighting systems. Particular attention should be paid to luminaire flexibility because orthopedic surgery frequently requires special positioning on the side of the operating (fracture) table. Fluoroscopy with image intensification and television screening permits the use of a room that is not darkened. The orthopedic surgeon also uses a surgical microscope.

For joint replacement, the orthopedist sometimes employs laminar airflow chambers, and surgical luminaires pose a problem both from their disturbance of the laminarity of the airflow and from the convection currents they cause. These situations are difficult to avoid, and the necessity for illumination of the surgical task is paramount.

Postanesthetic Recovery Room

This is an area of meticulous patient monitoring and equipment observation; it must also support certain emergency procedures. Color changes in the patient's skin are very important, so adequate light with good color rendering is important. Lighting should be variable, so that information on the specular oscilloscopes can be read. See Figure 16-9.

Figure 16-9. This post-anesthesia recovery room has indirect lighting that restricts glare to awakening patients.

Cystoscopy Room

The cystoscope is an instrument for examining the urinary tract. The procedure is started in a lighted room but examination is normally carried out in a dark room. Switching or dimming of ambient lighting is therefore required. Where surgery is performed, conventional surgical suite lighting is required. For female patients a gynecologic examining light should be provided. Flammable anesthetics are not usually used in the area; in such cases the light should be available at a level just above the urologist's shoulder while seated.

Obstetric Delivery Suite

Labor Rooms. Monitoring apparatus is often used to observe uterine contractions and responses from the unborn child. These data are usually recorded on paper and observed by attendants. Examinations performed in this room do not require control of the lighting. The lighting should be sufficient in the horizontal and vertical directions and should permit adequate modeling. Blood pressure measurements and observations of the patient's status require lighting with good color rendering so that any cyanosis (blueness) is obvious. Patients' morale tends to be heightened where colorful, noninstitutional lighting is provided and where flicker, direct glare, and reflected glare are absent.

Facilities often use a single labor and delivery room called a birthing room (Figure 16-10). This may be situated in a hospital or in an ambulatory facility called a childbearing center with lighting similar to a hotel room, except that a portable surgical lamp should be available,[8] as well as task lighting to illuminate the lower abdomen and perineum. The patient is conscious, so high brightness should not be in the visual field of the recumbent patient. Cleanliness is imperative; a luminaire that can be easily cleaned should be selected. In addition to the general lighting, reading lights can be provided.

Figure 16-10. A birthing room, with its soothing colors, inviting textures and soft lighting, is reminiscent of a residential bedroom. The patient can control the glare-free reading lamp positioned over the head of the bed.

Delivery Area. The delivery scrub area should have the same illumination as in the surgical scrub area. The general lighting of the delivery room should be achieved by recessed luminaires providing uniform illumination in the room.

The task luminaire should produce a local illuminance of 25 klx (2500 fc). Ideally, the lamp should have the capability of being centered over the shoulder of a sitting obstetrician. In some institutions the anesthesiologist bans the use of flammable anesthetic agents in the delivery suite because of the explosion hazard, so explosion-proof portable units have been manufactured.

A special lighting plan should exist for the area in which the newborn infant is resuscitated. The lamps should have good color rendering properties, both for a pleasing appearance of mother and baby and for the detection of cyanosis and jaundice.

Radiology Suite

The radiology suite contains a number of rooms where a variety of tests and treatments is performed. Each room should have sufficient horizontal and vertical illuminances to permit patient transfers and cleaning. The lighting must be flicker-free and arranged to avoid blockage of light from overhead x-ray units as well as glare to patient's eyes while lying on a stretcher or gurney. Some rooms need flexible floor or wall-mounted task lights to provide vertical illuminance or intense lighting for minor surgical procedures, introducing instruments into body cavities, and needles into vessels. When required, high color rendering sources should be used. In addition, every room should be equipped with a switch or dimmer to reduce the room illuminance while viewing images on an electronic screen. X-ray reading rooms, equipped with view boxes for viewing films, are placed at appropriate intervals throughout the suite. X-ray developing rooms must have special doors to keep out light during film development, yet must have good general lighting to permit cleaning and stocking of supplies. The appearance of the space, as perceived through the presence of room surface luminances and daylight, can contribute to the patient's sense of well-being.

Laboratories

Specimen Collecting (Venipuncture) and Donor Areas for the Blood Bank. Lighting should be flicker-free and provide illumination at the site of the venipuncture, usually at the height of the arm of an armchair. Veins are best seen in directional light; therefore, ceiling luminaires or task lights should be located to provide oblique illumination. Bright and cheerful surroundings are important. Good color rendering enhances the appearance of patient and staff and allows for easy detection of the vein pattern. The walls in this area should be pastel shades of low reflectance for donor comfort and reassurance. Control of daylight, if present, is also important.

Tissue Laboratory. Lighting in a tissue laboratory should provide excellent color rendering (see Figure 16-11). There are usually two counter heights, 760 mm (30 in.) and 910 mm (36 in.), the former to be used while the technician is sitting, the latter while standing. The same lighting arrangements are valuable in the room devoted to the preparation of cytology specimens. Backgrounds for microscope viewing should have very low reflectance to avoid glare. Recessed ceiling luminaires with remote controls should be considered for lighting a tissue laboratory.

Figure 16-11. High color rendering fluorescent lighting is used in this hospital tissue laboratory.

Microscopic Reading Room. A pathologist spends a considerable amount of time reading microscopic material. For this purpose the table tops on which the microscopes are placed are usually 810 mm (32 in.) from the floor and are of low reflectance, often in a mahogany or walnut finish. In facilities where microscope slides are viewed on a video monitor, special lighting is not required.

Central Sterile Supply

The inspection area of the central processing department should be flicker-free and have good general lighting with low glare and good color rendering. In special areas where delicate instruments and other equipment are inspected, the illumination should be increased. When required, vertical illuminance should be provided.

Dental Suites

In the dental operatory the illuminance ratios between the patient's mouth and face, the patient's bib, the instrument tray, and the surrounding areas should be no greater than 3:1. Illuminance should be provided at the level of the patient's face and the instrument tray. Illuminance inside the oral cavity should be supplied from a luminaire easily adjustable to keep high brightness and reflections from the patient's eyes. The dentist must be able to accurately judge the depth of drilling and the prepared area of the tooth for filling retention as well as teeth occlusions. The light should have good color rendering properties so that the dentist can judge the colors of teeth, dentures, and fillings any place within the mouth.

A luminaire for producing such a penetrating light, reasonably free of shadows at the oral cavity, must produce a convergent beam, focused at a distance of about 1 m (3 to 4 ft). It should be capable of lighting a semicircular area with a sharp cutoff to exclude bright light and reflections from the patient's eyes.

Prosthetic work in the laboratory requires speed, accuracy, close inspection, and a very close color match between the prosthesis and the patient's own coloring. Therefore, general lighting with excellent color rendering should be provided at the workbench. Color matching is particularly important in dental prosthetics. Metamerism of artificial versus natural teeth poses a great challenge, considering that the teeth will be seen under a variety of light sources.

If a dental suite is large enough to have a separate recovery room with a low illuminance level, provision should be made for higher illuminances for emergency examination or special treatments.

Examination and Treatment Rooms

For examination and nonsurgical treatment there should be general lighting with supplementary lighting on the table.

Emergency Suites and Trauma Units

Emergency suites are generally self-sufficient. Portable or fixed ceiling-mounted directional luminaires that provide lighting at the center of the operating area, in combination with a lower level of general illumination, are usually adequate for examination and emergency surgery. Illumination should be free of direct and reflected glare and offer excellent color rendering, since rapid and accurate diagnoses are required.

Autopsy Room and Morgue

Good lighting that is free from direct and reflected glare is imperative in the autopsy room because dissection must be performed there. Autopsies are performed in open cavities rather than in restricted cavities required for surgery. Therefore, highly directional surgical illumination is not needed. While some of the dissection is meticulous in order to expose the tissue, the placement of sutures and of instruments to control bleeding from fine blood vessels is not necessary. Some of the critical color and illumination level requirements when performing surgery on the living person can be compromised.

General lighting can be augmented by spotlights providing illumination at a level on the autopsy table 760 mm (30 in.) above the floor. Surgical lights are not necessary in this room. A spot lamp with IR filtering is valuable for the skull portion of the autopsy. Additional lighting for a scale placed over a counter is also valuable.

Scanning Rooms

Various types of scanning machines are used for diagnostic purposes. The patient is usually prone on a table that either moves under or into the scanning device, or the device may move over the patient. Light in these rooms is usually indirect so that the light source is not in the patient's direct line of sight. Many scanning rooms have valance or perimeter lighting with both upward and downward components. Some general lighting may be installed for cleanup, computerized axial tomography (CAT) units, and positron emission tomography (PET) and magnetic resonance imaging (MRI) systems. These systems are usually housed in three areas: a control room, a computer area, and the scanning room. Equipment consoles with VDTs are typically located in the control room, with a viewing window connecting to the scanning room for direct observation of the patient (Figure 16-12). General lighting controlled by a dimming system in the control and scanning rooms provides low illuminances during treatments and high illuminances for equipment maintenance and setup.

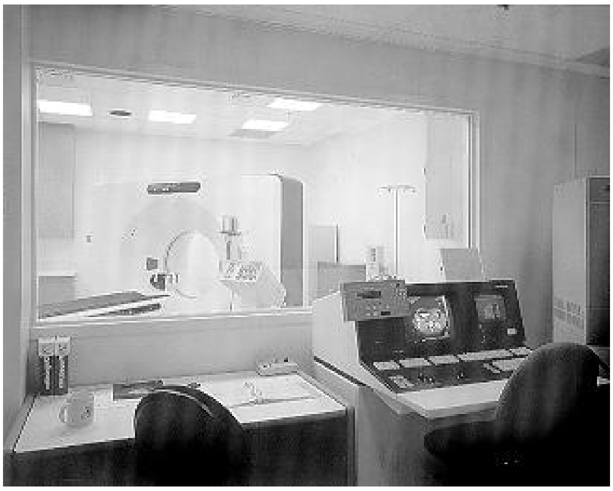

Figure 16-12. The control room of a diagnostic scanning unit, with lights switched off to reveal the image on the CRT monitor. A viewing window allows for patient observation during the procedure.

Figure 16-13. Dimmable incandescent downlights are used in this MRI scanning room.

Only general lighting is required for equipment maintenance in the computer room. MRI utilizes powerful magnetic fields in the diagnostic process. Therefore, nonferrous, direct-current-powered incandescent luminaires should be used in the scanning room, to eliminate the effects of the magnetic fields on the lighting system and also to reduce the interference of magnetic objects in the diagnostic image produced during the scanning process (Figure 16-13).

The psychological effect of lighting can be very important for scanning rooms, where the patient is required to spend long periods lying inside the equipment during scanning. Windows to allow daylight, combined with low glare, can do much to alleviate some of the patient's apprehension, by softening the hard look of the somewhat intimidating equipment.

Pharmacy

The pharmacy should be well illuminated so that the pharmacist can easily read labels and fine print of precautionary literature supplied with the medications. Illumination should be provided at the workbench, usually 910 mm (36 in.) from the floor, to allow prescriptions to be filled rapidly and accurately.

Emergency Lighting

Emergency lighting is needed to evacuate the building under adverse conditions and provide life support services to the patients who cannot be evacuated. The former type of emergency lighting is described in Chapter 29, Emergency, Safety, and Security Lighting. The latter requires higher illuminance levels that, in most applications, are equal to that provided by the regular lighting system. Therefore, highly reliable electric service to these areas is essential. Indeed, the regular room lighting becomes equivalent to the emergency lighting whenever the power supply to the critical care areas switches from the normal source to the emergency source.[7] The remaining areas of the hospital should have low-level emergency lighting as recommended in Chapter 29, Emergency, Safety, and Security Lighting.

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17

Retail Lighting

RETAIL LIGHTING DESIGN ISSUES

Stores

General Merchandise Display

- Appearance of Space and Luminaires
- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Light Distribution on Task Plane (Uniformity)
- Modeling of Faces or Objects
- Reflected Glare
- Sparkle/Desirable Reflected Highlights

Sales Transaction Areas

- Appearance of Space and Luminaires
- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Direct Glare
- Illuminance (Horizontal)
- Light Distribution on Task Plane (Uniformity)
- Modeling of Faces or Objects
- Reflected Glare
- Source/Task/Eye Geometry

Feature Display/Show Window

- Appearance of Space and Luminaires
- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Direct Glare
- Modeling of Faces or Objects
- Reflected Glare

Fitting Rooms

- Color Appearance (and Color Contrast)
- Modeling of Faces or Objects
- Illuminance (Horizontal)
- Illuminance (Vertical)

Alterations

- Color Appearance (and Color Contrast)
- Illuminance (Horizontal)
- Source/Task/Eye Geometry

Malls

Concourse

- Appearance of Space and Luminaires
- Color Appearance (and Color Contrast)
- Daylighting Integration and Control

Directory/Information Desk

- Direct Glare
- Light Distribution on Surfaces
- Point(s) of Interest
- Reflected Glare
- Source/Task/Eye Geometry

Kiosk

- Appearance of Space and Luminaires
- Flicker (and Strobe)
- Illuminance (Vertical)
- Point(s) of Interest
- System Control and Flexibility

Landscape

- Appearance of Space and Luminaires
- Direct Glare
- Light Pollution/Trespass
- Source/Task/Eye Geometry

New lighting techniques and equipment, as well as more efficient light sources, provide the designer with tools to meet the challenge and ever changing requirements of the retail world and the increasing cost of energy. Careful consideration must be given to visual cues that aid in establishing the image that a store wishes to project. The lighting system should be designed to create a pleasant and secure environment in which to do business.

Sophisticated consumers and the tendency toward fewer trained sales personnel make it essential to present merchandise under lighting that helps to increase sales. Attention should be given to the quality, quantity, and effectiveness of lighting and its ability to render colors in the displayed merchandise.

This chapter examines lighting application requirements within the store environment. The recommendations are largely based on merchandising techniques and activity types and images within the store. For best results in lighting retail spaces or where specialized merchandise lighting is required, a lighting professional should be consulted. Under ideal conditions the lighting professional should be added to the design team during the early stage of project development.

GOALS OF RETAIL LIGHTING[1]

There are three primary goals common in the lighting of retail areas.

Lighting Should Attract the Customer. The first step in the merchandising process is to attract the customer to the retail space and merchandise. Lighting creates an immediate impression of the merchandise and the appearance of the area (show window or store interior) that can draw customers toward merchandise or spaces when the selling process can begin. Show windows as well as store interiors are important to customer attraction.

Lighting Should Allow the Customer to Evaluate the Merchandise. The next step is to enable the customer to visually evaluate the merchandise. The customer must be able to visually evaluate characteristics such as texture, color, and quality and to read labels. Fitting rooms as well as sales areas are important for merchandise evaluation.

Lighting Should Facilitate the Completion of the Sale. Finally, proper lighting at the point of sale is necessary to complete a transaction. Sales personnel should be able to quickly and accurately perform services such as recording sales on the register, preparing paperwork, reading prices, using credit card transaction tools, and packaging. Points of sales as well as customer service areas are important to sales completion.

LIGHTING DESIGN CONSIDERATIONS

In order to achieve the goals of merchandise lighting, consideration must be given to task visibility, appearance of the space and its luminaires, appearance of people and objects, visual comfort, and health and well-being. Additionally, photodegradation, economics, maintenance, and energy management issues deserve attention in the beginning stages of lighting design development because these issues contribute to the lighting design solution.

Lighting requirements differ as the functional requirements of the space change. Consequently, identifying typical types of spaces within a retail environment, along with their functional requirements, helps to define the lighting design problem. There are basically four types of spaces that define a retail environment: sales areas, show windows, ancillary spaces, and exterior spaces. Each of these areas has different functional requirements, which consequently result in different lighting solutions. The lighting design solution unfolds when illuminance levels are defined, luminaires are selected, and lighting control strategies are generated.

Sales Areas

Retail spaces should be conducive to initiating and completing sales transactions. Each of the following factors should be considered in the design of sales-area lighting:

- Type and characteristics of merchandise
- Merchandising strategies
- Location of each merchandising area within the store and at outdoor areas
- General illuminance level
- Illuminance levels of adjacent spaces
- Feature and display illuminance levels
- Size and shape of space
- Surface reflectances, colors, and textures
- Flexibility requirements
- Size and location of graphics
- Method of display (racks, gondolas, and counters)
- Method and location of sales transactions
- Location of merchandise displays including feature displays
- Traffic patterns

A typical sales area is shown in Figure 17-1.

Figure 17-1. Typical sales area.

Show Windows

The show window should be a powerful attractor, providing the link between the potential customer passing by and the merchandise within the store. Show window lighting should be brighter than the ambient conditions to attract attention and to minimize the impact of reflections that can obscure the merchandise being shown. If daylight is a consideration, sun angles and shadows are important to address. Dimming and/or multistep on/off controls for the electric lighting should be installed to compensate for the highly variable nature of daylight and to provide much lower illuminance levels for nighttime conditions. Each of the following factors should be considered in the design of show-window lighting:

- Location of show window (outdoor or enclosed mall area, urban or suburban, solo or shopping center)
- Night and day use and associated ambient illuminances
- The nature of the overall competition as well as adjacent show windows
- Fully enclosed or open back configuration
- Size and shape
- Reflections, contour, and slant of show window glazing
- Architectural canopies, jalousies, or louvers
- Interior surface reflectances and colors
- Size and location of display graphics

Show window illumination is shown in Figure 17-2.

Figure 17-2. Show window.

Ancillary Spaces

Dressing and Fitting Room Lighting. The dressing and fitting room area in a clothing store is one of the most critical sales areas. This is where the final evaluation of the merchandise and where the decision to buy is often made. Fitting rooms usually consist of a bank of dressing rooms in combination with a fitting area or large dressing room where a tailor or seamstress measures and fits the customer for tailoring or alterations. Dressing rooms may be simple in design and semi-private like those in a discount or warehouse store. Upscale stores use elaborate, large, private rooms and incorporate amenities like sofas, chairs, portable luminaires, and refreshment areas (Figure 17-3).

Figure 17-3. Ancillary area.

Lighting this space requires the utmost sensitivity from the designer to ensure appropriate vertical illuminance, good color rendering, and the elimination of harsh shadows. Modeling of faces and color appearance is important. Lighting solutions should provide a combination of diffuse and directional light to accentuate facial features and fabric texture without deep shadows.

Careful choice and placement of overhead luminaires adds to color vibrancy, texture enhancement, and sheen or glitter of hair and materials and can create modeling effects. Lighting at the mirror should be used to complement and soften facial shadows without reflected glare. Vertical illumination should extend far enough down to enable the customer to easily evaluate full-length garments. Background finishes should be light colored, matte, and simple in design to avoid color distortion or distraction from the merchandise.

Lighting for basic dressing rooms is usually comprised of overhead fluorescent lamp luminaires strategically placed to provide vertical illumination when viewing one's reflection in the mirror. Upscale fitting rooms employ dedicated mirror lighting. Upscale and designer fitting rooms and dressing areas use a mix of incandescent and fluorescent lamp luminaires, as well as luminaires for decorative and mood lighting.

The correct lighting is especially important at fitting and dressing room mirrors. The luminaire should be positioned to light the customer standing in front of the mirror, rather than the mirror itself. The light source should be diffuse to minimize shadows, and the color quality of the source is crucial. Warm (approximately 3000 K), high-color-rendering fluorescent lamps are well suited to mirror lighting. Halogen incandescent is also excellent, provided the application results in a diffuse and well-distributed pattern of light. It should be noted that incandescent lamps produce excessive heat, so good ventilation systems are essential for customer comfort in small fitting rooms.

The proper angle of illumination is especially important for mirror lighting. Ceiling luminaires should be placed at the mirror wall, or mirror lights should be located above the mirror. Direct downlights over mirrors should be avoided, especially parabolic reflector (PAR) downlights. Downlights tend to create unflattering shadows that result in an unattractive and undesirable view for the customer. If downlights must be used, wide-distribution luminaires are preferred, equipped with either incandescent A lamps or compact fluorescent lamps.

Alteration Workrooms. High levels of illuminance (1000 lx [100 fc]) are needed to perform detailed sewing tasks, and color appearance and glare control are especially important. Other important criteria for alterations workrooms are:

- Low-glare task lights for extremely fine detail and low-contrast sewing
- High-color-rendering lamps, 75 CRI or greater
- Minimal shadows

General lighting should provide the base lighting for the general sewing operation. Supplementary or localized lighting provides the required illuminance for the different tasks. Here there is both hand and machine sewing, often with dark thread on dark material.

Wrapping and Packing. In addition to wrapping and boxing the customers' purchases, sample gift wrap displays are featured. The wall immediately behind the work area should have a reflectance above 40%. This reflected light is necessary to provide both good illumination on the task plane and uniform brightness for eye comfort. Ambient illumination also should be uniform for the worker who faces into the room. The luminaires should be positioned to avoid reflected glare from glossy materials at the user's normal position, unless reflections are desired for some special application.

Ceiling-mounted or suspended wide-distribution luminaires arranged over work areas provide uniform illumination. Portable equipment provides added directional lighting for special conditions.

Stock Rooms. Reading labels and identifing merchandise are the primary visual tasks in a stockroom; however, some stockrooms include a desk or table where other tasks occur. Attention to vertical illumination on storage shelves is important. Large (high-bay) storage/stock areas such as those associated with warehouse stores usually employ high-bay metal halide or fluorescent lamp luminaires. Color rendering can be important in some storage areas. Occupancy sensors and time delay switches, for turning off lights, are recommended in these intermittently occupied rooms for maximum energy efficiency.

Restrooms, Lounges, and Locker Rooms. Lighting for customer restrooms and lounges must be practical and aesthetically pleasing. Design of restroom counter and mirror lighting should follow the design concepts discussed above. However, restroom lighting systems need not be as elaborate as that for dressing and fitting rooms. Designs should focus on maintenance, brightness, and energy efficiency. The level of design and image should be in concert with the image and ambiance of the store.

Lounge lighting should include task illumination for reading and mirror lighting where appropriate. Luminaires should be located to provide enough light in the vicinity of the mirrors for adequate illumination of the face.

In public lavatories, visual tasks include grooming, which requires shadowless illumination on both sides of the face. Color rendering is important. Luminaires should be located so that their maximum light output is concentrated in sinks and urinal and toilet stall areas to encourage cleanliness.

The lighting of locker rooms and employee dressing areas is principally a matter of arranging the lighting equipment. The interior of the lockers should be illuminated, and general lighting should allow safe movement about the room.

Offices. Good office lighting is just as important in a store as it is in a corporate office tower (see Chapter 11, Office Lighting). Store offices should also reflect the store image.

Exterior Spaces

Emphasis should be placed on illuminating entrances. Lighting can enhance and enforce the architectural elements that define the entrance. Also, lighting as a design element can assist in projecting the store's character and image to the arriving customer (Figure 17-4).

Figure 17-4. Exterior entrance.

From the time the potential customer arrives in the vicinity of the shopping area, lighting plays an important part in the pattern of progression to the point of purchase. Consider the following goals when designing outdoor lighting for stores and shopping centers:

- Identifying key areas such as entrances, exits, parking facilities, anchor stores, and crosswalks
- Facilitating safe passage of motorists and pedestrians on the grounds
- Contributing to effective security and surveillance of people and property
- Visually unifying the shopping area
- Projecting the image and ambiance of the retail establishment

See Chapter 21, Exterior Lighting, and IES RP 20-1998, Lighting for Parking Facilities, for recommended practices for illuminating vehicular traffic areas.[2]

LIGHTING METHODS FOR RETAIL

The lighting system should help create an atmosphere that emphasizes the store's character and makes it a desirable place in which to shop. The lighting should permit easy, accurate examination of the features and qualities of the merchandise and minimize glare and harsh brightness differences.

Distribution and Direction of Light

In the initial phases of the lighting design process, the distribution of light must be defined. The luminous environment can range from uniform, diffuse light to very focused light with extreme contrast. The solution might include a combination of both. The target market plays a significant role in defining distribution characteristics of light in a retail environment.

Ambient Lighting

The ambient lighting system in a retail environment should provide a general diffuse layer of uniform illuminance throughout the store. Often referred to as the "general" lighting, the maintained average ambient light level can range from low (30 to 300 lx) to high (500 to 1000 lx) levels depending on the store image. Luminaires for ambient lighting are usually symmetrically arranged with broad distributions. Chromaticity and color rendering quality vary depending on the market target and the store concept. Daylight integration can be important.

Low-end (mass merchandising), middle, and high-end (exclusive) are the basic categories of retail markets. For low-end, mass-merchandising stores, the lighting system typically takes on a general lighting, single-system approach (Figure 17-5). Symmetrically located luminaires provide a uniform general lighting level. Illuminance levels are high (750 to 1500 lx), and the color expression is neutral to cool (3500 to 5000 K). The middle category uses a general lighting system with average illuminance levels (300 to 600 lx), coupled with accent lighting for specialty areas. Color temperature is typically neutral. Department stores often fall into this category (Figure 17-6). High-end, exclusive stores employ complex lighting systems. Luminaire styles include decorative, accent, and ambient. A zoned approach to regulating illuminance levels within the space creates contrast (Figure 17-7). Ambient lighting levels are low (30 to 240 lx), and color expression is typically warm (2700 to 3000 K).

Figure 17-5. Mass merchant/discount store.

Figure 17-6. Typical department store.

Figure 17-7. Designer boutique.

Ambient Lighting Systems. There are three basic approaches to the lighting of merchandise areas in stores: the general pattern system, the specific system, and flexible system. Each system should have supplemental lighting to attract attention to featured displays, to influence traffic circulation, and to create added interest.

In choosing a system or combination of systems, consideration must be given both to the architectural interior design requirements and to the flexibility and adjustment required for the merchandising task.

- The general pattern lighting system employs a pattern of luminaires to provide general lighting throughout the sales area, with or without display lighting, and without regard for the location of the merchandise (Figure 17-8). The system may include switching or dimming controls for flexibility of space use and for efficient energy utilization.
- The specific pattern system employs a layout of luminaires determined by the location of the merchandise displays (store fixtures, showcases, or gondolas). It is tailored to emphasize the merchandise and delineate sales areas (Figure 17-9).
- With the flexible pattern system a pattern of electric outlets of continuous or individual type is provided for temporary installation of luminaires. These may be wired for multiple circuit application and control. This system may be used for general or specific pattern lighting and offers the added advantage of interchangeability of luminaire types to create lighting tailored to the merchandise display (Figure 17-10).

Three types of lighting equipment frequently used in flexible pattern are: recessed adjustable luminaires, recessed adjustable pulldown luminaires, and track lighting. Recessed adjustable luminaires have the appearance of recessed downlights but provide aiming adjustability to between 30 and 45° from the vertical (depending on manufacturer) and usually 355° or more of horizontal rotation.

Figure 17-9. Specific pattern lighting.

Figure 17-8. General pattern grid lighting.

Figure 17-10. Flexible pattern lighting.

The recessed adjustable luminaire provides a clean ceiling line (see Chapter 7, Luminaires). The recessed adjustable pulldown luminaire adds the flexibility of being able to position the light source below the ceiling line and hence allows much greater vertical adjustment (0 to 90°). When properly positioned, the recessed adjustable pulldown luminaire appears as semi-recessed on the ceiling. The most flexible system is track lighting, where the luminaire can be positioned at any point on a linear electrified track of arbitrary length, and the luminaire is adjustable both horizontally (355°) and vertically (0 to 90°). Track may appear cluttered on the ceiling. Although pulldown and track luminaires are the most flexible, care must be taken when using these types of luminaires to assure that aiming angles do not create objectionable glare.

Perimeter Lighting

Perimeter lighting is an important consideration for proper illumination of a merchandising space because vertical surface brightness plays a significant part in the shopper's impression of the store. Perimeter lighting is an asset to a store environment, contributing to a sense of pleasantness and the perception of brightness and improving visibility and visual impact of displays at the walls. It provides the lighting necessary for merchandising walls and makes the space feel larger. If properly used, perimeter lighting draws the prospective customer out of the main aisle and into the merchandising space.

Perimeter wall lighting can be achieved by various techniques using either linear or point sources to create continuous or individual patterns of light. Architectural cornices, soffits, or valances with concealed fluorescent, cold cathode, or linear socket strip-luminaires using ceramic metal halide PAR lamps can be employed, as well as properly spaced wall-wash luminaires that provide a continuous luminous pattern (Figures 17-11 and 17-12). Patterns of light and concentrated accent light, which require precise beam control, can be accomplished by track or monopoint luminaires, recessed adjustable luminaires, or widely spaced wall-wash luminaires.

Figure 17-11. Valance/soffit lighting.

Figure 17-12. Wall washer lighting.

Figure 17-13. Accent lighting.

Accent Lighting

Accent lighting is an important component in most merchandising lighting applications. Except for mass market stores, retailers use some level of accent lighting to attract customers to the merchandise.

Accent lighting emphasizes the shape, texture, finish, and color of the product. Point sources are ideal for accent lighting because they can be controlled and directed, providing the focal lighting required. By elevating the attributes of the merchandise, customers become drawn to these defined focal points in a retail environment (Figure 17-13).

Comfortable lighting requires uniform brightness. Generally, luminance ratios should not exceed 5:l in any adjacent areas. Accent lighting requires brightness higher than the surround, however. This means that the merchandise and displays should be at least three times brighter than the surround. Dark men's suits, for example, may require an accent illuminance ten times higher than that in the surround. To really attract attention, very high illuminances are often used for feature displays at the end of long aisles or with jewelry (sometimes as high as l5:l).

In outdoor retail, it is imperative to limit brightness to those found in surrounding areas. Direct glare or reflected glare off merchandise should not impede motorist visibility or cause nuisance glare.

Decorative Lighting

Decorative lighting elements include sconces, chandeliers, table and floor lamps, torchieres, light sculpture, and light art (graphics). Decorative lighting is used in the retail merchandise environment to create ambiance and set the mood for a shopping experience. It is used primarily in specialty stores, high-end department stores, and designer boutiques. Decorative lighting must not compete or detract from the primary merchandise lighting scheme.

Feature and Supplementary Lighting

The proper balance of a general pattern or specific lighting system depends on the type of store and merchandise and the methods of presentation. Special consideration should be given to the store's most prominent feature, and supplemental lighting should be added to attain the results desired. Specific consideration should be given to placing the light sources at angles to prevent direct and reflected glare from reaching the eyes of the customers and sales personnel. The following is a discussion of merchandising areas that generally require supplementary lighting.

Rack Lighting (Clothing). Rack lighting should be designed to attract customers and for easy evaluation of the merchandise. Racks located in large, cased wall areas can be lighted from above by concealed light sources. The lighting system should fully illuminate the articles of clothing and reveal both color and texture. Where linear light sources are used, the lamps should render the colors of the merchandise in the same way as the fitting room lighting.

In the open rack areas, flush- or surface-mounted adjustable ceiling accent lights should be directed obliquely onto the displayed merchandise. The illuminance on the clothing should be greater than that provided by the ambient lighting. Caution must be exercised to avoid directing the accent light into the eyes of customers viewing clothing on adjacent racks. Louvers, baffles, and lenses help accomplish this important goal.

Shelf and Gondola Lighting. The principles of shelf and gondola lighting are identical to those for rack lighting.

Counter Lighting. A form of accent lighting in which merchandise displayed on counter tops or at the point of sale near the counter tops receives three to five times the illuminance in circulation areas. This is usually accomplished with focused downlights.

Modeling Lighting. The form and texture of merchandise may be more apparent through the use of directional lighting to supplement the general diffuse lighting needed for the overall effect. However, light should not be directed at too steep an angle because objectionable shadows may result. See the section "Museum and Art Gallery Lighting" in Chapter 14, Lighting for Public Places and Institutions.

Mirror Lighting. See the section "Dressing and Fitting Room Lighting" in this chapter.

Showcase Lighting. Another common technique is to light merchandise displayed in showcases (Figure 17-14). Generally, showcase lighting requires three times the illuminance of the circulation area lighting. Fluorescent lamps may be employed for a continuous line of light and to minimize the heat created in enclosed spaces. Despite the general use of fluorescent lamps, incandescent and miniature halogen lamps are sometimes used to add sparkle, especially for items such as jewelry and glassware. For a curved or irregular case, miniature halogen, compact fluorescent, and cold-cathode tubing can be used to conform to the shape of the case. Continuing developments in fiber-optics technology have also enabled fiber-optic illumination to be a viable source for some types of showcase lighting. See the section on "Museum and Art Gallery Lighting" in Chapter 14, Lighting for Public Places and Institutions.

Wall-Case Lighting. Wall-case lighting is similar in concept to showcase lighting. It falls into three categories: the free-standing vertical display mounted against a wall; the encased, open-front, wall-mounted display; and the glass-door, wall-mounted display case. Wall-case lighting is usually used in merchandise displays in upscale stores (Figure 17-15).

Free-standing vertical displays offer the greatest flexibility. This type of lighting may be accomplished by flush, surface-mounted or suspended adjustable luminaires, strategically located to produce highlights and shadows so as to create a three-dimensional display. Colored light may be considered to further dramatize the displayed merchandise or theme elements.

The open-front, wall-case display follows the lighting methods of the free-standing vertical display. The system should be planned to project light within the encased area. Added flexibility can be obtained by using adjustable luminaires installed at locations and aimed at angles that avoid reflected glare.

Figure 17-14. Showcase lighting.

Figure 17-15. Wall case lighting.

Display cases with glass doors present a different problem, namely that the merchandise displayed behind the glass panel is obscured by surface reflections from the glass. An extensive discussion of display case lighting principles can be found in Chapter 14, Lighting for Public Places and Institutions, in the section "Museum and Art Gallery Lighting."

FADING, BLEACHING, AND SHELF-LIFE

When the merchandiser displays a product, the color stability of merchandise should be considered. Not all products have the same color stability and products fade or change chemical composition because of varying environmental reasons. Fading of merchandise may be caused by exposure to high illuminances for extended periods of time. Other factors that could contribute to fading are duration of environmental exposure, spectral distribution of radiation, moisture, temperature, chemical composition of merchandise, saturation and stability of dye in merchandise, and composition of weave of fabrics.

Once merchandise is on display within the retail space, fading of individual items can be controlled by:

- Rotating merchandise so that no one item receives the maximum amount of light exposure
- Avoiding placement of merchandise directly under skylights or near store windows where light levels can be excessive
- Avoiding placement of merchandise considered "highly susceptible" to fading (for example, cottons and silks) close to light sources
- Sacrificing a few items to attract attention through higher accent lighting levels, and keeping the remainder of the merchandise under much lower light levels

See the section "Museum and Art Gallery Lighting" in Chapter 14, Lighting for Public Places and Institutions, for an extensive discussion of lighting techniques for photosensitive materials.

Design Considerations

Individual lighting needs and requirements of a store depend on many factors, including the type of store, type of merchandise sold, projected store image, and age of the typical customer. The selection of the appropriate illuminance for a specific task must also consider weighting factors such as age of the person, task importance, reflectance of task, and luminances of the environment. Also one should consider that certain stores may include a number of illumination scenarios in the same facility, resulting in deliberate nonuniform lighting. See Chapter 10, Quality of the Visual Environment, for more detailed information on the design issues that should be considered when lighting merchandising areas.

LIGHTING LIVE AND FRESH PRODUCTS

Like all materials, products like fresh and processed meats, fruits, vegetables, and floral displays have unique responses to light and heat. Meat display lighting systems must provide color balance to bring out the natural meat color and minimize deterioration of the product over expected shelf life. In contrast to textiles and other hardware and software items, turnover time for fresh products tends to be much shorter, a few days rather than perhaps several weeks. In the case of live or growing displays like potted plants, lighting must support basic growth processes over a potentially longer period of time.

Meat Case Lighting

Of particular concern in meat displays is discoloration, characterized by reduced redness and increased grayness (loss of chroma). Depending on the specific additives used, some processed meats may fade more quickly than fresh red meats; others may fade more slowly. Unwrapped meats dehydrate rapidly in refrigerated cases, causing darkening and shrinking. Wrapping with clear plastic film reduces dehydration and contact with atmospheric oxygen, but chroma loss still occurs.

Processed Meats. Discoloration of processed meats such as bologna or ham is caused by the reaction of the meat with oxygen in the presence of light. This reaction can occur quite rapidly with some processed meats and is proportional to the magnitude and duration of light exposure. Typically, light exposure is measured in lx·hr (fc·hr). Noticeable fading may occur after approximately 2000 lx·hr (200 fc·hr) under typical white light sources, i.e., some processed meats exposed to 1000 lx (100 fc) may begin to fade in as little as 2 hr. This discoloration is usually limited to the top layer and does not typically affect taste or smell. Currently, no published test data exist that indicate which colors of light can accelerate or reduce loss of chroma, or that UV filtering can extend the shelf life of processed meats.

Vacuum or nitrogen-filled packaging that eliminates the presence of oxygen can help solve the problem in self-service cases. In delicatessen-style cases illuminances of more than 1000 lx (100 fc) should be avoided, but illuminance inside the case should at least reach the illuminance outside the case for products to be visible. The amount of meat exposed to light should be minimized, for example, by covering excess sliced meat or by stacking slices so that only the top slice is exposed.

Fresh Meats and Fresh Frozen Meats. Because fresh meats generally have much shorter shelf lives than processed meats, one would expect lighting criteria to be less critical, as long as radiant heating effects are controlled. Currently there is no clear consensus about the effects of lighting on the shelf life of fresh meat.

Red meats, after cutting, react with oxygen and develop a fresh, red color. Removing oxygen from the meat surface reverts the meat to a purplish red color. For this reason, fresh meats are usually covered with oxygen-permeable wraps, unlike processed meats. Over time, the red color undergoes loss of chroma due to one or several of the following factors:[3]

- Oxygen on the meat surface
- Dehydration
- Temperatures above 5°C (41°F)
- Bacterial molds or other microbes growing on the surface
- Slow freezing

Other environmental factors, such as air contaminants, can contribute to a deteriorated product appearance. Historically, fresh meats, especially within a 2- to 3-day shelf life, have been considered resistant to discoloration from light. More often, discoloration issues have been correlated with meat cutting practices and higher surface temperatures. For example, a meat surface temperature of 7°C (45°F) may yield a display life of a few hours instead of 2 to 3 days at −1°C (30°F).[4] For delicatessens, retailers want to avoid freezing the merchandise, giving a smaller working range. Investigations on the role of light and UV on meat discoloration have yet to yield consistent results.

Recommendations for the lighting of fresh meats are as follows:

- Use moderate illuminances, preferably 500 lx (50 fc).
- Use fluorescent lamps with high CRI and strong content in the long-wavelength (red) visible portion of the spectrum to enhance color without distorting the appearance, particularly in relation to ambient lighting in the rest of the store.
- If halogen lamps are used for accent lighting, use lamps with dichroic cool beam reflector coatings to reduce emitted radiant heat.

Dairy Case Lighting

The exposure of dairy products, milk, butter, and cheese to light can cause flavor changes and vitamin loss. Fully lined cartons and packages can filter out most or all of the light, but the use of transparent packaging requires rapid product turnover product display rotation. An illuminance of 500 lx (50 fc) is recommended for dairy products. Higher light levels, however, are sometimes chosen to attract customers and, presumably, to enhance sales.

Floral Displays

In a floral department, lighting should make the products look appealing and contribute to the health of plants and flowers (Figure 17-16). For growing plants and cut flowers, 1500 to 2500 lx (150 to 250 fc) is recommended. This illuminance should hold flowering and foliage plants in their prime for several days to a full week. High-CRI lamps should also be considered to maximize attractiveness.

Figure 17-16. High illuminance contributes to the fresh, appealing look of the flowers and plants. The kiosks of the floral section of this supermarket are illuminated by compact metal halide track lights mounted on decorative tubing. Recessed luminaires housing T-8 fluorescent lamps provide general light to this area. Additional ambient light is provided by uplighting from the striplights above the display cases against the walls.

Figure 17-17. High-glare parking lot illumination.

Fluorescent and metal halide lamps, which blend with other store lighting systems, can provide a proper spectrum to support plant growth. All parts of the plant should receive sufficient light to maintain growth. This may necessitate plant rotation within the display.

For cut flowers and growing plants, radiant heating should be minimized to limit moisture evaporation from the foliage and other plant surfaces. If halogen lamps are used for accent lighting, they should employ cool beam reflectors.

Lighting for Produce Cases

Lighting requirements for fruits and vegetables in produce displays are similar to those in floral displays. Fruits and vegetables are still living in the post-harvest stage. Good-color-rendering fluorescent lamps in warm to cool color tones (3000 to 4100 K) are used for produce displays, as are other discharge types (e.g., metal halide or white high-pressure sodium) and halogen lamp types. As with cut flowers and growing plants, radiant heat on the procedure should be minimized.

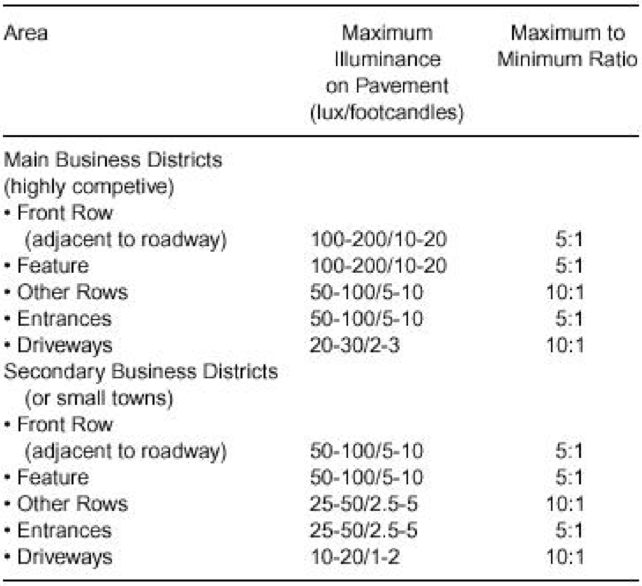
OUTDOOR RETAIL LIGHTING

Customers view and select merchandise in outdoor retail spaces such as car dealerships, automobile service stations, lumber yards, and pedestrian shopping malls. As with any retail space, lighting should attract shoppers, enable customers to comfortably review the merchandise, and provide for safe pedestrian passage. Security is also a consideration, especially when the merchandise is left outside all night.

Car Dealership Lighting

The merchandise located on lots surrounding an automobile showroom usually consists of a front row of cars or trucks adjacent to a primary road. Attracting customers to these vehicles can be artfully accomplished. The lighting should fill the area without producing excessive brightness. Luminaire brightness should be minimized at normal viewing angles by motorists on adjacent roadways and from the perspective of potential customers examining the merchandise close up. This can be accomplished by locating the luminaire support poles between the roadway and the front row merchandise, and specifing cut-off or low-glare luminaires to be directed at the front row. Naturally, good color rendering enhances merchandise appearance.

Other luminaires should be located on poles throughout the showroom lot. They should not cause disability glare for motorists nor create nuisance glare for the surrounding homeowners (Figure 17-17). Suggested illuminances and uniformity ratios are shown in Figure 17-18 (see also Chapter 10, Quality of the Visual Environment).



Area	Maximum Illuminance on Pavement (lux/footcandles)	Maximum to Minimum Ratio
Main Business Districts (highly competive)		
• Front Row (adjacent to roadway)	100-200/10-20	5:1
• Feature	100-200/10-20	5:1
• Other Rows	50-100/5-10	10:1
• Entrances	50-100/5-10	5:1
• Driveways	20-30/2-3	10:1
Secondary Business Districts (or small towns)		
• Front Row (adjacent to roadway)	50-100/5-10	5:1
• Feature	50-100/5-10	5:1
• Other Rows	25-50/2.5-5	10:1
• Entrances	25-50/2.5-5	5:1
• Driveways	10-20/1-2	10:1

Figure 17-18. Illuminance Levels and Uniformities for Car Dealerships

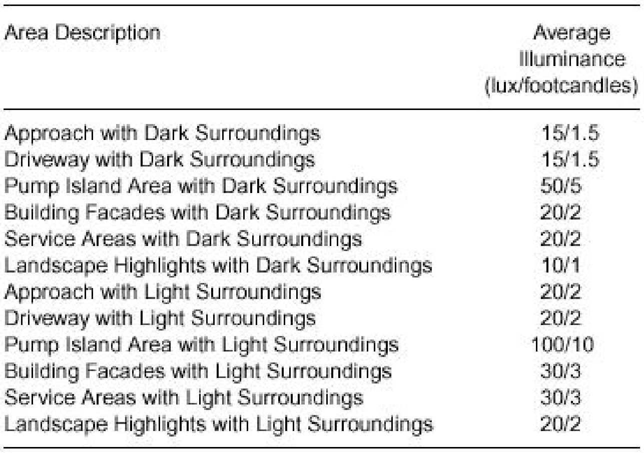
Service Station Lighting

The goal of high-quality outdoor retail lighting is to attract the customer to a safe, secure environment. Too often, this is translated into a call for bright lights. Automobile service stations can be lighted effectively with glow from the pump island canopy, as opposed to direct illumination from bright sources that may also create glare for those on the adjacent roadway. By lighting service station surfaces (like the pump canopy and the station's facade), customers can be drawn to a retail area that is attractive and yet free of the negatives associated with very bright light (Figure 17-19). The use of flat rather than dropped dish lenses in canopy lighting is recommended to reduce direct glare from the luminaires.

Service stations lighted to high illuminance levels may pose adaptation problems for customers leaving the station and re-entering the much darker street or roadway nearby. Glare, too, must be minimized to help avoid such adaptation problems.

Figure 17-20 lists recommended illuminance levels for automobile service stations (see also Chapter 10, Quality of the Visual Environment). This lighting should be provided with low-glare luminaires that do not cause light pollution or deliver nuisance glare to adjacent properties.

Figure 17-19. The illuminated canopy attracts customers to this gas station and convenience store at night. High pressure sodium lamps are used in luminaires with curvilinear dropped-dish lenses that are designed to cut down on glare. The high light level in the pump area gives customers a feeling of comfort and safety.



Area Description	Average Illuminance (lux/footcandles)
Approach with Dark Surroundings	15/1.5
Driveway with Dark Surroundings	15/1.5
Pump Island Area with Dark Surroundings	50/5
Building Facades with Dark Surroundings	20/2
Service Areas with Dark Surroundings	20/2
Landscape Highlights with Dark Surroundings	10/1
Approach with Light Surroundings	20/2
Driveway with Light Surroundings	20/2
Pump Island Area with Light Surroundings	100/10
Building Facades with Light Surroundings	30/3
Service Areas with Light Surroundings	30/3
Landscape Highlights with Light Surroundings	20/2

Figure 17-20. Service Station or Gas Pump Area Average Illuminance Levels

MALLS

Types of Shopping Centers

Definitions of shopping centers have been evolving since the early 1950s. A shopping center is a group of retail and other commercial establishments that is planned, developed, owned, and managed as a single property. On-site parking is provided. The center's size and orientation are generally determined by the market characteristics of the trade area served by the center. The two main configurations of shopping centers are malls and open-air strip centers.

Malls are typically enclosed, with a climate-controlled walkway between two facing strips of stores. The term represents the most common design mode for regional and super-regional centers and has become an informal term for these types of centers.

A strip center is an attached row of stores or service outlets managed as a coherent retail entity, with on-site parking usually located in front of the stores. Open canopies may connect the storefronts, but a strip center does not have enclosed walkways linking the stores. A strip center may be configured in a straight line or have an "L" or "U" shape.

Given the maturity of the industry, numerous types of centers currently exist that go beyond the main configurations. Industry nomenclature originally offered four basic types: Neighborhood, community, regional, and super-regional centers. However, as the industry has grown and changed, more types of centers have evolved and these four terms are no longer adequate. The International Council of Shopping Centers (ICSC) has defined eight principal shopping center types.

These definitions are meant to be guidelines for understanding major differences between the basic types of shopping centers. Size, number of anchor stores, and trade area should be interpreted as typical for each center type. As a general rule, the main determinants in classifying a center are its merchandise orientation (types of goods and services sold) and its size. A hybrid center may combine elements from two or more basic classifications, or a center's concept may be sufficiently unusual as to preclude it from fitting into one of the eight generalized definitions presented here.

Neighborhood Centers. A neighborhood center is designed to provide convenience shopping for the day-to-day needs of consumers in the immediate neighborhood. According to the ICSC, roughly half of these centers are anchored by a supermarket, while about a third have a drugstore anchor. These anchors are supported by stores offering drugs, sundries, snacks, and personal services. A neighborhood center is usually configured as a straight-line strip with no enclosed walkway or mall area, although a canopy may connect the storefronts.

Community Centers. A community center typically offers a wider range of apparel and other soft goods than the neighborhood center does. Among the more common anchors are supermarkets, super drugstores, and discount department stores. Community center tenants sometimes contain off-price retailers selling such items as apparel, home improvement and furnishings, toys, electronics, or sporting goods. The center is usually configured as a strip in a straight line or "L" or "U" shape. Of the eight center types, community centers encompass the widest range of formats. For example, certain centers that are anchored by a large discount department store refer to themselves as discount centers. Others with a large floor area allocated to off-price retailers can be termed off-price centers.

Regional Centers. A regional center provides general merchandise, mostly, and services. Its main attractions are its anchor stores: traditional, mass merchant, or discount department stores or fashion specialty stores. A typical regional center is usually enclosed with an inward orientation of stores connected by a common walkway and parking surrounding the outside perimeter.

Super-regional Centers. Super-regional centers are similar to a regional center, but because of its larger size, a super-regional center has more anchor stores, a deeper selection of merchandise, and draws from a larger population base. As with regional centers, the typical configuration is as an enclosed mall, frequently with multiple levels.

Fashion Specialty Centers. Fashion specialty centers are composed mainly of upscale apparel shops, boutiques, and craft shops carrying selected fashion or unique merchandise of high quality and price. These centers need not be anchored, although sometimes restaurants or entertainment can provide the draw of anchor stores. The physical design of the center is sophisticated, emphasizing a rich decor and high-quality landscaping. These centers usually are found in high-income areas.

Power Centers. Power centers are dominated by several large anchor stores, including discount department stores, off-price stores, warehouse clubs, or "category killers" (i.e., stores that offer tremendous selection in a particular merchandise category at low prices). The center typically consists of several freestanding (unconnected) anchor stores and a few small specialty tenants.

Theme/Festival Centers. Theme/festival centers typically employ a unifying theme that is carried out by the individual shops in their architectural design and, to an extent, in their merchandise. The biggest appeal of the centers is to tourists. They can be anchored by restaurants and entertainment facilities. These centers, generally located in urban areas, tend to be adapted from older and sometimes historic buildings and can be part of mixed-use projects.

Outlet Centers. Outlet centers are usually located in rural or occasionally in tourist locations and consist mostly of manufactures' outlet stores selling their own brands at a discount. These centers are typically not anchored. A strip configuration is most common, although some are enclosed malls and others can be arranged in a village center.

Design Concepts

Landscaping. Landscape lighting can add aesthetic beauty, expand the number of usable hours, improve safety, add security, and develop a desired image for any project. A well-designed landscape lighting system serves as a functional site amenity and marketing tool. Illuminated plant material can be used to highlight entrances (at the buildings and to the project). Downlights can be used to create functional light levels on the ground to facilitate traffic flow (pedestrian and vehicular). The dramatic effects created by uplights focus attention and reinforce the visual clues the designer is trying to provide to the shopper. Grade-mounted uplights can also be used to illuminate signs and architectural features. Source/task/eye geometry, color appearance, direct glare, points of interest, and shadows are important.

Landscape lighting includes a wide variety of outdoor areas including both natural and built environments. Projects may include natural meadows and woods or parks, corporate offices, hotels, theme parks, golf courses, residential gardens, boulevards, or entry features. In each of these settings lighting can effectively add aesthetic beauty, expand the number of usable hours, improve safety, increase security, and develop a desired image. Fixture types, sources, wattages, and techniques chosen vary based on project size, usage, needs, and expectations of the owner. In all cases the lighting designers' main task is to create a safe, attractive nighttime environment using an energy-efficient low-brightness system. See the section on landscape lighting in Chapter 21, Exterior Lighting.

Retail Tenant

Storefront Criteria. Proper storefront and show window lighting is important to the individual retailer and contributes to a customer's impression of the overall mood and retail image of the mall. It is important for all tenants to use good lighting techniques to attract attention to their products and store location and create a pleasant shopping experience for the customer.

Design criteria established by the mall, which address lighting and storefront design, may be in effect. Tenants should check to see how this might affect their design decisions. The following are guidelines that may be considered when planning storefront lighting.

Signage and Storefront Graphics. Store identification is important, and the mall leasing guidelines may control illumination of storefront signage design. Considerations for sign lighting include backlighted translucent materials, edge lighting, direct or indirect front lighting, and use of special lighting techniques such as fiber-optic systems.

Guidelines to control excessive luminances to prevent signs from becoming distracting or out of character with the mall image should be provided by the mall.

Facade and Entrance Lighting. Direct or indirect illumination of the storefront facade may be utilized to further enhance the store location. Appropriate illuminance levels also need to be considered at the store entrance areas to illuminate the pathway and product displays. Higher illuminances may be used to brighten this area, just to attract attention to passing customers.

Display Window Lighting. Display window lighting should be designed for the tenant to provide good product visibility and yet not produce distracting glare into the mall corridor. Flexibility is important to accommodate changes in product displays and to provide light from various angles. Illuminance requirements may vary depending on day and nighttime conditions. More lighting is required, for example, to compete with the high illuminance levels created by nearby skylights, whereas lighting should be reduced at night to save energy and lamp life.

Kiosks. Retail kiosks throughout the mall may be planned in the mall design as a fixed location or as a portable system. In both cases, electrical distribution systems must accommodate lighting that is built into the display and other systems requiring power. Kiosks lighting should be part of the display architecture. Surface-mounted display lighting from the mall ceiling and built-in showcase lighting are standard systems, which need to be considered by the tenant. The mall should provide design guidelines for these systems to assure design standards and to prevent excessive glare. In the design of a new mall, lighting locations from the ceiling can illuminate planned, fixed-position kiosks to help assure good lighting. Either recessed adjustable or surface-mounted luminaires can be used. Otherwise, provisions for future electrical use need to be considered.

When a portion of a concourse or court is used to stage entertainment performances and there is the potential for dimming the house lights in such an area, it is important to assure that the free-standing kiosks and movable carts have sufficient lighting on their merchandise, sales counters, and receipt areas. As with any retailer, the kiosk must be viewed as a store and should follow similar design guidelines.

Seasonal Events. Various seasonal holidays may be celebrated or marketed by using special lighting and display systems. Mechanical and electrical provisions should be planned indoors and outdoors to accommodate lighting and displays that may be utilized for such occasions. Electrical outlets specifically located to accommodate holiday lights in landscape areas or in mall architecture and ceilings help implement their installation. Eyebolts, hooks, and fastening devices for displays also need to be considered for hanging displays and running temporary electrical cables. Twist-lock receptacles may be used to prevent unwanted devices from being plugged into these circuits and help prevent them from being unplugged accidentally. Central or remote control switching of these special circuits may also be considered.

Feature Lighting

Decorative Elements and Structures. Special lighting treatments for elements of visual interest throughout the mall should be considered early in the design phase. These items include sculptures, fountains, art, or special architectural and interior design features. The lighting of these features should accentuate their form, shape, and color. Illuminance ratios of 5:1 over prevailing ambient lighting conditions should allow the displays to stand out. In areas where daylight has an impact, special controls should be considered to balance illuminances between daytime and nighttime conditions.

Stage and Special Event Lighting. Malls today have become more than just shopping centers by providing community services and entertainment to attract and entertain customers. Lighting for staging and display areas is important not only to improve visibility for the audience but also to attract large professional shows. These events may include music groups, theatrical presentations, puppet shows, exercise programs, video productions, art shows, and special corporate events.

Lighting Equipment Selection

Selection of Outdoor Luminaires. A wide variety of considerations enter into the selection of luminaires for lighting the exterior areas of a shopping mall. The designer needs to keep in mind that the lighting should promote the sales of the tenant stores in the mall and facilitate the safe and orderly movement of persons patronizing the mall. The exterior lighting should attract potential patrons to the mall, provide a sense of security and safety inside the mall itself and in the exterior mall areas, and facilitate the safe movement of patrons to and from parked vehicles.

Exterior mall lighting can also have architectural and aesthetic objectives, but the key objectives should be related to the primary business objectives of the mall itself. Naturally, safety and security are also important. In addition, prevention and minimization of light pollution and trespass should be considered in the design (see Chapter 21, Exterior Lighting).

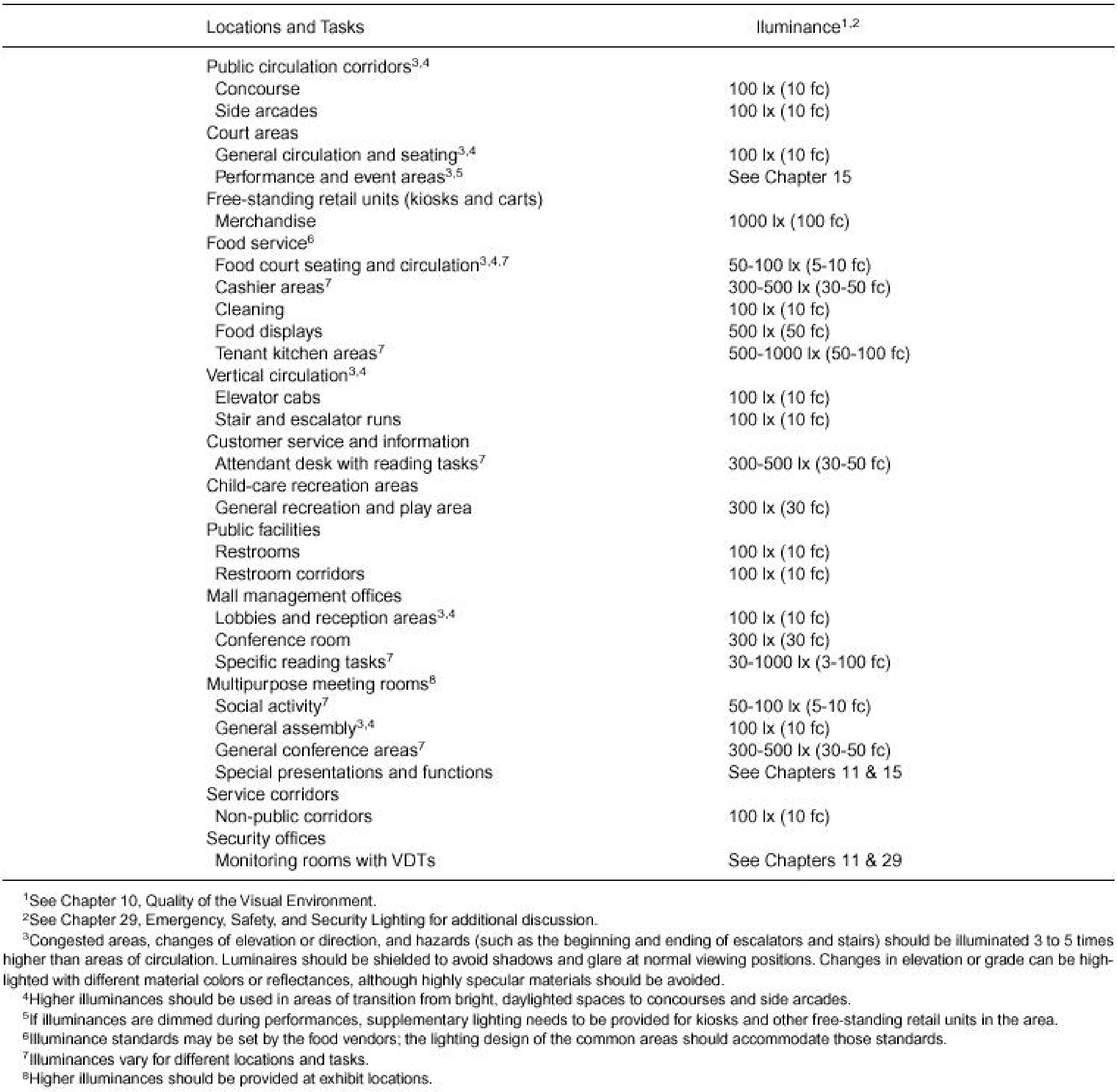
Physical Site Constraints. The actual geometry and scale of the shopping mall site are major considerations in the selection of the appropriate outdoor area lighting luminaires to illuminate the site. A general guideline is that small sites with primarily single-story buildings should use both lower-wattage sources and poles that have lower mounting heights, whereas larger sites with multistory building heights should use higher-wattage sources and higher mounting heights. While every guideline has its exception, the rule provides us with a reasonable starting point. For instance, a small center illuminated with low-wattage metal halide luminaires placed on 20-ft (6.2 m) poles likely provides more acceptable area lighting than high-wattage metal halide luminaires placed on 40-ft (12.4 m) poles. In the latter instance, the 40-ft pole appears out of scale in a small site, and quite possibly light would be spilled off the site onto adjoining properties. By the same token, a large multiacre regional shopping mall that was lighted with low wattage metal halide on 20-ft poles would not only be costly but would also appear as a virtual sea of poles.

Indoor Areas

Main Concourse. The main concourse must strike a balance between being a backdrop for the visual excitement of the storefronts and a lead attraction that draws shoppers back to the mall again and again. The decision as to whether the concourse plays more of a lead or a secondary role depends partly on the quality and appearance of the retail tenants and partly the proximity and competitiveness of other malls.

As part of a well-integrated design, the concourse lighting must support this marketing decision. In some cases it creates an understated atmosphere that leaves the main focus on the storefronts. In other instances it is part of a visual event that establishes the concourse as a destination in its own right.

The selection of illuminance levels and luminance ratios also requires a special balance. While excessive contrasts can be distracting or uncomfortable, appropriate variations in luminance ratios can facilitate effective merchandising at the storefronts and draw attention to special events and key circulation points. Illuminance ratios of 1:10 between the mall walkways and the adjoining retail displays focus attention on the retail tenant displays. Color appearance, daylighting integration, design composition, style, and image are important. See Figure 17-21 for illuminance recommendations for typical areas in malls.



Locations and Tasks	Illuminance[1,2]
Public circulation corridors[3,4]	
Concourse	100 lx (10 fc)
Side arcades	100 lx (10 fc)
Court areas	
General circulation and seating[3,4]	100 lx (10 fc)
Performance and event areas[3,5]	See Chapter 15
Free-standing retail units (kiosks and carts)	
Merchandise	1000 lx (100 fc)
Food service[6]	
Food court seating and circulation[3,4,7]	50-100 lx (5-10 fc)
Cashier areas[7]	300-500 lx (30-50 fc)
Cleaning	100 lx (10 fc)
Food displays	500 lx (50 fc)
Tenant kitchen areas[7]	500-1000 lx (50-100 fc)
Vertical circulation[3,4]	
Elevator cabs	100 lx (10 fc)
Stair and escalator runs	100 lx (10 fc)
Customer service and information	
Attendant desk with reading tasks[7]	300-500 lx (30-50 fc)
Child-care recreation areas	
General recreation and play area	300 lx (30 fc)
Public facilities	
Restrooms	100 lx (10 fc)
Restroom corridors	100 lx (10 fc)
Mall management offices	
Lobbies and reception areas[3,4]	100 lx (10 fc)
Conference room	300 lx (30 fc)
Specific reading tasks[7]	30-1000 lx (3-100 fc)
Multipurpose meeting rooms[8]	
Social activity[7]	50-100 lx (5-10 fc)
General assembly[3,4]	100 lx (10 fc)
General conference areas[7]	300-500 lx (30-50 fc)
Special presentations and functions	See Chapters 11 & 15
Service corridors	
Non-public corridors	100 lx (10 fc)
Security offices	
Monitoring rooms with VDTs	See Chapters 11 & 29

[1] See Chapter 10, Quality of the Visual Environment.

[2] See Chapter 29, Emergency, Safety, and Security Lighting for additional discussion.

[3] Congested areas, changes of elevation or direction, and hazards (such as the beginning and ending of escalators and stairs) should be illuminated 3 to 5 times higher than areas of circulation. Luminaires should be shielded to avoid shadows and glare at normal viewing positions. Changes in elevation or grade can be highlighted with different material colors or reflectances, although highly specular materials should be avoided.

[4] Higher illuminances should be used in areas of transition from bright, daylighted spaces to concourses and side arcades.

[5] If illuminances are dimmed during performances, supplementary lighting needs to be provided for kiosks and other free-standing retail units in the area.

[6] Illuminance standards may be set by the food vendors; the lighting design of the common areas should accommodate those standards.

[7] Illuminances vary for different locations and tasks.

[8] Higher illuminances should be provided at exhibit locations.

Figure 17-21. Illuminances for Typical Areas in Malls

When evaluating illuminance levels for concourse walkways, some contribution can be expected from the storefronts. However, the contribution typically varies from store to store, and the designer of the public concourse rarely has control over the individual tenant spaces. This is an important consideration, since many mall concourses have become gathering places for retirees and other exercise walkers who arrive during pre-shopping hours. By necessity, many facilities find themselves concerned with providing appropriate illuminance levels for such mall walkers before the stores even open.

Since it typically serves as an enclosed mall's main circulation artery, the concourse must provide adequate egress lighting during power outages and other emergencies. In these circumstances, although an average illuminance of 0.5 lx (0.05 fc) can provide sufficient visibility for people to recognize obstacles and avoid collisions during an exit procedure, it is recommended that the minimum horizontal illuminance measured at the floor be at least 1 lx (0.1 fc) at all points along the path of egress. Furthermore, it is recommended that the minimum maintained illuminance at the beginning of emergency operation be at least 10 lx (1 fc).

Chapter 29, Emergency, Safety, and Security Lighting, discusses many considerations related to emergency egress lighting and exit signs in more detail. For example, Figure 29-1 illustrates the relationship between evacuation rates from cluttered spaces and corresponding mean illuminance levels at the floor. In addition, Figure 29-2 recommends minimum illuminance levels for safety based on anticipated activity levels and hazard potentials.

Single-level Malls. In a single-level mall, the main concourse presents few if any changes in grade. As a result, the method of circulation is inherently safer, and there are fewer decision points that require the lighting designer's special attention.

The lack of interesting vertical relationships and circulation paths is often compensated for with kiosks and other special elements. When lighted as focal points that stand out from the general floor plan, these objects can help provide needed visual relief and variety across the single-level landscape.

Unlike multilevel malls, which are frequently punctuated with floor openings and high ceilings, the single-level mall typically presents less difficult maintenance situations. As a result, lamp life and life cycle maintenance costs may play a less critical role when evaluating potential alternatives.

Where lamp life and accessibility are not critical issues and directional light sources are required, incandescent and tungsten halogen reflector lamps are frequently selected. However, luminaires designed for a variety of metal halide and color-improved high-pressure sodium lamps can also provide well-defined directional light distributions with the benefits of longer lamp life and lower energy use (see Chapter 6, Light Sources, and Chapter 7, Luminaires).

Situations requiring more diffuse lighting effects tend to rely on compact fluorescent, linear fluorescent, and metal halide sources. These long-life lamps can be utilized in a variety of luminaires for both direct and indirect lighting applications. Their availability with moderate to high color rendering indices at a variety of color temperatures provides the designer with a variety of sources that can be coordinated with the architectural finishes and other color requirements of the public concourse.

Multilevel Malls. While considerations for the main walkways are similar to those in single-level malls, multilevel centers require more lighting cues to effectively manage key circulation routes, especially in urban malls that rise several floors. Besides highlighting the on/off points of stairs and escalators, the lighting also must help direct shoppers at secondary decision points that lead to and from the vertical circulation routes.

Illuminance ratios of 3:1 at important circulation points generally establish a perceivable contrast from the general concourse lighting. However, ratios of 5:1 or greater may be desirable at the ends of escalators, stairs, and other changes in grade that are negotiated under high-traffic conditions.

The leading edges and horizontal surfaces of stair and escalator treads should be well illuminated, as should any stairway landings. Wherever possible, the designer should suggest that the color/reflectance value of the nosings be different from the adjoining treads and landings to help visually emphasize the change in grade.

Luminaires should be carefully located to avoid glare in the line of sight. At the same time, the mounting positions should be selected to facilitate maintenance and to avoid shadows that might be cast by bodies and adjoining balustrades.

Unlike single-level concourses, multilevel concourses typically present interesting views through floor openings and interesting opportunities for highlighting trees, landscaping, and other architectural elements that can be appreciated from several viewpoints. However, the variety of possible views looking up from the main floor and down from the elevated walkways dictates that the designer pay close attention to the shielding characteristics of the selected luminaires.

Where maintenance accessibility is difficult, open luminaires with screw-based reflector lamps have traditionally been used to satisfy some of these opportunities for accent lighting, as well as the associated requirements for beam control and shielding. Although traditionally the domain of line-voltage incandescent and tungsten halogen sources, metal halide lamps are also now available in screw-based reflector versions.

In situations where maintenance can be more easily accommodated through top access, mechanical lifts, or clever positioning, low-voltage incandescent and tungsten halogen sources are frequently considered for long throws that require narrow beam distributions. However, luminaires with optical systems designed for compact metal halide and color-improved high-pressure sodium lamps can also meet these performance requirements often with the benefits of longer lamp life and lower energy use (see Chapter 6, Light Sources).

Presence of Skylights and Other Daylighted Elements. When skylights are present in a single or multilevel mall concourse, it is necessary to evaluate how much the daylight contributes to the illumination within the interior as well as how it might impact interior luminance ratios. If uncontrolled, excessive daylight can result in uncomfortable visual conditions. It can also illuminate the furnishings and shoppers in the concourse to the point where they become distracting reflected images in the storefront display windows.

In the multilevel concourse, excessive daylight penetration can also cause an unbalanced contrast condition between the upper and lower levels. To combat this problem, the amount of natural light allowed to enter the concourse should be controlled, or the illuminance levels and resulting surface luminances of the lower level should be designed to reduce the potential contrast.

Though it may seem contrary to the purpose of introducing skylights and the convention of turning lights off when daylight is present, it is sometimes necessary to provide electrical lighting for adjacent bulkheads and ceilings to reduce the perceived contrast between the skylights and mall interior. Without such attention, the visual quality of adjacent areas may appear dismal, even though the measured quantity of illumination may otherwise be appropriate for circulation.

The appearance of skylights at night is also a concern. While the glazing is often the brightest mall element during the day, it can become the darkest at night, giving the harsh appearance of a black mirror. To achieve a balance between this overhead canopy and the rest of the interior, it is sometimes possible to illuminate key structural members if they are significant in size and light in color. Another approach is to apply exposed light sources to the structural framing system, so that the resulting luminous effects are reflected and multiplied in the mirror-like glazing.

Alternatively, some glass suppliers can silk screen patterns of white ceramic frit over a portion of the skylight glazing, thereby giving the lighting designer an opportunity to illuminate these large surfaces after dark. While the portion of the glazing that is not covered with the ceramic frit still exhibits mirror-like reflective qualities at night, the portion that is coated behaves much like any painted ceiling surface. The result is a unique glazing system that allows shoppers to appreciate the open feeling of sun and sky during the day and the comforting sense of visual enclosure at night (Figure 17-22).

Figure 17-22. A mall's glazing should look appealing both day and night. In this atrium, exposed light sources are mounted to the structural framing system, resulting in luminous effects that are reflected and

multiplied in the mirror-like glazing.

Although laminated glass skylights may be the dominant method of admitting daylight into North American malls, translucent panel systems and "tent" fabrics are also frequently used. During the day, the natural illumination provided through these materials is more diffuse than that transmitted through typical glass skylight systems. The resulting nondirectional character of the natural light should be kept in mind, since it may or may not support the desired visual mood for a particular project.

Just as silk-screened fritted glass exhibits some of the reflectance characteristics of a painted surface at night, so do translucent panel and fabric systems. As a result, they can be lighted to provide indirect illumination for interior spaces. Depending on the mall's orientation, the combination of an indirect interior lighting system and a translucent roof structure can also create a unique exterior image (see Chapter 8, Daylighting).

Storefront Reflections. Just as uncontrolled daylight can create distracting reflected images in the storefront windows along a concourse, the same can be true of uncontrolled electric lighting. Downlights, accent lights, exposed decorative sources, and other lighting treatments all present a similar problem if their positioning, light distribution, and visible luminance are not carefully considered. For example, a row of downlights positioned too closely to the tenant lease line can highlight patrons as they approach shop windows. As a result, they see strong reflections of themselves in the glass-enclosed storefronts, which interferes with their appreciation of the retailers' merchandise.

Courts. Besides the quality of its anchor tenants and specialty shops, malls are also remembered for their special court areas. These courts can leave shoppers with a lasting impression by contributing to the mall's overall atmosphere and by playing host to special events. By enhancing the shopping experience, a successful court can play a large role in drawing shoppers back for future visits.

Event Courts. Malls schedule special events to attract shoppers, especially if the center must compete with other malls in the same region. In addition to their initial drawing power, well-timed events can entice patrons to stay longer and visit more merchants while waiting for a performance or exhibition.

Events can range from fairly static car and home shows, with few live demonstrations, to fully staged fashion shows and live entertainment. Depending on the marketing strategy of the mall and the events that it normally schedules, the spaces that host these events can range from common gathering areas, which are temporarily transformed with portable sets, to fixed performance stages, which are completely armed with permanent lighting and audio equipment.

Fashion shows and live entertainment typically create the broadest range of lighting requirements. It is important to provide adequate frontal lighting on stage participants. Furthermore, key and fill lighting from different directions with light sources of different color and/or intensity is desirable. To maintain focus on one person or object amid a flurry of motion, some type of follow spot may be required. For an overview of stage lighting techniques, equipment, and practices, see Chapter 15, for Theater, Television, and Photographic Lighting.

The range of anticipated events and the degree of the stage area's permanence influence the level of flexibility provided in the event lighting system. In turn, the desired level of lighting flexibility influences how the branch circuit wiring and electrical distribution points are designed.

When the event stage is permanent, the mall is more likely to maintain its own collection of event lighting equipment. As with theater lighting, it is common for such equipment to plug into a well-conceived system of hard-wired connection points that facilitate the frequent reconfiguration of lighting layouts.

If major events are less frequent and temporary stages must be assembled for such occasions, the facility may be more inclined to rent lighting equipment or ask that the party responsible for staging the event provide it. Even in such instances, it is still important that provisions are made in the branch circuit distribution system to facilitate the connection of temporary lighting equipment without the tripping hazards of excessive extension cords.

Similarly, an appropriate system of controls must be devised and coordinated with the control of the general mall lighting. If sophisticated fashion shows and live entertainment are anticipated, it may be desirable to dim some of the concourse or event court lighting much like dimming house lights in a theater.

If dimming is appropriate, it may be necessary to consider supplementary lighting for kiosks and other freestanding retail carts that occur in the event area. Changes in grade at ramps, stairs, and escalators should also be highlighted to call attention to key circulation points when people are in motion during a dimmed event condition.

Food Courts. Like event, gathering, and amusement courts, food courts are another key element in keeping shoppers in the mall longer. If food is available in an inviting setting, there is less likelihood of people going home or off-site during peak meal hours (see Chapter 13, Hospitality Facilities and Entertainment Lighting).

Gathering Courts. As important as it is to create interest in mall concourses and event courts, it is also important to provide a respite from physical movement and visual activity. Seating areas in gathering courts, which often serve as meeting places for shopping enthusiasts and less patient nonshoppers, fulfills this function. The atmosphere created in these courts can have much to do with both parties' wanting to return for future visits.

The design approach to a gathering court can range from restful and subdued to stimulating and entertaining, much like the design of a mall concourse. In some cases, the lighting and architectural solutions simply allow for a relaxed seating environment with people watching as the only diversion. At the other end of the spectrum, seating elements may be surrounded with water features and other landscaping elements. Any or all of these elements may warrant special lighting as part of the court's overall composition.

Entertainment and amusement courts. A large part of the entertainment value of a mall comes simply from the experience of people watching. People want to see and be seen. Nevertheless, many new large-scale centers faced with competitive surroundings or inhospitable climates have expanded the idea of large gathering and event courts into huge public spaces with all forms of entertainment. Be it a simple children's train ride, a wave pool, or an indoor roller coaster, these miniaturized amusement parks help draw a certain segment of the public that might not otherwise frequent malls. At the same time, even those who do not participate in the variety of amusement activities are typically entertained by watching those who do.

If such attractions are incorporated into the mall, the lighting designer should determine whether they are permanent or temporary, and whether they are being provided with or without any integrated lighting. Higher illuminance levels should be considered for entrance and exit points that might be prone to congestion or characterized by changes in grade.

Support Areas. Support areas vary from the fairly mundane service corridor to the more animated childcare playroom. All of these areas need to be addressed in a manner that is consistent with their use.

Restrooms. Restrooms are possibly the most frequented support area and one of the most likely to leave a positive or negative impression. On one hand, the lighting needs to facilitate routine clean up and convey a sense of well-maintained cleanliness. On the other hand, it should be flattering to skin tones and complimentary to the appearance of shoppers. Combined with proper maintenance, the restroom lighting can go a long way towards making a mall more accommodating. This can extend shopping trips and add to sales receipts. Source/task/eye geometry, color appearance, direct glare, reflected glare, luminance patterns and ratios, modeling of faces or objects, and vertical illuminance are important.

The lighting need not be uniform, since general lounge and circulation areas require less illumination than sink and toilet areas. See the section "Dressing and Fitting Room Lighting" in this chapter for a discussion of issues related to mirror lighting.

Customer Service and Information. Besides being identified on mall directories, it is helpful if the main information desk is given an advantageous position within the mall's space design. Whether or not that is the case, customer service areas can be highlighted for attention. Just as a luminance ratio of 3:1 to 5:1 can help draw attention to a special display in a store, the same is true of an isolated information desk set in a larger public space. The lighting should be adequate for the desk attendant to perform a variety of reading tasks in addition to providing verbal information to shoppers. Source/task/eye geometry, direct and reflected glare, luminance patterns and ratios, points of interest, and shadows are important.

Mall Management Offices. Areas that directly represent mall operations to the public should be treated much like any corporate reception area. As with the mall information desk, this is also true of the mall management offices (see Chapter 11, Office Lighting). Besides potential public visitation, existing tenants and parties interested in leasing opportunities also frequently visit mall offices.

Security Stations. The one service that most shoppers hope never to utilize is mall security. Assuming the security staff can be approached directly by shoppers, the office should convey an image that is both accommodating and businesslike. However, if the security staff is accessible only when paged, lighting considerations may be restricted to more specialized applications such as illuminance levels for closed circuit television (CCTV) cameras and video display conditions for monitoring rooms. Chapter 29, Emergency, Safety, and Security Lighting, discusses some of the special lighting requirements related to building interiors. In addition, Chapter 15, Theatre, Television, and Photographic Lighting, covers lighting for television and photographic lighting, and Chapter 11, Office Lighting, addresses general office lighting.

Multipurpose Meeting Rooms. In some malls, the management may expand the structure of its own office or dedicate a specific area of the mall to provide meeting and conference rooms that tenants can utilize by special arrangement. Such multipurpose spaces might be used for meetings between retailers and their suppliers, or mall management and event exhibitors. See Chapter 11, Office Lighting, for a discussion of conference room design issues.

Child Care Areas. As with properly designed restroom and food court areas, mall-provided child care areas can help extend the length of shopping visits and increase total sales. Whether a simple play room or a more sophisticated gym set, the lighting for the main activity areas should be appropriate for recreational activities. Color appearance, flicker, direct glare, modeling of faces and objects, shadows, safety and security, and horizontal and vertical illuminances are important.

Service Corridors. Unlike most mall spaces, service corridors typically offer little if any access to the public. A common exception is a segment of service corridor that doubles as a public access to restrooms, but such areas should be treated in a similar manner as any side mall arcade.

The true service corridor does not present the same requirements for high color rendition that exists in the main concourse and food court. Long-life fluorescent sources are often popular in such applications, given their efficacy and compatibility with occupancy sensors. Safety and security are important. Where security is a concern either in the corridors or at their discharge points to the outside, designers should ascertain whether or not a closed circuit monitoring system might be used, as well as determine the potential illuminance requirements of the selected cameras (see Chapter 29, Emergency, Safety, and Security Lighting).

Vertical Transportation. The unique structural designs of stairs, escalators, and elevators can often become highlighted features in a mall's landscape, along with the exciting movement of crowds along these dominant vertical elements. However, there are practical issues related to efficient circulation and safety that must be considered along with these aesthetic benefits. Source/task/eye geometry, direct and reflected glare, safety and security, and horizontal illuminance are important.

Stairs and Escalators. It is important to highlight the initial on/off points and major landings (Figure 17-23). Illuminance ratios of 3:1 at such points generally establish a perceivable contrast. However, ratios of 5:1 or greater may be desirable at locations that must be negotiated under high traffic conditions.

Figure 17-23. The on/off points and major landings of stairs and escalators should be highlighted.

The leading edges and horizontal surfaces of stair and escalator treads should be well illuminated, as should any stairway landings. Wherever possible, the designer should suggest that the color and reflectance values of the nosings be different from the adjoining treads and landings. This helps to visually emphasize the change in grade.

Luminaires should be positioned to minimize shadows created by approaching shoppers and to provide adequate shielding at normal viewing angles. In the case of multilevel malls, the selection of available luminaire mounting positions frequently dictates the use of light sources with long maintained lives.

Although long-life high-intensity discharge sources may be ideal to focus light on such key decision points from great distances, their inability to restart instantly after a power interruption typically makes them inappropriate as emergency light sources. Therefore, it is sometimes necessary to integrate dedicated emergency lights into the overall design. In many cases, a battery backup system or an emergency generator typically powers such instant-on luminaires. If emergency lights are not required for normal circulation conditions, a lighting contractor or control system can conserve their lamp life and increase their dependability in emergencies by holding them in a de-energized state. For a discussion of emergency egress considerations, see the discussion of concourse spaces above, as well as Chapter 29, Emergency, Safety, and Security Lighting.

To minimize visual confusion at on/off points, it is often wise to avoid highly specular finishes (particularly in the case of metal escalators). Luminaires integrated into handrails and balustrades can help minimize the shadowing effects of bodies as they approach a stair or escalator, but they must conform with codes governing hand holds on railings as well as allowable projection dimensions set forth in the American Disability Act (ADA). Most escalator manufacturers offer standard options for integrated lighting. However, as it is a specialized field, their willingness to modify or adapt standard designs is often limited.

Elevators. As freestanding elevators have become more common, so has the concept of highlighting an elevator tower as a major element in a concourse or court. However, accent lighting the architecture of the tower or applying visible lighting treatments directly to its structure only addresses the elevator's appearance from the viewpoint of nonpassengers.

Within the elevator cabs, lighting walls and ceilings can help enhance the feeling of spaciousness within what is an inherently constricted space. In the case of fully or partially glass-enclosed cabs that are open through the main structure to views of the surrounding mall, lighting surfaces within the cab can also increase the nonpassengers' ability to see into the moving cabs.

Another approach to lighting partially transparent cabs is to reduce the illuminance levels and resulting luminances within the cab, so that the luminance of the surrounding mall is greater than the cab interior. In this way, internally reflected images are less noticeable in the glazing, and views out of the cab become more of an attraction to the elevator passengers.

Entries. The lighting for mall entries must address three important issues: the image that the mall wishes to convey, the ease with which the entries can be identified from surrounding parking areas and adjoining structures, and the shopper's visual adaptation process when passing from one of these adjacent areas into the mall. A poorly presented image or a lack of clarity in identification may fail to attract shoppers in the first place as well as discourage their return. Security and safety are also important.

The most common situation encountered with suburban malls and festival marketplaces is the daytime visual transition from a bright exterior environment into a darker interior space. At night, this relationship is reversed, with the interior of the entry typically being brighter than the exterior nighttime surroundings.

Allowing daylight to penetrate overhanging canopies in a deliberate and controlled manner can help minimize the initial contrast between outdoor parking lots and covered mall entries. In addition, the use of high-reflectance finishes and the selective lighting of ceiling and wall surfaces can create comfortable brightness relationships that help daytime shoppers adapt to the mall's interior lighting. At night, these surface reflectances and lighting treatments can also facilitate shoppers' identification of the main mall entries (Figure 17-24).

Figure 17-24. High-reflectance surfaces and special lighting of walls and ceilings help shoppers find main mall entries.

It is sometimes necessary to provide more light in entry vestibules during the day than at night. This helps the transition between outdoors and indoors while also enhancing daytime views through the external reflections that commonly occur in glazed doorways and transoms.

While entries servicing surface parking lots may be the most common situation that designers encounter, the wide variety of retail centers presents many other situations where luminance relationships and adaptation requirements need to be considered. For entrances off a covered multilevel parking structure, an adjoining downtown office building, an underground transportation complex, or a daylighted system of urban skywalks, the initial transition from one environment to the next must be considered to provide for the visual comfort of shoppers.

It is also important that the entry lighting coordinate with the architectural design and mall graphic system to create a memorable distinction between entries. While some overall consistency in graphic presentation is important, some variety is also needed to help shoppers differentiate between circulation routes when their visits are over. Lighting can contribute to this differentiation process, while also relating interior directional cues to their exterior counterparts.

Side Arcades. Side arcades are most frequently connection passages between the mall entries and the main concourse. As such, they can act as intermediate transition spaces that further the process of visual adaptation discussed in relation to the entries. Color appearance, daylighting integration and control, and design composition, style, and image are important.

The perception of the side arcade as part of the mall entry and a link to the main concourse cannot be ignored. A second-class presentation in these corridors can leave shoppers with a negative impression of the entries and of the mall in general. Higher localized light levels may be appropriate to call attention to steps or changes in grade as well as to ease the daytime transition between mall entrances and the side arcades.

LIGHTING FOR ADVERTISING

Illuminated advertising signs, whether exposed lamp, luminous tube, or luminous element, are important to any promotional activity. Signs can quickly gain the observers' attention through the combined use of size, color, and motion.

Sign Characteristics

Electric signs may be classified by illumination method:

- Luminous-letter signs have illuminated letters and a nonilluminated background, such as those with exposed lamps, exposed luminous tubes, raised glass, or plastic letters.
- Luminous-element signs have panels of translucent plastic or glass, which are illuminated by interior light sources such as HID, fluorescent, or luminous tubing incandescent lamps.
- Floodlighted signs are those such as painted bulletins and poster panels.

Signs may also be classified by their application, as single-faced with luminous elements or as double-faced projecting.

Physical location, desired legibility range, and brightness determine the minimum letter height required for legibility. To attain advertising effectiveness, letter heights of twice the minimum height for legibility are generally employed. Vertical columns of letters, though usually an aid in increasing the apparent size of a sign, are more difficult to read than horizontal arrangements.

Brightness and Contrast.
Letter or background brightness and the contrast between letter and background are factors influencing the attention-grabbing capabilities as well as the legibility of a letter and the speed with which it is recognized. In general, the greater the contrast between the average brightness of a sign and that of its surround, the more it stands out; however, legibility might be impaired at very high contrast where the letters are much brighter than the background.

Location and Position.
The advertising value of a sign depends on the greatest possible number of persons seeing it. This is a function of its location.

Distinctiveness.
One of the elements of a good electric sign is that it is distinctive and individual. It should create a pleasing, favorable impression and should have public appeal and be remembered easily.

Motion.
Motion increases the attracting power and memory value of a sign. It capitalizes on the instinctive trait of people to be aware of and to give heed to moving things.

Color.
Color is an important factor in attraction. Often color is incorporated in a sign because it provides contrast. It can make a sign much more distinctive.

Exposed-Lamp Signs

Signs with Exposed Incandescent Filament Lamps.
These signs are constructed so that the lamps are exposed to direct view. This type is well suited to applications where long viewing distances are involved, as well as for small, high-brightness signs. Motion and color can be incorporated in such signs as shown in Figure 17-25.

Figure 17-25. An animated sign, with an image of the featured entertainer, draws guests to a Las Vegas hotel. Most hotels and casinos in that tourist-oriented city have colorful, elaborate signs in an attempt to attract tourist business

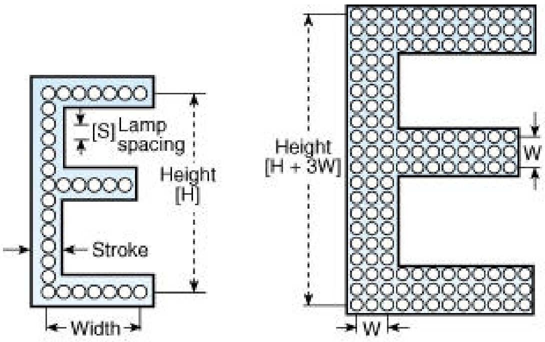


Figure 17-26. Important dimensions in the design of exposed lamp letters.

Legibility. The legibility of a sign is primarily a function of letter size and font type, letter spacing, the contrast between the letter and the background, and sign brightness. Block letters possess greater legibility than ornamental styles, script, or special forms, although the latter types may be used to increase distinctiveness. Wide, extended letters are more legible than tall, thin letters.

Reflectors. When wide-angle viewing is relatively unimportant, reflector lamps or reflectors may be used to enhance the lamp's directional candlepower. Reflectors can greatly increase brightness at the intended viewing angle as well as the sign's effectiveness during daylight hours. They can also lower lamp wattage for the same advertising effectiveness.

Letter Size. The letter height employed on an exposed-lamp sign usually is greater than the minimum height necessary to gain recognition. For quick reading of advertising, it is common practice to provide exposed-lamp signs with letter heights that are 1 to 2 times greater than those necessary for legibility.

For simple block letters where the width is equal to 60% of the height, with a single row of lamps, in typical locations the minimum height for legibility is given by the formula

$$H_r = \frac{D}{500} \qquad (29\text{-}1)$$

where

H_r = minimum vertical height of the letter, for recognition, from top lamp to bottom lamp, m (ft),
D = maximum distance at which the letter is legible to a majority of people, m (ft).

For letters with strokes consisting of multiple rows of lamps, the height should be increased by three times W, the distance between outside rows of lamps in a stroke:

$$H_r = \frac{D}{500} + 3W \qquad (29\text{-}2)$$

Letter width, height, stroke width, and lamp spacing are illustrated in Figure 17-26.

Lamp Spacing. The proper spacing between lamps to obtain an apparently continuous line of light is determined by the minimum viewing distance. Lamp spacing may be estimated by the following formula:

$$S = D\frac{D_{\text{min}}}{1500} \qquad (29\text{-}3)$$

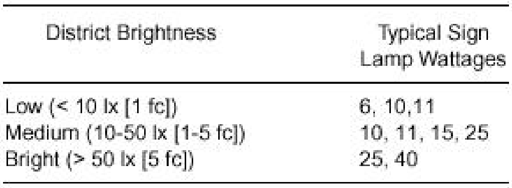
where

S = spacing between centerlines of lamps, m (ft),
D_{min} = minimum viewing distance, m (ft).

In very bright locations the above spacing should be decreased by 25 to 35%. To produce a smooth line of light, the above spacing should be decreased by 50%. At viewing distances of less than 150 m (500 ft), a smooth line of light generally is not possible, because low-wattage, medium-based lamps (S-14 lamps of 6-, 11- or 15-W) require spacings of 50 to 60 mm (2 to 2.5 in.) to permit easy maintenance.

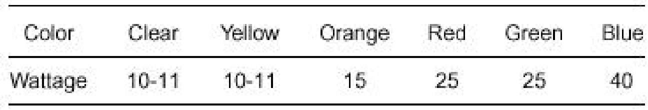
Lamp Wattage Rating. The incandescent lamp wattage employed depends on the general brightness of the surroundings and background against which the sign is viewed. Thus, a roof sign, even if located in a brightly lighted district in the business center of a city, might always be viewed against a dark sky at night. Such a sign would require the same lamps called for in low-brightness areas. Figure 17-27 indicates the typical lamp wattages found in signs in various areas, classified according to district brightness.

If incandescent lamps with colored bulbs or clear bulbs with colored accessories are employed, they are dimmer than clear bulbs at the same wattage. However, colored light has greater advertising effectiveness, so it is not necessary to increase lamp wattage in direct proportion to the lumen output of the colored lamps for equal effectiveness. This is taken into account in Figure 17-28.



District Brightness	Typical Sign Lamp Wattages
Low (< 10 lx [1 fc])	6, 10,11
Medium (10-50 lx [1-5 fc])	10, 11, 15, 25
Bright (> 50 lx [5 fc])	25, 40

Figure 17-27. Lamp Wattages for Various District Brightnesses



Color	Clear	Yellow	Orange	Red	Green	Blue
Wattage	10-11	10-11	15	25	25	40

Figure 17-28. Relative Wattage of Clear and Transparent Colored Incandescent Filament Lamps Required for Approximately Equal Advertising Value

Both transparent and ceramic coatings are used to color bulbs. In general, the transparent coatings have higher transmittances than the ceramic; thus the transparent coated lamps appear brighter. In addition, the filament is visible for added glitter at near viewing distances.

Note that signs lighted in cool colors and lamps, blue in particular, are generally less legible than those with clear or warm-colored lamps because cool colors appear to swell or irradiate more than warm.

Lamp Types. For exposed-lamp signs located where rain or snow can fall on the hot glass, vacuum-type incandescent lamps are recommended. They are available in 6-, 10-, 11-, 15-, 25- and 40-W ratings in both clear and colored bulbs.

For high-speed motion effects, a 20-W gas-filled clear lamp is available. The filament heats and cools very rapidly, producing a clean, sharp on-off action. It is used for scintillation effects, running borders, and traveling message signs and wherever afterglow is undesirable.

Channels. Incandescent lamps are often set into channels. This improves the legibility of the sign when viewed at an angle and increases contrast by reducing background spill light. It does not prevent the strokes of the letters from appearing to merge together when viewed at a distance.

It is desirable to employ electrically grounded metal channels to separate incandescent filament lamps and luminous tubing when combined in a sign. Without the channel, the electric field generated by the tubing causes the filament to vibrate, thereby reducing the life of the lamp.

Effective Daytime Exposed-Lamp Signs. Exposed, high-candlepower light sources can be used to create electric signs that have at least as much advertising value during the day as conventional exposed-lamp signs do at night. Since traffic is generally greater during daylight hours, greatly increased readership usually results, so that the cost per advertising impression remains comparable to that of night-viewed lamp signs. The technique is adaptable to signs ranging in size from small store signs to community bulletin boards (Figure 17-29) to major spectaculars (Figure 17-25).[5]

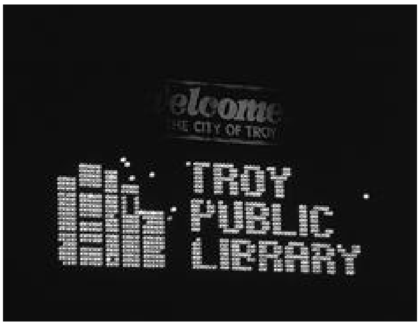
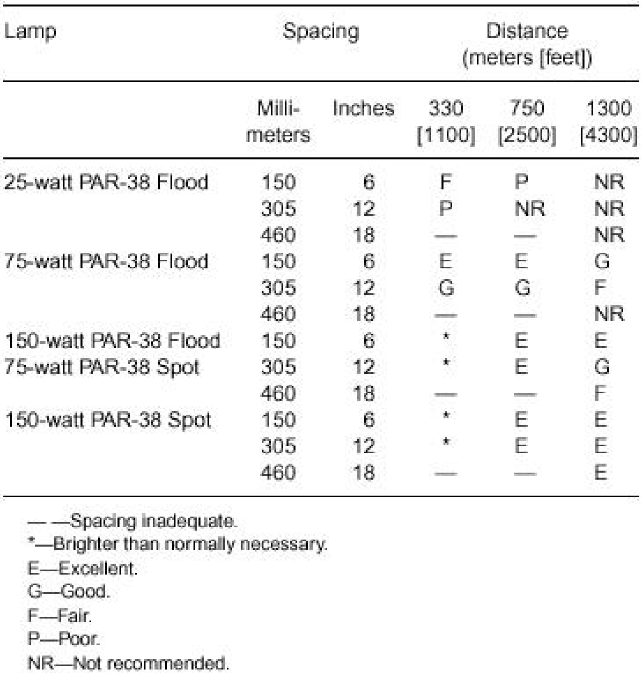


Figure 17-29. Animation panel with constantly changing graphics and messages.

The letter height and lamp spacing in a daytime lamp sign depend primarily on the lamp candlepower and on the maximum and minimum viewing distances.[6] For the great majority of daytime sign applications, 75-W PAR-38 floodlamps on 150-mm (6-in.) centers adequately meet advertising and identification needs. Higher-candlepower sources should be used with care, since there is a possibility of making the sign too bright for comfort. A guide for choosing lamp size is given in Figure 17-30. The minimum letter height for legibility is the same as for nighttime exposed-lamp signs.



Lamp	Spacing		Distance (meters [feet])		
	Millimeters	Inches	330 [1100]	750 [2500]	1300 [4300]
25-watt PAR-38 Flood	150	6	F	P	NR
	305	12	P	NR	NR
	460	18	—	—	NR
75-watt PAR-38 Flood	150	6	E	E	G
	305	12	G	G	F
	460	18	—	—	NR
150-watt PAR-38 Flood	150	6	*	E	E
75-watt PAR-38 Spot	305	12	*	E	G
	460	18	—	—	F
150-watt PAR-38 Spot	150	6	*	E	E
	305	12	*	E	E
	460	18	—	—	E

——Spacing inadequate.
*—Brighter than normally necessary.
E—Excellent.
G—Good.
F—Fair.
P—Poor.
NR—Not recommended.

Figure 17-30. Daytime Attraction Power of Several Lamp Types (Viewed Perpendicular to Plane of Sign)

It should be recognized that a daytime sign utilizing PAR-type lamps is a highly directional display. The sign's luminance is a function of the candlepower distribution of the lamp. With a PAR flood, for example, the luminance is reduced to 10% of maximum when viewed 30° off axis. This characteristic makes the sign appear less bright as a motorist drives toward it and under the beam of the lamp.

Nighttime Viewing. In most cases, a sign of sufficient brightness to compete successfully with daylight requires dimming at night in order to prevent loss of legibility due to irradiation and the possibility of excessive glare. The need for dimming appears to occur for the 75-W PAR-38 flood at about 250-lx (25-fc) daylight illumination, vertically, on the back of the sign. Except for the highest-candlepower lamps, dimming by line voltage reduction of 50% has generally proved satisfactory. An inexpensive and effective dimming method is to place the primary windings of 120- to 240-V supply transformers in series. Greater dimming through multiple-tap or variable transformers may be required, especially for very high candlepower sources. Continuously variable brightness depending on the sky brightness may be accomplished by regulating a dimming system with a photocell.

Luminous-Tube Signs[7]

Luminous-tube signs (see Figure 17-31) are constructed of gas-filled glass tubing which, when subjected to high voltage, becomes luminescent in a color characteristic of the particular gas used, of the gas and the color of the tubing combined, or of the fluorescent phosphors coating the inner wall. Additional information on luminous-tube lighting for advertising may be obtained from the National Electric Sign Association.

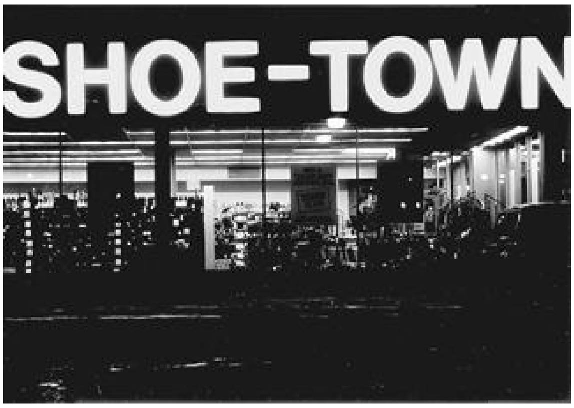


Figure 17-31. Luminous letter sign provides a distinctive and recognizable identification for pedestrians and motorists.

Color. Fluorescent tubing may be made to emit almost any desired color by mixing different phosphors. Most coated tubings have a higher lumen output per watt than the gaseous tubing without a fluorescent coating. Color produced by any one of the gases may be modified by using colored glass tubing, which transmits only certain colors.

Effective Range. The range of effectiveness for advertising purposes of tube signs is approximately that of exposed-incandescent-lamp signs of the same size, color, and luminance, from 75 m (250 ft) to over 3 km (2 miles).

Legibility. For block letters of width equal to three-fifths of their height, the minimum letter height that is legible to most people is approximately the same as that for exposed-lamp signs.

Tubing Sizes. Standard sizes of tubing for signs range from 9 to 15 mm (outside diameter), but larger tubing is available.

Transformers. Several forms of high-leakage-reactance transformers are manufactured to supply the high voltage necessary to start and operate sign tubing. This voltage is of the order of 3000 to 15,000 V. After a tube sign is lighted, 60% of the starting voltage is necessary to keep it operating. The usual range of operating currents for tube signs is between 10 and 60 mA.

Fiber-optic Sign Lighting

Several different illuminators are available for fiber-optic lighting. Halogen sources range from 20 to 200 W; metal halide lamps range from 150 to 575 W, and other lamp technologies such as xenon, xenon metal halide, and sulfur lamps are also employed. Lamp life and operating temperature must be considered in choosing the proper lamp in addition to the range of colors and the luminous intensities required. Care must be exercised by the designer and the installer to ensure that there is adequate ventilation at the site of the illuminator to allow the light source and its associated equipment to operate within its normal temperature ranges. Side-emitting and end-emitting optical fiber illumination technologies are used for advertising lighting.

Plastic optical fiber (POF) emits light along the entire length and has the appearance of a uniform neon-like surface, much like neon tubing (Figure 17-32). Closed loop applications (the fiber is illuminated at both ends by a single light source) is the most common approach for advertising. With recent improvements in the optical characteristics of side-emitting fiber, lengths of optical fiber as long as 100 feet have been used to achieve uniform brightness over its entire length when illuminated at both ends. The fiber also can be run in continuous, series runs between adjacent illuminators. This configuration is employed where it is necessary to have runs of larger than 100 ft (62 m).

The color of the light emitted by the fiber can be controlled by selecting an illuminator with color filters. Rotating wheels can provide dynamic colors. The wheels may be connected to continuous-drive motors or stepper motors with programmable control.

Typical advertising applications for side-emitting optical fiber include backlighting of signs, decorative and edge lighting of signs, and scripting and lettering. Although this technology does not presently provide the same levels of luminance as cold cathode gas discharge sources, it offers the unique capability of color changing with properly equipped illuminators.

Figure 17-32. The signage for a mall illuminated with fiber optics. The individual bands above the script lettering are each sourced by separate illuminators. Side-emitting fiber tubing was mounted in sections of mounting track to follow the contour of the bands. The script words were formed from fiber tubing that was penetrated in an out of the channel letter and mounted with silicone adhesive and sourced by illuminators.

Figure 17-33. End-emitting fiber tubing was introduced to a McDonald's sign to introduce an element of animation. The illuminator with a sparkle wheel sourced the fiber to create a twinkling effect and constant movement in the sign. The random sizes of points were created by using different combinations of fiber bundles.

End-emitting Fibers. End-emitting fiber bundles can be used to add sparkle and color to an otherwise static sign. The output ends of the fiber are bonded into holes in the sign face according to the design pattern. The patterns created by the bright fiber-optic illumination can either be stand-alone or used to enhance other graphic features. Small signs typically have a single light source, whereas larger applications may require a number of sources. Several manufacturers of end-emitting fibers are marketing high resolution, large-format, active-matrix fiber-optic screens, which have exceptional daylight brightness.

The addition of a color wheel or sparkle wheel can add color or animation to a sign to increase its attention-grabbing power (Figure 17-33). Color wheels for end light advertising are either handmade from theatrical gels, silk-screened on a plastic substrate, or composed of dichroic glass. Similar to side-emitting systems, the color wheels can be connected to continuous-drive motors or stepper motors with programmable controls.

Luminous-Element Signs

A luminous-element sign can be created by transilluminating or backlighting a plastic or glass panel that may be either integrally pigmented, externally painted, or opaque. The pigmentation or paint film diffuses the light, providing uniform brightness over the desired portion of the sign face (Figure 17-34). A wide variety of colors is possible with both the integrally pigmented media and the available translucent lacquers and films.

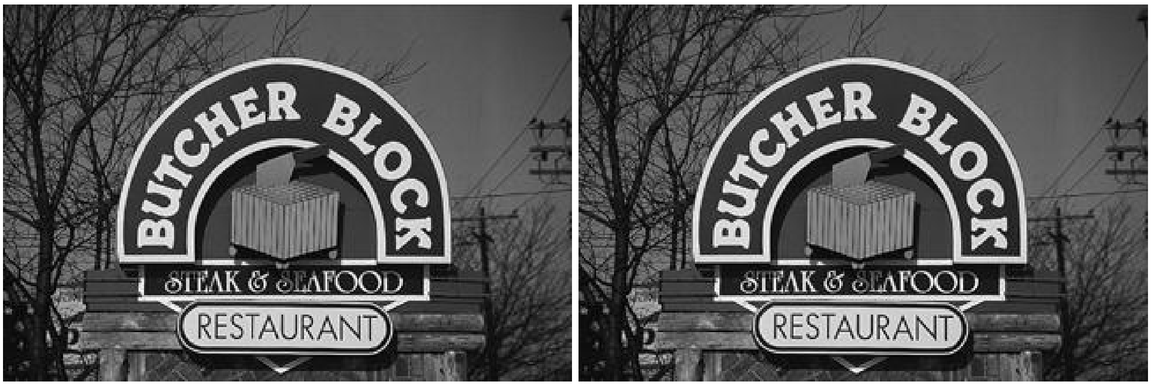


Figure 17-34. Luminous sign for attraction both day (left) and night (right)

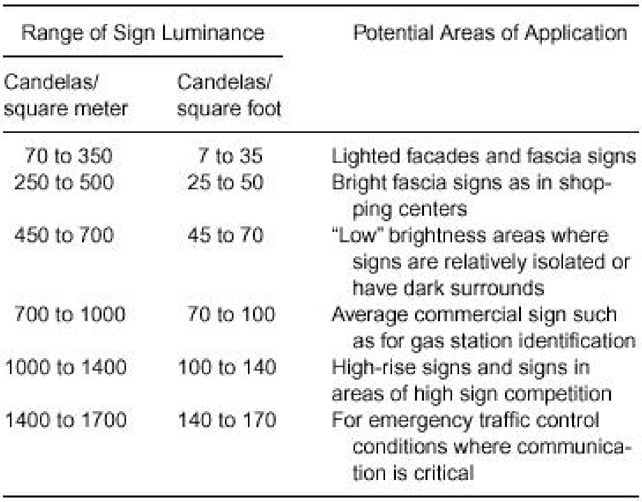
Design Data for Luminous Elements

Proper lighting is important to assure the best attraction and readability for these signs. Other points, however, must be considered along with the lighting.

Contrast. High color or brightness contrast between message and background panels should be provided. Opaque letters on a light background are generally preferred for commercial signs because of their attractiveness. Where communication is of prime importance, as with rental car return signs, light letters on dark backgrounds are generally specified.

Light Sources. Selection of the light source is based on the brightness required, size and shape of the sign, desired color effects, flashing or dimming requirements, environmental temperature conditions, and service access requirements. Linear sources such as fluorescent lamps, luminous tubing or custom sign tubing may be used as the lighting element. Special diffusing materials should be used with spot sources, such as incandescent or high-intensity discharge lamps, to prevent hot spots of brightness on sign faces. Specially designed HID luminaires are available for internally illuminated signs, which do not require diffusing screens because of a refractor designed specifically for this application. These luminaires effectively distribute the light from a single HID lamp across the entire face of such signs. Their use leads to cost- and energy-efficient signs.

Sign Brightness. Adequate sign brightness should be provided, but it is important that signs not be overly bright. The best brightness depends primarily on the desired sign visibility, its use, and the environment in which it is to be seen (Figure 17-35).



Range of Sign Luminance		Potential Areas of Application
Candelas/ square meter	Candelas/ square foot	
70 to 350	7 to 35	Lighted facades and fascia signs
250 to 500	25 to 50	Bright fascia signs as in shopping centers
450 to 700	45 to 70	"Low" brightness areas where signs are relatively isolated or have dark surrounds
700 to 1000	70 to 100	Average commercial sign such as for gas station identification
1000 to 1400	100 to 140	High-rise signs and signs in areas of high sign competition
1400 to 1700	140 to 170	For emergency traffic control conditions where communication is critical

Figure 17-35. Recommended Luminous Background Sign Luminances

Calculating the Number of Linear Lamps Needed. When white, yellow, or ivory backgrounds are used, a formula for estimating the spacing of linear lighting elements (usually fluorescent lamps) in meters (feet) is as follows:

$$d = \frac{K\tau \times \Phi/l}{L} \qquad (29\text{-}4)$$

where

K = 250 when l is in meters, or 9.4 when l is in feet (a constant for the combined interreflectance characteristics of the sign enclosure),
l = length of the lamp in m (ft),
L = luminance required (from Figure 17-35),
τ = transmittance of the medium (from manufacturer's literature or measurement),
Φ/l = number of lumens per m (ft) of lamp to be used.

This is obtained by dividing the manufacturer's initial lumen output for the lamp by the length in m (ft). This formula may be modified for maintained lumens by including an appropriate factor for lamp lumen depreciation [LLD] in the numerator.

This spacing is based on providing a clearance between the lighting elements and the sign face material equal to the center-to-center spacing value. However, with both internally pigmented media and with lacquer coatings, it is possible to obtain satisfactory diffusion in many cases with a smaller clearance. There is, of course, a minimum clearance distance, whereby an image of the light elements is seen through the sign face. Clearances between the lamps and the sign face can be determined in a test mockup when experience and published data are lacking.

Adaptation of Formulas for Point Sources. The formulas above may be adapted for point sources by using the following form:

$$\text{spacing between lamps (mm)} = 1000\sqrt{\frac{K\tau\Phi}{L}} \qquad (29\text{-}4a)$$

$$\text{spacing between lamps (in.)} = 12\sqrt{\frac{K\tau\Phi}{L}} \qquad (29\text{-}4b)$$

This gives the same spacing in the vertical and horizontal directions. The clearance between the surface of the lamps and the sign face media should be not less than that derived from the following formulas:

$$\text{minimum clearance (mm)} = 12.5\sqrt{\text{lamp wattage}} \qquad (29\text{-}5)$$

$$\text{minimum clearance (in.)} = 0.5\sqrt{\text{lamp wattage}} \qquad (29\text{-}6)$$

This prevents overheating of the sign face media by direct radiation from the lamp. Having determined the necessary spacing, the number of lamps can be readily calculated.

Obscuring Lamp Sockets. Where fluorescent lamps are to be used, the dimensions of the sign should be such that the lamp sockets are located just beyond the translucent face area. This prevents shadows at the edges directly over the lamp sockets. Series arrangement of tubes in large signs using more than one tube per row requires overlapping of the tubes by at least 76 mm (3 in.) to prevent shadows similar to those at the sockets. All internal sign components such as structural framing, sheet metal backgrounds, and ballasts should be coated with at least two coats of high-reflectance (85% or higher) white paint to derive maximum lighting efficiency and prevent shadows.

Venting. Provision for venting and air circulation may be necessary, depending on the environmental temperature conditions of the sign. This is primarily to maintain the efficiency and to prolong the life of the lighting elements and supporting equipment such as ballasts. In signs with lamps close together, forced ventilation may be necessary to prevent overheating of the sign face media.

Legibility. The legibility of a luminous panel sign depends primarily on four factors:

- Size and proportions of the letters and the letter design configuration
- Letter spacing
- Color and brightness contrast between letter and background
- Brightness of the sign face

Size and Proportions of Letters. With dark letters and light background colors, the following formula may be used to determine the minimum letter height:

$$H = \frac{D}{600} \qquad (29\text{-}7)$$

where

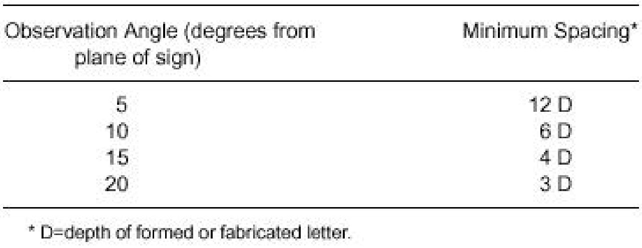
H = letter height, m (ft),
D = maximum distance of legibility, m (ft).

For maximum readability, the width of a letter should be 60% of the height, and a stroke should equal 15% of the height in a sans serif (block Gothic) style.

Spacing of Letters. The above width and stroke proportions are effective in preventing blending of letter lines where legibility at a distance is required. Considerable license is possible with the spacing of painted letters; however, for maximum legibility distance the spacing between letters should be 15% of the letter height, with allowance for visual equalization of white masses, such as between a letter W and a letter A.

Letters and illustrations, or insignia, of bold silhouette rather than fine detail are preferable for long-distance legibility. Fine detail and stylized script letters find their greatest use when they are observed from a relatively close distance, as in downtown shopping areas and in shopping malls. Three-dimensional formed and fabricated letters should be spaced on the basis of their depth of forming and the minimum observation angle acuteness, that is, the minimum angle parallel to the sign that allows the sign to be read (Figure 17-36).

The ratios given in Figure 17-36 are also useful in the design of letters to be formed or fabricated so that their legibility is a function of the observation angle. For example, based on a minimum observation angle of 10° and a proposed depth of forming of 50 mm (2 in.), the minimum opening in a letter such as O should be 6 times 50, or 300 mm (6 × 2 = 12 in.). Hence, for minimum observation angles letters are extended, and the average letter width is as large as the letter height, or more, to meet the requirements of acute observation angles.



Observation Angle (degrees from plane of sign)	Minimum Spacing*
5	12 D
10	6 D
15	4 D
20	3 D

* D=depth of formed or fabricated letter.

Figure 17-36. Maximum Spacing of Three-Dimensional Letters

Luminance and Readability of Sign Face. The brightness of the sign face has a significant influence on the readability of the sign. A sign that is too bright can suffer loss of readability from a halo effect around the letters. Insufficient lighting reduces the legibility distance. The recommendations for sign luminance in given applications, shown in Figure 17-35, are suitable guides. In some cases, where high background brightness is required, elimination of the halo effect is achieved by applying a stripe of opaque black paint, 13 mm (0.5 in) wide, around the outline of the letter. This applies particularly to those signs employing flat cut-out, formed, or fabricated letters attached to light-colored backgrounds. In signs using dark backgrounds with light letters, debossing, or forming depressed areas rather than the conventional raised letter areas, eliminates halation.

LUMINOUS BUILDING FRONTS OR FACADES

The same basic data for design of luminous elements applies, in general, to luminous portions of building fronts. However, the surface luminances need not be designed for more than 350 cd/m^2. In an area of low-level environmental lighting, 85 cd/m^2 of surface luminance is adequate.

Building Fascia (Belt) Signs. Lamps may be placed at either the top, bottom, or both the top and bottom of long fascia or belt signs installed on the face of a building. It is necessary to locate the lamps in such a way that they can be serviced. By selecting the dimensions of the sign carefully, it is possible to produce acceptable luminous uniformity over the entire face of the sign with lamps located in any of the above configurations. These configurations produce a low but acceptable sign luminance. This system produces a front surface luminance in the range of 70 to 350 cd/m^2. A double row raises the surface luminance to between 250 and 500 cd/m^2.

Major design considerations in systems for obtaining uniform light distribution or even lighting of the fascia surface are:

- The depth of the sign cabinet (from the face of the sign to the back of the cabinet)
- Specially shaped sign enclosures with sloping, parabolic, or elliptical contoured backs that do not improve the light distribution over the straight-back sign cabinet
- Luminous uniformity can be improved with special reflectors at the light source (in a shallow sign cabinet, for example, a parabolic-reflector fluorescent-lamp luminaire can provide more uniform illumination on the fascia than bare lamps alone)
- The luminance uniformity ratio of the sign face medium maximum to minimum, which can be determined from the following formula:

$$\text{uniformity ratio} = \frac{\text{highest sign face luminance}}{\text{lowest sign face luminance}} \qquad (29\text{-}8)$$

A ratio of 1 is best. A ratio of 2 may be tolerated in some installations but should be considered the maximum allowable. Ratios of 1.3 to 1.5 are satisfactory for most installations.

1. Very high output fluorescent lamps that are as efficient in obtaining uniform light distribution as aperture lamps

Examples of fascia signs may be found on automobile dealerships, food chain stores, and discount stores.

Luminous Fascia Colors Other Than White.

The information shown above is for signs using integrally pigmented sign face media, 3.2 mm (0.125 in.) thick, having a 40% transmittance. Whites and other colors with lower transmittance values produce surface luminance values below those shown. When using colors other than white, it is necessary to apply a spray coating of white paint to the inside surface of the sign cabinet in order to obtain comparable light distribution qualities.

FLOODLIGHTED SIGNS[8,9]

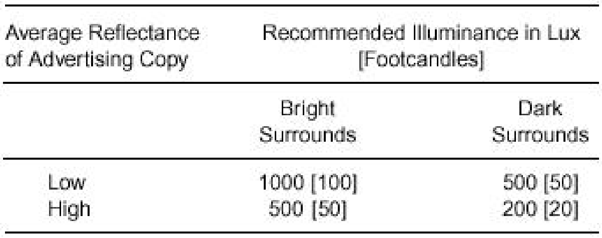
Lighting Poster Panels, Painted Bulletins, and Vertical Surface Signs

There are no hard rules in creating an outdoor advertisement. Since outdoor messages are viewed at distances ranging from 30 to 120 m (100 to 400 ft) by people in motion, logic dictates the need for brevity, simplicity, and clarity. In general, fewer words, larger illustrations, bolder colors, simpler backgrounds, and clearer product identification produce better outdoor advertisements.

The most important factors contributing to the conspicuity of an illuminated sign are area and brightness. However, several relatively complex factors affect legibility of signs, many of which are psychological as well as physical. See the section "Sign Characteristics" earlier in this chapter.

General Guides for Lighting Signs

The following is a list of recommendations to be considered in designing floodlighting of signs. The brightness of the sign panel should be sufficient for it to stand out from its surroundings. Figure 17-37 lists recommended illuminances.



Average Reflectance of Advertising Copy	Recommended Illuminance in Lux [Footcandles]	
	Bright Surrounds	Dark Surrounds
Low	1000 [100]	500 [50]
High	500 [50]	200 [20]

Figure 17-37. Recommended Illuminances for Poster Panels, Painted Bulletins, and Other Advertising Signs

- The luminance should be sufficiently uniform to provide equal legibility over the message area. A maximum-to-minimum luminance ratio of 4:1 is desirable. Sharp shadows should be avoided on the sign face. Uneven brightnesses detract from the communication impact of the sign.
- The lighting should cause neither direct nor reflected glare at the normal viewing positions.
- The lighting equipment should not obstruct the reading of the sign from normal viewing positions, nor produce daytime shadows on the sign.
- The lighting equipment should require minimal maintenance and have low annual operating cost.
- The system should be maintained to achieve the designed illuminances.

Location of Lighting Equipment

Some of the factors to be considered when determining whether luminaires should be mounted across the top or bottom of a sign are:

1. For top-mounted units:

   Advantages

   - The luminaire cover may collect less dirt, snow, and debris.
   - Luminaires do not hide the message.
   - The sign usually shields a direct view of lamps from opposing traffic.

   Disadvantages

   - Reflected glare is more apparent.
   - Luminaires may produce daytime shadows.
   - Luminaires may be more difficult to service.
   - The sign is more difficult to post (poster panels).
   - The panels are more difficult to change (painted bulletins).

2. For bottom-mounted units:

   Advantages

   - Reflected glare is minimized.
   - No daytime shadows are produced.
   - Luminaires may be easier to service.
   - Posting and message changing are more simply accomplished.

   Disadvantages

   - The luminaire cover may collect more dirt, snow, or debris.
   - Luminaires may hide the message from some viewing angles.
   - Shielding may be necessary to hide direct view of the lamp or luminaire optical system from opposing traffic.

Light Sources for Floodlighted Signs

There is no single type of source that can be described as best for sign floodlighting. Most lamps, regardless of type, can be used with different reflector and lens combinations to realize various beam patterns that may be required. Therefore, choices of light source for a given sign generally are made for reasons of initial cost, operating cost (including maintenance), desired end result, color, or novelty. Chapter 6, Light Sources, contains a detailed discussion of available light sources. The following lamp types are used in sign floodlighting:

Metal Halide. Advantages are good lamp life, efficacy, and color rendering capability, as well as low operating cost. One disadvantage is the high initial cost.

High-Pressure Sodium. Advantages are good lamp life and efficacy, but color rendering is poor.

Incandescent. Advantages include good color rendering, small size, accurate beam control, and good cold-weather operation. Disadvantages are low efficacy, short lamp life, and high operating costs.

Mercury. Advantages include long lamp life, high efficacy, and low operating cost. Disadvantages are high initial cost, fair beam control, and color rendering capability below that of incandescent or tungsten-halogen lamps.

Tungsten-Halogen. Advantages include good color rendering, high lumen maintenance, and good cold-weather operation. Disadvantages are low efficacy, medium lamp life, and high operating costs.

Fluorescent. Advantages are long life, high efficacy, and low operating cost. Disadvantages are high initial cost, lack of beam control, and variable output due to changing temperatures.

Lighting Systems for Floodlighted Signs

Concurrent with consideration of a particular light source, there should be an evaluation of other elements such as lamp housing, mounting arrangements, and auxiliary equipment. Due to improved lamp performance, metal halide lamp systems are becoming more prevalent. Many existing signs are still lighted by fluorescent equipment, however. Incandescent and tungsten-halogen lamps with their associated housings are generally less expensive to install, since they do not require auxiliaries such as ballasts, but their use has dwindled considerably in favor of longer-life and more energy-efficient sources.

Application Data

Regardless of which system is used, the most economical floodlighting system is one that utilizes the fewest floodlights containing the highest-wattage lamps. Such a system is easiest to install, control, and maintain. It also uses less power for the same illuminance than a system using more but smaller units. However, illuminance uniformity and appearance may require the selection of a system using a larger number of smaller units. It may be necessary to draw a careful balance between the two extremes. Particularly with shorter-lived lamps, such as incandescent and tungsten-halogen, the beam patterns should be overlapped so that any given area receives light from at least two units. This requirement is usually satisfied if an acceptable uniformity ratio is achieved.

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18

Residential Lighting

RESIDENTIAL LIGHTING DESIGN ISSUES

General

- Appearance of Space and Luminaires
- Color Appearance (and Color Contrast)
- Direct Glare
- Illuminance (Horizontal)
- Light Distribution on Surfaces
- Luminances of Room Surfaces
- Modeling of Faces or Objects
- System Control and Flexibility

Kitchen

- Color Appearance (and Color Contrast)
- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Reflected Glare
- Source/Task/Eye Geometry

Reading

- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Reflected Glare
- Source/Task/Eye Geometry

This chapter serves as a guide for lighting residential spaces.[1] It is intended to aid in creating lighted spaces that are rich and varied and have adequate lighting for tasks and good color rendition. It covers design objectives, criteria for the quantity and quality of illumination, lighting methods, typical equipment, and electrical energy considerations. Methods for lighting specific visual tasks are detailed. Every task description discusses the task plane, the range of recommended illuminances, lighting design considerations, and typical equipment locations.

FACTORS AFFECTING THE INTERIOR LIGHTING PLAN

Human Factors

Light influences the emotional responses of the people who occupy the space. The appearance and character of a space is greatly dependent on the distribution and pattern of light and shadow. Lighting design does not start with the selection of luminaires, but with an evaluation of the occupants' needs, visual and physical capabilities, age, and lifestyle. (Older people require much more light than younger people; a 55-year-old requires twice as much light as a 20-year-old.) Because needs, lifestyles, and occupants can change, consideration should be given to the use of portable, modular, and easily controlled luminaires.

Design Factors

The designer must gather information to identify the client's needs and develop solutions. Those elements that contribute to the design solution are the design issues. Following the evaluation of the design issues, the designer should then select the light sources and luminaires and finally determine quantity, location, and appropriate controls.

Several important criteria must be considered in residential lighting design. They include safe movement from one space to another, lighting people as well as objects, flexibility in multipurpose spaces such as kitchens and great rooms, a sense of aesthetics, and the concern for energy efficiency.[2-4]

Finally, the designer should consider how alternative sources, equipment, placement, or controls would improve the end results and affect costs. The designer should provide a maintenance schedule and lamp replacement list for the client to help keep the lighting system equipped to perform as planned. For more information on maintenance, see Chapter 28, Lighting Maintenance.

LIGHTING CRITERIA FOR INTERIOR SPACES

Quality of Light

Lighting may be diffuse or directional. Diffuse light minimizes shadows and provides a more relaxing and less visually compelling atmosphere. When diffuse light is used alone, no object in the visual scene is given prominence. Artful use of directional light can provide highlights and shadows that emphasize texture and form. Brilliance or sparkle can be achieved with small unshielded sources, such as a bare lamp or a candle flame. The glitter of crystal and polished brass, the luster of table settings, and the sheen of surface materials can be heightened by directional lighting to create a sense of warmth and festivity. Low-voltage cable systems can be used for ambient and directional illumination.

In many residential spaces, it is desirable to create more than one mood or to be able to vary the atmosphere. Lighting control systems can provide this flexibility and should be an integral part of the design (see Chapter 27, Lighting Controls).

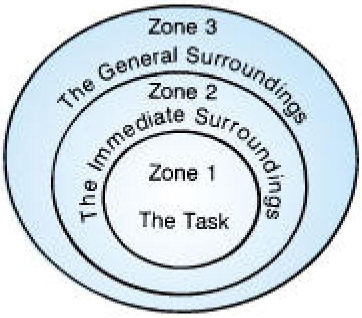
Brightness Relationships

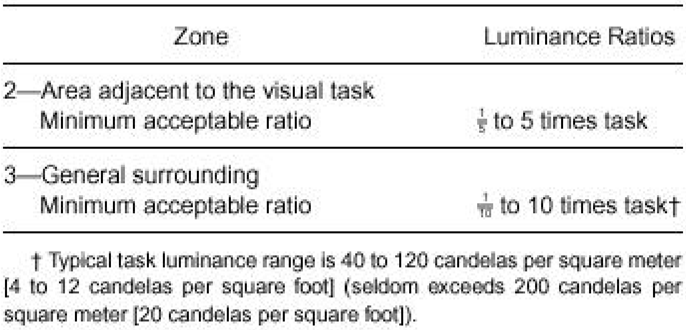
Brightness is an impression of the appearance of a light source or an illuminated surface, described in terms of its perceived relative luminosity. This subjective impression can be correlated with light-measuring instruments (see Chapter 2, Measurement of Light and Other Radiant Energy) that determine the luminance of the surface or of the source. Luminance is expressed in candelas per square meter (cd/m^2). Luminance ratios play an important role in the comfort, eye fatigue, and difficulty of visual tasks.

Seeing Zones

A person's visual field consists of three zones (Figure 18-1):

- Zone 1: The task area itself
- Zone 2: The area immediately surrounding the task
- Zone 3: The general surroundings





Zone	Luminance Ratios
2—Area adjacent to the visual task Minimum acceptable ratio	$\frac{1}{5}$ to 5 times task
3—General surrounding Minimum acceptable ratio	$\frac{1}{10}$ to 10 times task†

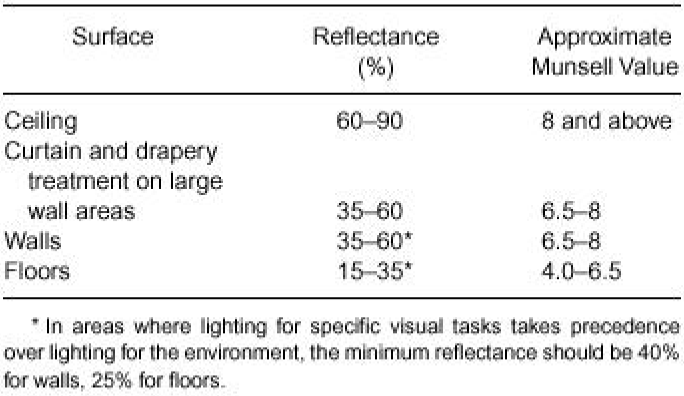
† Typical task luminance range is 40 to 120 candelas per square meter [4 to 12 candelas per square foot] (seldom exceeds 200 candelas per square meter [20 candelas per square foot]).

Figure 18-1. Seeing Zones and Luminance Ratios for Visual Tasks

For visual comfort the luminance of the immediate surround (zone 2) should range between one-fifth of the task luminance and 5 times the task luminance. The luminances of areas in the general surround (zone 3) should range between one-tenth of the task luminance and 10 times the task luminance. These relationships should not be exceeded for visual comfort in visually demanding tasks such as studying, sewing, or reading.

Reflectance

Reflectance is the ratio of the amount of light leaving a surface to the amount of light incident on it. Reflectance can be expressed as a percentage or more roughly as a Munsell value (see Chapter 4, Color). Pale, high-reflectance colors for room surfaces and furnishings are important and often essential in achieving desirable luminance ratios. To assist the designer in obtaining the recommended luminance ratios, recommended surface reflectances with approximate Munsell values are listed in Figure 18-2.



Surface	Reflectance (%)	Approximate Munsell Value
Ceiling	60–90	8 and above
Curtain and drapery treatment on large wall areas	35–60	6.5–8
Walls	35–60*	6.5–8
Floors	15–35*	4.0–6.5

* In areas where lighting for specific visual tasks takes precedence over lighting for the environment, the minimum reflectance should be 40% for walls, 25% for floors.

Figure 18-2. Recommended Reflectances for Interior Surfaces of Residences

Veiling Reflections

Light reflected from the task surface, which partially or totally obscures the details by reducing the contrast, is called a veiling reflection. When tasks involve specular glossy surfaces, such as high-gloss photographs and slick magazines, veiling reflections can be a problem (see Chapter 3, Vision and Perception).

Reflected Glare

When light sources are imaged on glossy glass-top tables or mirror-like surfaces in or near the visual task, the condition is known as reflected glare. If these reflections are excessively bright, they cause visual discomfort (see Chapter 3, Vision and Perception).

Light and Color[5]

Color recognition depends on the spectral characteristics of the light source and the spectral reflection characteristics of the object being lighted. These two factors provide object color to the observer.

Surface or object colors may match under one light source but not under another. For example, two colors may match under incandescent lighting but not under daylighting (see Chapter 4, Color). This fact should be noted when selecting materials, pigments, or dye lots for interior surfaces. One should examine and compare materials under the light sources that will ultimately illuminate them.

Surface Finish

Colors of objects sometimes appear to change with surface finish. Specular or mirror reflections from glossy surfaces may, in extreme cases, increase the chroma and saturation at one angle and obscure color at other angles. A matte finish reflects light diffusely and appears more or less the same from any viewing angle. Deeply textured finishes, such as velvet or deep-pile carpeting, cause shadows within the fibers that make the materials appear darker than smooth-surfaced materials such as satin, silk, or plastic laminates of the same color.

Fading

Light fades fabrics and finishes. Ultraviolet (UV) energy is one cause of fading (see Chapter 5, Nonvisual Effects of Optical Radiation). Since UV radiation cannot be completely eliminated, the amount, frequency, and length of exposure should be considered when materials or objects are of great value or irreplaceable (see the section on Museum Lighting in Chapter 14, Lighting for Public Places and Institutions). The use of appropriate UV and IR filters in luminaires to protect fabrics, furnishings, and art from light sources is recommended.

Quantity of Light

Visual activities in living spaces range from simple to extremely difficult tasks. For example, sewing is an activity with small visual details and low contrast that requires higher illuminance than determining orientation in an entry foyer. See Chapter 3, Vision and Perception, for a discussion of the factors involved in seeing, and Chapter 10, Quality of the Visual Environment, for the recommended quantities of illumination.

LIGHTING METHODS

General Lighting

Areas with Visual Activities. Residential lighting is planned on the basis of activities, occupants' ages, and physical capabilities and limitations, not on the basis of room type. The designer should provide enough general lighting for a range of activities. General illumination prevents a spotty effect, maintains recommended luminance ratios in the field of view, and provides light throughout the interior for safety and housekeeping activities. General illumination also prevents excessive differences in illuminance between adjacent rooms.

In some spaces, particularly utility areas, general illumination can be designed to supply all of the lighting needed for visual activities. For most living areas, high-illuminance, uniform general lighting would be unacceptable. The equipment most commonly used to light room surfaces and create a satisfactory background for visual work includes general-diffuse ceiling luminaires, wall luminaires, indirect luminaires, built-in lighting systems, or portable floor or table luminaires (Figure 18-3). In small rooms, general illumination can even be supplied by the luminaires used for specific task lighting, as in the case of a vanity mirror light or an open-shade portable luminaire used primarily for reading or studying. In addition to a system that provides general illumination, portable task lighting may be needed for demanding visual tasks.[6]

Areas for Relaxation. A low level of illumination in combination with small areas of bright light creates a relaxing atmosphere (Figure 18-4). Uniformity of illumination need not be the objective. The primary considerations for these spaces are comfort and aesthetic satisfaction.

Connection Areas. Illuminance levels for hallways and stairs should allow for visual adaptation. If they adjoin an interior area with a higher illuminance, the level in the hall or stair should be no less than one-fifth that of the adjacent area. Wall luminances are crucial in creating a sensation of brightness and reducing shadows on the stairs. Wall and floor finishes should have high reflectance values. Lighting in an entry hall should be flexible so that adjustments can be made for visual adaptation during the day and at night (Figure 18-5). On stairs, it is critical that treads be emphasized, and that the top and bottom steps be well lighted for safety. Under no circumstances should a built-in wall-mounted luminaire or portable luminaire be located where a person descending the stairway can see the light source directly.

Figure 18-3. A home office is illuminated with several types of lighting: recessed downlights for general lighting, undercabinet luminaires for task lighting on the desk top, and a wall sconce for style.

Figure 18-4. Lighting contributes to a room's aesthetics and atmosphere. This inviting living room, with its extraordinary view of the city, features downlighting in the seating area, accent lighting on the painting and sculpture over the fireplace, and shelf lighting to illuminate the stereo and highlight decorative items.

Figure 18-5. Left, a three-dimensional effect was created for the lighting of this hallway. Three recessed PAR-30 spotlights were used to wash the wall of the upper hallway and give depth to the view. The open passageway was lighted with wall-mounted up/down fluorescent lamp luminaires. A low voltage incandescent strip was used to light the railing. The bottom step of the staircase was illuminated with a downlight, while the dried reeds were illuminated with uplight. This lighting scheme plays with various brightnesses and emphasizes three-dimensional planes and depths. Right, a daytime view of the same hallway. While the skylight is pronounced, the three-dimensional features of the lighting scheme are not as noticeable.

Garages. Light is needed in a garage on both sides of the automobile and between automobiles, especially over the front and rear. Luminaires are usually located slightly to the rear of the trunk area and approximately in line with the front wheels. A portable trouble light can be provided for repair work.

Garages are often multipurpose spaces. In addition to ambient lighting, task lighting may be required for a work bench.

Closets. Light sources in closets should be located out of normal view, generally to the front of the closet and above the door. In walk-in closets, a ceiling luminaire should be mounted at the center of the traffic area so that shelves do not block the lighting of the garments. National and local electrical codes for closet lighting, which require enclosed luminaires, must be followed.[7]

High-color-rendering light sources should be selected, since color matching is a critical task in closets. Select lamps with a high color temperature and a color rendering index (CRI) of 80 or higher.

Lighting for Common Visual Tasks

In providing the recommended illuminance on the task, which corresponds to zone 1 in Figure 18-1, the essentials of good lighting quality, as previously discussed in this chapter and in Chapter 10, Quality of the Visual Environment, must not be overlooked. Rarely can the desired illuminance be provided by general lighting alone. At the same time, task lighting by itself is seldom totally satisfactory or comfortable; therefore, a combination of task and general lighting is needed (Figure 18-6).[8] Daylighting also improves the quality of the lighting in a residence.

Figure 18-6. This bath features a simple soffit with overlapping up/down 4 ft T-12 fluorescent striplights that provide an even wash of light. The luminaires are outfitted with wooden egg-crate louvers.

The common residential visual tasks are discussed in Figures 18-7 through 18-23. Included in this discussion is a description of the task and task plane, special design considerations, and typical equipment locations. For illuminance values see Chapter 10, Quality of the Visual Environment.

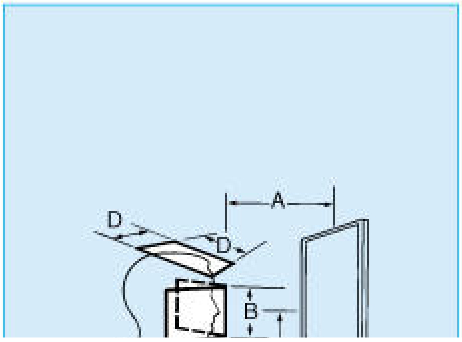


Figure 18-7. Grooming

Bathrooms require a combination of lighting, task, and mood. A high color rendering lamp, one that shows colors accurately, is best for grooming. Well-shielded incandescent or halogen lamps offer the greatest decorative options; fluorescent lamps with good color quality can provide high levels of light without the heat. The placement of the luminaires is especially important in using a mirror; elongated lighting alongside the mirror works best and should be at least 400 mm (16 in.) long. Lighting above the mirror should be at least 600 mm (24 in.) wide to properly illuminate both sides of the face. Recessed downlights are an excellent choice for mood and general lighting. These luminaires are most effective when placed on a dimmer.

1. *The task:* The chief tasks are shaving and applying makeup. Because the apparent distance of the face or figure as viewed in the mirror is twice its actual distance from the mirror, and because the details to be seen in shaving or makeup are usually small and of low contrast with their background, the visual task may be critical. Skin and hair reflectance can be quite low, below 30%, and speed and accuracy while grooming can be critical for a fastidious person rushed for time.

2. *Description of the task planes:*

(a) Standing position: The task area consists of two 150 by 220-mm (6 by 8-——58—— in.) planes at right angles with each other, converging at a point 410 mm (16 in.) out from the mirror and centered vertically 1550 mm (61 in.) above the floor. They represent the front and sides of the face. A third plane 310 mm (12 in.) square, its front edge also 410 mm (16 in.) out from the mirror, is tilted up 25° above the horizontal and represents the top of the head.

(b) Seated position: The two facial planes are identical in size and position to those mentioned above, except that the center of the planes is 1160 mm (45 in.) above the floor. The size of the third top-of-the-head plane is the same as above.

3. *Special design considerations:* Lighting equipment at a mirror should direct light toward the person and not onto the mirror. The luminance of surfaces reflected in the mirror and seen adjacent to the face reflection should not be in distracting contrast with it.

(a) Adjacent walls should have a 50% or higher reflectance.

(b) Luminaires should be mounted outside the 60° visual cone with a centerline that coincides with the line of sight.

(c) No luminaire should exceed 2100 cd/m^2 in luminance, that is, an illuminance meter held against it should not read more than 6500 lx (600 fc).

4. *Typical equipment locations:*

(a) Wall-mounted linear or nonlinear luminaires over the mirror

(b) Wall-mounted linear or nonlinear luminaires over and at the sides of the mirror

(c) Combination of wall- and ceiling-mounted luminaires flanking the mirror and over the head of the user

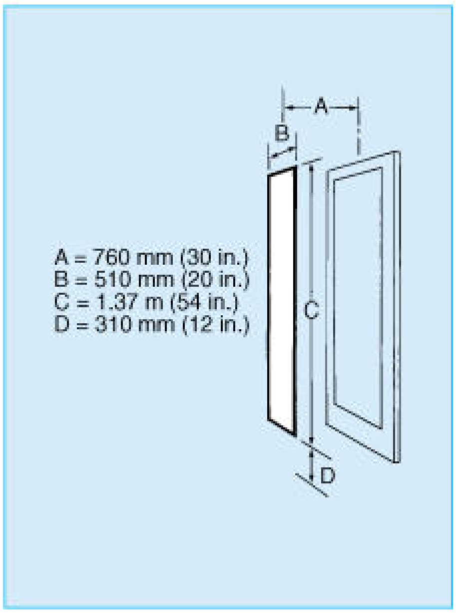
(d) Structural devices (such as soffits) extending the length of the mirror

(e) Portable luminaires with luminous shades flanking the mirror

(f) Pendant luminaires with luminous sides flanking the mirror

Note: If grooming is performed in a seated position, the relationship of the luminaires to the face should remain as specified above for standing.

Figure 18-8. Full-length mirror



1. *The task:* The task is the alignment of clothing, commonly with reflectance between 30 and 70%, and casual overall appraisal. Speed and accuracy may or may not be important.

2. *Description of the task plane:* The task area is a plane 510 mm (20 in.) wide by 1370 mm (54 in.) high with the lower edge 310 mm (12 in.) above the floor. It is centered on and parallel with the mirror, 760 mm (30 in.) from the mirror surface.

3. *Special design considerations:* Lighting equipment at the mirror should direct light toward the person and not onto the mirror. The luminance of surfaces reflected in the mirror and seen adjacent to the face reflection should not be distracting.

(a) Luminaires should be mounted outside the 60° visual cone with a centerline that coincides with the line of sight.

(b) No luminaire should exceed 2100 cd/m^2 in luminance, that is, an illuminance meter in contact with the surface should not read more than 6500 lx (600 fc).

4. *Typical equipment locations:*

(a) Vertical linear luminaires wall mounted beside the mirror

(b) Vertical linear luminaires supplemented by wall-mounted or ceiling-mounted over-mirror luminaires

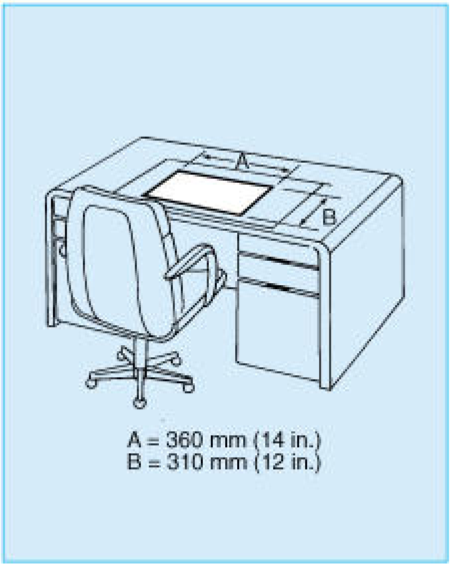


Figure 18-9. Home Electronic Office

1. *The task:* The task is reading the computer terminal screen, the keys and templates on the keyboard, and information written or printed on paper. In addition, printer and fax machine status settings must be read. Speed and accuracy may not be important for casual operation, but they may be important when doing work at home. Reflectances of equipment surfaces (other than the screen) are between 30 and 70%.

2. *Description of the task plane:* The terminal screen usually is in a vertical to near-vertical plane, while the keyboard is on a near-horizontal plane. The paper-based tasks can be on any plane from horizontal to vertical. Printer and fax status settings are usually in a near-horizontal plane.

3. *Special design considerations:* Luminance ratios between the terminal screen, the paper-based tasks, and the equipment and surface in the surround should be limited (see Chapter 11, Office Lighting). Luminaire, ceiling, and window brightness should be controlled to avoid reflections on the screen and specular surfaces of equipment.

4. *Typical equipment locations:*

(a) Desk-mounted or floor-mounted task lights for paper and keyboard tasks

(b) Wall-mounted direct/indirect luminaires at the front or side of the desk for ambient and task lighting (c) Ceiling-mounted low-brightness luminaires

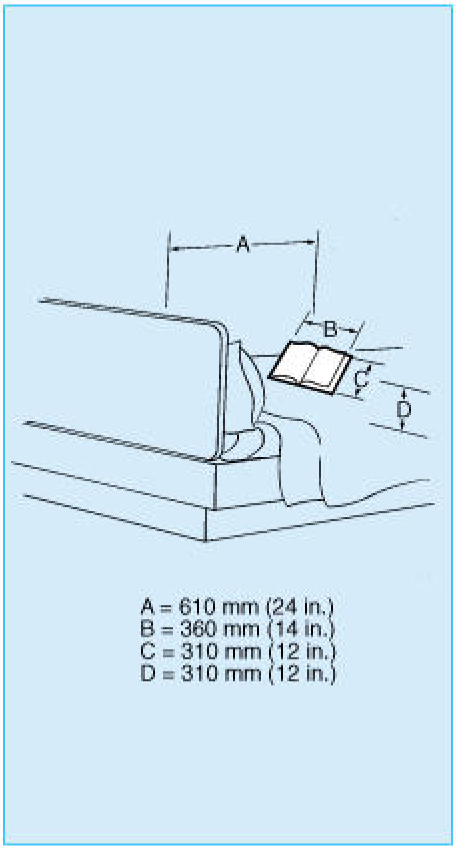


Figure 18-10. Reading in bed

1. *The task:* The majority of people who read in bed are only casual readers, perhaps reading for a few minutes before going to sleep. They are often interested in closely confining the light distribution so as not to disturb another occupant of the room. Such lighting arrangements are not satisfactory for comfortable reading over a long period. The following recommendations are for the person who reads for a more extended period, or for the person who performs critical seeing tasks while confined to bed. The normal materials vary from books and magazines to pocket editions and to newspaper print, with reflectances of 30 to 70%. Speed and accuracy vary from not important (for leisure reading) to important to critical (for critical tasks).

2. *Description of the task plane:* The task plane is 310 by 360 mm (12 by 14 in.), tilted at an angle of 45° from the vertical. The center of the task plane is 610 mm (24 in.) out from the headboard or wall and 310 mm (12 in.) above the mattress top. There are no customary reading positions or habits. These recommendations assume that the reader is in an upright or semireclined position.

3. *Special design considerations:* Equipment should be located so that no shadows are cast on the reading plane by the head or body, and so that the luminaire does not interfere with a comfortable position.

4. *Typical equipment locations:*

(a) Wall-mounted directly in back of or to one side of the user (both linear and nonlinear designs)

(b) Luminaire on bedside table or storage headboard

(c) Ceiling-mounted: (1) suspended, adjustable, or stationary; (2) surface-mounted, directional, or nondirectional; (3) recessed, directional, or nondirectional

(d) Luminaire incorporated into furniture design

(e) Track-mounted luminaires: Several types of lighting should be provided in the bedroom to accommodate different functions and moods--relaxing, romantic, and adequate for reading.

Figure 18-11. Reading in a chair

1. *The task:* Typical reading tasks encompass a wide range of seeing difficulty, from short-time casual reading of material with good visibility (large print on white paper) to prolonged reading of poor material (small type on low-contrast paper). The majority of tasks have reflectances between 30 and 70% or higher. Speed and accuracy may not be important for casual reading and may or may not be important for prolonged reading.

2. *Description of the task plane:* The task plane measures 360 mm (14 in.) wide by 310 mm (12 in.) high with the center of the plane approximately 660 mm (26 in.) above the floor. The plane is tilted at 45° from the vertical. The reader's eyes are approximately 1 m (40 in.) above the floor.

3. *Special design considerations:* The normal seated eye level is 0.97 to 1.07 m (38 to 42 in.) above the floor and is a critical consideration when the light source is to be positioned beside the user. The lower edge of the shielding device should not be materially above or below eye height. This prevents discomfort from bright sources in the periphery of the visual field, yet permits adequate distribution of light over the task area. Variations in chair and table heights necessitate selection and placement of equipment to achieve this relationship for each individual case.

4. *Typical equipment locations:*

(a) Table-mounted, floor-mounted, and wall-mounted beside or behind the user

(b) Ceiling-mounted, suspended beside or behind the user

(c) Directional small-area luminaires may be used (wall-, ceiling-, pole-mounted)

(d) Recessed downlight, placed over center of seat cushion (with a sofa, use an adequate number of luminaires to evenly distribute light over the cushions)

(e) Track-mounted luminaires for flexibility

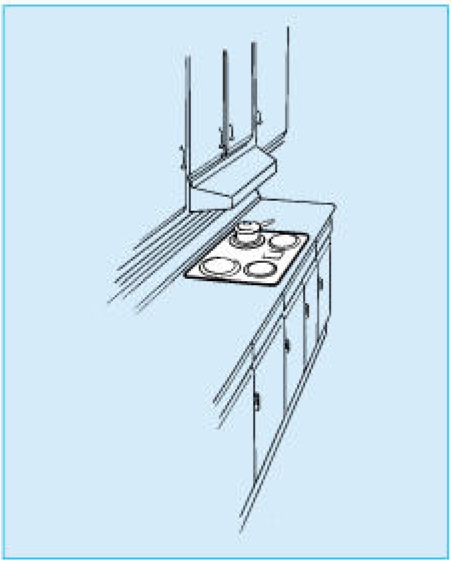


Figure 18-12. Kitchen range or cooktop

1. *The task:* Typical seeing tasks at the kitchen range or cooktop are the determination of the condition of foods in all stages of the cooking process (color and texture evaluation) and reading controls, instructions, and recipes. Food often has a reflectance of less than 30%. Speed and accuracy can be critical for some difficult preparation tasks.

2. *Description of the task plane:* The task area is a range top. Generally this is located 910 mm (36 in.) above the floor.

3. *Special design considerations:* Reflected glare is inherent in the shiny finish of utensils and range tops. Some reduction in the luminance of reflected images may be obtained by the use of diffuse luminaires or sources. Color rendering qualities of light sources are especially important in the kitchen. Controls, such as multiple-position switching and dimming equipment, can be utilized to lower the illuminance when there are no difficult seeing tasks.

Flexible general lighting should be provided for circulation and entertaining. Downlights properly spaced provide good overall illumination. Dimmers allow for adjustment to a range of light levels.

4. *Typical equipment locations:*

(a) Range hood

(b) Ceiling--recessed, surface-mounted, or suspended

(c) Structural--lighted soffits, wall brackets, or canopies

(d) Underside of wall cabinets

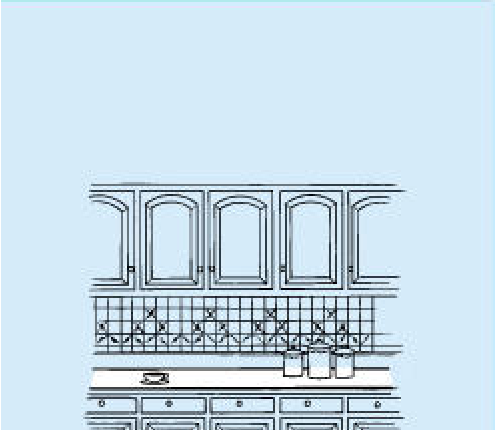


Figure 18-13. Kitchen counter

1. *The task:* Typical seeing tasks at the kitchen counter include reading fine print on packages and cookbooks, handwritten recipes in pencil and ink, and numbers for speeds and temperatures on small appliances. Other tasks include measuring and mixing, color and texture evaluation of foods, safe operation of small appliances, and cleanup. Task reflectances are usually less than 70% and often below 30%. Speed and accuracy may not be important for noncritical tasks, but they are critical for the difficult preparation and cleaning tasks.

2. *Description of the task plane:* The task area is a plane 510 mm (20 in.) deep (starting at the front edge of the counter) and as long as the counter.

3. *Special design considerations:* There are many ways to light counter surfaces, however, luminaires are commonly mounted under the wall cabinets, above the counter. These should be well shielded because of the cabinet structure itself, but if not, shielding should be added. Also, care should be exercised to see that the luminance of the luminaires is comfortable to other users of the room, particularly in seated positions. Controls, such as multiple-position switching

and dimming equipment, can be utilized to lower the illuminance when there are no difficult seeing tasks.

Special attention should be paid to task lighting. Make sure surfaces are evenly and properly illuminated with glare-free light to avoid shadows. Luminaires should be placed 25 mm to 50 mm (1 to 2 in.) from the front of the upper edge of cabinets to properly illuminate counter surface.

4. *Typical equipment locations:*

(a) Underside of wall cabinets

(b) Ceiling--recessed, surface-mounted, or pendant

(c) Structural--lighted soffits or wall brackets

(d) Architectural lighting--above suspended cabinets to reflect off ceiling surface

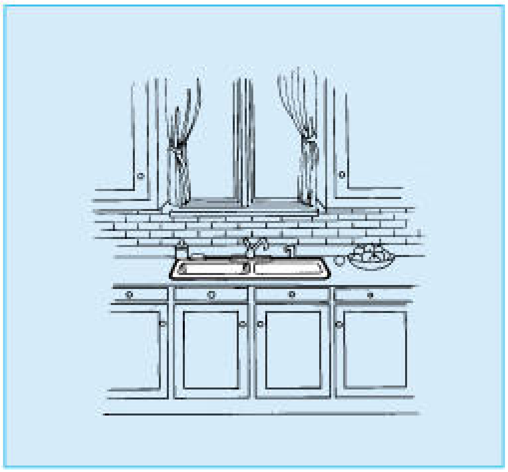


Figure 18-14. Kitchen sink

1. *The task:* Typical seeing tasks at the kitchen sink involve cleaning and inspection of dishes and utensils, evaluation of color and texture of foods in preparation, reading, and measuring. Task reflectances and speed and accuracy needs are similar to those at the counters.

2. *Description of the task plane:* The task area is determined by sink dimensions. It is usually at a height of 910 mm (36 in.) above the floor.

3. *Special design considerations:* Color rendering qualities of the light source are particularly important in kitchen illumination. The limited space available for luminaire mounting at the sink location increases the possibility of shadows being cast on the workplane by the head or body of the user. Controls, such as multiple-position switching and dimming equipment, can be utilized to lower the illuminance when there are no difficult seeing tasks.

4. *Typical equipment locations:*

(a) Ceiling--recessed, surface-mounted, or pendant

(b) Structural--lighted soffits or wall brackets

(c) Underside of wall cabinets

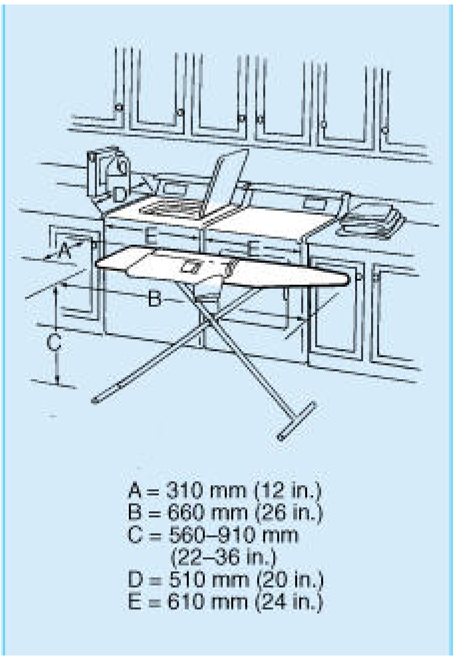


Figure 18-15a. Ironing

1. *The task:* The basic visual task in ironing is the detection and removal of wrinkles from garments and the detection of possible scorches. The majority of fabrics have a reflectance between 30 and 70%, but dark clothes have less than 30%. Speed and accuracy may be important.

2. *Description of the task plane:* The task plane is 310 by 660 mm (12 by 26 in.) and varies in its height, depending on the ironing board. In general, such boards are adjustable from 560 to 910 mm (22 to 36 in.) in height, for use either standing or sitting. The seat of the average stool is located 610 mm (24 in.) above the floor, which places the average seated person's eye level at 1350 mm (53 in.). In a standing position the eye level is 1550 mm (61 in.).

3. *Special design considerations:* A light source with a directional quality may frequently reveal shadows cast by small wrinkles or creases to the advantage of the user. Ironing and television viewing are often done at the same time. Under these circumstances it is important to ensure a good balance among the luminances of task, television screen, and other room surfaces in the line of sight.

4. *Typical equipment locations:*

Ceiling-mounted:

(a) Suspended, adjustable

(b) Fixed, directional

(c) Fixed, nondirectional

(d) Combination of luminaires (general diffusing plus directional component)

Figure 18-15b. Laundry

1. *The task:* In the preparation area, the tasks are sorting of fabrics by color and type, determination of location and type of soil, prewash treatment, tinting, bleaching, and starching. In the tub area, the tasks are soaking, hand washing, tinting, rinsing, bleaching, and starching. In the washer and dryer area, the tasks are loading, setting of dials and controls, and removal of clothes. Speed and accuracy may be important in the preparation and tub areas, but not important at the washer and dryer. Reflectances of fabrics and packaging vary widely but most are within 30 to 70%.

2. *Description of the task planes:* In the preparation area, the general task area is 510 by 610 mm (20 by 24 in.) with a critical seeing area 310 by 310 mm (12 by 12 in.). In the tub area, the task area is 510 by 610 mm (20 by 24 in.) on a single laundry tub, with a critical seeing area 310 by 310 mm (12 by 12 in.) in the middle. The washing machine and dryer area has no definable boundaries and can be illuminated by the general room lighting.

3. *Special design considerations:* Totally direct and not highly diffused light sources can contribute to the visibility of certain laundry tasks. In most laundry locations, task lighting equipment also must provide the general room illumination. Luminaires should in this case be selected and positioned to illuminate the ceiling and side walls for comfortable luminance relationships.

4. *Typical equipment locations:*

(a) Ceiling-mounted (suspended, surface, or recessed) linear or nonlinear luminaires centered over the front edge of the laundry equipment. As above, supplemented by wall-mounted or cabinet-mounted linear luminaires.

(b) Large-area luminous panels

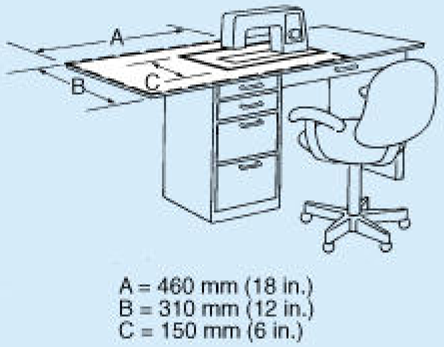


Figure 18-16. Machine sewing

1. *The task:* The small detail and low contrast between thread and material usually involved in machine sewing make it a visually difficult task. The degree of difficulty varies with thread and stitch size, reflectance of materials, and contrast between thread and fabric. Speed and accuracy may be critical.

2. *Description of the task plane:* The primary task area is a plane 150 mm (6 in.) square located so that the needle point is 50 mm (2 in.) forward from the center of the back edge. The secondary task area of less critical seeing measures 310 by 460 mm (12 by 18 in.) with the needle point centered on the shorter dimension and 150 mm (6 in.) in from the right-hand edge.

Maximum illuminance on the primary task plane should not exceed the minimum by more than 3:1. The minimum illuminance level on the secondary task plane should not be less than one-third of the minimum on the primary task plane, and not less than 200 lx (20 fc).

3. *Special design considerations:* Equipment should be located so that shadows are not cast on the task area by the user's hand. The use of light with a moderate directional component increases the visibility of threads by casting a slight shadow to increase contrast.

4. *Typical equipment locations (other than the light built into the machine):*

(a) Wall-mounted directly in front of the user (both linear and nonlinear sources)

(b) Ceiling-mounted (location of luminaire and machine should avoid the possibility of the user's head blocking out light or casting a shadow on the task): (1) suspended, adjustable; (2) fixed, directional (surface or recessed), or track-mounted; (3) fixed, nondirectional; (4) luminous area

(c) Floor-mounted or pole-mounted

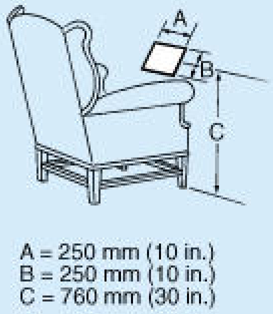


Figure 18-17. Hand sewing

1. *The task:* The seeing task encompasses a wide range of difficulty using coarse to fine threads, light to very dark materials, and high contrast to virtually no contrast at all. Speed and accuracy may be important.

2. *Description of the task plane:* The task area is a plane 250 mm (10 in.) square tilted at 45° toward the eye. The plane is centered at 760 mm (30 in.) from the floor. The eye position is approximately 1000 mm (42 in.) from the floor. Maximum illuminance on the task plane should not exceed the minimum by more than 3:1.

3. *Special design considerations:* Equipment should be located opposite the hand being used, so that shadows are not cast on the task area.

4. *Typical equipment locations:*

(a) Floor-mounted or pole-mounted

(b) Ceiling-mounted: (1) suspended, adjustable; (2) fixed, directional (surface or recessed); (3) fixed, luminous area; (4) combination luminaire (general diffusing plus directional component)

(c) Wall-mounted (both linear and nonlinear) sources located beside or behind the user

Figure 18-18. Music study at piano or organ

1. *The task:* The task is the reading of musical scores, usually 30 to 70% reflectance or higher, ranging from very simple ones with large notes and staff lines to very difficult substandard-size scores with notations printed on the lines. Speed and accuracy may not be important for very simple scores, but they are important for advanced music students and critical for professional musicians.

2. *Description of the task plane:* The primary task plane is on the music rack in an area 310 by 460 mm (12 by 18 in.); it is tilted back from the viewer about 17°. The lower edge is 810 to 890 mm (32 to 35 in.) from the floor. The secondary plane includes an additional 230 by 310 mm (9 by 12 in.) on each side of the primary plane. The piano keyboard, typically 1220 mm (48 in.) long and 710 mm (28 in.) above the floor, is also a secondary plane. Note that these dimensions vary greatly with electric organs and miniature pianos.

3. *Special design considerations:* The maximum task illuminance should not exceed the minimum by more than 3:1. The minimum on the secondary task plane should not be less than one-third the minimum on the primary task plane. The musical instrument is in the best position for control of luminance values if the player faces a wall.

4. *Typical equipment locations:*

(a) Ceiling-mounted or recessed above ceiling:

(1) Directional source:

(i) Should be adjustable to strike the plane of the task at about 90°.

(ii) Should be located above the user's head to avoid a shadow of his or her body.

(iii) Should be located and shielded to prevent glare to other persons occupying or passing through the area.

(iv) Downlights are not desirable; their distribution is inadequate, and reflected glare and veiling reflections may be a problem.

(2) Large-area nondirectional source: The luminance should be within the comfort range and aesthetic considerations of the room.

(b) Mounted on the instrument:

(1) Uniformity of distribution over the task plane may be difficult to achieve.

(2) There should be no luminous part within the user's field of view having a luminance of more than 170 cd/m^2 (16 cd/ft^2.

(c) Pole-type luminaires: Because of the directional quality of this type of light source, it is possible to get acceptable illuminance on the task as well as general surround light. Care should be exercised to avoid glare to other occupants in the room as well as veiling reflections on the task area.

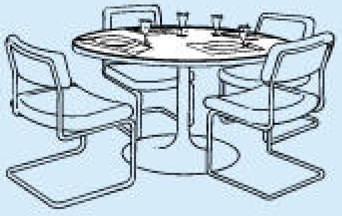


Figure 18-19. Dining area

1. *The task:* The main consideration is to enhance the color and texture of the food while creating a festive mood and providing adequate light levels.

2. *Description of the task plane:* The entire table top should be considered as the task plane. If carving and serving are done at a separate location, this becomes another task area and can generally be equated with the task plane for a kitchen counter.

3. *Controls:* Controls, such as multiposition switching and dimming equipment, can often add to the enjoyment of dining-area lighting by adapting the level of illuminance to the particular occasion. Room surface reflectances influence the selection of the level.

4. *Special design considerations:* Lighting with a strong downward component accents the table setting, creating attractive focal highlights; however, this type of distribution, if used alone, renders faces poorly, causing harsh shadows. Strong downward lights should be kept away from people's faces (that is, confined within the perimeter of the table itself) or should be well balanced by indirect light from table top, walls, or ceiling. The nature of the table top may also influence the choice of lighting distribution: downlighting may cause annoying specular reflections from glossy table tops such as glass or marble; if all the light is directed on the table, a colored tablecloth may appreciably tint the light by reflection. Exposed sources such as unshielded low-wattage bulbs can often be tolerated, especially if some general lighting is provided and the background is not too dark. The darker the walls, the more general lighting is required to keep luminance relationships in the room within a comfortable range. In situations where the dining table is moved from time to time, a flexible means of mounting a pendant luminaire is desirable.

5. *Typical equipment location:*

(a) Task area--center-of-table luminaires:

(1) Recessed (a group of recessed units is generally required)

(2) Surface-mounted

(3) Suspended, generally mounted so that the bottom of the luminaire is 690 to 910 mm (27 to 36 in.) above the table top

(b) Area surrounding the task:

(1) Luminous ceiling or large luminous area

(2) Luminous wall

(3) Cornice

(4) Valance

(5) Cove

(6) Brackets, for example, linear fluorescent or decorative incandescent

(7) Recessed luminaires, for example, incandescent downlights or wall washers

(8) Ceiling-mounted luminaires, for example, shallow large-area types

(9) Suspended luminaires, for example, small pendants

(10) Table lamp

(11) Floor lamp or torchiere

Figure 18-20. Multipurpose table

1. *The task:* The task includes both the creation of the desired mood or atmosphere for dining (Figure 18-19) and provision for other general visual tasks such as sewing, reading, hobbies, and table games. Task reflectances are generally 30 to 70%, and speed and accuracy can be important, particularly when sewing.

2. *Description of the task plane:* The entire table top must be considered as the task plane.

3.*Special design considerations:*

(a) A broad distribution pattern of light is required to illuminate the entire table top uniformly. To minimize veiling reflections, the light sources should have a high degree of diffusion or have substantial direct components.

(b) It is difficult for a single static light source to provide drama and atmosphere for dining while also providing widespread, diffused lighting (at a higher level) for other table activities; therefore, a multipurpose table usually requires more than one lighting system or a means of switching from one effect to another.

4. *Typical equipment locations:*

(a) Task area--center-of-table luminaires:

(1) Recessed (a group of recessed units is generally required)

(2) Surface-mounted

(3) Suspended--generally mounted so that the bottom of the luminaire is 690 to 910 mm (27 to 36 in.) above the table top

(4) Track-mounted luminaires

(b) Area surrounding the task:

(1) Large luminous area

(2) Luminous wall

(3) Cornice

(4) Valance

(5) Cover

(6) Brackets, for example, fluorescent or decorative incandescent

(7) Recessed luminaires, for example, incandescent downlights or wall washers

(8) Ceiling luminaires, for example, shallow large-area types

(9) Track-mounted luminaires

(10) Pendant luminaires, for example, small pendants

(11) Table lamp and floor lamp or torchiere

(12) Chandelier with or without downlight

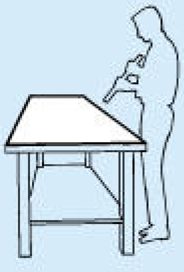


Figure 18-21. Workbench hobbies

1. *The task:* Activities carried on at the workbench include woodworking (sawing, hammering, vise operation, planing, assembling parts, and drilling) and craft hobbies. The majority of task reflectances may be below 30%, and speed and accuracy can be critical for power-tool operation. Hobbies vary greatly in visual difficulty and often require additional illumination and consideration of directional quality. Leather work, ceramic enameling, pottery, mosaics, wood carving, block cutting (linoleum-wood), model assembly, electrical and electronic assembly, and fly tying are considered to be difficult tasks. Metal engraving, embossing, lapidary work (gem polishing), and jewelry making are considered to be critical tasks. Among these, block cutting and jewelry making require large-area low-luminance reflections in order to see fine detail, which shows up as an interruption in a surface sheen. All of these tasks require a lot of light. In addition, good lighting is essential for safety. Care should be taken to avoid glare or shadows.

2. *Description of the task plane:* The task plane area is 510 mm (20 in.) wide, 1220 mm (48 in.) long, and 910 mm (36 in.) above the floor. (Home workbenches vary in length. The task plane extends the full length of the bench.)

3. *Special design considerations:*

Luminance balance within the visual field:

(a) The wall immediately behind the workbench should have a reflectance above 40%. The light reflected is necessary to provide illumination on the task plane as well as eye comfort from the standpoint of luminance differences.

(b) Additional room illumination should be provided to contribute to the luminance balance in the visual surroundings when the worker faces into the room.

(c) If the user is facing a window while working, then daylight should be controlled by blinds or shades, and light-colored window coverings should be used at night. The light source should be so positioned that its image reflected in glossy materials is not visible to the user in normal position, unless desired for some special application.

4. *Typical equipment locations:*

(a) Ceiling-mounted track or suspended linear luminaire running parallel with the task plane

(b) Ceiling-mounted or suspended nonlinear luminaires in a symmetrical arrangement over the work area to provide uniform distribution of light

(c) Wall- or shelf-mounted luminaire or luminaires with adequate shielding directly in front of the user

(d) Luminous ceiling area

(e) Portable equipment to provide added directional lighting for special conditions

Figure 18-22. Table tennis

1. *The task:* These lighting recommendations are for recreational play, where the speed of play is low to moderate and the player's skill is minimal.

2. *Description of the task plane:* In recreational play the task plane area is the 1.5 by 2.7 m (5 by 9 ft) table only.

3. *Special design considerations:* Although the general guides for luminance balance within the

visual field still hold true in table tennis, the background surfaces seen by the player should not be too light, or they will not provide sufficient contrast with the white ball for good visibility. Wall and ceiling surfaces must not have strong, distracting patterns. Spottiness or uneven distribution of light can cause seeing difficulty. In table tennis, since the ceiling plane is the major part of the visual field, the luminance ratios at the ceiling become more important than usual.

4. *Typical equipment locations:*

(a) Ceiling-mounted linear sources with the centerlines of the luminaires crosswise over the table, located approximately 0.3 m (1 ft) in from each end, plus one or more in each runback area

(b) Ceiling-mounted linear sources positioned lengthwise above the table, centered over its outer edges and extending into the runback areas

(c) Ceiling-mounted nonlinear sources arranged in a symmetrical pattern over the entire task area

(d) Large-area luminaires of low luminance symmetrically located to cover the task area, and equipped with louvers or other material providing a minimum of 45° shielding

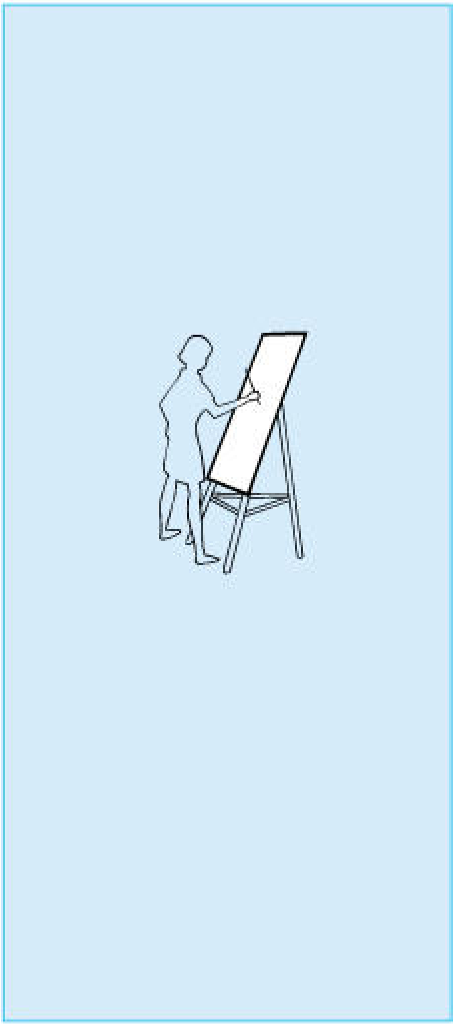


Figure 18-23. Easel hobbies

1. *The task:* Easel hobbies include painting, sketching, and collage. Unlike most tasks, which can be described in relatively exact terms, easel hobbies include widely diverse activities. In many cases the task reflectance can be less than 30%, and speed and accuracy can be important. It is impossible to define a "standard painting." If it is assumed the artist wishes to see small applications of nearly identical colors, a standard task may be described as the application of a spot of color 6.4 mm (0.25 in.) in diameter on a background of the next nearest color in a scale comprising 1800 different colors (Munsell).

2. *Description of the task plane:* The task area is a surface up to 0.9 m (3 ft) square. The plane of the task is inclined from the vertical to suit the user and the task. The average eye height is 1220 mm (48 in.) sitting and 1580 mm (62 in.) standing. There is also a palette and often an object being copied. The locations of these are not fixed.

3. *Special design considerations:*

Luminance balance within the visual field:

(a) The reflectance of wall surfaces should be above 35%.

(b) Additional room illumination should be provided to contribute to the luminance balance in the visual surroundings when the painter looks away from his or her work.

(c) If the artist faces a window while working, the glare should be controlled by blinds or shades, and light-colored window coverings should be used.

(d) The light source should be so positioned that its image reflected in glossy materials is not visible to the artist in normal working position, unless specifically desired. For instance, a large low-luminance reflection may be required in order to see fine detail in a glossy paint surface; the detail shows up as an interruption on a surface sheen. A general recommendation is to paint under the light source by which the painting will ultimately be seen.

4. *Typical equipment locations:*

(a) Ceiling-mounted track or suspended linear luminaires running parallel with the task plane

(b) Ceiling-mounted or suspended nonlinear luminaires in a line to provide uniform distribution of light

(c) Portable equipment to provide added lighting for fine detail

Figure 18-24. This living room features a 25-ft wooden ceiling to which 4-circuit track is mounted on both sides of the beam. All the track heads are positioned at less than a 25 degree aiming angle. The lighting contributes to the feeling of calm, spaciousness, and relaxation.

Figure 18-25. Wall washing adds drama to this elegant foyer.

Figure 18-26. Playing light against darkness can create a striking visual effect.

OTHER INTERIOR LIGHTING DESIGN CONSIDERATIONS

Sparkle, Highlight, and Spatial Effects

In addition to lighting tasks and providing general illumination, lighting can be important in reinforcing spatial perception, activity, and mood. These effects depend on a person's previous experience, perception, attitude, and expectations. Specific impressions include perceptual clarity, spaciousness, relaxation, privacy, and pleasantness.[9] Lighting can set a mood, render people flatteringly, and enhance colors and textures in a space (Figure 18-24). To create these effects, many factors have to be considered. One is the luminance between a highlighted space and its adjacent spaces. The contrast of a brightly lighted area adjacent to a dim area can create a dramatic effect. A minimum ratio of 10:1 is required for dramatic effects and to focus attention.

Wall washing provides smooth, even illumination that emphasizes the vertical plane and minimizes texture (Figure 18-25). When wall washing, the wall should be illuminated as close to ceiling planes as possible. Wall washers should be spaced 600 mm (24 in.) from the wall and 600 mm (24 in.) on center for a recessed adjustable accent or wall-wash downlight. Wall grazing provides drama and accentuates the textures of wall surfaces. Grazing luminaires should be spaced 300 mm (12 in.) from the wall and 300 mm (12 in.) on center. This technique is very effective for brick, marble, and stone.

Sparkle is a small brilliance of light used to add visual interest to objects in a space and to attract attention. Glare results if the area of sparkle is too big, if the source is too bright, or if adjacent reflective surfaces are mirrorlike. The angle, intensity, and shielding of the source must be evaluated to assure visual comfort.

Playing light against darkness can create a striking visual effect within a space (Figure 18-26). The brightness ratios between luminaires and their background are very important. For example, the brightness of a translucent portable luminaire against a dark wall may result in a dramatic effect, but it can cause discomfort if the shade is excessively bright.

Lighting can reinforce spatial perceptions. It can make a space appear larger or smaller.[9] Uniform lighting can make a space seem larger, but at the same time it can make the space seem flat or dull if there are no shadows. In contrast, nonuniform lighting can make a space seem smaller, particularly if walls, ceilings, and corners are dark, and can also create a sense of intimacy. Pretesting spatial effects is always recommended.

Art Created by Light

Light as an art medium is a way to enhance interior spaces. Art can be created by projections onto surfaces or transmission through surfaces of glass, acrylic, or neon and should be designed as part of the overall luminous environment (Figure 18-27). The effect that a luminous piece of art has on the space must be evaluated by the same criteria as other lighting effects, including luminous contrast, glare, and day and nighttime impact.

Figure 18-27. An example of light as an art medium.

Design Effects

The visual effects that can be created with lighting are almost limitless. Some of these possibilities are organized for easy reference in Chapter 10, Quality of the Visual Environment.

LIGHT SOURCES FOR INTERIOR SPACES

The most common electric light sources used in residential interiors are incandescent, tungsten-halogen, linear fluorescent, and compact fluorescent lamps. Tungsten-halogen sources provide whiter light, longer life, and higher efficacy than standard incandescent lamps. Incandescent and tungsten-halogen lamps are available for line voltage as well as low voltage, and are used extensively in portable luminaires, recessed downlights, track lights, wall sconces, and chandeliers.

Fluorescent sources are appropriate for most rooms in a residential space. Even the slender T-5 and T-2 lamps are being used in residential lighting.

T-8 lamps are more energy efficient than T-12 lamps and provide very good color rendering properties. They are available in a variety of lengths and color temperatures. T-12 lamps are still available but are gradually being replaced by the more readily available and efficient T-8 products.

Compact fluorescent lamps offer good color rendering and an energy-efficient alternative to standard incandescent lamps. For best results, luminaires designed specifically for compact fluorescent lamps should be used.

When choosing luminaires for a room, the designer should select more than one light source (layering the light) to create interest and to define a particular object, wall, or painting. A variety of light sources allows the designer to create a mood, enhance a focal point, and create a warmer, friendlier place for living and entertaining.[10]

See Chapter 6, Light Sources, for further information on incandescent, tungsten-halogen, linear fluorescent, and compact fluorescent sources.

Retrofitting

Compact, self-ballasted screwbase fluorescent lamps are commonly used to replace standard incandescent A-type lamps. These lamps can reduce energy consumption. They may not fit in existing luminaires, and the light may not be distributed properly when using a luminaire intended for an incandescent source. Typical applications are downlighting, wall sconces, and portable luminaires. Compact fluorescent lamps often require a special harp or extender for portable table or floor lamps. In downlighting luminaires and wall sconces, the dimension of the luminaire must also be checked to assure proper fit. The operating temperature may cause the lumen output to be lower than expected. The color appearance of compact fluorescent lamps differs slightly from incandescent sources. Fluorescent retrofit kits for downlights, available from luminaire manufacturers, include ballast, cone, lamp, and trim. Some "energy saver" incandescent lamps reduce the wattage while producing nearly the same light output as their equivalent incandescent lamps.

LUMINAIRES FOR INTERIOR SPACES

Luminaires for interior living spaces range from portable luminaires to custom-made architectural lighting. Luminaires are categorized by their different light distributions by CIE designation as to the type of luminaire used (direct, indirect, or general diffuse). The choice depends on structural conditions, aesthetics, and economics. To select lighting equipment wisely, the designer should interpret manufacturers' literature, photometric data, and charts for estimating illuminance.

Several types of luminaires are used in residences. A discussion of their types and applications can be found in Chapter 7, Luminaires.

In typical residential applications, the average luminance of the luminaire that provides general illuminance to the space should not exceed 1700 cd/m^2, except in utility areas. For equipment used in utility spaces, luminances as high as 2700 cd/m^2 are acceptable. Within the diffusing element, the luminance of the brightest 645 mm^2 (1 in.^{2}) area should not exceed twice the average luminance of the overall element. Luminance ratios between the luminaire and the ceiling should not exceed 20:1. Even with the best diffusing glass or plastic, spottiness occurs if the lamps are widely spaced or too close to the diffuser.

When selecting interior luminaires, the designer needs to consider appearance, efficiency, and the luminaire's ability to properly distribute light. Color rendering ability, color temperature, energy use, detailing, durability, finish, cost, and ease of maintenance are important considerations when choosing light sources.

EXTERIOR LIGHTING

Exterior residential lighting includes functional and aesthetic lighting that can add charm, appeal, and value to a home. Light at the door, in the landscape areas, and for plantings, providing focal points for sculptures, water features, and specimen trees, as well as for steps and walks, can heighten the appearance of the residence and contribute to its safety (see Chapter 21, Exterior Lighting). Lighting front yards and structures should be given as much attention as the backyard and family activity areas.

Purpose

Residential landscape lighting serves several purposes. It provides safety, security, and aesthetics for both the family and guests. Each of these three issues addresses specific needs, and all can be integrated into a cohesive, pleasing lighting composition. Safety lighting addresses the visibility of potential obstacles in the landscape such as the edges of pools, changes in elevation such as stairs and terraces, and other objects, whether permanent features of the landscape or household items left outside (Figure 18-28). Security lighting allows people to feel comfortable. The main purposes of night lighting are aesthetic, to accentuate the features of the landscape and to expand the hours of enjoyment of residential property. A lighting composition integrating safety, security, and aesthetics allows the option of having several lighting schemes within the overall composition through the inclusion of multiple control options.

Figure 18-28. Swimming pool lighting must illuminate potential obstacles such as the edge of the pool, stairs, and landscape features such as fountains and brick terracing.

Exterior lighting addresses specific needs and uses, including welcoming people to a residence with walkway and entry lighting, providing views from the interior to the exterior (and vice versa), and allowing nighttime activities. The overall effect may be subdued, stimulating, or dramatic, depending on the design and application of light.

Guiding Principles

Lighting ideas develop from an evaluation of the daytime landscape composition and the elements within the landscape. Nonuniform lighting provides the most interesting visual composition. The designer needs to assess the visual importance of all the elements and assign a nighttime role to each element in the composition. This process establishes a hierarchy of luminance values to create order and cohesion in the nighttime scene.

Concept development must consider the following:

- The users' preferences and feelings about light
- The atmosphere they would like to create in the landscape
- The uses they intend for the space
- The condition of their eyes

While visual task needs such as food preparation, dining, and sports need to be considered, the view through windows, in many cases, has greater significance.

In many locations, landscape areas cannot be used during much of the year due to weather restrictions (snow, low temperatures, wind, and rain). However, a view of the landscape can be retained at night by balancing luminances on both sides of the windows to eliminate reflections that make them appear as black mirrors. Landscape lighting can serve as an extension of the interior lighting, expanding the apparent visual size of the interior space. To achieve this, luminances need to be balanced according to the direction of view. In most cases, the primary view is from interior to exterior, requiring the landscape lighting levels to match or exceed those of the interior. When the primary view is from the landscape into the interior, the interior lighting levels need to be higher. When the two directions of view are equally important, the lighting levels on the two sides of the window need to be nearly equal.

To create the desired composition, the designer must know the layout of pavement, plant materials, and features in the landscape. Knowing the reflectances of all elements in the landscape to be lighted is important. The lighting effects evolve from the reflection of light off the elements in the landscape. The importance of an object in the landscape depends on the contrast of brightness between it and the other elements in the composition. Contrast is the most important element in landscape lighting, because it directs where and how people see the features of the landscape.

Elements that serve as primary focal points can be as much as ten times brighter than the general grounds, and three to five times brighter than secondary focal points. To achieve these ratios, higher illuminance may be required on background elements that have lower reflectances than focal points. Providing fill lighting between focal points is critical to creating cohesion. The actual level of light required depends on the ambient level of the surroundings. Residential neighborhoods in downtown sections of cities tend to have higher street lighting levels than suburban and rural areas. In these areas, the exterior lighting levels can be higher without creating visual disturbance in the neighborhood.

Locating and aiming the lighting equipment should be done in such a way as to avoid creating glare in the landscape area or in surrounding properties. Generally, luminaires should not be aimed more than 35° off axis. This applies to both uplight luminaires and downlight luminaires. Further, shielding of the light source should be provided by recessing the lamp into the luminaire housing and using a glare shield.

Techniques

Consider the texture, form, line, reflectance, and relationship to the background of all objects to be lighted in the landscape. Head-on floodlighting tends to make objects appear flat; modeling is obtained by lighting from one or more sides with either equal or unequal illuminance levels. Light striking a surface at a near-grazing angle emphasizes texture. Lighting a surface behind the object accentuates form. The last technique works best when objects have strong shapes and the detail and color are not important.

Walkways. Providing a clear view of walkways constitutes an important aspect of all landscape lighting. Walkway lighting works best when the lighting is as even as possible. For example, luminaires should be placed on one side of the walk, rather than alternating sides along its length.

One option for path lighting is the use of decorative path lights. In selecting luminaires use caution to shield direct view of and brightness from the light source. Luminaires with optical systems that direct light to the path provide good task lighting and do not create distracting brightness or glare in the overall lighting composition. Adjustable accent luminaires either in trees or on a structure such as a roof overhang, a side of a wall, or a trellis to downlight a path can accentuate the landscape and light the path at the same time (Figure 18-29). This technique provides visual interest and increases psychological comfort by identifying the boundaries of the walk.

Figure 18-29. Low-voltage luminaires, mounted on stakes, uplight the structure (trellis) and the roses. MR-16 lamps are used as the light source.

Entrances. Light is needed at doorways to help guests identify the entrance, for safety of passage, and for identifying callers. Lighting the doorway surface provides a visual destination for guests and lights their faces for identification. The designer should also be aware of the attraction of some insect species to certain light sources (see Chapter 5, Nonvisual Effects of Optical Radiation).

The foyer is where your first impression is created and where important transitions take place between public and private areas of the home and between the outdoors and indoors. The lighting in this area is important because one must be able to comfortably adapt from one environment to another. This area should maintain a fairly high light level for safety as well as for grooming purposes. Downlights are appropriate for overall ambient lighting and for lighting stairs. Wall sconces or portable table-top luminaires, placed on the sides of a mirror, add a decorative touch and are suitable for checking one's appearance.

Steps and Staircases. To provide for safe movement in a landscape, all changes in elevation must be lighted. The light on stairs must differentiate between risers and treads. As with pathway lighting, even illumination along the length of the staircase provides the most comfortable effect. Lighting the entire width of the staircase is typically less important; however, it becomes more important as traffic frequency and the occurrence of two-way traffic on the staircase increases.

Buildings and Structures. The residence and any auxiliary structures serve as part of the daytime view of the property and should remain as part of the nighttime composition. The importance of the structure needs to be considered along with the other elements in the composition. Often just a shadow pattern on the wall from an uplighted tree may be enough. In other cases, the architectural shape requires or deserves enhancement. The lighting on buildings should be planned to enhance their appearance. Typically nonuniform lighting enhances the appearance of the building.

Plant Materials. The lighting of plant materials requires more attention than other elements in the landscape. The designer should strive to understand the characteristics of all plants to be used in the landscape, even those that are not lighted. Evaluating the planting plan identifies plants that should be lighted and potential conflicts between plant locations and luminaire locations.[11] The characteristics important to consider include: overall shape and size; growth rate; mature height and width; trunk and branching structure; leaf characteristics, including shape, size, density, translucence, and color; flowering characteristics; and dormancy. These issues affect which plants to light, where to locate luminaires, what type of light source to use, and how to light specific plants (Figure 18-30).[11]

Figure 18-30. Comparison of landscape lighting, same site, for summer and winter. The native willow tree was illuminated with just one eave-mounted luminaire housing a 50-W MR-16 lamp. The difference in depth is due to seasonal conditions and leaf life cycle.

Plants are alive and continually change over time. Lighting plants requires careful planning and flexibility so that changes can be made in the luminaire aiming angle or location, the lamp beam spread or wattage, and the number of luminaires.

The physical characteristics of plants affect the types of lighting. For example, dense evergreen trees or those that produce branches close to the ground, such as junipers, must be lighted with luminaires located away from the tree and aimed towards it. Birches, maples, and other deciduous trees with an open trunk form or translucent leaves glow when lighted from inside the tree canopy. The trunk should have some light on it to tie the tree visually to the ground.

When the tree serves as a focal point, the designer must consider the overall appearance of the lighting on it. To make it appear natural, luminaires must be placed around the canopy to show the overall shape and provide depth. When the tree is seen from limited viewing angles, lighting only one side may be appropriate.

Sculptures. When lighting a sculpture, the designer should consider its size, its physical characteristics, and any special features that might be accentuated (Figure 18-31).[11] When the sculpture represents a life form, such as a human or animal, the sculpture should not be uplighted or downlighted from a grazing angle. This creates unnatural shadows that detract from the appearance. Luminaires should be positioned far enough away from the sculpture to avoid creating exaggerated shadows. Life forms should be lighted from one or more sides, as with theatrical lighting. One-side lighting can enhance movement. Lighting from two sides provides the most natural appearance. See the remarks on three-dimensional objects and outdoor sculpture lighting in the section on Museums in Chapter 14, Lighting for Public Places and Institutions, and in Chapter 21, Exterior Lighting, respectively.

Figure 18-31. The view at the end of a residential hallway, which features the fountain, the sculpture, and the plant material (papyrus). The lighting was accomplished with two surface-mounted underwater luminaires that employ 116-W long-life incandescent A lamps.

Water Features. Lighting of water features such as fountains, pools, waterfalls, and ponds differs from other landscape lighting in that the luminaires used must be rated for submersible use. Lighting water features also requires a greater maintenance commitment than other kinds of landscape lighting. A burned-out lamp can ruin the entire effect. As with any element, the importance of the water feature must be evaluated. Often, water features represent the primary focal point and need to have the highest luminance.

Some physical characteristics of light must be understood in order to provide effective lighting of water features. As light moves from water into air, the angle at which it is traveling changes. This change affects the placement of luminaires for illuminating objects outside the water such as sculptures or plant materials. Light also loses intensity by approximately 10% for every 5 cm (2 in.) of water it travels through.

To make a fall of water visible, the characteristics of the water must be understood. Water falling over a rough surface has air bubbles in it. The bubbles catch light and make the water glow. Therefore, the luminaire needs to be located directly beneath where the falling water hits the surface of the lower water body. When water falls over a smooth edge, there are no air bubbles in it. This application requires luminaire placement in front of the falling water and aimed at it so that light is reflected back.[11]

Water features do not always have to be lighted from beneath the water surface. Downlighting from a tree or nearby structure can be very effective, especially if air bubbles are present. Typically, downlighting does not create as dramatic an effect, but it is less costly and maintenance is easier. Another approach is to use a remote-mounted light source with a collecting lens and fiber-optic cabling to deliver light into the water feature. The benefit of this system is simplified maintenance.

Lighting Equipment

Light Sources. The appropriate lamps to be used in landscape lighting depend on the size of the project, the scale of the feature elements to be lighted, and the desired effects. A white light source normally provides the best effects and creates a natural appearance. Which white light source to select depends on the color and reflectance characteristics of the objects to be lighted. For residential landscapes, standard or low-voltage halogen incandescent sources offer flexibility through a wide selection of low wattages, beam spreads, and dimming capabilities. Sometimes metal halide or mercury vapor sources would be appropriate. On properties with large-scale trees (i.e., tree canopies 30 to 40 ft across, or 40 ft off grade or higher) or on large properties where the goal is to light a group of trees from a distance, higher-wattage lamps might be beneficial and would possibly decrease the number or luminaires required to create the desired effect (Figure 18-32).

Figure 18-32. The front yard of this California residence features illumination of selected redwood trees, pruned up to 100 feet above the ground, to emphasize the detail and texture of the trunks and the spread of the canopy. The impressive, almost spiritual effect is achieved with 90-W quartz PAR-38 spotlights.

Luminaires. The selection of luminaires constitutes perhaps the most important decision in landscape lighting. The daytime appearance of luminaires needs to complement the landscape or disappear from view. All the equipment must be able to stand up to the weather conditions. Rain, snow, fog, temperature variation, and other outdoor conditions encourage corrosion. Lamps should be protected from weather, since even lamps rated as weatherproof may fail sooner if exposed to water.[11]

The construction of luminaires needs to be evaluated. The outdoor environment can damage the appearance and structure of luminaires and cause them to stop functioning. Since the landscape is continually changing due to plant growth, luminaire maintenance and refocusing need to be simple. Lamp access should be easy, requiring no tools and little disturbance of other components.

CONTROLS

Controls should be installed to make a lighting system easy to operate and flexible. A control should be conveniently located at the entry point of every space (both indoors and outdoors) and, ideally, luminaires should be controlled separately or collectively to achieve a desired lighting effect. Well-designed and conveniently located controls save energy by allowing the user to operate only those luminaires necessary to produce the desired effect.

Controls can range from wall-box switches and dimmers, to programmable dimmers that control several scenes, to home automation systems that control other systems (i.e., heat/air, audio/visual) along with the lighting. See Chapter 27, Lighting Controls, for more information.

ENERGY CONSIDERATIONS

Lighting decisions should include energy considerations. The criteria and information in Chapter 26, Energy Management, can be used to develop the most energy-efficient solutions. In new construction, early planning enables the use of energy-efficient techniques. In existing structures, luminaires and light sources previously installed influence how energy efficiency can be achieved. The choices are retrofitting with more efficient sources, modifying the existing lighting systems, or replacing luminaires and controls. In addition, daylight can be used in interior spaces to reduce dependence on electric light whenever it is suitable to the task and to the space.

CODES AND STANDARDS

Several types of codes and approvals affect residential lighting design both indoors and out. They can be federal, state, or locally based. Check with local code enforcement agencies to determine which regulations apply to the area.

Most electrical codes merely set minimum requirements for electrical wiring methods, but others may dictate specific requirements for lighting systems (e.g., lighting systems used in kitchens and storage closets). Additional requirements relate to energy consumption, minimum amount of light, and lamp or luminaire efficiencies.

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19

Industrial Lighting

INDUSTRIAL LIGHTING DESIGN ISSUES

- Color Appearance (and Color Contrast)
- Daylighting Integration and Control
- Direct Glare
- Flicker (and Strobe)
- Illuminance on Task Plane
- Intrinsic Material Characteristics
- Luminances of Room Surfaces
- Modeling of Faces or Objects
- Reflected Glare
- Shadows
- Source/Task/Eye Geometry

Visual tasks have special requirements that must be addressed by providing lighting suitable for the task. These include, among others, material surface characteristics, orientation, and size of the task. Manufacturing, to be successful, is fast-paced and competitive, and therefore speed and accuracy are always considerations. Many manufacturing functions are now controlled to some degree by computers; thus, as with offices, the visual display terminal (VDT) screen must be considered in the lighting design (Figure 19-1). For those who require data on lighting for a specific industry, information on the lighting for these industries can be found in the IESNA publication RP-7-1991, *Recommended Practice for Industrial Lighting*,[1] or earlier editions of this Handbook.

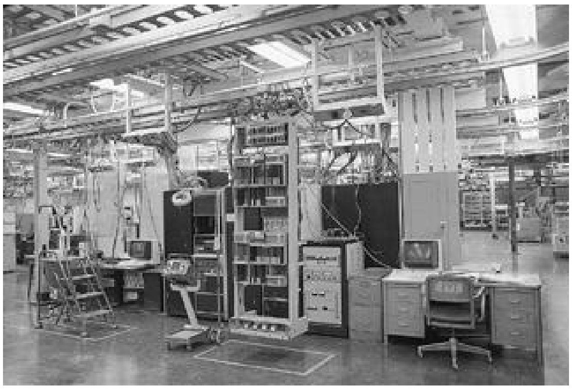


Figure 19-1. VDTs are now commonplace in manufacturing facilities, and proper placement of luminaires improves the visibility of information on the screen. Note the luminaires reflected in the screens of the VDTs in this photo. Consideration should be given to luminaire locations to reduce this effect.

This chapter is intended to provide a means to communicate standards and practices for industrial lighting design in North America. The information herein should be usable for all lighting designers, from novices to seasoned professionals.

This chapter also addresses key industrial lighting design issues such as task visibility, glare, visual comfort, and spatial aesthetics. The reader is directed to Chapter 10, Quality of the Visual Environment, for a listing of the factors affecting lighting design decisions. Topics related to industrial lighting, such as economics, emergency, safety and security lighting, and energy management, can be found in separate chapters of this Handbook.

FACTORS OF GOOD INDUSTRIAL LIGHTING

Industry encompasses a wide range of visual tasks, operating conditions, and economic considerations.[1-3] Visual tasks may be small or large; dark or light; opaque, transparent, or translucent; on specular or diffuse surfaces; positioned in horizontal, vertical, or inclined planes; and involve flat or contoured shapes. In addition, the task may involve movement of the object, the viewer, or both. With each of the various task conditions, the lighting must provide adequate visibility so that materials can be transformed into finished products. Physical hazards exist in manufacturing processes, so lighting is of the utmost importance as a safety factor in preventing accidents. The speed of operations may be such as to allow only minimum time for visual perception, and therefore lighting must be a compensating factor to increase the speed of seeing (see Chapter 3, Vision and Perception).

Quality of Illumination

There are certain quality factors that should be considered when designing a lighting system for an industrial facility. The term "quality" as used here implies that all luminances are designed to contribute favorably to visual performance, visual comfort, ease of seeing, safety, and aesthetics for the specific visual task involved. Glare (direct, reflected, and veiling reflections), diffusion, direction, shadows, uniformity, color, luminance, and luminance ratios all have a significant effect on visibility and the ability to see accurately and quickly. Modeling of the task, material characteristics, and the relationship of the eye to the light source are also important considerations for a high-quality lighting design for an industrial task. Certain visual tasks, such as discernment of fine details, require much more careful analysis and higher-quality illumination than other industrial tasks. Areas where the visual tasks are critical, or where they are performed over long periods of time, require much higher quality lighting than visual tasks that are casual or of relatively short duration. Chapter 10, Quality of the Visual Environment, contains a matrix of issues for industrial lighting. Chapter 3, Vision and Perception, provides guidance for the control of glare.

Poor-quality industrial lighting can be uncomfortable and possibly hazardous. Unfortunately, moderate deficiencies in the lighting are not easy to detect. Even minimal glare, for instance, can result in measurable loss of seeing efficiency and undue fatigue.

Direct Glare. Direct glare is caused by having a light source within the field of view, whether daylight or electric lighting. To reduce direct glare in industrial areas, the following steps can be taken: (1) decrease the luminance of light sources or lighting equipment, or both; (2) reduce the area of high luminance causing the glare condition; (3) increase the angle between the glare source and the line of vision; (4) increase the luminance of the area surrounding the glare source and against which it is seen (Figure 19-2); and (5) place louvers or refractors between the glare source and the line of sight.

Figure 19-2. High-reflectance finish on structural elements increases the luminance surrounding the luminaires and reduces the effect of the luminaire as a "glare" source.

The required luminance control depends on the task, the length of time to perform it, and those factors that contribute to direct glare. In production areas, luminaires within the normal field of view should be shielded to at least 25° from the horizontal, preferably to 45°.

A frequent cause of direct glare is unshaded factory windows, which allow a direct view of the sun, bright portions of the sky, or bright adjacent buildings. Unshaded windows often constitute large areas of very high luminance in the normal field of view and can be very distracting and uncomfortable.

Luminaires that are too bright for their environment can produce discomfort glare, disability glare, or both. The former produces visual discomfort without necessarily interfering with visual performance or visibility. Disability glare reduces both visibility and visual performance and is often accompanied by visual discomfort. While disability glare is not usually considered a problem in interior lighting applications (see Chapter 3, Vision and Perception), in an industrial environment glare can become disabling if it interferes with the vision of the worker and disables adequate seeing.

To reduce direct glare, luminaires should be mounted as far as possible above the normal line of sight. They should be designed to limit both the luminance and the quantity of light emitted in the 45° to 85° zone above nadir, because such light, likely to be well within the field of view, may interfere with seeing. Luminaires with louvers or refractors can also be used to control glare. These precautions may require the use of supplementary task lighting equipment. Discomfort glare, for many years, has been measured in North America by a metric called visual comfort probability, or VCP. Because the principal research for VCP involved luminaires having luminance magnitudes in the range of those produced by fluorescent lamps, the procedure has not been validated for luminaires that are commonly used in a large percentage of industrial lighting applications. In most parts of the world, the preferred metric for measuring glare is the uniform glare rating, or UGR, developed by the CIE. Some technical organizations, consultants, and designers in North America use the UGR in lighting design. The IESNA and other organizations are evaluating the adoption of the UGR as well, but consensus has not been reached. Refer to Chapter 3, Vision and Perception, and Chapter 9, Lighting Calculations, for more on the various glare measurement systems.

Reflected Glare. Reflected glare is caused by the reflection of high-luminance light sources from shiny surfaces. In manufacturing processes this may be a particularly serious problem where critical seeing is involved with very shiny surfaces such as polished or machined metal, vernier scales, and digital displays.

Reflected glare can be minimized or eliminated by using light sources of low luminance or by orienting the work so reflections are not directed in the normal line of vision. It should be noted, however, that it is often desirable to use reflections. Large-area, low-luminance sources can be used for certain specular tasks to accentuate flaws and defects in the finished product. In special cases it is practical to reduce the specular reflection (and the resultant reflected glare) by changing the specularity of the offending surface.

Veiling Reflections. Where the task materials are specular or semi-specular, veiling reflections can reduce, or in some cases increase, task visibility. Source/task/eye geometries should be carefully considered in the design process to ensure high visibility. See Chapter 3, Vision and Perception, for additional information on veiling reflections.

Figure 19-3. Uniform lighting for areas with similar seeing tasks provides a good visual environment and a flexible operation that allows for relocating the task without changing the lighting.

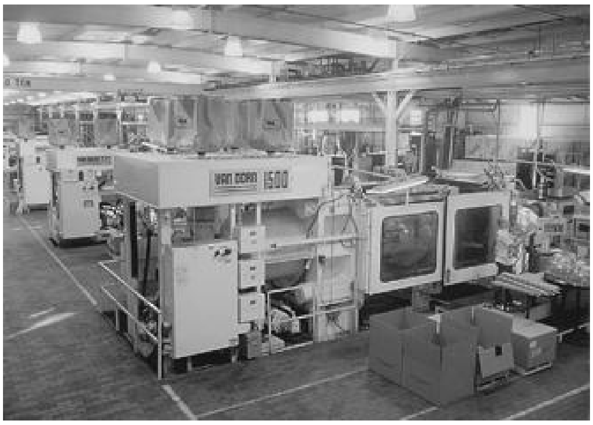


Figure 19-4. Improved vertical illuminance allows the worker a better view of the interior portions of

production equipment and the ability to see finished parts that require inspection in many different planes.

Glare Control. There is such a wide range of industrial tasks and environmental conditions that it is impossible to provide guidelines on a degree of glare control that suits all needs. Chapter 10, Quality of the Visual Environment, particularly the Lighting Design Guide therein dedicated to industrial lighting, identifies the types of tasks for which discomfort glare control is recommended. Glare control is not limited to only those conditions indicated in the Guide. The designer should work closely with the users, management, production personnel, and plant safety departments to determine where additional glare control may be required.

Distribution, Diffusion, and Shadows. Uniform horizontal illuminance (where the maximum level is not more than one-sixth above the average level, and the minimum, not more than one-sixth below) is frequently appropriate for specific industrial interiors where tasks are closely spaced and where there are similar tasks requiring the same amount of light. In such instances, uniformity permits flexibility of functions and equipment and assures more uniform luminances. See Figure 19-3. Neighboring areas with extreme luminance differences are undesirable because continual adaptation to significantly different luminance levels can be tiring to the worker.

Diffuse light, including uplighting, from luminaires with very wide distribution (such as low-bay high intensity discharge (HID) luminaires) can be very beneficial in an industrial environment. The wide distribution can mitigate the effects of lamp outages in a single luminaire and allow production to continue in a normal manner without having to spot replace lamps immediately as they fail. Wide-distribution luminaires also tend to produce a higher level of vertical illuminance (and luminance) than luminaires with narrow distributions, with some sacrifice in horizontal illuminance. This can be a definite advantage where the visual task is in a plane other than horizontal, and it is desirable to increase the vertical component of the lighting for task identification. See Figure 19-4. Care must be exercised, however, to assure that the wider light distribution does not produce discomfort or disability glare beyond the worker's tolerance.

Harsh shadows should be avoided, but some shadow effect may be desirable to accentuate the depth and form of objects. There are a few specific visual tasks where clearly defined shadows improve visibility, and such effects should be provided by supplementary lighting equipment arranged for the particular task. See the section "Supplementary Task Lighting in Industry" later in this chapter, for more details.

Uniformity. Uniform lighting is used more often in industrial lighting than in other applications. While nonuniform lighting can add interest to lighting applications that are of a more aesthetic nature, uniform lighting in industrial applications can provide higher-quality lighting where the task is three-dimensional (e.g., milled material) rather than two-dimensional (e.g., office paper tasks). Uniform lighting allows for repositioning the task locations or production machinery without the need to relocate the lighting. It is particularly useful for high-bay industrial facilities where the cost and inconvenience of moving luminaires located 10 m (30 ft) or more above the factory floor can be substantial (Figure 19-5).

At the same time, there are instances where nonuniform lighting is appropriate. Maintaining uniformity between contiguous areas that have significantly different visibility (and illumination) requirements (for example, a storage area adjacent to a machine shop) wastes energy. In such instances, it is prudent to design and apply nonuniform lighting between those areas. This can be accomplished by using luminaires of different wattages or by adjusting the density of luminaires.

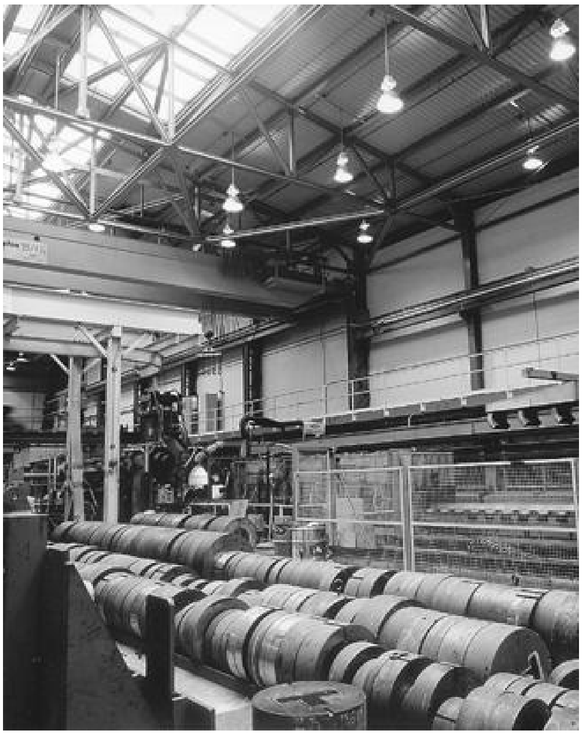
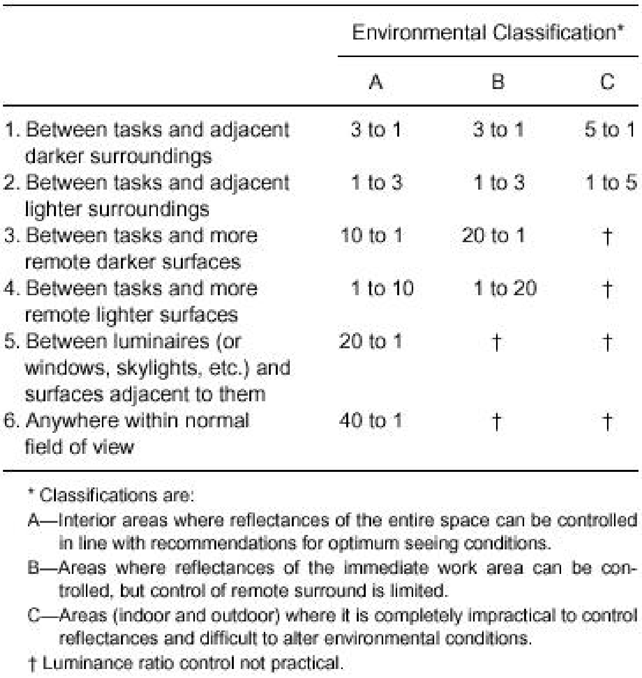


Figure 19-5. Uniform lighting in a location such as this allows flexibility in the use of the space without the expense of relocating luminaires.

Color Quality of Light. For general visual tasks in industrial areas, there appears to be no effect on color perception for "white" light sources of different spectral power distribution (SPD). However, where color discrimination or color matching is a part of the work, such as in the printing industry, the SPD of the light source can be critical and should be selected very carefully.

A color rendering index (CRI) of approximately 65 is adequate for most industrial environments. Higher CRIs are required where color discrimination or color matching takes place. Once a light source has been selected, it is important to use the same source throughout the space or, at least, to maintain the same CRI throughout.

Flicker. The use of magnetic ballasts in lighting systems, with both fluorescent and HID lamps connected to a 60 Hz ac power system, results in lamp flickering at twice the frequency of the power system, or 120 times/second. Some people are conscious of this flickering and find it annoying. Response to flicker includes distraction, eyestrain, nausea, and fatigue. Inspection stations are particularly prone to flicker. One way to eliminate flicker is to use high-frequency (10 to 50 kHz) electronic ballasts, which operate the lamps at frequencies high enough to mitigate the effects of flicker. Another is to circuit lamps on different phases of a three-phase electrical supply.



	Environmental Classification*		
	A	B	C
1. Between tasks and adjacent darker surroundings	3 to 1	3 to 1	5 to 1
2. Between tasks and adjacent lighter surroundings	1 to 3	1 to 3	1 to 5
3. Between tasks and more remote darker surfaces	10 to 1	20 to 1	†
4. Between tasks and more remote lighter surfaces	1 to 10	1 to 20	†
5. Between luminaires (or windows, skylights, etc.) and surfaces adjacent to them	20 to 1	†	†
6. Anywhere within normal field of view	40 to 1	†	†

* Classifications are:

A—Interior areas where reflectances of the entire space can be controlled in line with recommendations for optimum seeing conditions.

B—Areas where reflectances of the immediate work area can be controlled, but control of remote surround is limited.

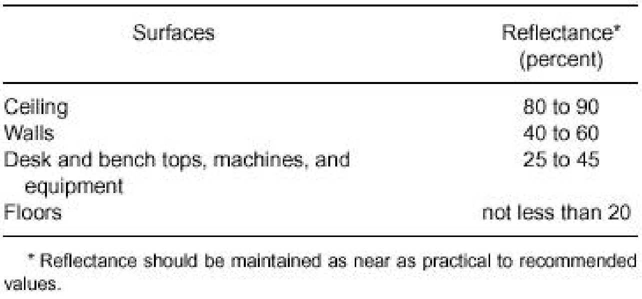
C—Areas (indoor and outdoor) where it is completely impractical to control reflectances and difficult to alter environmental conditions.

† Luminance ratio control not practical.

Figure 19-6. Recommended Maximum Luminance Ratios

Luminance and Luminance Ratios. The ability to see detail depends on the contrast between the item being examined and its background. The greater the contrast, or difference in luminance, the easier it is to see detail. However, the eyes function more comfortably and efficiently when the luminances within the rest of the space are kept uniform; thus, all luminances in the field of view need to be carefully controlled. In manufacturing, it is not practical to achieve the same luminance ratios as can be achieved in offices. Most industrial areas have luminance ratios that lie between the extremes of heavy manufacturing and office spaces. Figure 19-6 is a practical guide to recommended maximum luminance ratios for industrial areas.

To achieve the recommended luminance relationships, the designer must know the reflectances of all the finishes of the room surfaces and equipment and be able to control the illuminance distribution of the lighting equipment. Figure 19-7 lists the recommended reflectance values for industrial interiors and equipment. High-reflectance surfaces are generally desirable to provide the recommended luminance relationships and utilization of light. They also improve the appearance of the work space.



Surfaces	Reflectance* (percent)
Ceiling	80 to 90
Walls	40 to 60
Desk and bench tops, machines, and equipment	25 to 45
Floors	not less than 20

* Reflectance should be maintained as near as practical to recommended values.

Figure 19-7. Recommended Reflectance Values (Applying to Environmental Classifications A and B in Figure 19-6)

In many industries, machines are painted so that they present a completely harmonious environment from the standpoint of color. The background should be slightly darker than the area for the visual task. Stationary and moving parts of machines should be painted with contrasting colors to reduce accident hazards.

Quantity of Illumination

The recommended illuminance for an installation depends primarily on the visual task, the worker, and the importance of the task parameters in performing the work (see Chapter 10, Quality of the Visual Environment).

The illuminance determines the workers' adaptation level in the visual environment. Adaptation level is determined by the workers' visual scene and therefore may be set by the entire room or by the small area where the task is being performed. Hazards such as cranes, fork-lift trucks, conveyors, and rotating machinery should be seen clearly, and therefore they affect the illuminance requirements of an industrial space.

The illuminance for the design can be calculated using the procedures included in Chapter 9, Lighting Calculations, or using a commercially available computer calculations program. (The IESNA, through its *LD+A* magazine, publishes a regular "Software Survey," which lists the features of new software on the market.) It is important that the lamp and luminaire characteristics, light loss factors, and room characteristics be carefully determined to ensure the accurate calculation of illuminance. In locations where dirt accumulates rapidly or adheres readily to luminaire and room surfaces, and where adequate maintenance is not performed to keep lighting systems operating at design levels, allowances must be made for dirt "light loss factors," both for the luminaire and the room, during the design stage. Where workers wear protective eyewear (glasses, goggles, or face shields) with occupationally required tinted lenses that materially reduce the light reaching the eye, the illuminance for the task should be increased accordingly.

General Considerations for Industrial Lighting Design

The designer of an industrial lighting system should consider the following important factors:

- Quality and quantity of illumination suitable for the manufacturing processes involved, as well as the necessary safety requirements.
- Lighting equipment that satisfies the design requirements by considering photometric characteristics as well as the mechanical performance required to meet installation and operating conditions.
- Equipment that is safe, easy, and practical to maintain. Certain lamps may be prone to possible violent end-of-life failures, and they should be used only in properly shielded luminaires. See Chapter 6, Light Sources for more information on these conditions.
- Energy, economic, and operating characteristics of the selected lighting system. All of these factors must be properly weighted prior to finalizing the design.
- Quality, quantity, and safety. All three design issues should be properly weighted and addressed in the design implementation.

Daylighting has not been included in this chapter, but it should be understood that daylighting can provide a viable contribution to the lighted environment during certain hours and should be used where appropriate. Refer to Chapter 8, Daylighting, for information on daylighting design.

Types of Lighting Equipment.

Luminaires control, distribute, and diffuse the light from the lamps and should be designed to minimize glare and shadows. Luminaires are classified according to the way they control the light. Chapter 7, Luminaires, describes how luminaires are used and how their performance is evaluated and provides a general luminaire classification system. Additional information can be obtained from manufacturers.

Figure 19-8. The importance of a white ceiling in an industrial facility is shown in this plant under construction. Note the improved visual environment in the right bay (where the painters have finished the ceiling) compared to that in the left (as yet, unpainted). The illuminance in the right is substantially higher, too.

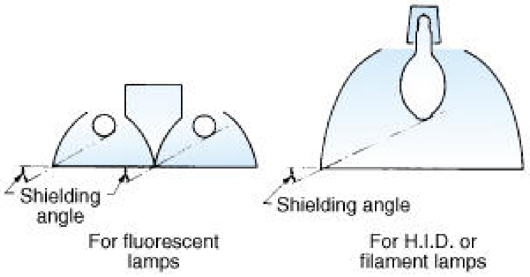


Figure 19-9. Luminaires require adequate shielding for visual comfort. This is particularly important for higher luminance sources. An upward component also contributes to visual comfort by balance of luminances between luminaires and their backgrounds. Top openings help minimize dirt accumulation.

Most industrial applications call for luminaires designed to provide a direct or semi-direct light distribution. Luminaires with an upward component of light, usually 10 to 30%, are preferred for most areas, because providing light on the ceiling or upper structure reduces luminance ratios between luminaires and the background. The upward light reduces the perception of glare from the luminaire, mitigates the "dungeon" effect of totally direct lighting, and creates a more comfortable and more cheerful environment (Figure 19-8). Industrial luminaires for fluorescent, HID, and incandescent lamps are available with upward components (Figure 19-9). Good luminance relationships can be achieved with direct lighting equipment if the illuminances and room surface reflectances are high, and if all components of the space have been carefully positioned.

Factors that lead to more comfortable and effective industrial lighting installations include:

- Light-colored finishes on the outside of luminaires to reduce luminance ratios between the outside of the luminaire and the inner reflecting surface and light source.
- Higher mounting heights to raise luminaires out of the normal field of view.
- Better shielding of the light source by deeper reflectors, cross baffles, louvers, or well-designed diffusers. This is particularly important with high-wattage incandescent or HID sources and very bright fluorescent lamps.
- Selection of luminaires that contain specular or nonspecular aluminum or prismatic configured glass or plastic for light control, so that luminaire luminance in the viewing zone can be limited.
- Top openings in luminaires, which generally minimize dirt collection on the reflector and lamp by allowing convective air circulation to move dirt particles upward, through, and out the luminaire. Ventilated types of luminaires have proven their ability to reduce maintenance of fluorescent, HID, and incandescent types of luminaires. Gasketed dust-tight and dirt- and moisture-resistant luminaires are also effective in minimizing dirt collection on reflector surfaces. Even gasketed luminaires, no matter how effective the gasket seal, have an exchange of air between the ambient environment and the inside of the luminaire. For particularly dirty areas, there are luminaires available that are fitted with various types of filters that allow the luminaire to "breath" and still control the accumulation of dirt and contaminants on the inner surfaces of the luminaire. These luminaires should be carefully evaluated for effectiveness against the contaminated air in the application area in order to justify the added expense of "filtered" luminaires.

Direct Lighting Equipment. Luminaires that direct 90 to 100% of their lumen output downward form a "direct" lighting system. Distributions of direct lighting equipment vary from "widespread" to "highly concentrated" (see Chapter 7, Luminaires). The widespread distribution types include diffuse and diffuse-specular white reflecting surfaces. Aluminum, mirrored glass, prismatic glass, and other similar materials may also be used to provide a wide distribution when the reflector is designed with the proper contour. Also, this type of light distribution is advantageous in industrial applications where mounting heights are relatively low (see Figure 19-10) or where a large proportion of the visual tasks are vertical or nearly vertical. Highly concentrated distributions are obtained with prismatic-glass, mirrored-glass, and aluminum reflectors. In addition, this type of light distribution is useful where the mounting height is approximately equal to, or greater than, the width of the room, or where tall machinery and processing equipment necessitate directional control for efficient illumination between the equipment. This type of distribution produces relatively high horizontal illuminance in proportion to the vertical illuminance, and so may require the use of supplemental lighting when vertical illuminance is required on the visual task.

In making a choice between widespread and highly concentrated distribution equipment on the basis of horizontal illuminances, a comparison of coefficients of utilization and spacing criteria for the actual room conditions involved serves as a guide in selecting the most effective distribution. The coefficients of utilization should be based on the best estimate of the actual ceiling, wall, and floor reflectances as well as actual room proportions. However, if it is desired to determine illuminances at a specific location or task orientation, then a point calculation method should be used (see Chapter 9, Lighting Calculations). This is particularly true for luminaires at high mounting heights.

Figure 19-10. Wide distribution HID luminaires can be effective at low mounting heights if glare is controlled by good luminaire design and light background colors.

Figure 19-11. Semidirect HID luminaires mounted from the roof structure. Uplight improves the visual environment. The bottom of the luminaires is usually located above the bottom chord of the lowest truss.

Other Types of Direct Lighting Equipment. Where a low-brightness luminaire is required, a large-area type of low-luminance luminaire should be used. Such a luminaire can be a diffusing panel placed on a standard type of fluorescent reflector, an indirect light hood, or a completely luminous ceiling.

Semidirect Lighting Equipment. This classification of distribution is useful in industrial areas because the upward component (10 to 40%) is particularly effective in creating more comfortable seeing conditions. A variety of fluorescent and HID luminaires of this distribution is available and designed specifically for industrial applications (Figure 19-11). While the semidirect type of distribution has a sufficient upward component to illuminate the ceiling, the downward component of 60 to 90% of the output contributes to good efficiency, particularly where ceiling obstructions may lessen the effectiveness of the indirect component.

Industrial Applications of Other Distribution Classifications. The general diffuse, semi-indirect, and indirect systems are suitable for industrial applications where a superior quality of diffused, low-luminance illumination is required and where environmental conditions make such systems practical. An example of such an application includes the precision manufacturing industry where a completely controlled environment, including lighting and air conditioning, is important. Room surface reflectances are important in the application of these lighting systems as is the maintenance of the room surfaces to ensure proper illuminance from the system throughout its life.

Building Construction Features that Influence Luminaire Selection and Luminaire Placement. The skeletal framework used in the construction of some types of industrial buildings forms an interior subspace called a bay. The selection and placement of luminaires in a bay may be influenced by the height of the bay. For this reason, the interior spaces in industrial buildings are classified as low-bay or high-bay areas. Low-bay areas are generally considered to be those where the height of the luminaire above the floor is approximately 7.6 m (25 ft) or less (Figure 19-10). In a high-bay area (Figure 19-11), the height of the luminaire is more than 7.6 m (25 ft) above the floor.

Luminaires are usually mounted from the ceiling or from bar joists, beams, or other overhead structural elements in a uniform array called the ceiling plane. The lighting provided by this type of luminaire placement is called general lighting (Figure 19-12). General lighting is intended to provide uniform illumination throughout an area, exclusive of any provision for special local requirements (see the section "Distribution, Diffusion, and Shadows" above). Localized general lighting can be used for areas containing visual tasks that require illuminance values that are higher than the levels provided by general lighting. This additional illuminance can be achieved by increasing the numbers (or rows) of luminaires, the light output per luminaire, or both. For more difficult visual tasks, supplementary task lighting may be required (see the section "Supplementary Task Lighting in Industry" below).

Figure 19-12. Luminaire spacing is influenced by mounting height and structural elements. It is usually desirable to coordinate luminaire location with the structural design to enhance aesthetics.

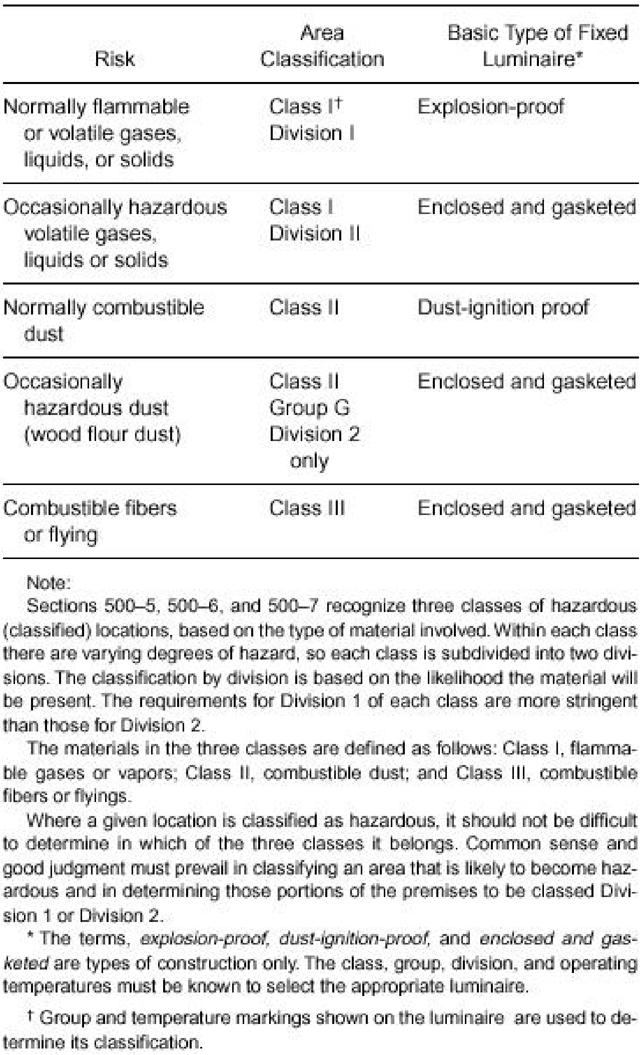
Factors of Special Consideration

Lighting and Space Conditioning. Sometimes lighting, heating, cooling, and atmospheric control are combined in an integrated system. The lighting system may provide a significant amount of the heat energy during winter months. When cooling is required, much of the lighting heat can be removed by the ventilation system. See Chapter 7, Luminaires, for further details on thermal considerations.

High Humidity or Corrosive Atmosphere and Hazardous Location Lighting. Enclosed and gasketed luminaires are used in nonhazardous areas where atmospheres contain nonflammable dusts and vapors. Enclosures protect the interior of the luminaire from conditions prevailing in the area. Steam processing, plating areas, wash and shower rooms, and other areas of unusually high humidity require enclosed and gasketed luminaires. Severe corrosive conditions necessitate knowledge of the atmospheric content to permit selection of proper material for the luminaires. Enclosed and gasketed luminaires are also required in food preparation areas of manufacturing plants, in dairy and ice cream plants, and food processing plants to permit the hosing-down of the areas for cleaning and sanitary reasons. See the section "Corrosive Area Lighting" later in this chapter.

Hazardous locations are areas where atmospheres contain flammable dusts, vapors, or gases in explosive concentrations.

They are grouped by the National Electrical Code (NEC) on the basis of their hazardous characteristics, and all electrical equipment must be tested and listed (or approved) for use in areas of specific classes and groups. Luminaires are available that are specifically designed to operate in these areas, which are noted in Article 500 of the NEC as Class I, Class II, and Class III locations (divisions). See Figure 19-13 and the section "Classified Areas" later in this chapter. For definitions of luminaires used in these areas, such as explosion-proof, dust-tight, dust-proof, and vapor-tight, see the Glossary in this Handbook.



Risk	Area Classification	Basic Type of Fixed Luminaire[*]
Normally flammable or volatile gases, liquids, or solids	Class I[†] Division I	Explosion-proof
Occasionally hazardous volatile gases, liquids or solids	Class I Division II	Enclosed and gasketed
Normally combustible dust	Class II	Dust-ignition proof
Occasionally hazardous dust (wood flour dust)	Class II Group G Division 2 only	Enclosed and gasketed
Combustible fibers or flying	Class III	Enclosed and gasketed

Note:

Sections 500–5, 500–6, and 500–7 recognize three classes of hazardous (classified) locations, based on the type of material involved. Within each class there are varying degrees of hazard, so each class is subdivided into two divisions. The classification by division is based on the likelihood the material will be present. The requirements for Division 1 of each class are more stringent than those for Division 2.

The materials in the three classes are defined as follows: Class I, flammable gases or vapors; Class II, combustible dust; and Class III, combustible fibers or flyings.

Where a given location is classified as hazardous, it should not be difficult to determine in which of the three classes it belongs. Common sense and good judgment must prevail in classifying an area that is likely to become hazardous and in determining those portions of the premises to be classed Division 1 or Division 2.

[*] The terms, *explosion-proof, dust-ignition-proof,* and *enclosed and gasketed* are types of construction only. The class, group, division, and operating temperatures must be known to select the appropriate luminaire.

[†] Group and temperature markings shown on the luminaire are used to determine its classification.

Figure 19-13. Area Classifications (Based on National Electrical Code)

Abnormal Temperature Conditions. Low ambient temperatures exist in unheated heavy industrial plants, frozen food plants, and cold storage warehouses. Equipment has to be selected to operate under these cold conditions, and particular attention should be given to lamp starting and light output characteristics if fluorescent equipment is considered. With HID equipment, temperature variations have practically no effect on light output, but the proper starting conditions must be provided. With incandescent lamp equipment, neither starting nor operation is a problem at low temperatures.

Abnormally high temperatures are common at truss height in foundries, steel mills, and forge shops. Caution should be exercised in selecting lighting equipment for mounting in these locations. It is particularly important to consider the temperature limitations of fluorescent and HID ballasts. Ballasts should be remotely located at a lower and cooler level or located within a cooled enclosure, or special high-temperature equipment should be used. Reduced fluorescent lamp output at high operating temperatures should be recognized. Incandescent lamps operated under high-temperature conditions, as in an oven, may experience a reduction in life. The luminaire chosen should be designed to withstand the ambient temperature conditions of its surroundings at the intended mounting height (see Chapter 7, Luminaires).

Maintenance. Regular cleaning and prompt replacement of failed lamps having the same operating and performance characteristics are essential to maintain the lighting system. The lighting designer should analyze the luminaire construction and reflector finish and also make provisions for maintenance access so that the system can be properly serviced. Sometimes the servicing has to be performed during plant operating hours. Further details on maintenance, access methods, and servicing suggestions are found in Chapter 28, Lighting Maintenance.

SUPPLEMENTARY TASK LIGHTING IN INDUSTRY[4]

Difficult visual tasks, such as inspection, often require a specific quality and quantity of lighting that cannot readily be obtained by general lighting methods. Supplementary luminaires are often used to provide better visibility in small or restricted areas. They can also be used to furnish a certain luminance or color or to permit special aiming or positioning of light sources to produce or avoid highlights or shadows so as to best portray the details of the visual task. See Figure 19-14.

Figure 19-14. Supplementary general lighting with diffusers, permanently installed at a lower level to improve visibility where more demanding visual tasks occur. Note the circular fluorescent magnifying luminaire to aid critical inspection tasks.

Before supplementary task lighting can be specified, the designer must understand the nature of the visual task as well as its light-reflecting or transmitting characteristics. In analyzing the situation, the lighting designer may find that poor visibility is caused by insufficient illuminance or poor contrast (such as veiling reflections). On the other hand, tasks of small size or tasks with too little time provided to accomplish them may not have lighting solutions. Other solutions (e.g., optical magnifiers) may be needed to improve visibility.

Planning for supplementary task lighting also requires consideration of the visual comfort of those performing the task and those who are in the immediate area. Supplementary equipment must be carefully shielded to prevent glare for the user and neighboring workers. Luminance ratios have to be carefully controlled. Ratios between task and immediate surroundings should follow those recommended in Figure 19-6. To attain these limits the supplementary task lighting and the general lighting have to be coordinated.

Luminaires for Supplementary Task Lighting

Supplementary task lighting units can be divided into five major types listed below, according to candlepower distribution, luminance, and other construction features. See Figure 19-15 for a graphic representation of the different types of supplementary lighting.

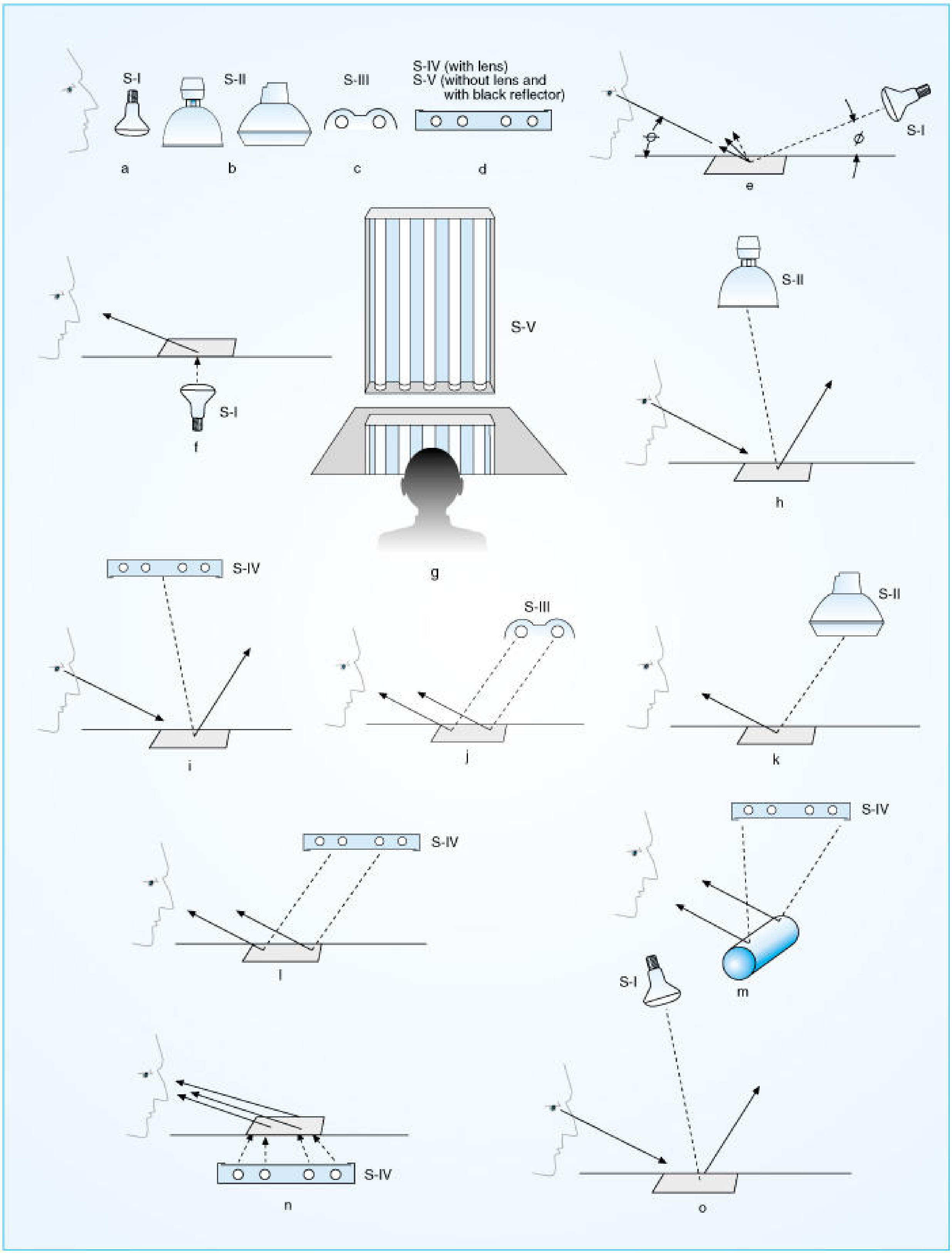


Figure 19-15. Typical configurations of supplementary lighting luminaire types. Refer to Figure 19-17 for luminaire applications.

Type S-I--Directional. Includes all concentrating luminaires. Examples are reflector or narrow- beam spot lamps or units that employ concentrating or collimating reflectors or lenses. Also included in the group are concentrating linear units such as a well-shielded fluorescent lamp within a concentrating reflector or lens, or both.

Type S-II--Spread, High-Luminance. Includes small-area sources, such as incandescent, tungsten-halogen, or HID. An open-bottom luminaire that has a deep-bowl reflector with a diffuse reflecting surface is an example of this type.

Type S-III--Spread, Moderate-Luminance. Includes all fluorescent-lamp luminaires having a variance in luminance greater than 2:1 across the light-emitting surface.

Type S-IV--Uniform-Luminance. Includes all units having less than 2:1 luminance variance across the light-emitting surface. Usually this luminance is less than 6800 cd/m^2. An example of this type is a group of fluorescent lamps behind a diffusing panel, or concealed fluorescent lamps producing a linear arrangement of reflected light on a diffuse reflective surface.

Type S-V--Uniform-Luminance with Pattern. Includes all units described in Type S-IV except that a pattern of stripes is superimposed over the lighted image. An example of this is a group of bare fluorescent lamps, arranged in a regular, directional spacing, with a black background or nonreflective surface between the lamps. This unit is used to project a precise series of high-contrast lines across the surface of the task or the object being inspected.

Portable Luminaires

Wherever possible, supplementary luminaires should be permanently mounted in the location to produce the best lighting effect; adjustable arms and swivels provide flexibility (Figure 19-14). Portable equipment (Figure 19-16), however, can be moved in and around movable machines or objects, as in airplane assembly, in garages, or where internal surfaces must be viewed. The luminaires must be mechanically and electrically rugged to withstand possible rough handling. Lamps should be guarded and of the rough-service type. Guards or other means should protect the user from excessive heat. Precautions such as ground fault circuit protection should be taken to prevent electrical shock, and electrical connections must be suitable for the service to which they will be subjected.

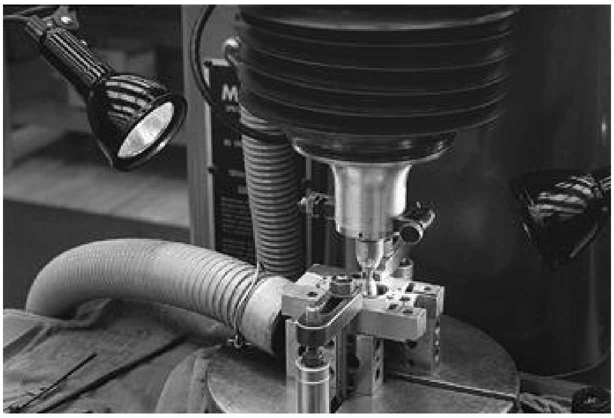


Figure 19-16. Small portable luminaires provide localized lighting on the task.

Classification of Visual Tasks and Lighting Techniques

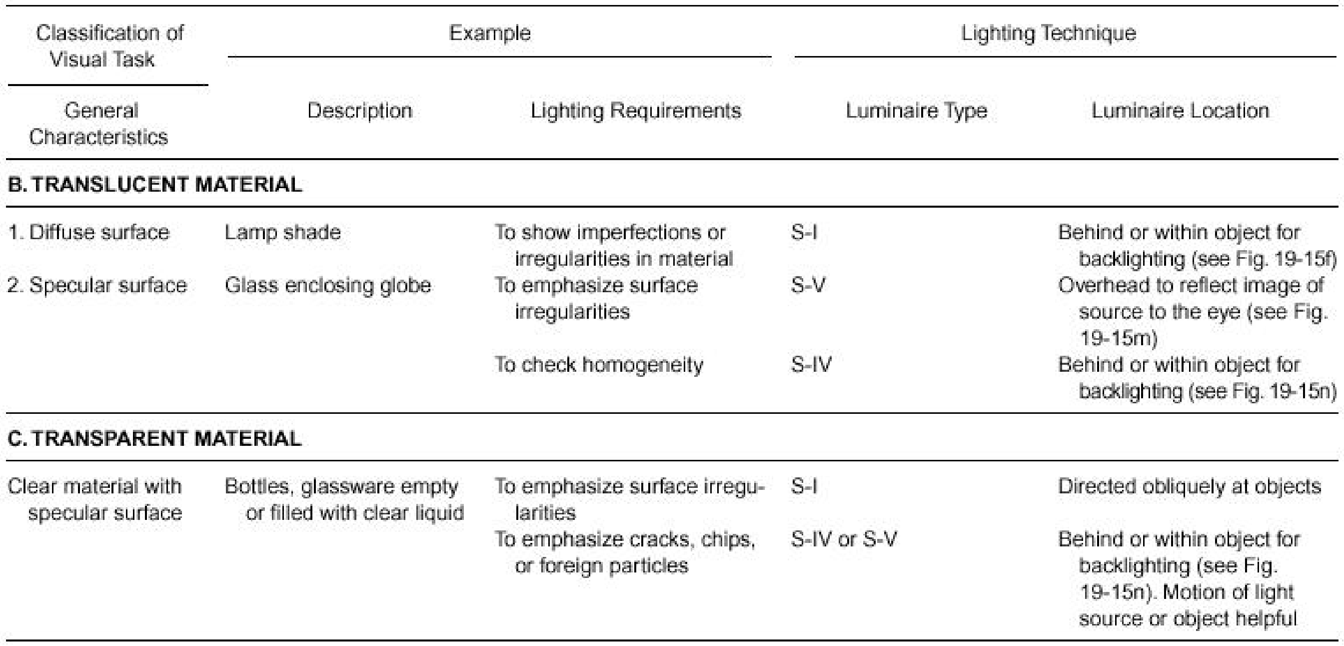
Visual tasks requiring supplementary lighting are unlimited in number but can be classified according to certain common characteristics. The detail to be seen in each task group can be emphasized by an application of certain lighting fundamentals. Figure 19-17 classifies tasks according to their physical and light-controlling characteristics and suggests lighting techniques for good visual perception. It should be noted that when using Figure 19-17 the classification of a visual task is based on the task's characteristics and not on its application. For example, on a drill press the visual task is often the discernment of a punch mark on metal. This could be specular detail with a diffuse, dark background, classification A-3(b) in Figure 19-17. Luminaire types S-II and S-III are recommended. S-II on an adjustable arm bracket may be a practical recommendation where space in limited. Several or all of the luminaire types are applicable for many visual task classifications, and the best luminaire for a particular job depends on physical limitations, possible locations of luminaires, and the size of the task to be illuminated.

Classification of Visual Task	Example		Lighting Technique	
General Characteristics	Description	Lighting Requirements	Luminaire Type	Luminaire Location
PART I—FLAT SURFACES				
A.—OPAQUE MATERIAL				
1. DIFFUSE DETAIL AND BACKGROUND				
a. Unbroken surface	Proofreading printed text	Prevent direct glare and shadows	S-II or S-III	At 45° to page, opposite viewer
b. Broken surface	Scratch on unglazed title	Emphasize surface breaks	S-I	At grazing angle to surface
2. SPECULAR DETAIL AND BACKGROUND				
a. Unbroken surfaces	Dents, warps, uneven surfaces	Emphasize uneven surface	S-V	So image of source/pattern is reflected to viewer
b. Broken surface	Scratch, scribe, engraving, punch marks	Create contrast of cut edge against specular surface	S-III or S-IV when not practical to reorient task	Source/pattern is reflected to viewer and edge or mark is dark
c. Specular coating over specular background	Inspection of finish plating over specular base material	Emphasize unplated surfaces	S-IV with color of source selected to create maximum color contrast between two coatings	To reflect large, diffuse source image toward viewer
3. COMBINED SPECULAR AND DIFFUSE SURFACES				
a. Specular detail on diffuse, light background	Reflective varnish or foil applique on matte paper stock	Produce maximum contrast without veiling reflections	S-III or S-IV	Off-center so image of source does not reflect directly
b. Specular detail on diffuse, dark background	Punch or scribe marks on dull or dyed metal	Create uniform, bright reflection on detail	S-II or S-III	So that light reflects from detail
c. Diffuse detail on specular light background	Graduation marks on a steel scale; reverse print on a glossy stock	Create uniform, low-brightness reflections in specular background	S-III or S-IV	So that image of source is reflected toward viewer
d. Diffuse detail on specular dark background	Soapstone marks on black paint	Produce high-brightness detail against dark background	S-II or S-III	So that image of source is not reflected into view
B. TRANSLUCENT MATERIAL				
a. With diffuse surface	Frosted/etched glass or plastic, lightweight fabrics, hosiery	Visibility of surface detail	S-II or S-III	Treat as opaque, diffuse surface (see A.1)
		Visibility of detail within the material	S-I or S-IV	Backlight through material (see Fig. 19-15f and n)
b. With specular surface	Scratch on opal glass or plastic	Visibility of surface detail		Treat as opaque, specular (see A.2)
		Visibility of detail within the material	S-II, S-III, or S-IV	Backlight through material (see Fig. 19-15f and n)
C. TRANSPARENT MATERIAL				
Clear material with specular surface	Plate glass; plastic glazing sheet	To produce visibility of details within the material, such as bubbles and details on the surface, or scratches and waviness	S-V and S-I	Transparent materials should move in front of Type S-V then in front of black background with Type S-I directed to prevent reflected glare

Figure 19-17. *Continued*

Classification of Visual Task	Example		Lighting Technique	
General Characteristics	Description	Lighting Requirements	Luminaire Type	Luminaire Location
D. TRANSPARENT OVER OPAQUE MATERIAL				
a. Transparent material over diffuse background	Instrument panel	Visibility of pointer and scale without veiling reflections from the scale background or cover	S-I	So reflection of source does not coincide with the angle of view (see Fig 19-15o)
	Varnished desk top	Visibility of detail on or in the transparent coating or on the opaque base material	S-IV	So that image of source and pattern is not reflected to the eye (see Fig. 19-15i)
		Emphasize uneven surface		
b. Transparent material over specular background	Glass mirror	Visibility of detail on or in transparent material	S-I	So reflection of source does not coincide with the angle of view the mirror should reflect a black background
		Visibility of detail on specular background	S-IV	So that image of source and pattern is reflected to the eye (see Fig. 19-15l)
PART II—THREE-DIMENSIONAL OBJECTS				
A. OPAQUE MATERIAL				
1. Diffuse detail and background	Dirt, checking, cold-flow or blow-holes in castings	To emphasize detail having poor contrast	S-III or S-II (standard source)	To prevent direct glare and shadows (see Fig. 19-15h)
			"Black-light" source when object has a fluorescent coating	To direct ultraviolet radiation to all surfaces to be inspected
			S-I (standard source)	To emphasize detail by means of highlight and shadow (see Fig. 19-15o)
2. Specular detail and background				
a. Detail *on* the surface	Dent on silverware or chrome	To emphasize surface variation	S-V	To reflect image of source to eye (see Fig. 19-15g)
	Inspection of finish plating over underplating	To show areas not properly plated	S-V plus proper selection of color	To reflect image of source to eye (see Fig. 19-15g)
b. Detail *in* the surface	Scratch on watch case	To emphasize surface break	S-IV	To reflect image of source to eye (see Fig. 19-15m)
3. Combination Specular and diffuse				
a. Specular detail on diffuse background	Scribe marking on casting	To make line reflect light over dull background	S-III or S-II	Adjust in relation to task for best visibility (adjustable luminaire required) Overhead to reflect image of source to eye (see Fig. 19-15j)
b. Diffuse detail on specular background	Micrometer scale	To create luminous background against which dark scale markings are in high contrast	S-IV or S-III	Position with axis normal to axis of micrometer
	Coal picking	To make coal glitter in contrast to dull impurities	S-I or S-II	To prevent direct glare

Figure 19-17. *Continued*



Classification of Visual Task	Example		Lighting Technique	
General Characteristics	Description	Lighting Requirements	Luminaire Type	Luminaire Location
B. TRANSLUCENT MATERIAL				
1. Diffuse surface	Lamp shade	To show imperfections or irregularities in material	S-I	Behind or within object for backlighting (see Fig. 19-15f)
2. Specular surface	Glass enclosing globe	To emphasize surface irregularities	S-V	Overhead to reflect image of source to the eye (see Fig. 19-15m)
		To check homogeneity	S-IV	Behind or within object for backlighting (see Fig. 19-15n)
C. TRANSPARENT MATERIAL				
Clear material with specular surface	Bottles, glassware empty or filled with clear liquid	To emphasize surface irregularities	S-I	Directed obliquely at objects
		To emphasize cracks, chips, or foreign particles	S-IV or S-V	Behind or within object for backlighting (see Fig. 19-15n). Motion of light source or object helpful

Figure 19-17. Classification of Visual Tasks and Lighting Techniques

Special Effects and Techniques

Color as a part of the visual task can be very effectively used to improve contrast. Certain color combinations are good at drawing attention. Black on yellow is most legible, and the next combinations in order of preference are green on white, red on white, blue on white, white on blue, and finally black on white.

The color of light can be used to increase contrast by either intensifying or subduing certain colors inherent in the visual task. To intensify a color, the light source should provide high spectral power in that region of the spectrum; to subdue a color, the source should have relatively low spectral power in that region. For example, it has been found that imperfections in chromium plating over nickel plating can be emphasized by using a bluish light such as a daylight fluorescent lamp.

Three-dimensional objects are seen in their apparent shapes because of the shadows and highlights resulting from certain directional components of light. This directional effect is particularly useful in emphasizing texture and defects on uneven surfaces (Figure 19-18).

Silhouette is an effective means of checking contour with a standard template. Illumination behind the template shows brightness where there is a difference between the contour of the standard and the object to be checked. Fluorescence under ultraviolet (UV) radiation is often useful in creating contrast. Surface flaws in metal and nonporous plastic and ceramic parts can be detected by the use of fluorescent materials.

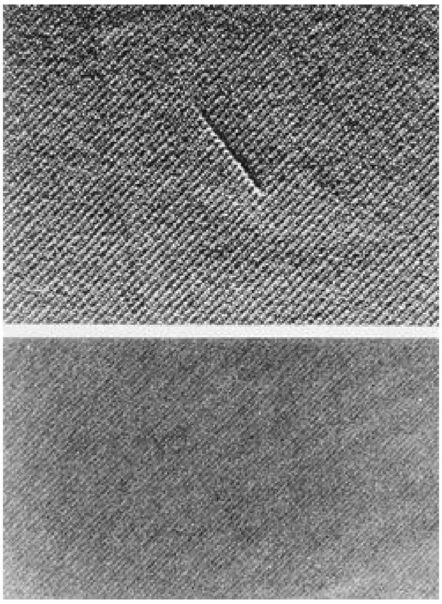


Figure 19-18. Directional lighting (right) reveals a pulled thread unseen by diffuse lighting (left).

The detection of internal strains in glass, mounted lenses, lamp bulbs, and transparent plastics may be facilitated by transmitted polarized light. The nonuniform spectral transmittance of strained areas causes the formation of color fringes that are visible to an inspector. With transparent models of structures and machine parts, it is possible to analyze strains under operating conditions.

Inspection of very small objects may be greatly simplified by viewing them through lenses (Figure 19-14). For production work the magnified image may be projected on a screen. Because the projected silhouette is many times the actual size of the object, any irregular shapes or improper spacings can be detected readily. Similar devices are employed for the inspection of machine parts where accurate dimensions and contours are essential. One typical device now in common use projects an enlarged silhouette of gear teeth on a profile chart. The meshing of these production gears with a perfectly cut standard is examined on the chart.

It is sometimes necessary to inspect and study moving parts while they are operating. This can be done with stroboscopic illumination, which can be adjusted to "stop" or "slow" the motion of constant-speed rotating and reciprocating machinery. Stroboscopic lamps give flashes of light at controllable intervals (frequencies). The flashing can be timed so that, when the flash occurs, an object with rotating or reciprocating motion is always in exactly the same position and appears to remain stationary. It should be noted that the stroboscopic effect produced by fluorescent or HID lamps may be dangerous where there is rotating equipment such as drilling, milling and lathe machines. High-frequency ballasts or three-phase circuitry are common techniques for minimizing the stroboscopic effect.

Figure 19-19. Lamp selection should include consideration of color rendering safety indicators such as exit signs and floor stripping.

Emergency, Safety, and Security Lighting

Each of these subjects is covered at some length in Chapter 29, Emergency, Safety, and Security Lighting. Chapter 10, Quality of the Visual Environment, provides a matrix of design issues for emergency, safety, and security lighting.

Reference to this chapter is recommended for further details on the design and selection of hardware for these very important systems.

Emergency Lighting. Emergency lighting is a very important part of an industrial lighting system. The buildings are usually large, complicated, and subject to materials being moved in and out continuously. In the event of an emergency where normal illumination is lost, a worker could become confused. Emergency lighting requirements are often covered in codes or local ordinances that detail the levels of illuminance required, the duration of the lighting in the event of a loss of power, and the types of power supplies that are acceptable to "the authority having jurisdiction." Reference to these codes and ordinances is essential to ensure compliance with them.

Lighting designers must put themselves in the place of building occupants and mentally walk themselves through the facility to ensure that they have provided lighting for exit and emergency egress that covers all foreseeable conditions. Touring the facility after construction is complete is usually necessary to demonstrate to all parties that the emergency lighting is satisfactory. Additions to the system are often needed to fill in where unexpected pieces of machinery or owner-furnished obstructions have been installed during the project that change the emergency lighting requirements.

Safety Lighting. Unlike emergency lighting, safety lighting is required at all times that the building or outdoor space is occupied in order to ensure that the occupants of the areas can safely move throughout the facility without danger. Safety lighting is particularly important in industrial facilities where there are many obstructions, hazards associated with the manufacturing process, and dangers from moving equipment and manufactured goods. Minimum recommended illuminance levels for safety are indicated in Chapter 29, Emergency, Safety and Security Lighting. These levels should be treated as "minimum" and may require modification in some instances to provide proper visibility in particularly hazardous locations. Care must be taken in the design of industrial lighting systems to ensure that the system provides not only the necessary illuminance for the tasks to be performed, but also adequately indicates dangers and hazards within the facility and is free of glare, shadows, and extreme illuminance changes that can contribute to accidents.

Lamp selection is important in planning lighting for safety so that there is proper rendering of the safety colors used throughout the facility. Many industries use color as an indicator of danger, and selecting a lamp that does not render all of the colors within the facility properly can compromise the identification of these safety indicators by occupants and lead to dangerous conditions. See Figure 19-19.

Security Lighting. Security lighting in an industrial facility is usually required for protection of property. Security lighting should be designed in consultation with the owner and personnel responsible for the safety of property and employees. Consulting with local law enforcement departments can also aid in the design of security lighting systems by ensuring that the lighting system aids, and not hinders, those officers in the performance of their duties. Security lighting methods for interior and exterior installations are discussed at length in Chapter 29, Emergency, Safety, and Security Lighting.

LIGHTING FOR SPECIFIC TASKS

Foundry Mold Rooms and Inspection Areas.[5,6] Metal castings are made in a variety of sizes and shapes, from a few ounces to many tons. Some are made to very close tolerances, while others require less accuracy. The lighting requirements for foundry operations vary with the required accuracy and the importance of the visual task.

Melting, molding, and coremaking usually involve equipment with nonspecular matte surfaces. In high-bay areas, HID luminaires can be installed without introducing reflected glare.

Maintenance can be minimized with ventilated luminaires or enclosed and gasketed luminaires. Some luminaires have filters that permit "breathing" but minimize the ingress of dust. It is prudent to install the fewest number of luminaires that satisfy the recommended lighting design criteria.

Coremaking. Three general methods are used to form sand cores: hand ramming, machine ramming, and blowing. Rammed cores are formed by packing sand in the core boxes by hand or by machine. Core-blowing machines use compressed air to inject the sand into the core box and pack it tightly.

The most critical visual tasks in coremaking are inspecting empty core boxes for foreign material or sand, and inspecting the cores for such defects as missing sand or heavy parting lines. The severity of the visual task varies with the size of the cores and with the degree of tolerance. Coremaking is a rapid and continuous operation that requires almost instantaneous inspection at frequent intervals.

Contrast is fairly good between light sand and metal boxes; it is extremely poor between brown sand and orange shellacked boxes or between black sand and black boxes. Contrast and seeing conditions can be improved by finishing the inner surfaces of wooden boxes with white paint.

Bench tops having a light, natural wood finish are both practical and desirable. They can be kept clean and can provide a comfortable visual environment with low luminance ratios. Benches lighted with apertured industrial fluorescent-lamp luminaires provide good visibility. Centering the luminaires on a line above and parallel to the worker's edge of the bench minimizes reflected glare and shadows.

Molding. The visual tasks in forming molds from treated sand are:

- Inspecting the pattern for foreign material
- Setting the pattern in the flask and packing sand around it
- Removing the pattern and inspecting the mold for loose sand and for accuracy of mold contour
- Inserting core supports and cores (the operator must be able to see the core supports)
- Smoothing mold surfaces, checking core position, and checking clearance between parts

The critical visual tasks are inspecting the mold and placing the cores (and chaplet supports, if employed). The size and detail of the visual tasks may vary. The smallest task has a visual angle of about 10 minutes of arc, corresponding to the size of separate grains of sand. A defect involving the misplacement of only five or six grains of sand causes imperfections in small castings. The more exacting visual tasks are repetitive and of interrupted short-time duration.

Lighting should be designed for the intermittent, critical seeing of materials that have low reflectances and unfavorable contrasts. The varying depths of mold cavities demand adequate vertical illumination that does not produce harsh shadows. Figure 19-20 illustrates an example of good lighting practice for molding machine areas where small castings of 460 mm (18 in.) maximum dimension are made.

Deep pit molds require additional consideration in planning proper lighting. The walls of the pit may block some of the light from the general lighting system and result in shadows and lower luminance, especially on the vertical surfaces of the molds. The pit areas benefit by the installation of additional general-lighting luminaires, located to avoid conflict with materials-handling equipment.

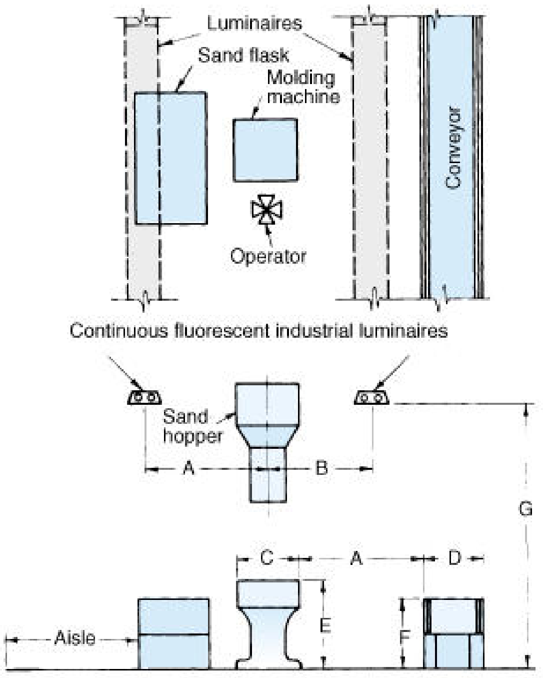


Figure 19-20. Lighting layout for molding machines used for small castings. A = 1070(42), B = 910(36), C = 560(22), D = 510(20), E = 760(30), F = 610(24) and G = 2440 millimeters (96 inches).

To improve visibility within the mold, contrast is sometimes increased by placing white parting sand around the opening. When weights are used, the opening in the weight indicates the general location of the pouring basin.

Supplementary lighting is sometimes recommended for locations where sand is supplied from overhead ducts and conveyors (Figure 19-21); however, it is usually preferable to install a general lighting system that satisfies these requirements.

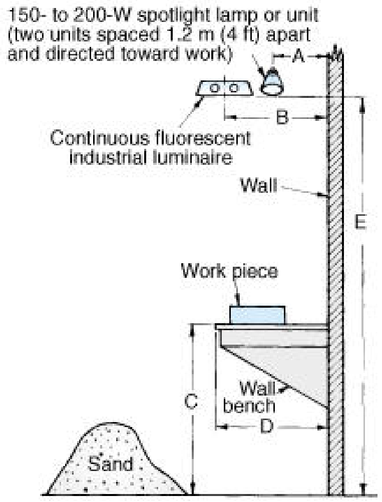


Figure 19-21. A lighting layout for core or bench molding (wall area). A = 300(12), B = <FT56>560(22), C = <FT56> 910(36), D = <FT56>610(24) and E = <FT56>2130 millimeters (84 inches).

Charging Floor. The weighing and handling of metal for charging furnaces is a simple, nonexacting task; thus the design of the lighting should be guided primarily by safety considerations.

Pouring. The most crucial visual task in pouring is that of directing the molten metal into the pouring basin. If the flow is not directed accurately, splashing may occur and cause injury to the workers. It can also displace sand in the mold and spoil the casting.

General illumination contributes to safety. The eyes of the workers become adapted to the bright, molten metal contrasted with dark surroundings. This adaptation may cause difficulty in seeing any obstructions on a poorly illuminated, dark-colored floor. Adequate lighting reveals such obstructions.

Inspection. Quality control depends largely on visibility. A casting meets the specified tolerances when:

- Patterns are carefully checked against the drawings
- Flasks are inspected for fit
- Cores and molds are inspected for size, accuracy, and alignment
- Core clearances are gauged prior to mold closing
- Castings are checked against templates and gauges
- Surfaces are inspected and defective castings are culled

Inspections are generally conducted at intermediate stages during the manufacture of the product. The inspections at some stages are either combined with the functional operation or performed in the same area. The type of inspection dictates the proper quality and quantity of illumination.

A typical inspection is that of cores by the coremaker prior to baking. Later, the castings may be inspected and scrapped as necessary by the shake-out handlers or by the grinder operators, avoiding subsequent waste of labor on defective parts. Small castings are frequently inspected and sorted simultaneously.

In sorting areas, a simple lighting system of ventilated fluorescent-lamp industrial luminaires can be mounted 1.2 m (4 ft) or more above the sorting table or conveyor. Atmospheric and maintenance conditions determine the type of luminaires (open, enclosed, or filtered) to be used.

For medium inspections, fluorescent-lamp luminaires may reduce reflected glare and improve diffusion of light. Medium-fine and fine inspections sometimes require special lighting equipment, such as task lighting.

Parts Manufacturing and Assembly. Common tasks in manufacturing facilities include the manufacture of parts and the joining of those parts into larger subassemblies.

Incoming Raw Materials. Raw materials are delivered to manufacturing facilities by truck or rail shipment. Both open-top and closed-top vehicles may be used. The visual task is to identify the materials and compare the material and shipping documents. General lighting with supplementary lighting for trailer or rail car interiors is required.

Active Storage Areas. Raw materials are often unloaded in the receiving areas by lift trucks or overhead cranes. They are transported to the active storage areas or directly to the production process by the same means. The visual task is to identify the materials (labels or markings) from the cab of an overhead crane or lift truck and to move the materials and deposit them at a designated location. General illumination is required on horizontal and vertical surfaces.

Parts Manufacturing Processes. Several different types and sizes of parts may be manufactured in a single plant using many unique processes. The designer should refer to other sections of this chapter for major activities that occur in manufacturing plants such as machining, sheet metalsmithing, castings, and so on. A number of different tasks may be performed, including machining and metal work. General lighting with properly positioned supplementary lighting in areas or on equipment is required.

Parts Assembly. In many manufacturing plants, individual components are assembled into subassemblies. The assembly processes can combine manual, semiautomatic, and automatic activities. The visual tasks are to select, orient, install, and fasten a component to the subassembly. General lighting with supplementary lighting added to specific work stations is required.

Testing. Highly diversified and complicated procedures and test equipment determine compliance with design specifications for many subassemblies. Testing activities can be manual, semiautomatic, or automatic. The visual tasks are to secure the assembly to the test fixture, to perform tests on electrical or mechanical connections, to run tests and read gauges and meters, to perform mechanical or electrical adjustments as required, to complete test reports, and to disconnect and remove the assembly from the test fixture. General lighting and properly positioned supplementary lighting are required.

Final Inspection. Inspection determines whether the manufactured part or subassembly is in total compliance with the design specifications. The visual tasks are to inspect the part or subassembly for specification compliance and to ensure that all intermediate inspections and tests are satisfactory. General lighting with supplementary lighting to inspect the part or subassembly is required. When required, good color rendering of light sources is important.

Packing. Parts are manually or semiautomatically placed in boxes, containers, or racks for shipment. The visual tasks are to identify the part and place it in a destination-designated shipping container or rack. General area lighting is required.

Shipping. Parts may be shipped to other plants or warehouses in enclosed rail cars and trucks. Lift trucks are generally used to load these vehicles. The visual tasks are to identify a shipping container or rack by part and destination and load it into the designated rail car or truck. General lighting with adjustable or portable supplementary lighting is required to enhance the illuminance within the rail car or truck trailer interior.

Machining Metal Parts. Machining of metal parts consists of the preparation and operation of machines such as lathes, grinders (internal, external, and surface), millers (universal and vertical), shapers, and drill presses; bench work; and inspection of metal surfaces. The precision of such machine operation usually depends on the accuracy of the setup and the careful use of the graduated feed-indicating dials rather than the observation of the cutting tool or its path. The work is usually checked by portable measuring instruments, and only in rare cases is a precision cut made to a scribed line. The fundamental visual task is to discriminate detail on planar or curved metallic surfaces.

Visibility for Specific Visual Tasks

This section describes certain industrial visual tasks as well as techniques for addressing these issues with the lighting system.

Convex Surfaces. Discriminating detail on a convex surface, as in reading a convex scale on a micrometer caliper, is a typical visual task. The reflected image of a large-area low-luminance source on the scale provides excellent contrast between the dark figures and divisions and the bright background without producing reflected glare. The use of a near-point source for such applications results in a narrow, brilliant (glaring) band that obscures the remainder of the scale because of the harsh specular reflection and loss of contrast between the figures or divisions and the background (Figure 19-22).

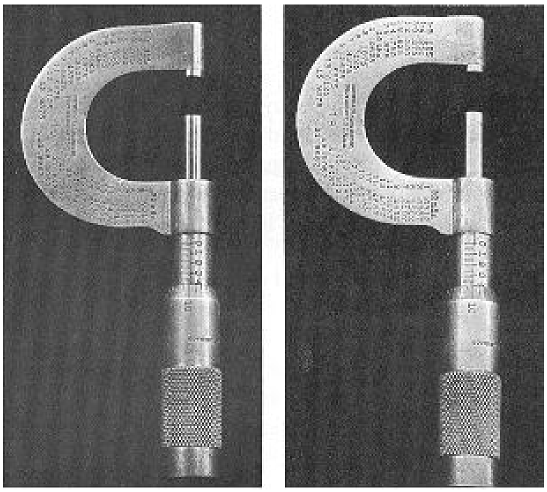


Figure 19-22. (Left) Micrometer illuminated with a system of small, bright sources is seen with bright streak reflections against a dark background. (Right) When illuminated with a large-area, low-luminance source, the micrometer graduations are seen in excellent contrast against a luminous background.

Flat Surfaces. In viewing a flat surface, such as a flat scale, the visual task is similar to that of reading a convex scale. With a flat scale, however, it is possible, depending on the size, location, and shape of the source, to reflect the image of the source either on the entire scale or on only a small part of it. If the reflected image of the source is restricted to too small a part of the scale, the reflection is likely to be glaring.

Scribed Marks. The visibility of scribed marks depends on the characteristics of the surface, the orientation of the scribed mark, and the nature of the light source. Directional light produces good visibility of scribed marks on untreated cold-rolled steel if the marks are oriented for maximum visibility, so that the brightness of the source is reflected from the side of the scribed mark to the observer's eye. Unfortunately, this technique reduces the visibility of other scribed marks. Better results are obtained with a large-area low-luminance source. If the surface to be scribed is treated with a low-reflectance dye, the process of scribing removes the dye and exposes the surface of the metal. Such scribing appears bright against a dark background. The same technique is appropriate for lighting specular or diffuse aluminum. In this case, the scribed marks appear dark against a bright background.

Center-Punch Marks. A visual task quite similar to scribing is that of seeing center-punch marks. Maximum visibility is obtained when the side of the punch opposite to the observer reflects the brightness of a light source. A directional source located between the observer and the task provides excellent results when the light is at an angle of about 45° with the horizontal.

Concave Specular Surfaces. The inspection of concave specular surfaces is difficult because of reflections from surrounding light sources. Large-area, low-luminance sources provide the best visibility.

Lighting for Specific Visual Tasks

In the machining of small metal parts, a low-luminance source of approximately 1700 cd/m^2 is desirable. The size of the source required depends on the shape of the machined surface and the area from which it is desired to reflect the brightness. The techniques applicable to specular reflections can also be applied to semispecular surfaces.

Flat Specular Surfaces. The geometry for determining luminous source size is illustrated in Figure 19-23. First, draw lines from the extremities of the surface that is to reflect the source, to the location of the observer's eye, forming angle α. At the intersections of these lines with the plane of the surface, erect normals to that plane, forming angles β_1 and β_2. Project these lines to the established luminaire location to define the luminaire width; extend them in the opposite direction until they intersect, forming an angle equal to angle α.

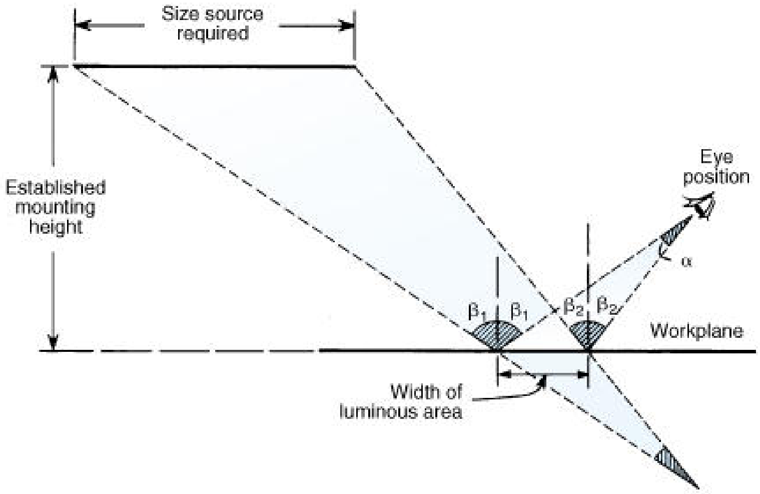


Figure 19-23. Procedure used for establishing the luminaire size necessary to obtain source reflections on a flat specular surface.

Convex Specular Surfaces. The appropriate width of the luminous area of the convex surface is shown in Figure 19-24. Draw lines from the location of the observer's eye to the edges of the surface's luminous area, forming angle α. Erect normals at intersections of lines with the surface.

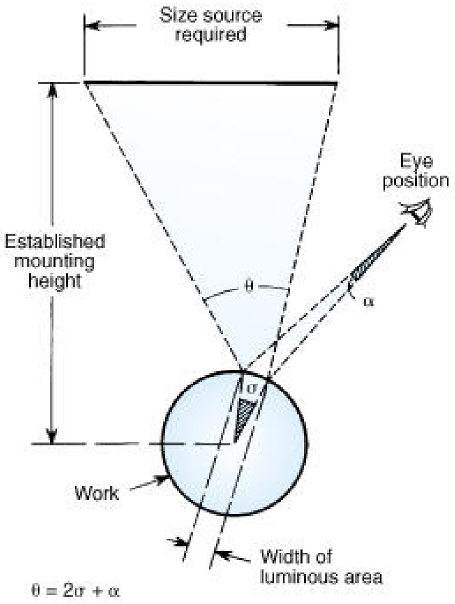


Figure 19-24. Procedure used for establishing the luminaire size necessary to obtain source reflections on a convex specular surface. In the diagram, $\theta = 2\sigma + \alpha$.

At these intersections and on the other side of the normals, construct lines to form angles equal to those to the eye (the same procedure as that for flat surfaces described above). Project lines (as for flat surfaces) to define the luminaire width. The same general procedure can be applied to concave surfaces.

General Lighting. Most of the visual tasks in the machining of metal parts are best lighted by large-area low-luminance sources. The ideal general lighting system would have a large indirect component. While both fluorescent and HID sources can be used for general lighting, fluorescent-lamp luminaires, particularly in a grid pattern, are usually preferred by specifiers for their low mounting heights. High-reflectance room surfaces improve utilization of illumination and thus visual performance.

Sheet Metal Fabrication. Visual tasks in the sheet metal shop are often difficult because sheet metal (after pickling and oiling) has a reflectance similar to the working surface of the machine, resulting in poor contrast between the machine and work. Low reflectance of the metal results in a low task luminance; high-speed operation of small presses reduces the available time for seeing. Bulky machinery obstructs the distribution of light from general-lighting luminaires. Noise contributes to fatigue, which can affect performance of visual tasks.

Punch Press. The visual task is essentially the same for a large press as it is for a small press, except that with a small press less time is available for seeing. The shadow problem, however, is much greater with a large press. With either, the operator must have adequate illumination to move the stock into the press, inspect the die for scrap after the operating cycle is completed, and inspect the product. Where an automatic feed is employed, the speed of operation is so great that the operator only has time to inspect the die for scrap clearance.

The general lighting system in press areas should provide a light level adequate for the safe and rapid handling of stock in the form of unprocessed metal, scrap, or finished products. In large press areas, such as that shown in Figure 19-25, illumination should be furnished by high-bay lighting equipment or by a combination of high-bay and supplementary task lighting. For medium-bay areas such as that shown in Figure 19-26, the illumination should be supplied by luminaires having a widespread distribution to provide uniform illuminance for the bay and the die surface area. Where the mounting height exceeds 6 m (20 ft), careful consideration should be given to maintenance costs.

Figure 19-25. High bay roll storage area lighted with deep reflector, direct luminaires with high efficacy HID lamps having suitable color rendering characteristics. The luminaire row located close to the wall improves luminance on the wall surface.

Figure 19-26. Widespread HID luminaires provide improved vertical luminance on the interior portions of the press to allow the operator to more accurately see the task.

The operator's ability to inspect the die is more directly related to the reflected brightness of the die surface than to the amount of light incident upon it. For example, a concentrated light placed on the operator's side of the press and directed toward the die may produce results much less satisfactory than a large-area source of low luminance placed at the back or side of the press. The luminance required for optimum visibility of the die has not been established; consensus suggests that 1700 cd/m^2 is satisfactory.

Paint applied to both the exterior and the throat surfaces of a press contributes to the operator's ability to see. The reflectance of the paint selected for the exterior of the press should be no less than 40%. This treatment of vertical surfaces on the exterior improves the utilization of light from the general lighting system. Similarly, the paint selected for throat surfaces should have a reflectance of 60% or higher.

Shear. The operator must be able to see a measuring scale in order to set the stops for gauging the size of cut. When a sheet has to be trimmed, either to square the sides or to cut off scrap from the edges, the operator must be able to see the location of the cut in order to minimize scrap. The general lighting system should provide adequate illuminance in the area around the shear for safely feeding the sheets at the front, collecting the scrap at the back, and stacking the finished pieces in preparation for removal.

Local lighting produces a line of light to indicate where the cut will be made and the amount of scrap that will be trimmed. It also provides light to enable the operator, who is responsible for pressing the foot-release bar, to see quickly that all hands are clear of the guard.

Lighting for Large Component Sub- and Final Assembly. This phase of manufacturing has special requirements not usually found in other types of manufacturing. Modern industrial requirements have necessitated the construction of buildings with clear bay areas that can exceed 26,000 m^2 (300,000 ft^2) and truss heights of more than 24 m (80 ft) from floor level (Figure 19-27). The lighting issues in buildings of this size are not limited to engineering systems and design concepts but include maintenance and lamp replacement. Catwalks or traveling-bridge cranes may be appropriate to allow access to the lighting units. In some cases, mobile telescoping cranes can be used to reach luminaires from the floor, but the heights involved and obstructions on the floor can make this method of maintenance impractical. Where access is available from the floor, disconnecting hangers and lowering chains or cables can be an effective method for maintaining luminaires in high-bay areas.

Figure 19-27. Widespread high-bay HID luminaires with uplight provide proper horizontal and vertical illuminance for large parts assembly while lighting the ceiling and walls to improve environmental surroundings.

In high-bay areas the lighting is usually designed for specific task levels, as if the areas were completely open, whereas in reality that is seldom so. The lighting from overhead systems is often reduced by large assemblies or large production equipment. Aircraft and automobile subassemblies or subsystems of these assemblies are typically housed in high-bay areas. Often, supplementary lighting is required in these locations.

Assembly of large aircraft sections, for instance, can present special lighting problems. Exterior lighting for joining together these sections requires both horizontal and vertical illumination as well as lighting installed in such a manner that it lights the underside of the body and wings. Use of floodlights can give both components of light on the exterior body and also provide light to the undersides of the body and wings. Specially mounted luminaires or portable lighting would be required to light areas such as landing-gear pockets.

Control Room. The control room is the nerve center of facilities such as electric generating plants, electric-dispatch facilities, steam- or hot-water generating plants, and chemical plants, and it must be continuously monitored. Its lighting must be designed with special attention to the comfort of the operator: direct and reflected glare and veiling reflections must be minimized, and luminance ratios must be low. Giving operators full control of illuminance levels through the use of multiple switching or dimming systems increases lighting flexibility.

Along with ordinary office-type visual tasks, the operator has to read meters, often 3 to 4.5 m (10 to 15 ft) away. Reflected glare and veiling reflections must be eliminated from meters, including those with curved glass faces.

While the practice is not standardized, most control-room lighting involves one of two general categories: diffuse lighting or directional lighting. Diffuse lighting may be from low-luminance, indirect lighting equipment, solid luminous plastic ceilings, or louvered ceilings (Figure 19-28). Directional lighting may be from recessed troffers that follow the general contour of the control board. (These luminaires must be accurately located to keep reflected light out of the glare zone.) Illumination for the rest of the room may utilize any type of low-luminance general lighting equipment.

Figure 19-28. Control room of a nuclear generating station with a louvered ceiling.

Graphic Arts and Printing. The graphic arts industry is one of the oldest. Its history includes that period when daylighting was the major source of interior illumination. Experience in the industry has shown, however, that a modern, well-designed lighting installation, excluding daylighting, has a beneficial effect on quantity and consistent quality of work.

Receiving Area. The most difficult tasks in this area are those of reading markings on shipments, labels, and bills of lading. General illumination provides sufficient light for these tasks and for the operation of manual or powered forklift trucks, as well as for general traffic in the area.

Supplementary illumination may be necessary for the interior of transport carriers bringing material to the plant. Angle or projector-type luminaires may be used, but care must be taken to avoid glare from these sources. If the conveyances are deep, reel-type or other portable equipment may be necessary. Yard or loading-dock lighting should be installed for night operation.

Stockroom Area. Identification marks on the sides of bulky materials, rolls of paper, and crates or boxes require vertical illumination. Additional illumination should be provided over the aisles where high piles of stock interfere with general lighting. Local building code requirements should be checked as to permissible luminaires for lighting areas where hazardous materials are stored or used.

Copy Preparation Area. Functions preliminary to printing take place here (layout, art, and design), as do decisions about point size and style of type, size and placements of cuts (photos, line drawings, and charts), and size of page. Colors are specified (see the section "Color Appraisal Area" below). Well-diffused, glare-free illumination is essential.

Composing Room Area. Most composition today is done on personal computers with video display terminals (VDTs). See Chapter 11, Office Lighting, for guidance on lighting for VDT screens. Proofreading is also done in this area. Well-shielded diffuse illumination is recommended.

Color Appraisal Area. In 1957, a joint report was prepared by the Illuminating Engineering Society and the Research and Engineering Council of the Graphic Arts Industry[7] to define a standard light source for the color appraisal of reflection-type material. In 1972, a more comprehensive report, incorporating the CIE color rendering system, was issued.[8] It suggests a light source with a correlated color temperature of 5000 K for appraisal of color quality and 7500 K for appraisal of color uniformity. Both sources should have a color rendering index of 90 or higher (Figure 19-29).

Figure 19-29. This console operates the printing press and functions as an inspection station for printed sheets. The inspection task is made easier through the console's dedicated task light with built-in baffles that are designed to shield the light and eliminate glare. High color rendering fluorescent lamps provide the light source.

Plate Preparation Area. The visual task in this area is severe and prolonged. However, the galley (camera) area needs only enough general illumination for traffic. Light source glare must be kept away from the camera lens. Packaged lighting units for photography are usually furnished by the camera supplier.

Stripping and opaquing are done on a luminous-top table. The table design should provide good low-luminance diffusion to assure visual comfort. Any part of the luminous area not covered by the negative should be masked. General overhead, low-level lighting for traffic in this area should be so located as to prevent table-top reflections.

Platemaking requires low levels of illumination. Higher levels are injurious to plates requiring extended processing. Colored lamps are frequently utilized.

Pressroom Area. The pressroom is usually a large high-ceiling area (necessitated by the dimensions of the equipment), which reduces the utilization of light. The tasks can be divided into three groups:

- Tasks with type for make-ready, register, and correction of errors at the press (Figure 19-29). Included are the movement of semifinished products from one part of the press to another, the movement of finished sheets from presses to other departments, and the movement of raw materials to the presses.
- Mechanical functions such as adjusting the presses, installing frames and cylinders on the presses, adjusting ink fountains for the inking rollers, and feeding the paper.
- The inspection of semifinished and finished products. If this involves color appraisal, see the section "Color Appraisal Area" above.

General illumination is recommended, using a luminaire with good shielding and with at least 10% of the light directed upward. Ceiling reflectance should be at least 60%. Supplementary lighting is often required, and the need for it can be determined only by careful examination of the equipment. Low-mounted luminaires, tilted at an angle to penetrate recesses in the presses, may be necessary. Workers in this area need a large-area high-luminance light source. Ink and drying compounds in the atmosphere make frequent maintenance necessary; therefore, ease of maintenance is an important factor in luminaire selection.

Bindery Area. After printing is completed, if binding or any other bindery function is required, the finished product of the printing plant becomes the raw product of the bindery.

Practically all bindery production involves hand labor: collating, folding, stapling, stitching, gluing, backing, and trimming pages. In many operations, critical seeing is not important, but speed is. Diffuse general lighting should be provided by well-shielded luminaires with an upward component. Ceiling reflectance should be at least 60% to make use of this upward component.

In bookbinding, there are frequent additional operations that are more tedious and exacting, such as corner rounding, indexing, cover imprinting, and applying gold leaf or gold ink. Additional luminaires (or closer spacing) are necessary to provide a higher illuminance for these activities.

Corrosive Area Lighting. A variety of corrosive chemicals is generally present in an industrial plant. Further, outdoor plants may be exposed to rain, snow, fog, high humidity, and salt-laden sea air. The usual methods to protect against these elements involve the use of metals that resist attack, special surface preparation, epoxy finishes, polyvinyl chloride coatings, or nonmetallic parts. In addition to these protections, it is common to hose down an area in which corrosive conditions are present. Luminaires should be selected that are protected against the prevalent corrosion and the ambient conditions common to such locations.

Classified Areas. Some areas may be exposed to the release of flammable gases, vapors, or dusts. The National Electrical Code[9] requires that these areas be classified and sets forth rules for the types of luminaires that may be installed. These luminaires must be correct for the class, group, and division of the hazardous material present in the areas where they are to be used. Improper application of a lighting unit can result in fire or explosion and could cause serious injury or death to the occupants. Classification of these areas within a plant must be made prior to selection of equipment. A general classification is shown in Figure 19-13.

General Practice. Once the environmental conditions of classified locations, corrosive vapors, and other ambient atmospheric conditions such as moisture and temperature have been considered, task lighting should follow accepted industrial practice. Industries in which these conditions exist prefer the use of HID lamps for process and other industrial areas. Fluorescent-lamp luminaires are used in control rooms, switch rooms, shops, and administration areas. Luminaires within reach of personnel, or where exposed to breakage, should always be equipped with strong metal guards.

The outdoor process unit, storage areas, loading and unloading areas, and other such areas can be effectively illuminated by combinations of high-wattage floodlights and low-wattage local luminaires (the latter located to reduce shadows). Designers should also investigate the feasibility of floodlighting outdoor classified locations by locating non-explosion-proof floodlights beyond the boundaries of the hazard. The use of exterior floodlighting entails preventing light pollution or spill light that will cause annoyance outside the facility.

Warehouse and Storage Area Lighting. Placing items in storage, accounting for them, and later retrieving them are some of the most common activities requiring electric lighting in industrial facilities. Storage activities are found in business operations of every type, from small local operations to multinational corporations. Since rapid changes are taking place in the business world, the traditional concept of the warehouse must be expanded to encompass new techniques, including automation, high-rise storage, barcoding, cold storage, and shrink-wrap packaging (see Figure 19-30).

Figure 19-30. Even in automated storage areas, proper lighting is required to allow for necessary movement in the area, for required maintenance operations, and to facilitate closed circuit TV (CCTV) where it is included in the system.

Figure 19-31. General lighting systems can be effective in storage areas where no established racks are installed, and materials may be stored on the floor or on stacked pallets.

A variety of specific tasks can occur in a warehouse:

- Open storage. Areas of material stored without the use of rack systems. This includes storage on the floor and on pallets that may be stacked on each other (Figure 19-31).
- High rise. Areas generally automated, where storage bins may be rotated so that unused bins are kept high up, and with storage levels rising to over 30 m (100 ft).
- Offices. Paperwork areas located within warehouses.
- Cold storage. Areas that warehouse normally perishable food items and require low (sometimes below freezing) temperatures.
- Hazardous materials storage. Areas where there are containers of materials with special requirements.
- Exit and emergency. Areas within warehouses that must provide safe exit from the building or that must conform to the Life Safety Code in case of emergency.
- Shipping and receiving. Areas where materials are received into the warehouse for sorting and placement in storage areas. Such areas also serve as staging areas for coordination of products to be sorted and placed on trucks or trains for shipping.
- Loading docks and staging areas. Areas, generally just outside the shipping area, that may be outdoors but are often covered. These areas are used to place items on and off trucks and railroad cars and to assemble goods.
- Maintenance shops, forklift recharging areas, and refrigeration equipment rooms. Locations where general plant housekeeping activities occur. Separate areas or rooms are generally set aside for these purposes.
- Mobile racking. A storage system widely used in North America. Entire blocks of racking move on floor-mounted rails to open and close aisles as needed. In order to obtain maximum use from any lighting provided, the actual visual task should be defined.

The majority of critical visual tasks encountered in the warehouse occur on a vertical plane. Therefore, lighting the vertical surfaces of stored goods is essential in a warehouse. However, adequate horizontal illumination for aisle activities must also be provided. See Figure 19-32.

Figure 19-32. Storage areas must provide good vertical illuminance to facilitate reading labels and adequate horizontal illuminance to allow safe movement and proper location identification.

Adequate illumination should be distributed uniformly over the entire vertical seeing surface from top to bottom and along the entire length of storage aisles. This requires special care when discrete HID luminaires are used because there may be unacceptable drop-off of illuminance between luminaires. Luminaires using HID lamps with distributions designed specifically for storage aisle lighting are available.

Some racks and storage locations may be partly or wholly empty at times, and the darkness of the empty shelves may reduce the illuminance. This effect should be anticipated and included in the design parameters.

Horizontal-plane illuminance must be adequate for safety and navigation, as well as for reading documents. This is not as critical as illuminating vertical task surfaces.

The reflectances of exposed surfaces can significantly affect lighting results. While these reflecting characteristics of stored goods cannot be controlled at the warehouse operating level, they should be considered when cartoning and container decisions are being made. Light-colored packing material can contribute to efficient utilization of available light and increase visibility through greater contrast.

Since storage in fixed-location racking generally results in long narrow aisles, lighting layout and calculation procedures should be based on the dimensions of the aisle space rather then the overall building size parameters. Luminaires should be located over the aisles (generally in the middle), regardless of the overall building configuration. Care must be taken to locate the luminaires so that there is sufficient clearance for removing items from the top of the storage rack, recognizing that these items are often lifted several inches before that are brought into the aisle.

Because of the special geometry of aisle space and because the determination of vertical illuminance is a key task, the standard zonal cavity method of illuminance determination is not useful for warehouse lighting calculations. Fortunately, computer programs for the point-by-point calculation of both horizontal and vertical illuminance are now readily available.

To assure a productive work environment, glare from light sources should be minimized. This becomes particularly important with concentrated HID sources, especially for operators located beneath luminaires while looking at the tops of stacks, since they may encounter disability glare under such conditions. Proper shielding of the source needs to be considered here, as well as viewing along the aisles.

Indirect lighting systems for warehouses, while not as efficient in producing task illuminance, can be useful in providing excellent visibility. They have proven particularly useful in areas with computer terminals and where storage and selling both take place.

Aisles or narrow rooms can be served by HID sources with classical high-bay-type luminaires spaced reasonably close together. The spacing can be increased with luminaires that have a substantial uplight component when the ceilings have high reflectance, with low-bay luminaires, or with special aisle luminaires that have an asymmetric light distribution. At higher mounting heights when the wider spacings are used, sufficient illuminance must still be produced. While HID sources in appropriate luminaires can be used at various mounting heights, they are generally most effective at mounting heights of 5 m (15 ft) or more.

Fluorescent lighting is frequently used for warehouse aisles. While it can be applied at various mounting heights, it is generally most effective in low-mounting-height installations up to about 6 m (20 ft). These designs are implemented either with continuous rows along an aisle (in reflector, lensed, or open strip types) or with individually mounted units.

Since storage spaces may be used intermittently, it is possible to save energy by switching light sources off or operating them at reduced output during inactive times. Multilevel fluorescent and HID lamp ballasts have been developed for this purpose.

Outdoor Tower Platforms, Stairways, and Ladders. Luminaires should provide uniform illumination and be shielded from direct view by persons using these facilities. Enclosed and gasketed or weatherproof luminaires equipped with refractors or clear, gasketed covers may be used for reading gauges. Luminaires above top platforms or ladder tops should be equipped with refractors or reflectors. Reflectors may be omitted on intermediate platforms around towers, so that the sides of the towers receive some illumination and so that the reflected light mitigates deep shadows. If luminaires are attached to equipment, care should be taken in mounting the luminaires to reduce damage from equipment vibration.

Special Equipment. Special lighting equipment may be needed for such functions as illuminating the insides of filters or other equipment whose operation must be inspected through observation ports. If the equipment does not include built-in luminaires, concentrating-type reflector luminaires should be mounted at ports in the equipment housing.

Portable luminaires can be used where access holes are provided for inside cleaning and maintenance of tanks and towers. Explosion-proof types (where hazardous conditions may exist) with 15 m (50 ft) portable cables can be connected to industrial receptacles (either explosion-proof or standard, as may be appropriate for the atmospheric conditions present) located near tower access holes or at other locations.

Outdoor Area Lighting. Two different systems of lighting are commonly used to illuminate large, outdoor areas of industrial facilities: projected (long-throw) lighting and distributed lighting. Each has its advantages under specific situations.

Projected Lighting System. The function of this system is to provide illumination from a minimum of locations throughout the various outdoor work areas (Figure 19-33). Advantages are:

Figure 19-33. High-mast floodlights located to illuminate the dock area while reducing glare for the crane operators and cargo handlers.

- Use of high poles on towers reduces the number of mounting sites.
- The light distribution is flexible. Both general and local lighting are readily achieved. (Aiming of luminaires, however, may be more critical.)
- The luminaires are effective over long ranges.

- Maintenance problems are restricted to a few concentrated areas.
- Physical and visual obstructions are minimized.
- The electrical distribution system serves a small number of concentrated loads.

Distributed Lighting System. Distributed lighting differs from projected lighting in that luminaires are at many locations. Advantages are:

- Good illuminance uniformity on the horizontal plane
- Good utilization of light
- Reduction of undesirable shadows
- Less critical aiming
- Lower mounting heights (floodlight maintenance is facilitated)
- Reduced losses to atmospheric absorption and scattering, as well as reduced light pollution
- The electrical distribution system serves a large number of small distributed loads.

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20

Sports and Recreational Area Lighting

SPORTS AND RECREATIONAL LIGHTING DESIGN ISSUES

- Direct Glare
- Flicker (and Strobe)
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Task Plane (Uniformity)
- Reflected Glare
- Shadows

OVERVIEW[1-7]

Advancements in illuminating engineering design and technology have allowed sporting events to be increasingly played and watched at night. During the last decade, light source efficacies have improved, and therefore the electrical power required for a sports facility has been reduced despite the higher illuminances required.

In addition to higher illuminance, low glare and high uniformity are necessary for good visual performance and high-quality television broadcasting. Lighting design for sports requires sophisticated computations, and therefore designers need a thorough understanding of illuminating engineering principles and associated computer programs. Additional information can be found in the IES Recommended Practice for Sports and Recreational Area Lighting (RP6).[1]

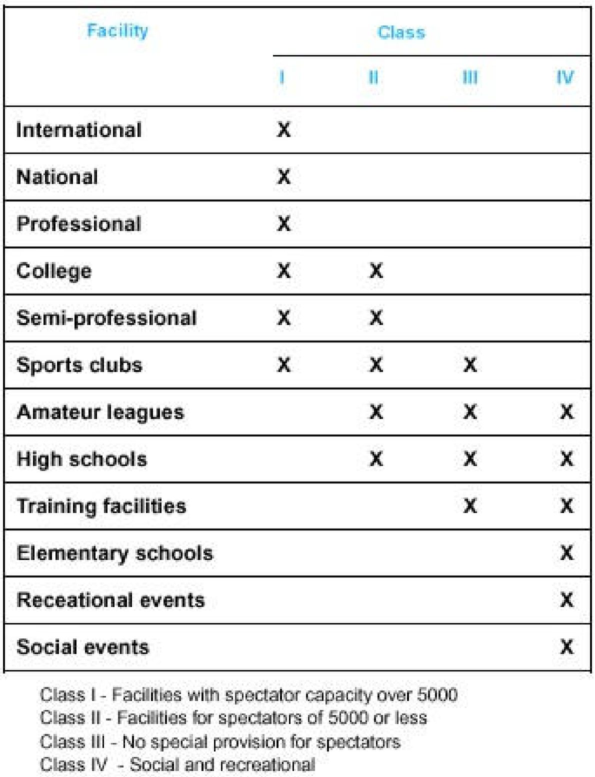
CLASS OF PLAY AND FACILITIES

The traditional way of classifying sports as amateur and professional is no longer meaningful. Modern practices allow both amateurs and professionals to compete in the same events (e.g., golf and tennis). Furthermore, some amateur sports, such as basketball and football, are played at nearly the same skill level and in the same facilities as professional sports.

In general, as the skill level of play is elevated, players and spectators require a better-lighted environment. A correlation exists between the size of a facility and the skill level of play, that is, the number of spectators is directly related to the skill level of play. Accordingly, facilities should be designed to satisfy the highest skill level to be played as well as the greatest spectator capacity. To determine the appropriate illumination criterion, facilities are grouped into four classes:

- Class I. For competition play in large-capacity arenas and stadiums with up to 200,000 spectators. (In this chapter, the recommendations of illumination criteria for individual sports are limited to audiences of 10,000 or fewer. Stadiums with spectator capacity greater than 10,000 generally require considerably higher horizontal and vertical illuminances due to the needs of spectators seated farthest from the playing field and of the camera for television broadcasting. The required illuminances under these circumstances are frequently more than double those recommended in this section.)
- Class II. For competition play with fewer than 5,000 spectators.
- Class III. For competition play primarily for players, though with due consideration for spectators.
- Class IV. For social and recreational play only, with secondary consideration for spectators.

There is, of course, some overlap between illumination criteria for various skill levels of play and facility sizes (Figure 20-1).



Facility	Class I	Class II	Class III	Class IV
International	X			
National	X			
Professional	X			
College	X	X		
Semi-professional	X	X		
Sports clubs	X	X	X	
Amateur leagues		X	X	X
High schools		X	X	X
Training facilities			X	X
Elementary schools				X
Receational events				X
Social events				X

Class I - Facilities with spectator capacity over 5000
Class II - Facilities for spectators of 5000 or less
Class III - No special provision for spectators
Class IV - Social and recreational

Figure 20-1. Classes of Play and Facilities

TYPES OF SPORTS

Based on illumination requirements, sports may be divided into two groups, aerial sports and ground-level sports. Within these two groups, they can be further divided into multidirectional sports and unidirectional sports.

Aerial Sports

Aerial sports involve the playing of an object (usually a ball) in the air as well as on the ground.

Multidirectional Aerial Sports. The players and spectators view the playing object from multiple positions and viewing angles. For aerial sports, vertical illumination over the playing field is more critical than horizontal illumination at ground level. It is important to control direct glare from luminaires by locating the luminaires away from the most frequent viewing directions of players and spectators. Typical multidirectional aerial sports include badminton, baseball, basketball, football, handball, jai alai, soccer, squash, tennis, and volleyball.

Unidirectional Aerial Sports. The playing object is viewed in the air from a fixed position on the ground. General horizontal illumination is required at the starting end and vertical illumination at the finishing end. This is normally done by aiming some luminaires downward at the starting end and at high angles toward the finishing end. Luminaires must be shielded from the player's view. Typical unidirectional sports include golf, skeet and trap shooting, and ski jumping.

Ground-Level Sports

These sports are played on the ground or a few feet above the ground. Players and spectators in the normal course of play do not look upward.

Multidirectional Ground-Level Sports. The players and spectators view the playing object from multiple positions, normally looking downward or horizontally, but occasionally upward. These sports require well-distributed horizontal illumination, although vertical illumination should be considered. Typical multidirectional ground-level sports include boxing, curling, field hockey, ice hockey, skating, swimming (excluding high board diving), and wrestling.

Unidirectional Ground-Level Sports. The object is aimed at a fixed position, usually in a vertical plane close to ground level. For these sports, vertical illumination is critical at this vertical plane. This is normally accomplished by aiming luminaires toward the plane, shielded from view of the players and spectators at the starting end. Typical unidirectional ground-level sports include archery, bowling, and pistol shooting. Skiing is also a unidirectional ground-level sport, where the sloped ground surface is the illuminated plane and the luminaire beam is directed down the slope.

POWER AND ENERGY

Since most sports involve the critical viewing of a fast-moving object, such as a baseball or an ice hockey puck, sports facilities normally require high illuminance, ranging from 300 to 1500 lx (30 to 150 fc). The lighting load requires high power densities (watts per unit area), high power demand (kilowatts, kW), and in some facilities, high energy consumption (kilowatt-hours, kWh) because of extended time of operation. It is noteworthy that energy is consumed only when the system is being operated. For major sports facilities, the lighting load may require high power demand for short periods of time, and thus have fairly low energy consumption.

For example, a major league stadium for professional baseball and football might be lighted with 700 luminaires equipped with 1.5-kW metal halide lamps. The power demand would be approximately 1130 kW. If the operating schedule of the stadium is 40 night games annually for an average of 5 h per game, the annual energy consumption for arena lighting is in the range of 1130 × 40 × 5 = 226,000 kWh. In comparison, a municipal park might consist of four softball fields and be lighted with only 240 luminaires equipped with 1-kW metal halide lamps. The power demand would be only 260 kW for the lighting. However, the operating schedule of a typical complex might be 200 nights per year for an average of 5 h per night. This would result in an annual energy consumption for the field lighting of 260 × 200 × 5 = 260,000 kWh. For every professional sports stadium, there are hundreds of public parks and municipal recreational facilities. The lighting energy consumption due to these recreational facilities is considerably greater than that of a few stadiums.

QUALITY AND QUANTITY OF ILLUMINATION

The goal of sports lighting is to provide an appropriate luminous environment by controlling the brightness of an object and its background so the object appears clear and sharp to the players, spectators, and television viewers. To achieve this goal, both qualitative and quantitative factors of illumination must be considered. These factors are discussed in the following sections. Illumination recommendations for indoor, outdoor, and specialty sports are listed in Figure 20-2. See also Chapter 10, Quality of the Visual Environment, for additional discussion of lighting quality considerations.

Illuminance

It is very important that the illuminance levels satisfy the requirements of the players and the spectators, as well as any television cameras. These requirements should be known at the beginning of the design process, since lighting needs for spectators and television cameras frequently exceed the recommended level for the sport itself. Factors affecting recommended illuminance levels and other lighting design issues for all sports are determined by:

- Speed of sport. Visual tasks of various sizes must be seen when playing sports at a wide range of speeds against various background luminances and colors.
- Skill level of players. As the skill level of players increases, the speed of objects and the importance of accuracy also increase, which in turn calls for higher illuminances. Professional or competitive playing requires higher illuminance than unskilled or recreational playing.
- Age of players. It has been recognized that older players require a higher illuminance and are less tolerant of glare than younger players.
- Spectator capacity. The visual size of tasks diminishes as the inverse square of the distance. This smaller visual size demands increased illuminance to compensate. For sport stadiums the illuminance is determined by the lighting required for the spectators seated farthest from the playing area.
- Television broadcasting. The illuminance required for television cameras and photographic film depends on the sensitivity of the photosensitive media, aperture of the camera, and depth of field to be rendered. Television cameras using an extended telephoto lens may require twice the illuminance required for a regular telephoto lens.

A. Indoor Applications*								
SPORT	Lighted Area	Class of Play	Horizontal		Vertical		Uniformity	
			Lx	Fc	Lx	Fc	CV	Max: Min
Archery	Shooting Line	III	300	30			0.21 or Less	2.5:1 or Less
	Target @ 18.3m (60′)				500	50		
	Target @ 91.4m (300′)				700	70		
	Shooting Line	IV	200	20			0.25 or Less	3:1 or Less
	Target @ 18.3m (60′)				300	30		
	Target @ 91.4m (300′)				500	50		
Basketball‡		I	1250	125			0.13 or Less	1.7:1 or Less
		II	800	80			0.21 or Less	2.5:1 or Less
		III	500	50			0.25 or Less	3:1 or Less
		IV	300	30			0.3 or Less	4:1 or Less
Bowling	Approach†	I	800	80			0.13 or Less	1.7:1 or Less
	Lane†		1200	120				
	Target				1200	120		
	Approach†	II	500	50			0.21 or Less	2.5:1 or Less
	Lane†		800	80				
	Target				1000	100		
	Approach†	III & IV	300	30			0.25 or Less	3:1 or Less
	Lane*		500	50				
	Target				800	80		
Boxing and Wrestling		II	1000	100			0.25 or Less	3:1 or Less
		III					0.25 or Less	3:1 or Less
Curling	Hack to Hog†	I	1500	150			0.13 or Less	1.7:1 or Less
	Hog to Hog†		1000	100				
	Hack to Hog†	II	1000	100			0.21 or Less	2.5:1 or Less
	Hog to Hog†		800	80				
	Hack to Hog†	II & IV	500	50			0.25 or Less	3:1 or Less
	Hog to Hog†		300	30				
Gymnastics		II	800	80			0.21 or Less	2.5:1 or Less
		III	500	50			0.25 or Less	3.1 or Less
		IV	300	30			0.3 or Less	4:1 or Less
Ice Hockey and Figure Skating		I	2000	200			0.13 or Less	1.7:1 or Less
		II	1500	150			0.21 or Less	2.5:1 or Less
		III	1000	100			0.25 or Less	3:1 or Less
		IV	500	50			0.3 or Less	4:1 or Less
Ice Skating (Speed†)		III	300	30			0.25 or Less	3:1 or Less
		IV	200	20			0.3 or Less	4:1 or Less
Racquetball and Squash		II	800	80			0.21 or Less	2.5:1 or Less
		III	500	50			0.25 or Less	3:1 or Less
Rifle and Pistol Ranges	Shooting Line	II	300	30			0.21 or Less	2.5:1 or Less
	Target				1000	100		
	Shooting Line	III	200	20			0.25 or Less	3:1 or Less
	Target				500	50		
Roller Skating†		II	750	75			0.21 or Less	2.5:1 or Less
		III	500	50			0.25 or Less	3:1 or Less
		IV	300	30			0.3 or Less	4:1 or Less
Rodeo		II	500	50			0.21 or Less	2.5:1 or Less
		III	300	30			0.25 or Less	3:1 or Less

Figure 20-2. *Continued*

A. Indoor Applications*

SPORT	Lighted Area	Class of Play	Horizontal		Vertical		Uniformity	
			Lx	Fc	Lx	Fc	CV	Max: Min
Indoor Soccer - Arena Football		I	2000	200			0.13 or Less	1.7:1 or Less
		II	1500	150			0.21 or Less	2.5:1 or Less
		III	1000	100			0.25 or Less	3:1 or Less
		IV	500	50			0.3 or Less	4:1 or Less
Swimming (Water Sports)	Luminances of the Pool Surface (Candelas per Square Meter)	I	35				0.13 or Less	1.7:1 or Less
		II	25				0.21 or Less	2.5:1 or Less
		III	15				0.25 or Less	3:1 or Less
		IV	15				0.3 or Less	4:1 or Less
	Illuminances on Pool Deck	I	750	75			0.13 or Less	1.7:1 or Less
		II	500	50			0.21 or Less	2.5:1 or Less
		III	300	30			0.25 or Less	3:1 or Less
		IV	300	30			0.3 or Less	4:1 or Less
Tennis		I	1500	150			0.13 or Less	1.7:1 or Less
		II	1000	100			0.21 or Less	2.5:1 or Less
		III	750	75			0.25 or Less	3:1 or Less
		IV	500	50			0.3 or Less	4:1 or Less
Volleyball		II	700	70			0.21 or Less	2.5:1 or Less
		III	500	50			0 25 or Less	3:1 or Less
		IV	300	30			0.30 or Less	4:1 or Less
Specialty Sports								
Animal Shows		III	500	50			0 25 or Less	3:1 or Less
		IV	300	30			0.3 or Less	4:1 or Less
Fencing		III	500	50			0.25 or Less	3:1 or Less
		IV	300	30			0.3 or Less	4:1 or Less
Shuffleboard		III	300	30			0.25 or Less	3:1 or Less
		IV	200	20			0.3 or Less	4.1 or Less
Table Tennis		II	700	70			0.21 or Less	2.5:1 or Less
		III	500	50			0.25 or Less	3:1 or Less
		IV	300	30			0.3 or Less	4:1 or Less

* See text for illuminance recommendations for general-purpose facilities.
† Readings taken at grade. All other readings taken at 36″.
‡ See text for National Football League and National Basketball Association games.

Figure 20-2. *Continued*

B. Outdoor Applications

SPORT	Lighted Area	Class of Play	Horizontal		Vertical		Uniformity	
			Lx	Fc	Lx	Fc	CV	Max: Min
Archery	Shooting Line	III	100	10			0.21 or Less	2 5:1 or Less
	Target @ 30.4 m (100′)				300	30		
	Target @ 91.4 m (300′)				500	50		
	Shooting Line	IV	100	10			0.25 or Less	3:1 or Less
	Target @ 30.4 m (100′)				200	20		
	Target @ 91.4 m (300′)				300	30		
Baseball & Softball	Infield	I	1500	150			0.13 or Less	1.7:1 or Less
	Outfield		1000	100				
	Infield	II	1000	100			0.21 or Less	2.5:1 or Less
	Outfield		700	70				
	Infield	III	500	50			0.25 or Less	3:1 or Less
	Outfield		300	30				
	Infield	IV	300	30			0.3 or Less	4:1 or Less
	Outfield		200	20				
Basketball		III	300	30			0.25 or Less	3:1 or Less
		IV	200	20			0.3 or Less	4:1 or Less
Bicycle Racing	Track	III	300	30			0.25 or Less	3:1 or Less
	Final 100′ & Finish*		500	50				
	Track*	IV	200	20			0.3 or Less	4:1 or Less
	Final 100′ & Finish*		300	30				
Dog Racing*		III	500	50			0.25 or Less	3:1 or Less
Drag Racing	Area 1*	I	200	20			0.25 or Less	3:1 or Less
	Area 2*		300	30			0.21 or Less	2.5:1 or Less
	Area 3A*		250	25			0.13 or Less	1.7:1 or Less
	Area 3B*		200	20			0.13 or Less	1.7:1 or Less
	Area 4*		100	10			0.21 or Less	2.5:1 or Less
	Area 1*	II	100	10			0.25 or Less	3:1 or Less
	Area 2*		200	20				
	Area 3A*		150	15				
	Area 3B*		100	10				
	Area 4*		50	5				
Field Hockey		II	500	50			0.21 or Less	2.5:1 or Less
		III	300	30			0.25 or Less	3:1 or Less
		IV	200	20			0.3 or Less	4:1 or Less
Football*		I	1000	100			0.13 or Less	1.7:1 or Less
		II	500	50			0.21 or Less	2.5:1 or Less
		III	300	30			0.25 or Less	3:1 or Less
		IV	200	20			0.3 or Less	4:1 or Less
Golf Course	Tee Boxes*		50	5			0.25 or Less	3:1 or Less
	Fairways*		30	3			0.35 or Less	5.7:1 or Less
	Greens*		50	5			0.25 or Less	3:1 or Less
Golf: Driving	Tee Boxes*		200	20			0.25 or Less	3:1 or Less
	At 183 m (600′)				100	10	0.25 or Less	3:1 or Less
Handball		III	300	30			0.25 or Less	3:1 or Less
Horse Racing	Track		200	20			0.25 or Less	3:1 or Less
	Home Stretch		1000	100				
	Finish Line				700	70	0.13 or Less	1:71 or Less
Ice/Roller Hockey*		II	500	50			0.21 or Less	2.5:1 or Less
		III	300	30			0.25 or Less	3:1 or Less
		IV	200	20			0.3 or Less	4:1 or Less
Ice Skating (Speed*)		III	300	30			0.25 or Less	3:1 or Less
		IV	200	20			0.3 or Less	4:1 or Less
Lacrosse		II	500	50			0.21 or Less	2.5:1 or Less
		III	300	30			0.25 or Less	3:1 or Less
		IV	200	20			0.3 or Less	4:1 or Less

Figure 20-2. *Continued*

B. Outdoor Applications

SPORT	Lighted Area	Class of Play	Horizontal		Vertical		Uniformity	
			Lx	Fc	Lx	Fc	CV	Max: Min
Motor Racing	Track	II	300	30			0.21 or Less	2.5:1 or Less
	Finish Line		750	75				
	Track	III	800	80			0.25 or Less	3:1 or Less
	Finish Line		500	50				
Pistol/Rifle Ranges	Shooting Line	III	100	10			0.17 or Less	2:1 or Less
	Target				500	50		
Platform Tennis		II	500	50			0.17 or Less	2:1 or Less
		III	300	30				
		IV	200	20				
Rodeo And Animal Shows		II	500	50			0.21 or Less	2.5:1 or Less
		III	300	30			0.25 or Less	3:1 or Less
Skeet And Trap Shooting	Shooting Line	III	50	5			0.21 or Less	2.5:1 or Less
	Target @ 18.3 m (60′)				300	30		
	Target @ 30.5 m (100′)				400	40		
	Shooting Line	IV	50	5			0.25 or Less	3:1 or Less
	Target @ 18.3 m (60′)				200	20		
	Target @ 30.5 m (100′)				200	20		
Skiing			5	0.5	2	0.2	No Criteria	
Soccer		II	1500	150			0.21 or Less	2.5:1 or Less
		III	1000	100			0.25 or Less	3:1 or Less
		IV	500	50			0.3 or Less	4:1 or Less
Swimming (Water Sports)	Luminances of the Pool Surface (Candelas per Square Meter)	II	25				0.21 or Less	2.5:1 or Less
		III	15				0.25 or Less	3:1 or Less
		IV	15				0.3 or Less	4:1 or Less
	Illuminances on Pool Deck	II	500	50			0.21 or Less	2.5:1 or Less
		III	300	30			0.25 or Less	3:1 or Less
		IV	300	30			0.3 or Less	4:1 or Less
Tennis		I	1500	150			0.13 or Less	1.7:1 or Less
		II	1000	100			0.21 or Less	2.5:1 or Less
		III	750	75			0.25 or Less	3:1 or Less
		IV	500	50			0.3 or Less	4:1 or Less
Track & Field		II	500	50			0.21 or Less	2.5:1 or Less
		III	300	30			0.25 or Less	3:1 or Less
		IV	200	20			0.3 or Less	4:1 or Less
Volleyball		III	300	30			0.25 or Less	3:1 or Less
		IV	200	20			0.3 or Less	4:1 or Less

C. Specialty Sports

SPORT	Lighted Area	Class of Play	Horizontal		Vertical		Uniformity	
			Lx	Fc	Lx	Fc	CV	Max: Min
Badminton			100	10			0.25 or Less	3:1 or Less
Bowling Green			50	5			0.25 or Less	3:1 or Less
Miniature Golf			100	10			0.25 or Less	3:1 or Less
Horseshoes (General Area)			50	5			0.3 or Less	4:1 or Less
Night Fishing (At Dock)			100	10			0.3 or Less	4:1 or Less

Figure 20-2. *Continued*

C. Specialty Sports

SPORT	Lighted Area	Class of Play	Horizontal		Vertical		Uniformity	
			Lx	Fc	Lx	Fc	CV	Max: Min
Quoits (General Area)			50	5			0.25 or Less	3:1 or Less
Shuffle Board (General Area)			50	5			0.25 or Less	3:1 or Less
Skating Pond (General Area)			10	1			0.3 or Less	4:1 or Less
Washer Pitching			50	5			0.3 or Less	4:1 or Less

* Readings taken at grade. All other readings taken at 36″.

Figure 20-2. Sports-lighting Illumination Recommendations

Horizontal Illuminance. The horizontal illuminance specified for sports as the target illuminance is normally taken on the ground or 3 ft above the ground. It should be noted that for most aerial sports the task is played and viewed in the air rather than on the ground. Therefore, vertical illuminances should be of primary concern. However, horizontal illuminance is normally used in design calculations for two reasons:

- Horizontal illuminance values are much less complicated and time consuming to compute and to measure in the field.
- The vertical illuminance values are acceptable when the horizontal illuminance meets the recommended value and the design complies with recommended design factors, such as mounting height, aiming, and beam spread.

Vertical Illuminance. Factors to be considered when determining vertical target luminance values specified for sports are:

- Viewing direction. There are an infinite number of vertical planes from the perspective of players, spectators, or television cameras. Generally, the planes normal to the four principal directions of the playing field are considered adequate for calculation. Vertical illuminances at given points in space from different directions are not additive. Vertical illuminance must occur on the principal viewing planes to be effective.
- Elevation. Elevations vary with the sport and skill level of play, and the background luminance varies with facility design and whether it is indoors or outdoors. For example, major league baseball requires high vertical illuminance up to 150 ft above the ground; whereas the height needed for basketball is only around 20 ft.
- Illuminance ratios. For multidirectional sports, the ratio of illuminances at ground level is also important and should be less than 3:1 between horizontal and vertical planes as well as between vertical illuminances in the four primary viewing directions.

For both horizontal and vertical illuminances, the following terms should be understood:

- Initial Illuminance. The initial illuminance is that calculated or measured for new installations using rated lamp lumens provided at 100 h of operation (corrected for any lamp position or tilt factor, ballast factor, and voltage variation losses). See Chapter 6, Light Sources, for a discussion of factors affecting lamp output.
- Maintained Illuminance. The maintained illuminance is the average illuminance at a point, or throughout an area, after a specific period of time or after relamping and cleaning. Based on a designated maintenance schedule and using known light loss and field factors, a close approximation of the actual maintained value can be calculated. The values used to approximate the light loss and field factors should always be identified when calculating maintained illuminance values.
- Target Illuminance. The target illuminance is the value used for calculations during system design to determine if the system meets a desired performance standard. This value may be the initial illuminance, but more often an initial value is reduced by a designated percentage to approximate maintained values. Initial field measurements of the resultant system are then corrected by this reduction to evaluate whether the design illuminances have been achieved. Target illuminances for various sports recommended in this section are based on 70% of rated life. If the designer chooses to use the mean lumens of a lamp as a basis for design calculations, the illuminances should be modified accordingly.

For example, suppose the lamp to be used for the design is rated for 10,000 h and initially delivers 90,000 lm. However, the lamp manufacturer's lumen maintenance data also indicate the lumen output at 70% of rated life (7000 h) is only 75,000 lm. Then the designed target illuminance should be based on 75,000 rather than 90,000 lm. Note that field measurement for verification usually takes place shortly after installation. The initial illuminance measured naturally is higher than the target illuminance by a factor of 90,000/75,000, as well as by other light loss factors (LLFs). Refer to Chapter 6, Light Sources, and Chapter 9, Lighting Calculations, for further discussion of LLFs.

Illuminances, horizontal and vertical, are not the only important design criteria. The following is a list of other design criteria that need to be considered.

Uniformity (Horizontal). Uniformity is a measure of relationships of the illuminances over an area. It is particularly important for high-speed sports on a large playing field, such as baseball, football, ice hockey, and tennis. Poor uniformity, especially shadows, may distort the visual perception of tasks both in speed and in position, thus affecting player performance. There are many methods to express uniformity. One or more of these methods may be used to evaluate an installation:

- Coefficient of Variation (CV). This method is a measure of the weighted average of all relevant illuminance values and is commonly used in statistics, where the variance of a set of values is calculated as the ratio of standard deviation σ of all values to the mean *x*. We have

$$\sigma = \sqrt{\frac{\Sigma_{i=1}^{n}\,(x_i - \bar{x})^2}{n}} \qquad (20\text{-}1)$$

where

x_i = illuminance at point *i*,
n = number of points measured (see the section "Field Measurements and Performance Evaluations," later in this chapter, for guidance on the number and distribution of points to be measured),
$\bar{x}$ = mean illuminance.

Then

$$\mathrm{CV} = \frac{\sigma}{\bar{x}} \qquad (20\text{-}2)$$

)

As a rule, the value of the CV for Classes I, II, III, and IV should not exceed 0.13, 0.21, 0.25, and 0.30, respectively.

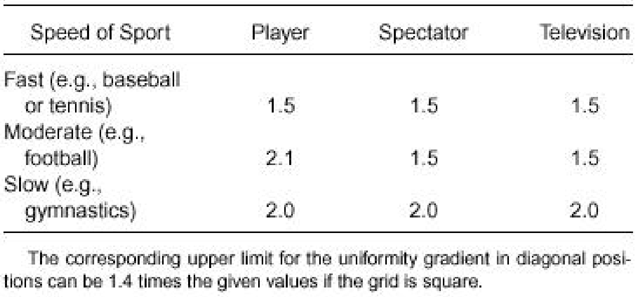
- Maximum to Minimum (L_{max}/L_{min}). The uniformity *U* can also be defined in terms of the extremes, that is, the highest and lowest values of the calculated or measured illuminances on the field at any given time.

$$U = \frac{E_{\max}}{\mathrm{E}_{\min}} \qquad (20\text{-}3)$$

The uniformity ratio for Classes I, II, III, and IV should not exceed 1.7, 2.5, 3.0, and 4.0, respectively.[1] This limit needs to be tightened for some high-speed sports if play is televised.

- Uniformity Gradient. The uniformity gradient (UG) is the rate of change of illuminance on the playing field. It is extremely important for high-speed sports because a fast-moving object passing from a light space to a dark space may appear to change speeds due to different visual processing times for different adaptation levels; the visual system responds more slowly at lower adaptation levels. The UG is expressed as a ratio between the illuminances of adjacent measuring points on a uniform grid. The recommended upper limit of UG values varies with the speed of the sport and is shown in Figure 20-3.[1]

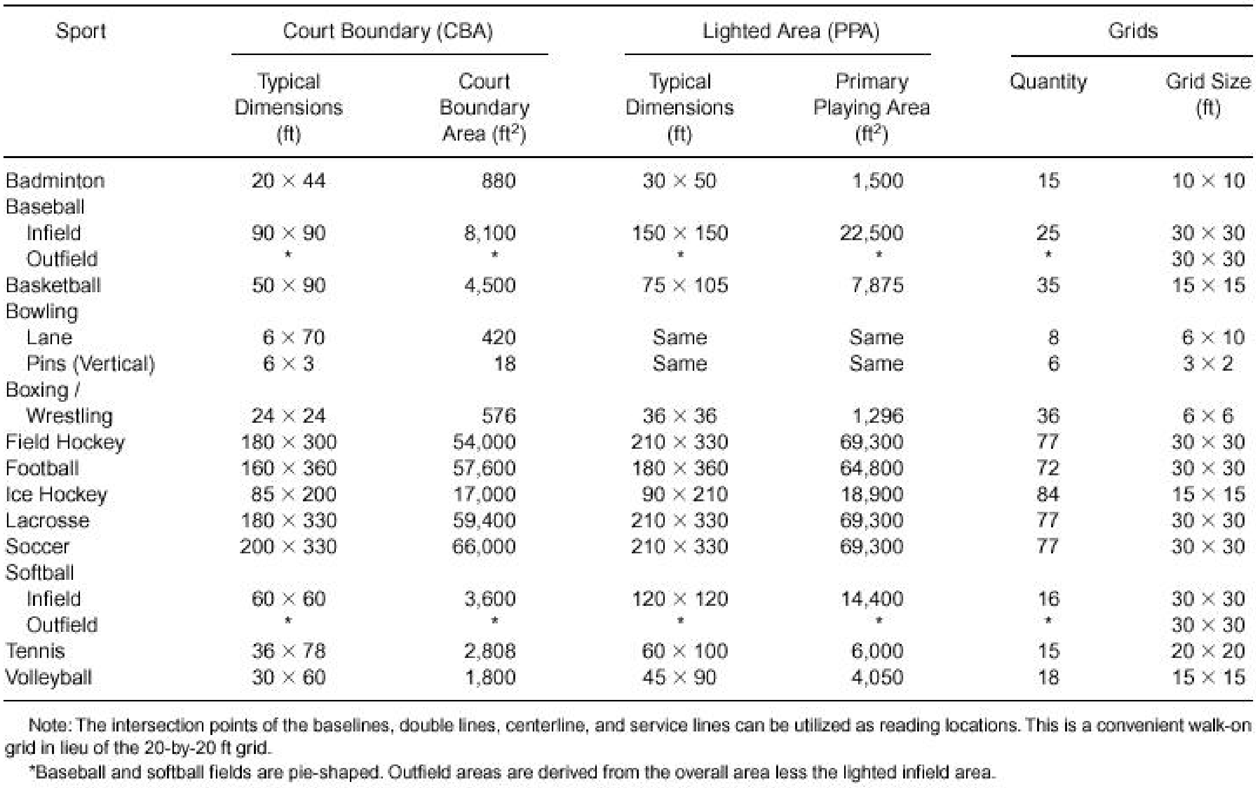
For most sports, the recommended field measurement grid is in a pattern of squares (e.g., 20 ft by 20 ft each; see Figure 20-4). The illuminance values at the adjacent grid points can be compared along the *X* and *Y* directions to determine the UG values. When comparing illuminance values along the diagonal directions, the UG criteria should be increased proportionately.



Speed of Sport	Player	Spectator	Television
Fast (e.g., baseball or tennis)	1.5	1.5	1.5
Moderate (e.g., football)	2.1	1.5	1.5
Slow (e.g., gymnastics)	2.0	2.0	2.0

The corresponding upper limit for the uniformity gradient in diagonal positions can be 1.4 times the given values if the grid is square.

Fig. 20-3. Upper Limit of Uniformity Gradient for Comparing Two Adjacent Areas



Sport	Court Boundary (CBA)		Lighted Area (PPA)		Grids	
	Typical Dimensions (ft)	Court Boundary Area (ft^2)	Typical Dimensions (ft)	Primary Playing Area (ft^2)	Quantity	Grid Size (ft)
Badminton	20 × 44	880	30 × 50	1,500	15	10 × 10
Baseball						
Infield	90 × 90	8,100	150 × 150	22,500	25	30 × 30
Outfield	*	*	*	*	*	30 × 30
Basketball	50 × 90	4,500	75 × 105	7,875	35	15 × 15
Bowling						
Lane	6 × 70	420	Same	Same	8	6 × 10
Pins (Vertical)	6 × 3	18	Same	Same	6	3 × 2
Boxing / Wrestling	24 × 24	576	36 × 36	1,296	36	6 × 6
Field Hockey	180 × 300	54,000	210 × 330	69,300	77	30 × 30
Football	160 × 360	57,600	180 × 360	64,800	72	30 × 30
Ice Hockey	85 × 200	17,000	90 × 210	18,900	84	15 × 15
Lacrosse	180 × 330	59,400	210 × 330	69,300	77	30 × 30
Soccer	200 × 330	66,000	210 × 330	69,300	77	30 × 30
Softball						
Infield	60 × 60	3,600	120 × 120	14,400	16	30 × 30
Outfield	*	*	*	*	*	30 × 30
Tennis	36 × 78	2,808	60 × 100	6,000	15	20 × 20
Volleyball	30 × 60	1,800	45 × 90	4,050	18	15 × 15

Note: The intersection points of the baselines, double lines, centerline, and service lines can be utilized as reading locations. This is a convenient walk-on grid in lieu of the 20-by-20 ft grid.

*Baseball and softball fields are pie-shaped. Outfield areas are derived from the overall area less the lighted infield area.

Fig. 20-4. Recommended Field-Measuring Grids of Typical Class I and II Facilities

Some sports fields have more than one design illuminance. In that case, the transitions between design illuminances should be gradual. For example, if the infield of a major baseball stadium is designed for 1500 lx (150 fc) and the outfield for 1000 lx (100 fc), the illuminance at the grid points in the outfield adjacent to the infield should be higher than 1000 lx (100 fc), say 1250 lx (125 fc), in order to achieve an acceptable UG.

Glare. Glare is a particularly important quality factor in sports lighting in that it can impair visibility (and thus the level and quality of play) and can cause discomfort to both players and spectators. These two types of glare are classically known as disability glare and discomfort glare, respectively (see Chapter 3, Vision and Perception). Glare of both types can result either from directly viewing the luminaire (direct glare) or from viewing its reflection in a glossy or semiglossy surface (reflected glare).

Direct Glare. The present methods of assessing disability and discomfort glare for sports lighting are inadequate because of the very large number of viewing positions required to perform and to view the various sports. The Commission Internationale de l'Eclairage (CIE) is currently working on a system to assess direct glare for sports lighting.

Whenever possible, it is imperative to diminish the effects of glare by locating the luminaires or daylight sources away from the normal lines of sight. For example, luminaires should not be located directly above the basket on a basketball court because players can then be blinded when looking up at the basket (Figure 20-5a). In those instances where glare cannot be avoided in positioning the luminaires, consideration should be given to the type of lamp and the use of glare control devices on the luminaires to reduce their brightnesses.

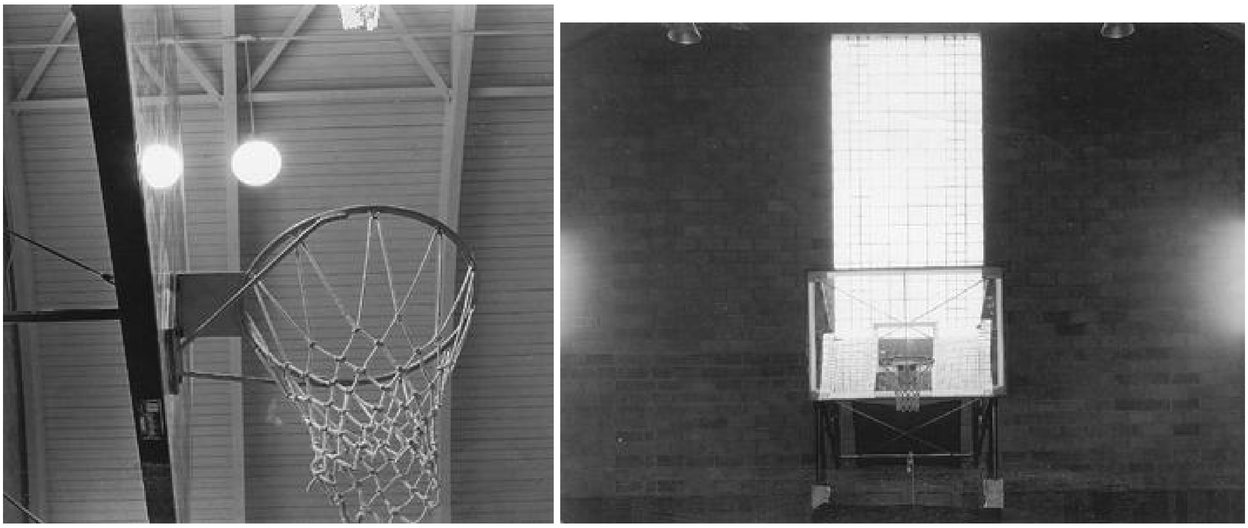


Figure 20-5. Luminaires directly over the basket (a) or windows behind the basketball board (b) produce direct glare to players.

Windows in an indoor sports facility are not considered desirable, particularly behind the basket of a basketball court and at either end of an indoor tennis court (Figure 20-5b.) Skylights should be screened and be placed away from the normal line of sight.

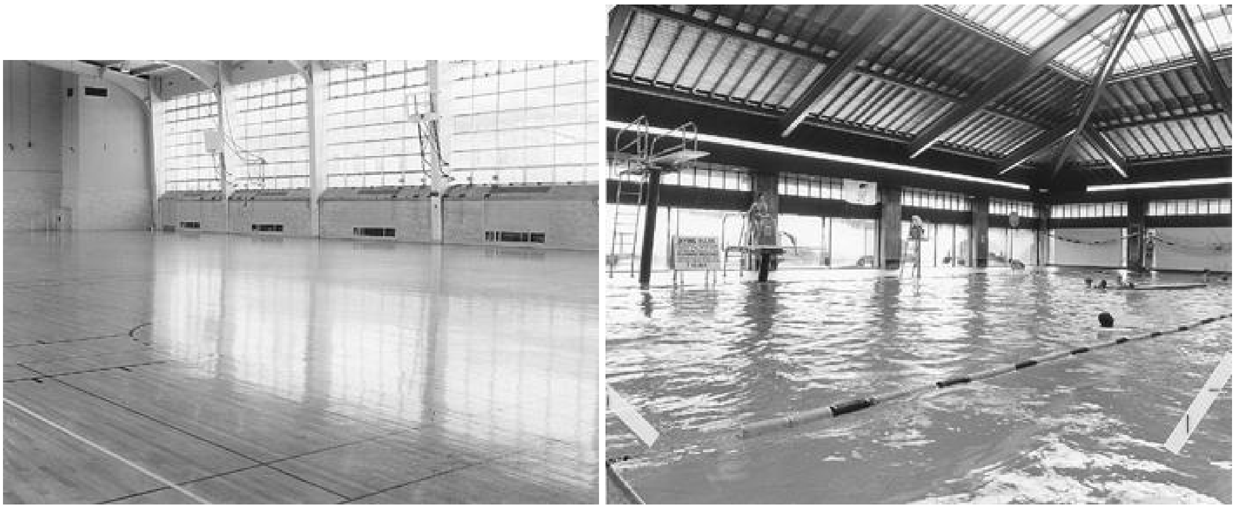


Figure 20-6. (a) Specular surfaces can cause reflected glare as illustrated on the floor of a gymnasium. (b) Windows can produce unwanted glare from the water surface of a swimming pool and can reduce the ability of the lifeguard to see certain objects on the water surface or see beneath the surface.

Reflected Glare. To reduce reflected glare, surfaces within the field of view should have low reflectance values, preferably in matte finishes (Figure 20-6).

Glare Control. Glare makes visual observation more difficult and reduces visual comfort. It must therefore be controlled for both players and spectators by controlling the apparent brightness of light sources in the main direction of view. This is relatively easy to achieve for sports facilities that have a main direction of view below the horizontal. Glare control is achieved in a number of ways:

- Select luminaires with an intensity distribution suited to the required illuminance, uniformity, size of area, and mounting height.
- Mount luminaires out of the main field of view of players and spectators, and if necessary use additional screening devices on the luminaire to control the brightness in certain directions.
- For indoor areas, ensure adequate illumination of spectator areas, upper walls, and roof. Select suitable surface reflectances to ensure that the lighting equipment is not seen against a dark background.

The reflectances recommended for major surfaces are 60% for ceilings and 30 to 60% for walls. The reflectance of the ceiling should be high, so that the difference between the luminance of luminaires and that of the ceiling is as small as possible. Where it is difficult to achieve an effective ceiling reflectance as high as 60%, the luminance contrast can be improved by directing light on the roof area.

Reflected glare can be caused by reflection of the luminaires off surfaces such as ice or polished wood courts. This should be avoided by suitable positioning of the luminaires and appropriate screening.

Contrast. Contrast is the relationship between the luminances of an object and its immediate background. It is essential to have contrast to see. For example, it would be difficult to detect a fast-moving white baseball against a white background (Figure 20-7a), or even against a predominantly white background, such as the seating area of a baseball stadium during hot summer days when many spectators wear white clothing (Figure 20-7b). However, too much contrast, such as using a black background on a baseball field, may be aesthetically unpleasant. The use of harmonious color combinations, such as a dark green court surface with a yellow tennis ball, can significantly improve the seeing tasks.

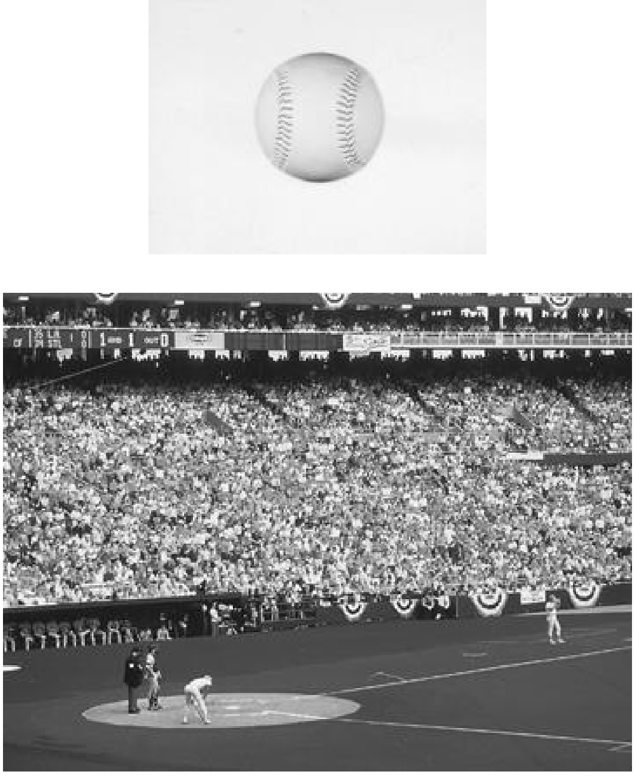


Figure 20-7. The visibility of a white baseball can be seriously reduced against a predominantly white background (a) where many spectators are wearing white clothing during warm weather (b).

Modeling. Modeling is the ability of the lighting system to reveal the three-dimensional form of an object, such as a ball, target, or player. With regard to modeling, illumination may be described as flat or directional.[1] Effective illumination for sports depends in large part on modeling by directional lighting. This is especially important for high-quality television broadcasting. Lighting from two or more directions is required to eliminate deep shadows and separate the visual target, such as a ball, from its background.

Flicker. The lumen output of a lamp varies with its power input on a 50- or 60-Hz ac circuit; the light varies 100 or 120 times per second, respectively. The cyclic variation of light, termed flicker, can cause a stroboscopic effect.[8] Incandescent lamps produce the least flicker, since the filament retains the incandescent heat during the cyclic variation in current. High-pressure sodium lamps have the greatest flicker. Illuminating a plane with lamps controlled by ballasts that shift the lamp current (and thus the light output), either leading or lagging the voltage, minimizes flicker. Luminaires connected on different phases of a three-phase power system can also minimize flicker. Metal halide lamps have the least flicker among the HID sources and can be used on single-phase systems.[9] See Chapter 2, Measurement of Light and Other Radiant Energy, and Chapter 6, Light Sources, for a discussion of light source flicker.

Spill Light. Spill light is sometimes referred to as "light trespass" or "light pollution." Light trespass is light shining beyond the sports facility that may annoy occupants of the adjacent property. Light pollution is light shining into the night sky that obscures astronomical observation. Because spill light frequently creates political issues, many municipalities have enacted ordinances to limit it.

Spill light can be controlled by certain design procedures. For example, select luminaires with an intensity distribution that does not illuminate areas outside the sports facility. Also, use cutoff luminaires or, where direct glare from luminaires is not a problem, high mounting poles with luminaires having a low aiming angle. A combination of design factors must be evaluated in order to achieve optimum solutions.

Luminaire Noise. Another important consideration in some sports is the audible noise created by the lighting equipment. Sound ratings are available for many ballasts, but a good sound rating for a ballast does not ensure a quiet luminaire. Some large retailers have developed maximum noise levels for luminaires, but no industry standards are currently in place for sports applications. It is recommended that lighting designers advise clients of the potential for noise and that the supplier provide some assurances as to luminaire performance in this regard.

LIGHT SOURCES

Three basic types of light sources are commonly used for sports lighting applications: incandescent, fluorescent, and high-intensity discharge (HID). Each type has advantages and disadvantages. The proper selection depends on particular requirements of the installation being considered, economics, and the designer's preference. Detailed information on light sources is given in Chapter 6, Light Sources.

LUMINAIRES

General

A luminaire is a complete lighting unit consisting of one or more lamps (light sources) together with the parts designed to control the light distribution and other mechanical and electrical components. The optical characteristics of a luminaire affect the direct and reflected glare, shadows, distribution, and pattern; these should all be considered when selecting the correct luminaire for a particular application. See Chapter 7, Luminaires, for more information.

Floodlights

Floodlights are the most common type of luminaire used for sports lighting. The following are some types of floodlights.

Enclosed Heavy Duty (HD). This class of luminaire includes a substantially constructed housing in which a separate reflector is placed. The assembly is enclosed by a weatherproof hinged door with a cover glass to provide an unobstructed light opening at least equal to the effective dimensions of the reflector (Figure 20-8a).

Enclosed General Purpose (GP). This class is weatherproof and may be constructed so the housing forms the reflecting surface. The assembly is enclosed by a cover glass (Figure 20-8b).

Full Cutoff Type. This class is designed to shield the light source above the plane of the luminaire. This shielding angle is chosen to minimize the direct glare to the observer at a normal viewing angle and also to provide broad coverage on the sports field (Figure 20-8c).

Reflectorized Lamps. This class consists of a lampholder and a lamp with an integral reflector.

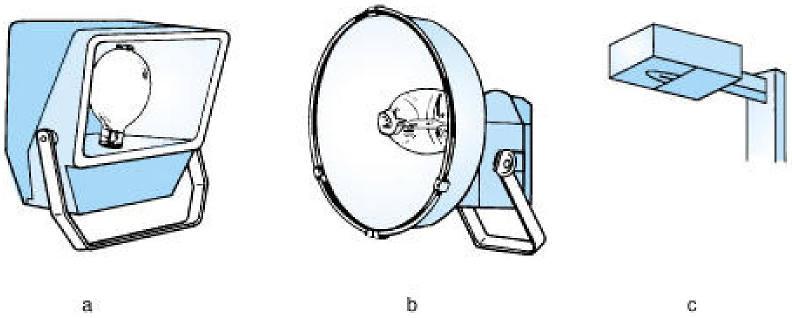


Figure 20-8. Types of floodlights used for sports lighting. (a) Enclosed rectangular type. (b) Enclosed round type. (c) Shielded type.

Beam and Field Angles

The light distribution of a luminaire may be classified by its beam and field angles. The beam and field angles are determined from the intensity distribution pattern; circular beams have one value for each angle, and oval beams have separate horizontal and vertical values for each. The beam angle is the included angle between points of 50% of maximum intensity, and the field angle is the included angle between points of 10% of maximum intensity (see Figure

20-9).

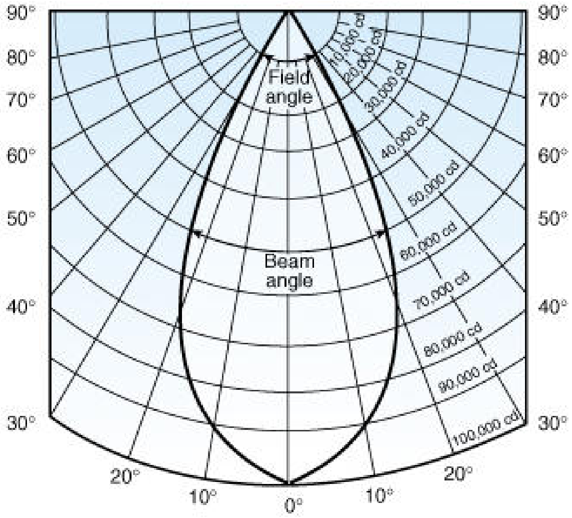
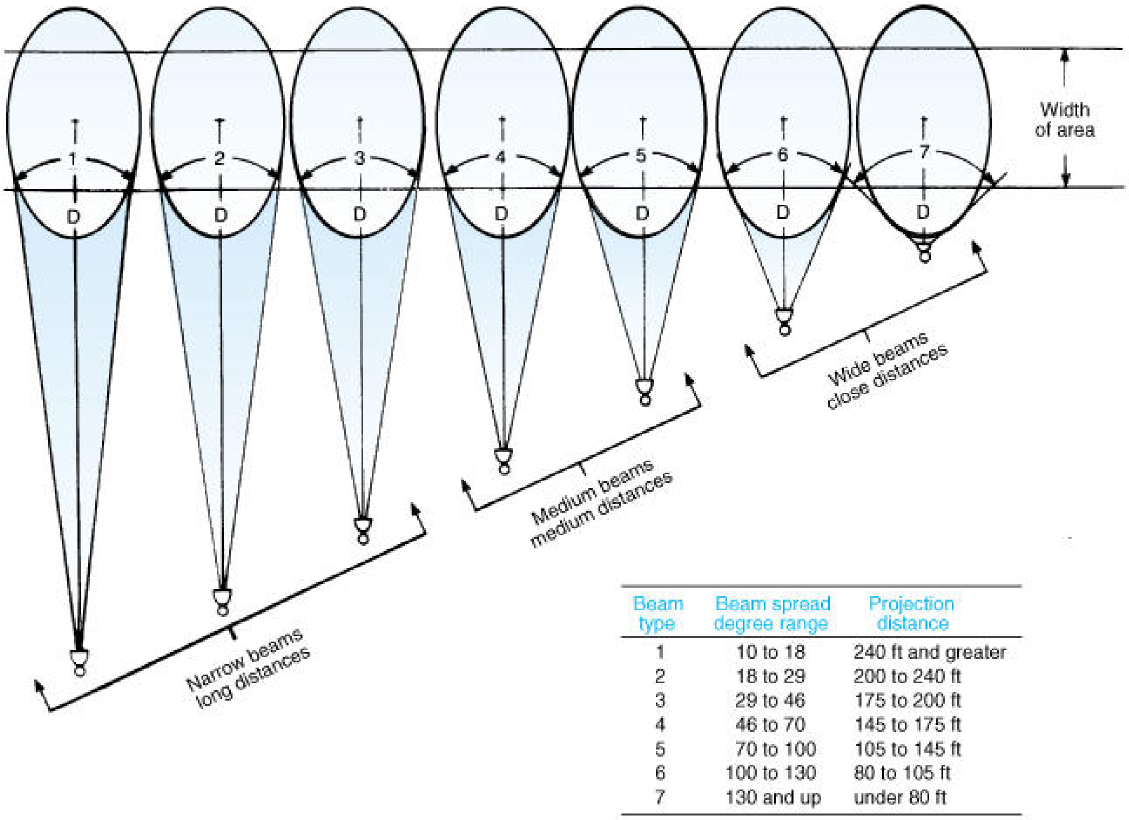


Figure 20-9. As illustrated in this intensity distribution curve on polar coordinates, the maximum intensity is 100,000 cd. The field angle is 60°, the angle included between the intersecting points of the curve at 10,000 cd (10% of 100,000 cd). The beam angle is 48°, the angle included between the intersecting points of the curve at 50,000 cd (50% of 100,000 cd). According to NEMA classification, the illustrated floodlight is classified as Type 4, having a field angle between 46° and 70°.



Beam type	Beam spread degree range	Projection distance
1	10 to 18	240 ft and greater
2	18 to 29	200 to 240 ft
3	29 to 46	175 to 200 ft
4	46 to 70	145 to 175 ft
5	70 to 100	105 to 145 ft
6	100 to 130	80 to 105 ft
7	130 and up	under 80 ft

Figure 20-10. NEMA field angle (formerly beam spread) classifications and their effective projection distances.

The National Electrical Manufacturers Association (NEMA) field angle classification (Figure 20-10) is widely used by the lighting industry to classify the overall candlepower distribution pattern of a floodlight. It is also useful to the designer for preliminary design selections. However, the coefficient of utilization (CU) of each design application should be based on the total luminous flux (in lumens) of the luminaire rather than the NEMA field angle.

Asymmetrical beam floodlights may be designated according to the horizontal and vertical beam spreads in that order; that is, a floodlight with a horizontal beam spread of 75° (Type 5) and a vertical beam spread of 35° (Type 3) may be designated as a Type 5 × 3 floodlight.

Luminance Control

Glare and spill light control devices include visors, lenses, filters, internal and external louvers, lamps, and special lamp shields. They should be considered during design, because some of them cannot be retrofitted after initial installation. The use of such control devices reduces the efficiency of luminaires. Proper lighting design should minimize their use by selecting luminaires that provide the desired beam control.

DESIGN CONSIDERATIONS FOR SPORTS FACILITIES

Sports lighting design follows the same principles and practices as the design for other spaces or facilities given in Chapter 10, Quality of the Visual Environment. Chapter 27, Lighting Controls, and Chapter 26, Energy Management, provide additional information on the techniques and economics of controls and operations. Included below are considerations that are particularly applicable to sports lighting design.

General-Purpose Facilities

Most sports facilities, especially indoor facilities, are intended to be used for various sports, social, educational or entertainment functions. The lighting, therefore, must be adaptable to all intended functions. General-purpose facilities, ordered by size and spectator capacity, may be classified as exercise rooms, gymnasiums, field houses, arenas, and stadiums.

Exercise Rooms. These rooms are usually small, for general exercise such as physical fitness, aerobic dancing, weight lifting, and machine exercise. General uniform and diffuse lighting of 300 lx (30 fc) is recommended.

Gymnasiums. Gymnasiums are generally a part of a school facility designed to serve school programs during the day and community functions at night. A wide choice of illuminances may be desirable because of the diverse seeing tasks and activities that can be encountered. Variations in general illumination can be achieved through dimming, split switching, or other means of lighting control between 50 and 500 lx (5 and 50 fc).

Field Houses. Field houses and gymnasiums have common uses; however, field houses are generally larger and serve a wider range of sports, such as indoor track and field events. Illuminance levels are normally 500 to 1000 lx (50 to 100 fc).

Arenas. Arenas are large multipurpose facilities. Playing areas of arena floors are generally 50 m (150 ft) or more in each direction, with seating spaces designed to serve a few thousand to 20,000 spectators. Vertical and horizontal target illuminances for arenas are normally in excess of 1000 lx (100 fc) and are suitable for a variety of sports.

Stadiums. Stadiums are large, completely open facilities for major league baseball and football and can accommodate 100,000 spectators, or more. Their lighting design should be similar to that of arenas. Multiple light sources, distributions, and controls must be used to provide illuminances suitable for players, spectators, and television cameras.[10]

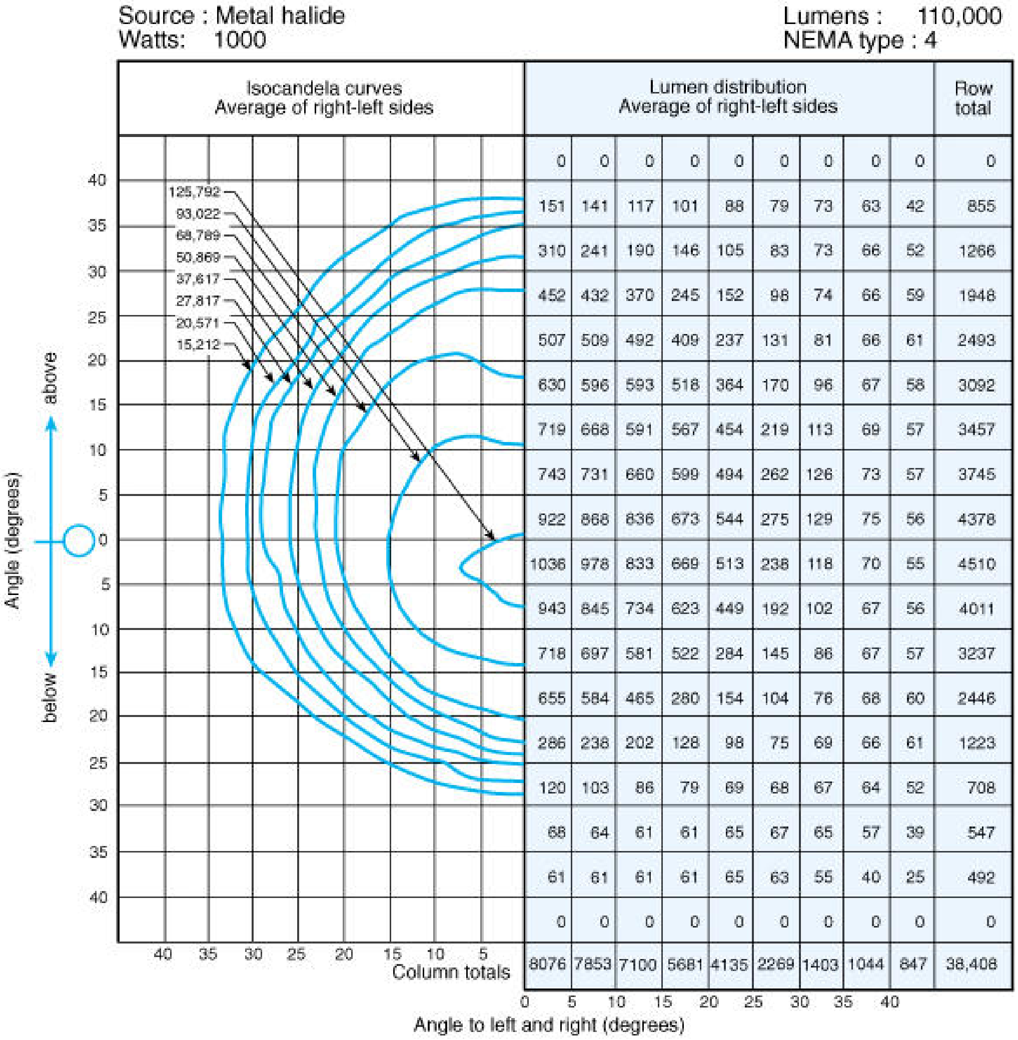
System Selection Considerations

Outdoor Facilities. A direct lighting system is the only kind of system that can be used for outdoor facilities. When the facility contains roofed areas covering spectator seating, the roof structure is normally utilized to serve as structural support for the lighting system. Lighting underneath the covered roof can also serve to soften the glare of the luminaires. Since outdoor lighting is generally visible at distances far beyond the boundary of the facility and is subject to environmental conditions, careful consideration should be given to spill light on neighboring property (see Chapter 21, Exterior Lighting), light added to the sky glow, and durability of equipment and wiring under the continuous exposure to the environment.

Indoor Facilities. There are more system choices in indoor applications. The system may be a totally indirect distribution system for a small multipurpose facility, a direct-indirect system for an indoor tennis center, or a direct system for arenas and stadiums, which demand a high level of illuminance not economically achievable by other systems. The design of lighting systems must be closely interfaced with the architectural and structural design of the facility to form an integrated design. The design should also include the coordination of interior finishes (colors, reflectances, and textures), daylighting (if desired), and acoustics. For most facilities, the use of light-finished surfaces enhances the appearance of the space and minimizes direct glare. The addition of supplementary uplights (indirect lighting) reduces direct glare by softening the contrast between the bright luminaires and their background.

Luminaire Selection Considerations

Photometric Data. These data are the important technical information about a luminaire, specifying and illustrating its optical performance characteristics, such as its intensity distribution (Figure 20-9), isocandela curve, and lumen distribution (Figure 20-11). These data should be obtained from manufacturers. See also Chapter 9, Lighting Calculations, and Chapter 7, Luminaires.



	Lumen distribution Average of right-left sides									Row total
	0	0	0	0	0	0	0	0	0	0
	151	141	117	101	88	79	73	63	42	855
	310	241	190	146	105	83	73	66	52	1266
	452	432	370	245	152	98	74	66	59	1948
	507	509	492	409	237	131	81	66	61	2493
	630	596	593	518	364	170	96	67	58	3092
	719	668	591	567	454	219	113	69	57	3457
	743	731	660	599	494	262	126	73	57	3745
	922	868	836	673	544	275	129	75	56	4378
	1036	978	833	669	513	238	118	70	55	4510
	943	845	734	623	449	192	102	67	56	4011
	718	697	581	522	284	145	86	67	57	3237
	655	584	465	280	154	104	76	68	60	2446
	286	238	202	128	98	75	69	66	61	1223
	120	103	86	79	69	68	67	64	52	708
	68	64	61	61	65	67	65	57	39	547
	61	61	61	61	65	63	55	40	25	492
	0	0	0	0	0	0	0	0	0	0
Column totals	8076	7853	7100	5681	4135	2269	1403	1044	847	38,408

Figure 20-11. Photometric data of a typical sports luminaire indicating the isocandela curves on the left side and lumen depreciation values on the right side. The last column at the extreme right indicates the accumulated lumens within each horizontal row. These values should be doubled to obtain the total accumulated lumens for both sides of the luminaire.

Beam and Field Angles and Lamp Wattage. The selection of the floodlight beam and field angles is determined by the design illuminance on the playing field and the distance from the floodlight to its aiming point on the ground. The maximum beam intensity should not produce an illuminance on the field greater than the average design level. Thus, the distributions from adjacent luminaires must overlap to some extent. The lamp wattage and lumen output are chosen so that the playing field can be uniformly lighted with the minimum number of floodlights. Manufacturer's recommendations and photometric data should be consulted.

Ballast. All HID and fluorescent light sources require ballasting. Ballasts are designed to work with available, nominal voltages. Voltage fluctuation and voltage drop directly affect light output; thus, branch circuit and feeder wiring should be designed to minimize the voltage drop, normally less than 5% of the system voltage.

Structural. The location of the ballast (either integral to the luminaire or remotely mounted) has to be decided. The size and shape of the luminaire determine the effective projected area (EPA), which should be considered when determining the structural strength needed to support the luminaires under wind loading in outdoor applications. The impact of weather (e.g., hail that can distort reflector geometries) must also be carefully considered.

Lamp Tilt Factor. The lumen output of a lamp may be sensitive to its operating position. The lowest output for a metal halide lamp is usually at a tilt of 60 to 75° off vertical, that is, when the lamp is closer to horizontal than to vertical. The tilt factor, which is to be included in determining the overall light loss factor (LLF), ranges from 0.8 to 1.0. Tilt factor information should be obtained from the supplier.

Light Source Selection Considerations

The selection of light sources (lamps) goes hand in hand with the selection of luminaires. Metal halide lamps are used for most sports. Incandescent or tungsten-halogen lamps are used for sports requiring lower initial illuminance and for facilities with limited annual usage. Fluorescent lamps are normally used indoors or where the lamp is less than 20 ft from the lighted area. High-pressure sodium lamps are used for applications where color rendition is less critical and where three-phase power is available, and at least two beams are aimed in the same direction from luminaires operated on different phases. Consideration should be given to:

- The methods to minimize flicker of HID light sources
- The effect of luminaire noise, especially in indoor facilities
- The effect of ambient temperature on the performance of the lamps, on the lumen output, and on starting characteristics
- The estimated annual operating hours, which may influence the economics of the lamp selection
- The starting and restarting characteristics of lamps. HID lamps should be avoided in applications where starting and restarting is frequent
- The effect of color shift. Some HID lamps have a significant color shift during their life; the color of a lamp may also be affected by the input voltage. Color shift can be minimized by better voltage regulation of the power system and by group relamping

ILLUMINANCE CALCULATIONS

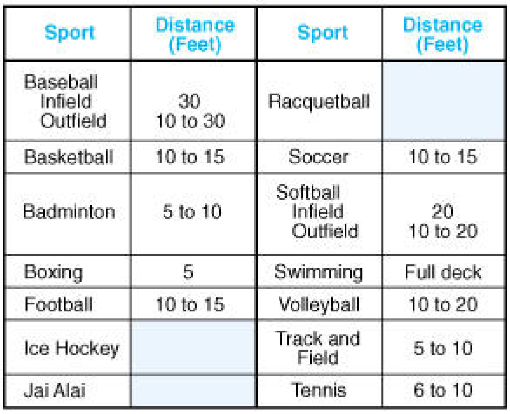
The general methods of illuminance calculation are given in Chapter 9, Lighting Calculations. However, more specific methods are necessary for sports lighting calculations. A more complete description of these algorithms is given in RP6.[1] The following factors should be understood when making sports lighting design calculations.

Playing Area

Although every sport has a defined dimension and court boundary, some sports require an additional area outside the court boundaries for the sport to be played. Perhaps baseball requires more outside playing area than any other sport. Others, such as badminton, football, tennis, and volleyball, also require some additional area to allow unobstructed play. For illumination design purposes, the playing field can be divided into three areas.

Court Boundary Area (CBA). This is the area within the prescribed boundaries at the playing field.

Primary Playing Area (PPA). This is the total area extending beyond the playing boundary in which a nearly equal illuminance level must be maintained. For example, in baseball the foul zone must be counted as PPA. This zone extends a minimum of 30 ft behind home base, up to the end of the infield, and gradually diminishes to about 10 ft in depth at the far end of the outfield. The recommended minimum dimensions of the PPA beyond the court boundary for some major sports are given in Figure 20-12.



Sport	Distance (Feet)	Sport	Distance (Feet)
Baseball Infield Outfield	30 10 to 30	Racquetball	
Basketball	10 to 15	Soccer	10 to 15
Badminton	5 to 10	Softball Infield Outfield	20 10 to 20
Boxing	5	Swimming	Full deck
Football	10 to 15	Volleyball	10 to 20
Ice Hockey		Track and Field	5 to 10
Jai Alai		Tennis	6 to 10

Figure 20-12. Primary Playing Areas for Class I or Class II Facilities Beyond Court Boundaries that Require Equal Illuminances

Secondary Playing Area (SPA). This is the playing area between the PPA and a physical barrier, such as a fence or a spectator stand. For example, the court boundary of a tennis court is 78 by 36 ft, having an area of 2808 ft^2. The PPA of a tennis court, as defined by United States Tennis Association (USTA), is the area bounded by lines 6 ft beyond the sidelines and 10 ft behind the baselines, having an area of 4704 ft^2 (use 4700 ft^2 as an approximate value.) However, the overall playing area of a tennis court is considerably larger, ranging from 7200 to 10,000 ft^2, depending on the class of the facility. Thus, the SPA varies from 2500 to 5300 ft^2. The illumination for the SPA should not be less than 50% of that for the PPA, with a gradual transition complying with the guidelines for the uniformity gradient (UG) discussed earlier in this chapter.

Calculation Procedure

The following procedure applies to sports lighting design using the point method calculations with direct distribution luminaires.

1. Based on the type of sport, skill level of play, size of the facility, television broadcasting circumstances, and architectural or structural requirements, determine the design criteria, such as illuminances and uniformity.

2. Make a preliminary selection of light sources and luminaires based on their photometric data, such as lumen output, beam angle, candela and lumen distributions, color rendition, and lamp life.

3. Use the modified lumen method (see Annex A RP-6[1]) to determine the approximate number of luminaires with one or more luminaire selections. If the designer is experienced, this and the next four steps can be by-passed (i.e., go to step 8).

4. Assign locations and mounting heights of these luminaires based on the guidelines given.

5. Determine the grid pattern or number of uniform areas for which the illuminance value should be calculated.

6. Confirm the selection of beam spread and rough aiming by manual calculations at a few selected grid points.

7. Determine the applicable light loss and field factors to be used.[11]

8. Use a computer program to calculate the appropriate design criteria at the recommended grid points.

9. Repeat the process by varying the number of luminaires, locations, mounting heights, and aiming directions until the target illuminance levels at each grid point meet the design criteria for illuminances, uniformity, and other quality factors.

DESIGN AND LAYOUT RECOMMENDATIONS

With the availability of choices of light sources, luminaires, and mounting techniques, there are a large number of design options to achieve excellent results for both illuminance distribution and glare control. Representative layouts for several major sports are given in reference publication IES-RP-6.[1] Two of the representative layouts are included in Figures 20-13 and 20-14.

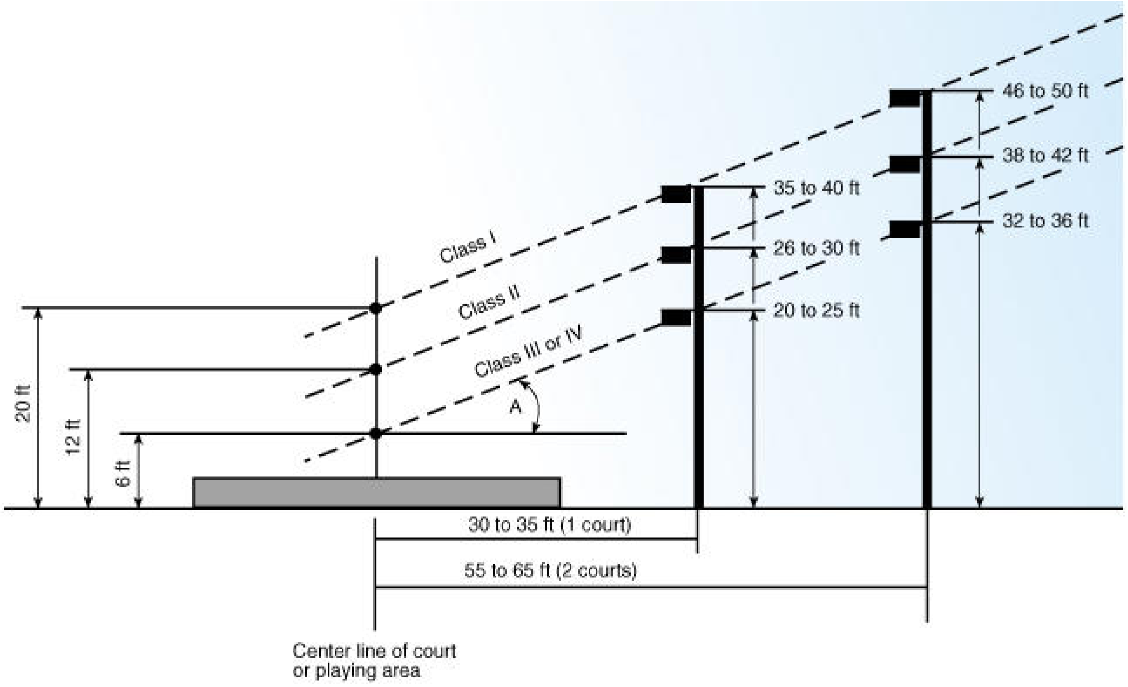


Figure 20-13. Outdoor tennis. Recommended mounting heights of luminaires on poles for various setbacks, classes of play, and facilities. Angle *A* should be a minimum of 25°for sharp cutoff-type luminaires and a minimum of 30°for floodlights.

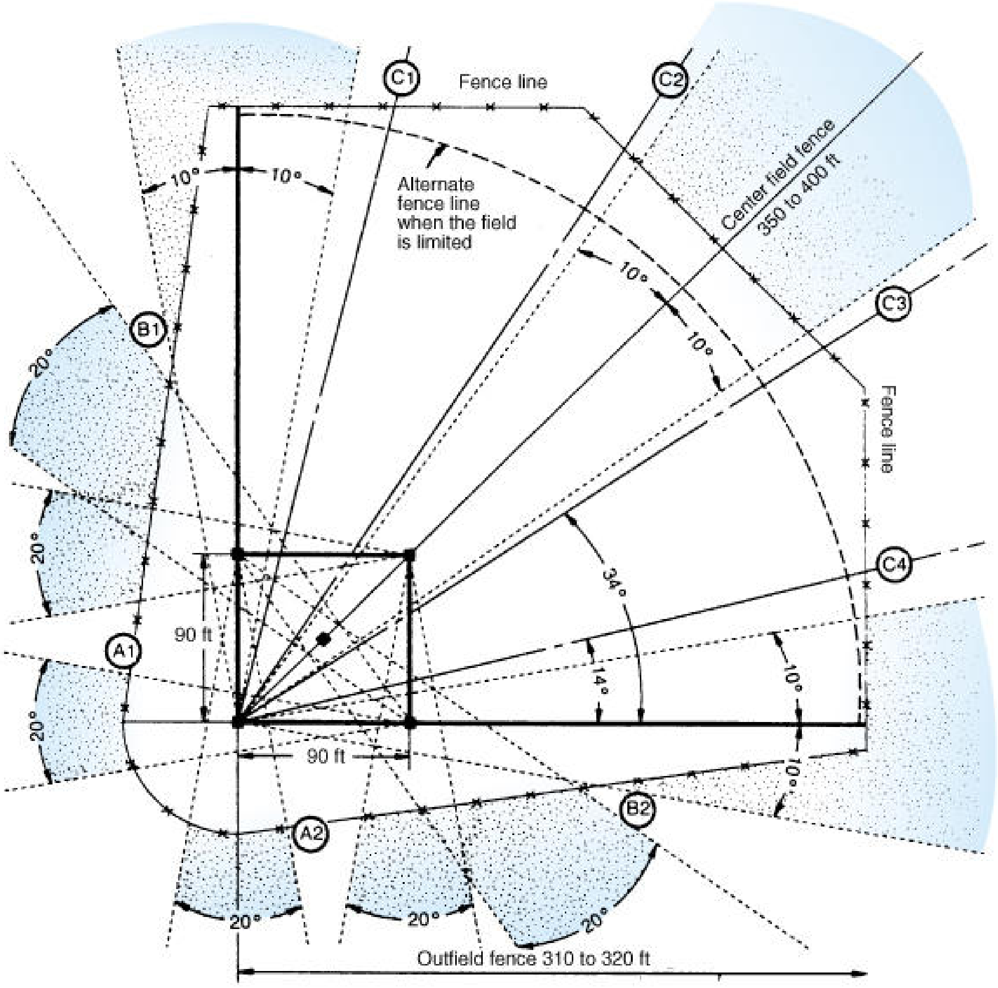


Figure 20-14. Recommended location of poles for a regulation-size baseball field. Shaded area indicates critical glare zone where poles should not be located.

ILLUMINANCE RECOMMENDATIONS

It is important that illuminances be sufficient for comfortable and accurate seeing by the players, the spectators, and the television viewers. In those sports where large numbers of spectators are expected, as in large football and baseball stadiums, the illuminance required is the amount for the spectators seated farthest from the playing area to follow the course of play. This condition may require several times the amount of light found satisfactory to the players. The recommended illuminances are those that are currently considered good practice, taking into consideration both players and up to 10,000 spectators.

Professional sports in facilities designed for more than 10,000 spectators require higher illuminances than those recommended in the tables. For example, current practice for National Football League (NFL) facilities is 2000 lx (200 fc) vertical and 3000 lx (300 fc) horizontal, and for the National Basketball Association (NBA) is 1250 lx (125 fc) vertical and 2500 lx (250 fc) horizontal.

The recommended illuminances are in most cases stated as horizontal illuminances in service. It is recognized that the vertical component of the illumination on the playing area is important in most sports. This is particularly true in the aerial games, where both players and spectators rely to a considerable degree on the vertical illumination on or near the playing area, and in some cases well above the playing area. The vertical components of illuminance usually have been found adequate where the horizontal illuminances meet the values in the table, except where noted otherwise, and the lighting equipment is positioned at mounting heights and locations conforming to accepted good practice. Careful attention should also be paid to the quality factors outlined at the beginning of this chapter and described in Chapter 10, Quality of the Visual Environment.

FLOODLIGHT AIMING

Aiming floodlights is the final step in completing a floodlighting installation. Only with proper aiming can the original design objectives for illuminances and uniformity be met.

Aiming Methods

There are two methods used for floodlight aiming: target aiming, where the floodlights are in place, and degree aiming, where the floodlights are present on poles, usually prior to poles being installed.

Target Aiming. For target aiming, the primary playing area (PPA) to be lighted is divided into a uniform grid. Targets large enough to be seen from the floodlight location are placed on the grid line intersections or at the center of each grid area. The grids are identified with the actual field dimensions from a given reference point.

Degree Aiming. Degree or present aiming orients the floodlight by setting a horizontal and vertical protractor supplied with the floodlight. The angles must be set in reference to one of the field dimensions. Normally, the horizontal degree setting is defined with 0° along the line drawn perpendicular to the sideline of the field. For baseball outfield poles, 0° is along the line drawn from the pole to home plate. The vertical setting is based on 0° being directly below the floodlight. Degree aiming is less accurate than target aiming and normally is not used for larger fields.

Aiming Considerations

The following guidelines should be considered when aiming floodlights:

- The lighting design practitioner should be familiar with the intensity distributions of the floodlights, because these are critical in determining the illuminance and amount of spill light.
- The initial aiming may often be accomplished by aiming consecutive floodlights so that the angular positions of the half-maximum candlepower points coincide.
- In general it has been found that the actual final aiming points needed to achieve the expected illuminances over the playing field tend to be farther from the poles than the calculations predict.
- The presence of television cameras or spectators may influence the aiming selection. Television cameras and spectators require a greater degree of vertical illuminance than may be necessary just to meet the horizontal illuminance criterion.
- All systems should be fine-tuned after the aiming is complete. The fewer the floodlights, the greater the need to make adjustments.

Recommended Illuminances for Sports

The recommended illuminance values for popular indoor sports are given in Figure 20-2a. All illuminance values are target values. It should be noted that the recommended value for underwater illumination is in lumens per square meter (or square foot) of swimming surface area. The reader should refer to IES Publication RP-6[1] for additional recommendations.

LIGHTING ECONOMICS

Lighting design should be evaluated in terms of its economic feasibility. Analysis of costs associated with the design, purchase, ownership, and operation of a lighting system assists in comparing alternatives. Analysis should also include evaluating maintenance techniques and procedures, determining the effect of lighting on other building systems, budgeting and cash flow planning, and cost-benefit evaluation. See Chapter 25, Lighting Economics, for more details on economic analysis in lighting applications.

FIELD MEASUREMENTS AND PERFORMANCE EVALUATIONS

To evaluate the actual performance of a lighting installation in comparison with the design intent, illuminances and uniformity measurements should be made. For complete report procedures and measurement layouts, see LM-5-96[12] and Chapter 2, Measurement of Light and Other Radiant Energy.

Field Verification

Every sports lighting installation must be verified by a site survey to achieve the following three objectives:

- Confirm performance of the luminaires, the electrical system, and the accuracy of the aiming.
- Provide the owner with a benchmark for future evaluation of maintenance programs and their effectiveness.
- Provide the lighting design practitioner feedback on the accuracy and effectiveness of the designs for evaluation.

The values measured in the site survey vary from the laboratory photometry and computer calculations. This is due to the many uncontrollable factors, such as product tolerance, electrical power variations, and errors in aiming the floodlights. (See Lighting Operating Factors for Installed HID Luminaires, LM-61-96,[11] and Chapter 6, Light Sources). Every effort should be made to keep these inaccuracies to a minimum and to record all conditions so that a proper evaluation can be made. The following is a checklist for field verification or survey. Refer to Chapter 6, Light Sources, regarding product tolerance guidelines.

- All luminaires should be operating and properly aimed.
- HID lamps should have been operating for 50 to 100 hours prior to testing. If the lamps and luminaires have been operated for substantially more than 100 hours, the approximate operating hours should be recorded (see Lamp Seasoning in LM-54-91[13], and Chapter 6, Light Sources).
- For HID lamps, the system should be turned on at least 30 min prior to testing.
- Tests should be taken when the air is clear and extraneous light is at a minimum.
- Care should be taken that the operator and other test personnel do not cast shadows or reflected light from clothing on the measurement instruments.
- The photometer should be of good quality and accuracy, either recently calibrated or with its accuracy otherwise verified. The meter should also be cosine corrected for incident light up to an incident angle of 80°.

The measurement record should include the following information:

- Name of the installation
- Date and time of the measurements
- Description of the illumination system, including luminaire and lamp type, mounting heights, quantities, and other pertinent details
- Age of the system and number of operating hours since the last lamp change
- Type, make, and serial number of the photometer, and date and source of the calibration

Evaluation of the Measured Results

Plans or other design documents should show the computer-predicted performance of the installation, including the calculated mean, the calculated coefficient of variation (CV), LLF, and maintained illuminances. A variation between predicted performance and the actual site survey results is to be expected. However, the actual results should be within plus or minus ten percent of the predictions. Corrective actions should be taken to bring the installation into conformance with the expectations.

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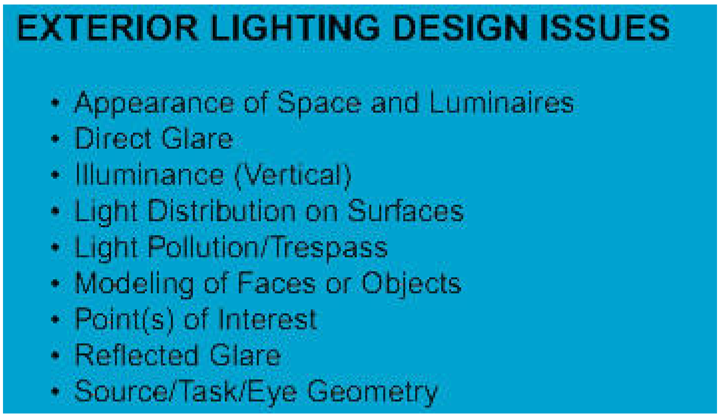
21

Exterior Lighting



EXTERIOR LIGHTING DESIGN ISSUES

- Appearance of Space and Luminaires
- Direct Glare
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Light Pollution/Trespass
- Modeling of Faces or Objects
- Point(s) of Interest
- Reflected Glare
- Source/Task/Eye Geometry

Lighting the outdoor environment is different from lighting an interior space. Outdoors, the universal standard is the daytime sun and sky. The night outdoor environment presents the following design challenges:

- Electric lighting cannot light the sky as the sun does; therefore, the nighttime ceiling is always dark, often resulting in greater object contrasts.
- No single fabricated light source is as powerful as the sun; numerous, smaller sources in close proximity to the objects and area being illuminated must be used.
- At low light levels the eye works differently from the way it works at high daylight light levels.
- People experience different emotions at night. Lighting can affect these emotions, not only when viewing dramatic scenery, sporting events, and outdoor entertainment, but it also affects feelings of personal safety and security such as in a parking lot.
- Outdoor lighting can be seen at great distances, and nighttime visual clutter can be distracting and disturbing.
- Nighttime tasks, such as playing sports or driving automobiles, have very specific lighting requirements so people can perform these tasks safely and effectively.
- There is an expectation (or need) to control the light added to the outdoor environment. Some people want the dark for sleeping, star-gazing, or privacy. This need for darkness comes in close proximity to other people's need for light, making the optical control of light critical.

This chapter provides guidance in dealing with the preceding design considerations, allowing electric lighting systems to solve multiple design objectives. See Chapter 22, Roadway Lighting, and Chapter 20, Sports and Recreational Area Lighting, and the appropriate IESNA Recommended Practices[1-5] for additional information about specific outdoor lighting applications.

VISUAL ISSUES

The design issues surrounding outdoor lighting are complex. Some of the technical factors that need to be considered when designing and evaluating an exterior lighting system include glare, visibility, color, illuminance, luminance, and brightness.

Glare

Glare can be disabling, discomforting, or simply a nuisance (Figure 21-1).

Disability glare is caused by stray light scattered within the eye, which reduces the contrast of the retinal image. Streetlights, pedestrian lights, floodlights, and landscape lights, as well as bright reflectors contribute to disability glare.

Figure 21-1. Wet roadway surfaces, reflecting light from streetlights and oncoming traffic, will produce glare that can make night time driving difficult and possibly treacherous.

Discomfort glare from a light source produces a sensation of discomfort. It is caused by high contrast or a non-uniform distribution of luminance in the field of view. Discomfort glare can be reduced by decreasing the luminance of the light source, by increasing the background luminance around the source, or by adjusting the aiming angle.

Nuisance or annoyance glare has not been quantified, though research is ongoing. Essentially, nuisance glare occurs when light appears where is does not belong. It may be defined as glare that causes complaints, such as the "light shining in my window" phenomenon.

The Operating State of the Visual System

In exterior environments, the human eye's processes of visual adaptation and recognition operate in three categories of vision: photopic, scotopic, and mesopic. These categories are defined with reference to the adaptive state of the rod and cone photoreceptors (see Chapter 3, Vision and Perception). Under photopic conditions, above approximately 30 lx, only the cones are active for visual perception. Under scotopic conditions, below approximately 0.01 lx, only rods are active. Scotopic conditions are generally irrelevant for photopic conditions. Under mesopic conditions, between photopic and scotopic conditions, both rods and cones operate.

It should be noted that the fovea contains only cones and therefore is photopic under any light level.[6,7] The majority of exterior lighting conditions are mesopic (see Chapter 3, Vision and Perception).

Illuminance

Illuminance (in lux or footcandles) is a measure of flux density incident on a surface. Too often illuminance is the only metric used to design and evaluate exterior environments. It is strongly recommended that all the factors described in Chapter 10, Quality of the Visual Environment, and in this chapter, be included in every exterior lighting design.

Luminance and Brightness

Often, the terms "brightness" and "luminance" are used interchangeably, but they have different meanings. The luminance of a source or surface is the intensity of the source or surface in the direction of an observer. Brightness is what an individual sees or perceives largely as a result of the luminance of the source or surface.

Source size, temporal frequency (flash or flicker), and spectral power distribution (color) also affect perceived brightness. Subjective brightness is affected by the environment in which the luminaire resides. As the background luminance of a scene increases, the subjective brightness of a luminaire decreases. Viewing car headlights during the daytime is a good example of a situation involving high luminance but low subjective brightness. Also, due to the subjective nature of a lighting scene, one person may feel a particular luminaire is bright while another person may not.

Figure 21-2. The lighting for this church uses varied surface brightness to add interest and depth.

Surface luminance and source luminance are two important factors in the outdoor environment. Examples of lighted horizontal surfaces outdoors are roadways, bike paths, sidewalks, and parking lots. Lighted vertical surfaces include people's faces and bodies, building facades, signs, structures, statues, and landscape features such as trees. Surface luminance adds interest and depth to an outdoor scene and can be necessary for good outdoor visibility and security (Figure 21-2). It is important to see the *effect* of lighting, not the source.

Luminaire luminance results from not only the lamp but also the luminaire's reflector, refractor, lens, or louver. In order to minimize glare, luminaire luminance in the typical direction of view should be minimized. Typical viewing angles lie between 45°and 85°. Luminance data indicate the brightness of some outdoor luminaires. Luminances from bollards, landscape lights, and floodlights should be low to attract minimal attention.

Luminaires that produce high-angle light (at a vertical angle 80° above nadir) can improve visibility and elicit feelings of safety by delivering high vertical illuminances on people, buildings, and scenery. Higher-angle light can also yield a more economical installation with wider spacings and fewer poles. However, this approach contributes to glare, especially with low mounting heights and high lumen packages. Even so-called full cutoff luminaires can produce excessive luminances if poorly designed. At the same time, noncutoff luminaires can be comfortable to view. As designers specify cutoff, semicutoff, or noncutoff luminaires, attention should be paid to the luminaire's luminance and potential for excessive brightness.

Luminance Ratios. Excessive luminance differences between surfaces or areas within the field of view can reduce the ability to see a task, create a safety hazard, cause an annoyance, or disrupt the theme of a community.

Consideration of safety, visibility, annoyance, and community appropriateness in exterior lighting designs suggests the importance of establishing luminance ratio criteria for the site being lighted or for the community. These ratios should set the maximum permissible luminance levels between the site being illuminated and neighboring sites from which that site might be viewed. As a general rule, the luminance ratios should not exceed 20:1. However, flexibility with this value should be used. A community may opt for lower or higher luminance ratios in order to preserve lower overall lighting levels. An urban community may opt to permit higher luminance ratios in order to provide flexibility in facade and advertising lighting.

Figure 21-3. The height and location of poles contributes to the hierarchy of exterior lighting equipment along this street.

As the scene's background luminance changes from light surroundings (urban scenes) to darker surroundings (suburban scenes) to the darkest surroundings (rural scenes), luminaire luminance is more and more important. The relationships between adjacent luminances in the field of view (luminance ratios) indicate how the visual system perceives luminaire brightness.

The interaction of all the variables discussed above leads to the final perception of brightness. Because of its subjective nature, brightness is difficult (if not impossible) to measure. A mock-up of the scene or examination of an existing site can be helpful in predicting the final impressions of the scene.

COMMUNITY-RESPONSIVE DESIGN

Traditionally, street lighting has been the basic component of public outdoor lighting. In urban settings, it is the street lighting, along with traffic signals and signs, that organizes and defines the visual environment at night. The quality of this visual information is critical for both traffic safety and a pedestrian's sense of security.

Public lighting systems can help define urban character and image. These lighting systems may illuminate for streets, roadways, sidewalks, pedestrian malls, pathways, bikeways, parks, monuments, buildings, structures, statues, fountains, and landscapes. A hierarchy of public lighting connotes the relative importance and character of cityscapes and enhances their information-giving value. The height and location of poles and the size and shape of equipment all contribute to the lighting hierarchy (Figure 21-3).

Special features and amenities of urban environments should be lighted to reveal their importance. Buildings and monuments can serve as markers or reference points to provide visual orientation. Urban landscape elements can also act as visual anchors and serve as points of arrival for neighborhood residents. Consistency and coordination applied to lighting special features strengthens a public lighting design and can improve the sense of community. Also, the streetscape or pedestrian spaces should appear consistent with the community theme, both day and night so the lighting equipment should be integrated into the daytime scenes (Figures 21-4 and 21-5).

Figure 21-4. Uncluttered and well-integrated luminaires with a streetscape.

Figure 21-5. The same uncluttered lighting scene as that shown in Figure 21-4.

Figure 21-6. Extreme glare will cause a loss of visibility.

There are seven steps (see IESNA RP-33[8]) that comprise an effective community-responsive design process for implementing a public lighting system.

1. Determine community lighting goals. List and prioritize community goals such as aesthetics, community identity, safety, security, crime prevention, light pollution, light trespass, equipment location, equipment appearance, energy effectiveness, and economics.

2. Determine a community theme. Establish the style of lighting desired, such as historical, modern, active, or subdued. The theme should relate to the architectural style of the area.

3 Develop a family of luminaires. Select luminaires that complement the community theme. Establish pole styles and mounting heights. Develop a hierarchy of luminaires matching the application.

4. Consider how luminance ratios impact visibility. Luminance ratios should not exceed 20:1 between primary focal point and general surround, but lower ratios can be established for adjacent areas (e.g., advertising signs and pedestrian malls) through the design process.

5. Determine how luminaire luminances affect perceptions of the environment. High luminances projected directly from luminaires and excessive luminance differences between surfaces and areas within the field of view can be distracting, uncomfortable, and even disabling.

6. Provide design guidelines. Design guidelines that establish the steps for planning public and private lighting (residential and commercial) for communities, owners, and developers. These guidelines should explain community themes and goals, including the family of luminaires or related families for different districts selected to provide visual consistency and set the standard for construction and glare control.

7. Educate developers of lighting ordinances. Consideration might be given to developing a lighting ordinance in areas where light trespass or light pollution are important to the community.

SAFETY AND SECURITY LIGHTING

Safety can be defined as freedom from danger, whereas security is freedom from worry. Security is often considered the psychological version of safety. Features of the environment that compromise safety can be identified and illuminated, but because security involves psychology as well as vision, it is a more difficult design criterion for exterior lighting. In general, comfortable, well-defined exterior environments with clear zones of recognition are perceived as secure. This design approach provides a feeling that there is enough response time to avoid or escape potential threats. People often associate higher illuminance or greater luminance with safer surrounds, but poorly directed light can reduce visibility and thereby reduce both safety and security (Figure 21-6). For additional information, see Chapter 29, Emergency, Safety, and Security Lighting.

Figure 21-7. Effective hazard lighting on stairs. This lighting is unidirectional, emphasizing stair treads.

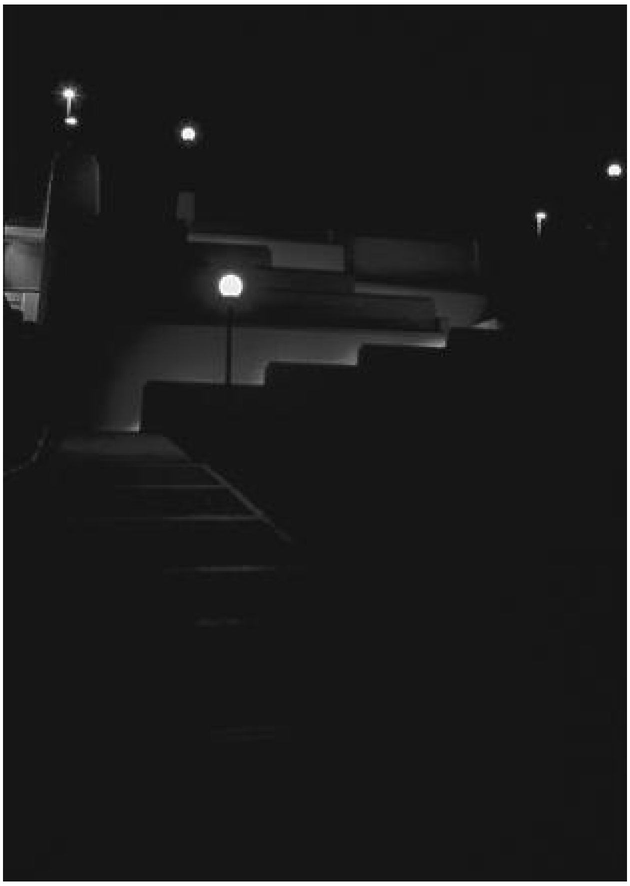


Figure 21-8. Layered lighting emphasizing the stair hazard with silhouette outlining.

Figure 21-9. A satellite view of North America at night illustrates the magnitude of direct and reflected light from urban areas.

Successful exterior lighting employs layers of light. Layered lighting provides minimal ambient illumination with accents on hazards, destinations, and architectural features. Sidewalks, trees, and building facades can be used as reference points and backdrops for such important features as crosswalks and intersections on roadways, or stairs and changes in elevation on pathways (Figure 21-7). Highlights can also be provided on gathering places and on interesting features such as bridges, statues, or plantings. Layered lighting defines the spatial characteristics of the environment and helps minimize dark areas that would otherwise serve as areas of concealment (Figure 21-8).

Streets, of course, are important features to be illuminated at night. They should be illuminated according to IESNA recommendations.[2] Special consideration should be given to illuminating vertical surfaces where pedestrians and automobiles intermingle. The reflected light from vertical surfaces helps illuminate the pedestrians sharing the roadway with the automobiles. This same technique is useful in pedestrian parks and on pathways. Face recognition and identification is extremely important to a pedestrian's sense of security, and vertical illumination is essential to achieving this design objective.

UNWANTED LIGHT AT NIGHT

Light Pollution

Dust, water vapor, and other particles reflect and scatter light that is emitted into the atmosphere. The result is the sky glow found over all urban areas, sometimes called atmospheric or astronomical light pollution (Figure 21-9). Although this sky glow is not injurious, it does deprive urban residents of the opportunity to stargaze and can hamper astronomers' attempts to view the night sky through telescopes.

Light pollution is of special concern in areas near astronomical observatories. Professional astronomers prefer that low-pressure sodium be used outdoors because most unwanted light, which is essentially monochromatic, can be removed by filtering the light that enters their instruments. The methods that best control light pollution are:

- Limit flux above horizontal. Street and area-lighting systems, including lighting for sports activities, parking lots, and vehicle sales lots, should be designed to minimize or eliminate direct upward flux emission. A full cutoff luminaire does not emit light above the horizontal plane.
- Minimize non-target illumination. Lighting systems that project light upward, such as architectural and sign lighting, should be designed to minimize light that does not illuminate the target area.
- Turn off outdoor lighting during times of low use. Designers should discuss with owners turning off some or all of the outdoor lighting, including advertising sign lighting, building elevation lighting, and interior high-rise office building lighting, after normal hours of operation or before midnight unless needed for safety and security.

Light Trespass

The topic of light trespass is somewhat subjective, because it often relates to unmeasurable and undefinable factors. A typical example is the "light shining in my window" complaint (Figure 21-10). A simple solution to this problem is to shield the offending luminaire so that its luminance is not directed toward the complainant.

Light trespass usually falls into one of two categories: unwanted light received in adjacent properties (high illuminance levels), and excessive brightness occurring in the normal field of vision (nuisance glare). Efforts have been made in numerous jurisdictions to write ordinances or laws controlling light trespass. Laws defining vertical and horizontal illuminance address only the former problem. See RP-33[8] for a more complete discussion of lighting ordinances.

Figure 21-10. The wall-pack lighting causes light trespass into the building's windows.

The following suggestions help control light trespass problems, including nuisance glare:

- Inspect areas adjacent to the lighting design location to identify and consider any potential problems involving residences, roadways, and airports.
- Select luminaires that have tightly controlled intensity distributions, using full cutoff reflectors and refractors.
- Contain light within the design area by carefully selecting, locating, mounting, and aiming (when appropriate) the luminaires.
- Use well-shielded luminaires (or select equipment that can be shielded) if a potential problem is found after installation.
- Keep floodlight aiming angles low so that the entire beam always falls within the intended lighted area during (and after) the design and installation process.

See RP-33[8] for a more complete discussion of light trespass.

LIGHT SOURCES AND BALLASTS

Light sources for illuminating outdoor environments should be selected according to their application. If color rendering is important, then a light source with a high color rendering index (CRI) and appropriate correlated color temperature (CCT) is important. See Chapter 6, Light Sources, for more information on light sources.

Lamps should be selected that have lumen maintenance and rated life commensurate with the lighting installation's mission, the degree of difficulty involved in relamping, and the lamp maintenance schedule. A high crime area, for example, should emphasize color rendering, lamp life, and lumen maintenance.

Proper ballast selection is crucial. Select and specify ballasts that match the lamp and make sure that the starting temperature of the ballast is at or below the coldest winter temperature for the site. See reference 9 for a comprehensive discussion of ballasts.

LUMINAIRE CLASSIFICATION

Outdoor luminaires are classified by the manner in which they are mounted, by the intensity distribution they exhibit, by the degree to which they provide cutoff, and, if floodlights, by their beam patterns. See also Chapter 7, Luminaires, for additional information.

Pole-Mounted Luminaires

Pole-mounted luminaires are commonly used for roadway and parking lot lighting. The IESNA outdoor roadway luminaire classifications by intensity distributions are Type I, II, III, IV, and V. Degrees of cutoff are full cutoff, semicutoff, and noncutoff. A description of these classifications can be found in Chapter 22, Roadway Lighting.

One of the most common luminaires used in roadway applications employs a dropped-dish (ovate) refractor. These luminaires typically produce wide light intensity distributions, which permit extended pole spacing. In most cases, average horizontal illuminance and uniform horizontal illuminance are among the most important design criteria. Therefore, the luminaire intensity distributions used exhibit maximum values at high angles above nadir (typically 65° to 70°).

These luminaires are mounted on brackets off a vertical support pole. Based on appearance, they are generically referred to as cobra-head luminaires. Poles for roadway lighting applications are usually mounted back from the roadside to minimize collision with traffic. As stated previously in the section "Luminance and Brightness," care should be taken to prevent excessive brightness. Cutoff cobra-head luminaires with flat lenses that provide better optical control are an alternative.

Parking lot lighting often uses cutoff luminaires with either flat-bottomed or clear dropped lenses. A dropped lens generally yields a slightly more efficient optical system, but higher glare. These luminaires are mounted on short arms and can be arranged in single, twin, or quad configurations. Symmetric and asymmetric distributions and mounting schemes are used to provide the necessary flexibility in pole placement for parking lots.

Small luminaires mounted on short poles can be used to provide walkway and grounds lighting. Sometimes referred to as post-top luminaires, they can satisfy both functional and aesthetic needs.

Surface-Mounted Luminaires

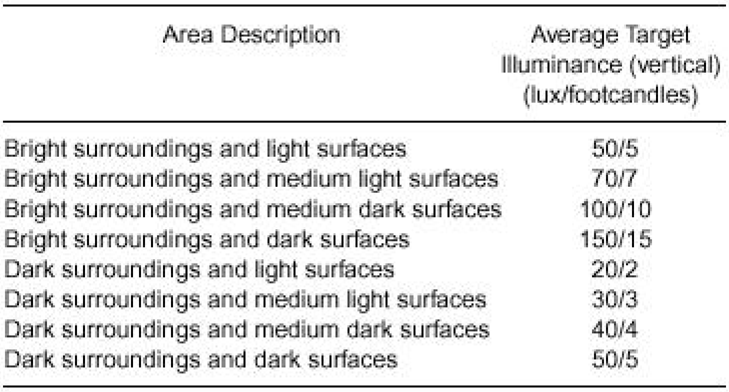
Wall-mounted luminaires are often used for small parking lots or walkways adjacent to a building or inside parking structures. These luminaires usually have an asymmetric distribution necessary for lighting adjacent areas.

Surface-mounted luminaires are mounted on walls or ceilings of parking structures, and their lighting performance is enhanced by interreflection within the structure. Care should be taken to use wall-mounted and ceiling-mounted luminaires that distribute light onto surfaces without glare to motorists or pedestrians.

Bollard Luminaires

Walkway and grounds lighting is often accomplished with bollards. These luminaires have the appearance of a short, thick post, similar to those found on a ship or wharf, hence the name (Figure 21-11). The optical components, usually top mounted, produce an illuminated area in the immediate vicinity. Thus bollards are used for localized lighting, because their size is appropriate to the architectural scale of walkways and other pedestrian areas. They are not satisfactory as the only source of illumination because they do not provide illuminance to higher vertical surfaces, such as faces.

Figure 21-11. Bollard luminaires illuminate the immediate surroundings in a docking area.



Area Description	Average Target Illuminance (vertical) (lux/footcandles)
Bright surroundings and light surfaces	50/5
Bright surroundings and medium light surfaces	70/7
Bright surroundings and medium dark surfaces	100/10
Bright surroundings and dark surfaces	150/15
Dark surroundings and light surfaces	20/2
Dark surroundings and medium light surfaces	30/3
Dark surroundings and medium dark surfaces	40/4
Dark surroundings and dark surfaces	50/5

Figure 21-12. Illuminances for Floodlighting Building and Monuments

Floodlight Luminaires

Floodlights are the most common type of luminaire used for sports lighting. Several types of floodlights are in common use for this application, including enclosed rectangular floodlights, enclosed round floodlights, shielded floodlights, and reflectorized lamps. The National Electrical Manufacturers' Association (NEMA) field angle is widely used by the lighting industry to classify the overall intensity distribution pattern of a floodlight. The NEMA classification is also useful to the designer for making preliminary design selections. See Chapter 20, Sports and Recreational Area Lighting, for a discussion of floodlight types and NEMA beam angles.

Building facade lighting, sports lighting, and other special applications often use floodlight luminaires. See Figure 21-12 for information on illuminances for lighting buildings and monuments. These applications can have wide-ranging intensity distributions (from narrow to very broad), depending on the angular size of the object being illuminated and the desired effect. Floodlight intensity distributions are usually not symmetric. Floodlights should have glare shielding (external or internal shields) to prevent light trespass and light pollution.

Building facade lighting uses luminaires with narrow and wide intensity distributions, depending on what portion of the building is being illuminated and the distance to the luminaire's mounting location. Column lighting, accent lighting, and distant mounting locations all require narrow distributions. Illuminating large areas from nearby locations requires very wide distributions. In these situations, the chosen luminaire often has an intensity distribution that produces a square or rectangular illuminance pattern.

Sports lighting often uses luminaires with very narrow intensity distributions, mounted to the side of the playing area, and luminaires with medium intensity distributions (and short cutoffs), mounted over the playing area. The use of the narrow-intensity-distribution luminaires almost always requires careful computations during design to correct horizontal and vertical illuminance levels and uniformities.

Floodlight luminaire mounting usually includes a mechanical arrangement that permits aiming. Such luminaires are often grouped in banks, since their application usually involves limited mounting and access availability. However, each luminaire is aimed independently. Both sports and building facade floodlight luminaires require careful aiming during installation and locking of all movable fixture components to retain aiming. For more information, see Chapter 20, Sports and Recreational Area Lighting.

Application-Sensitive Choices

When specifying luminaires, select those that are suitably rugged for the application, adapted to the environment, and designed to give years of trouble-free service. As an example, when luminaire doors, lenses, or globes are involved, their latching or securing mechanisms should be capable of proper resealing after repeated relampings. Luminaires with air-filtering devices can maintain clear optic chambers despite dirty environments. Insect accumulation on interior optical surfaces may seem inevitable, but a well-designed door and continuous gasketing system can greatly reduce this problem. Whenever possible, luminaire components should be captive. Juggling glass, frames, nuts, and bolts creates an unnecessary burden for relampers on ladders or in bucket trucks. Luminaires selected for high vandalism areas should be mounted out of harm's way or rated to withstand heavy physical abuse. Luminaires installed in a seaside setting must be made of materials that withstand the ravages of salt air. The selection of high-quality luminaires may involve a higher initial cost, but the investment is returned in reduced maintenance costs and increased reliability.

Any lighting equipment installed underwater must be accompanied by a maintenance commitment, because servicing is complicated. Fiber optics in swimming pools, building facades, signage systems, and an increasing number of other applications can deliver convenient light source locations, reduced maintenance costs, and increased reliability.

ENERGY CONSERVATION AND MAINTENANCE ISSUES

Even a perfectly designed and installed outdoor lighting installation does not provide design illumination levels continually. Lamps lose their efficacy and ultimately fail. Dirt and insects accumulate on light sources and optical surfaces. In addition, luminaire aiming may be disturbed due to vibration, pole-foundation settling, vehicle collisions, or routine maintenance. Sometimes plant growth can block a luminaire's intended distribution.

Properly maintained equipment results in a functional lighting system that suffers little from wasted power, misaligned luminaires, and lamp burn-outs (see Chapter 26, Energy Management). When outdoor lighting equipment is operating as designed, it suggests civic pride and a continuing concern about public safety and security.

Planned Accessibility

Good maintenance starts in the design phase and includes more than just keeping the luminaires clean and relamped. Important decisions affecting maintenance include selecting the proper luminaire, lamp, and other system components; accommodating luminaire accessibility; and considering the level of system maintenance that will actually be implemented.

Lighting system designs should be considered in realistic rather than optimistic terms when selecting maintenance factors that truly represent the lamp and luminaire lumen maintenance characteristics, ambient conditions (e.g., operating temperatures, the presence of air-entrained particulate matter), and the proposed relamping and luminaire cleaning schedule.

Pole Mounting. When laying out pole locations, especially aluminum standards, place poles on pedestals or mount them away from vehicular traffic. Always check the local department of transportation's setback requirements for poles adjacent to vehicular travelways. Break-away pole bases should not be used near pedestrian traffic since falling poles could inflict major injuries and property damage. Elsewhere, poles may include the use of 760 mm [30 in.] high pedestals to minimize pole damage from car bumpers.

The specification of suitably sized foundations and piers to accommodate soil conditions, pole and luminaire configuration, and ice and wind loadings is vital because replacement costs for downed poles are high, and a fallen pole obviously does not perform its lighting mission. Pole-mounted luminaires can become misaligned if the support pole is nudged by a vehicle. Misaligned poles may not place light where it is needed and may contribute to unanticipated light trespass.

Other Mounting Systems. Bollards, if improperly placed, can be vulnerable to damage from snow removal equipment, lawn maintenance equipment, and vehicles such as bicycles and golf carts. Bollards should be installed on low bases, or surrounded by edging or mulch to reduce the chance that lawn maintenance equipment or snow plows come into contact with them. Because of their low mounting height, bollards can be particularly vulnerable to vandalism. Care should be exercised to select rugged, vandal-proof luminaire construction for public settings.

Step lights, if improperly specified and maintained, can be rendered useless over time and fail to properly perform their important safety function. Because step lights in public spaces are easily accessed, they should be specified with tamper-proof hardware. Their bodies should have a construction and finish suitable for the application (e.g., corrosion resistance, preferably using a tempered-glass face). Placing step lights off to the side of the riser (rather than on the face) helps minimize opportunities for physical damage.

Uplights, especially when recessed into the ground, present a particularly difficult maintenance challenge. Fallen leaves, foliage, mud spatter, and other debris can quickly reduce an installation's effectiveness. Spreading foliage must be kept trimmed, and suitable mulch may be required around the luminaires to prevent mud spatter. The lens of any uplight recessed into a sidewalk can quickly become scratched, reducing its light output. Light-attracted insects can quickly build into a thick layer, blocking light output and trapping heat. Adequate gasketing is essential for these luminaires. Anti-flotation methods may be required for installations in marshy areas. Uplight housings should be specified that are impervious to prevailing local conditions such as soil acidity (or alkalinity), corrosive elements, and moisture.

Installations that Complement Maintenance

Several steps can be taken during installation to facilitate the future maintenance process:

- Mount the ground-based equipment where it is accessible for easy inspection and maintenance.
- Clearly label all switching devices such as breakers, contractors, and switches regarding the circuits and equipment they control.
- Except under rare circumstances, run luminaire feeds underground in conduit. Avoid using overhead wiring.
- Securely fasten and tighten all luminaire components and aiming devices.
- Thoroughly test the equipment to make sure it is operating as specified.

Maintaining System Operation

Following the preceding steps during design and installation should result in a lighting installation that employs components and layouts that facilitate regular upkeep. This must be coupled with a maintenance program during normal operation that ensures that the installation continues functioning in accordance with the original design criteria. See Chapter 28, Lighting Maintenance, for a general discussion of lighting maintenance.

Maintenance Program Choices. The facility manager should establish a periodic relamping and cleaning program and decide whether to perform the maintenance in-house or hire outside contractors. Specialty contractors, who have the proper expertise and equipment to reach high-mounted luminaires and replace faulty components, are available.

Consideration should be given to both spot and group relamping programs. Spot relamping involves replacing each lamp when it burns out. With group relamping, all lamps are replaced after a predetermined operating period or when a predetermined percentage of the lamps are burned out. Spot relamping of critical lamps may still be required between regularly scheduled group relampings.

Lamp lumen depreciation also must be considered in determining the relamping schedule. In the long term, a combined relamping and luminaire cleaning program can be more cost effective than climbing a ladder, rolling out a bucket truck, or calling a contractor every time a lamp burns out. Planned periodic maintenance keeps the luminaires operating efficiently at design illuminances and prevents burnouts from forming dark patches in the lighting installation, which can cause significant safety and security hazards.

Certain lamp types, such as mercury vapor, continue to emit some light long after they need replacement. High pressure sodium ballasts continually restrike failed lamps. If ignored, this restriking can cause ballast failure. Relamping should not await burnout or failure but should be performed whenever illuminances fall below the design level.

Optimum Relamping. Regardless of the relamping scheme employed, several precautions must be taken during the relamping process. Lamp manufacturers give specific warnings about the operation and treatment of their lamps, and such warnings must be heeded. There are many discrete variations between lamps, such as the lamp's orientation in the luminaire, that can significantly influence its operation.

Always be sure that the replacement lamp has exactly the same catalog nomenclature, including CCT and coating characteristics, as the lamp being replaced. Failure to match the original lamp characteristics exactly may result in reduced light output, reduced lamp life, reduced lumen maintenance, and even violent failure of the lamp or ballast.

Be aware that the envelopes of standard tungsten-halogen lamps and certain high intensity discharge lamps are especially vulnerable to contamination from skin oils. This means that direct finger contact with the new lamp during relamping must be avoided. Failure to avoid such contact could result in reduced lamp life.

After an old lamp has been replaced, take care that the luminaire's sealing and gasketing devices have been returned to their proper location, and that all fastening devices are properly seated and functioning as intended. This prevents foreign materials from entering the luminaire and keeps wind or vibration from subsequently dislodging components such as an optical assembly or globe. Also check that all mounting hardware is secure and that any aiming device alignments are verified. This ensures that no luminaire misalignment occurs during relamping.

Automatic Switching Devices. Photocontrols, time clocks, and motion detectors can operate luminaires only when they are needed, thereby contributing to lighting system longevity. Such devices, however, are not maintenance free. Malfunction can cause the lighting installation to be on during the day or off during hours of darkness, defeating the energy-saving mission and expectations that light trespass/pollution will be reduced. All automatic switching should be checked regularly for proper functionality, and then adjusted, repaired, or replaced as appropriate.

Trees and Shrubs. Tree and shrub growth around a lighting installation acts as a barrier that may prevent light from reaching the intended area. Even perfectly operating luminaires can leave streets or sidewalks unacceptably illuminated unless the blocking vegetation is pruned periodically.

Sometimes plants are purposely used to reduce or eliminate light trespass. Vegetation is constantly changing, however; trees and bushes die, the seasons determine leaf population, branches break off, and growth eventually places most tree leaves well above the luminaires they are supposed to be shielding. The best solution is to incorporate light-trespass controls into the lighting design through proper luminaire selection, placement, shielding, and aiming rather than relying on living screens.

Where it is not possible to incorporate certain glare control devices into the lighting design, any vegetation used against light trespass should be carefully maintained through the timely replacement of dead, dying, or rangy growths. Summer versus winter foliage variation must also be considered. Pine and other coniferous trees are usually effective as living screens.

STRUCTURE LIGHTING

During clear days, structures are lighted with strong, direct light from the sun. The sun casts deep shadows from every textured detail on an edifice. As the day progresses, the structure's image continuously evolves, even into the reddening, horizontal light of a sunset. On overcast days, shadows diminish from the flat light.

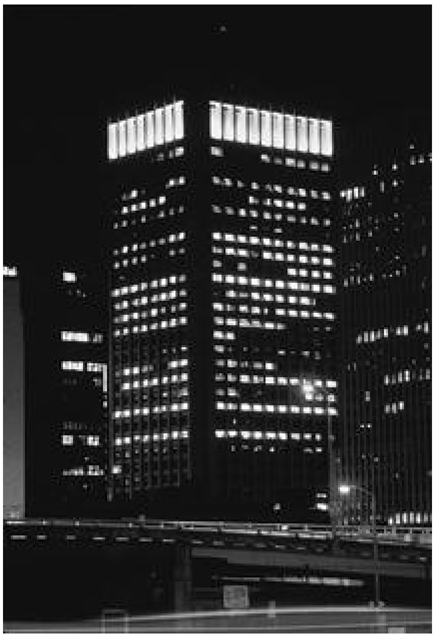


Figure 21-13. Architectural lighting can emphasize an exterior's vertical structural elements.

At night, structures look completely different from their daytime appearance. It is impossible to duplicate the intense sunlight and daylighting effects. Electric lighting brings its own unique element to the nighttime scene. The lighting designer's challenge is to define and enhance the building appearance, adding ambiance to the night scene (Figure 21-13).

Structure lighting serves many purposes and communicates prestige, safety, symbolism, and recognition (Figure 21-14). Whatever the application, distinctive, well-designed lighting is one of the best ways to attract attention and make a favorable impression on the viewer with a small investment. Modern light sources, when properly applied, can help enhance the intrinsic charm, beauty, and utility of any setting. The focus here is on essential principles of structure lighting.

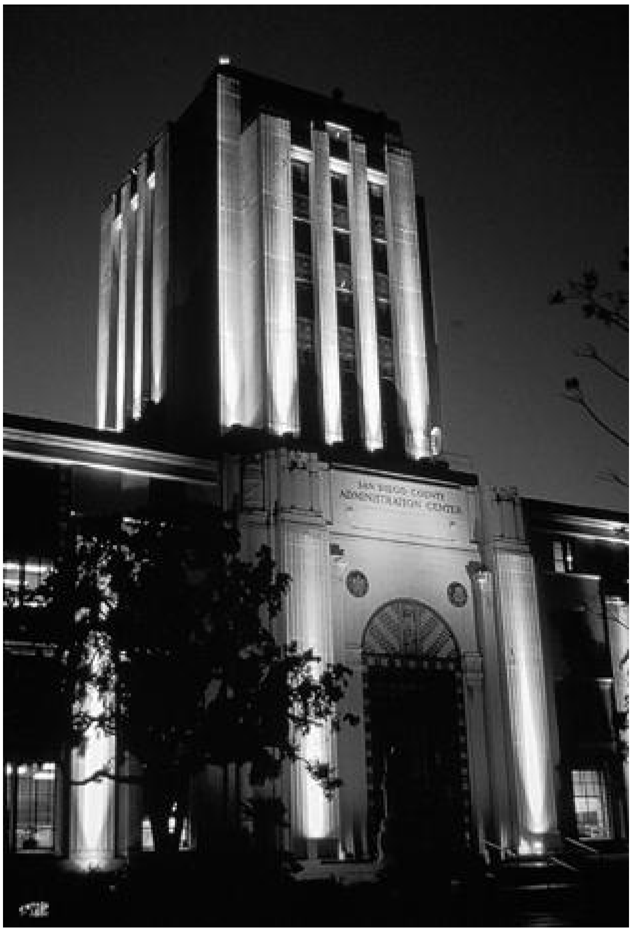


Figure 21-14. Architectural lighting can accentuate a structure's massive presence.

Lighting and Architecture

Daylighting effects have always been given prime consideration by architects. The relationship of major masses, planes, and details are critically studied with regard to changing daylight conditions, which vary in direction and quality depending on latitude, season, time of day, and local weather.

At night, the dynamic visual effects of natural daylight are lost. Structural identity is often destroyed. With optical control, the structure can be rendered in light to enhance its architectural characteristics (Figure 21-14). Major elements can be strengthened or subdued. There are many dynamic possibilities, including lighting structural members in a hierarchical manner. Subordinate details can be emphasized to create patterns and textures not dependent on sun location.

Architectural lighting may include floodlighting, outlining (Figure 21-15), spotlighting, or any applicable combination of these techniques. Projecting images on a structure is yet another dramatic effect. Whenever emphasis is placed on nighttime activities such as recreation, shopping, and traveling, lighting offers an opportunity to create architectural impressions.

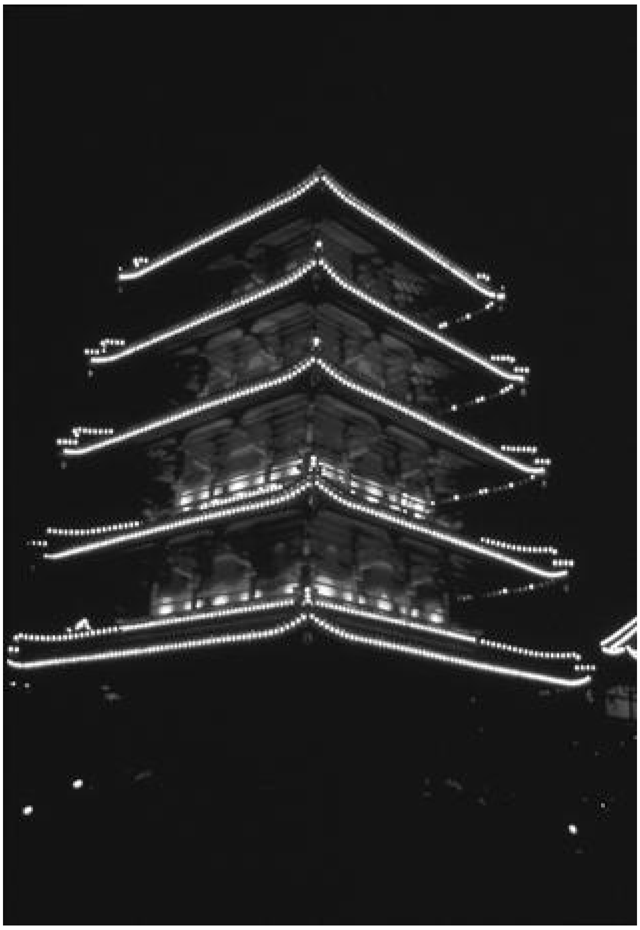


Figure 21-15. Structure outlining can convey the character of a building.

Structure Lighting and Urban Design

Nighttime lighting can be applied to areas surrounding a building and to related groups of buildings and, perhaps most important, can unify portions of a community. Focal points can be established through careful highlighting of major buildings, with more subdued lighting for secondary buildings. Circulation patterns can be reinforced and the entire area unified with street lighting and landscape lighting. Modern, well-planned nighttime lighting can make an important contribution to the success of any urban planning project.

Principles of Floodlighting

The techniques of floodlighting are few and simple. When used correctly, they let designers create anything from the most dramatic, exciting statement to the most subtle impressions.

When floodlights are aimed directly at a surface, shadows are essentially nonexistent. Details are flattened out and hard to see. The effect is somewhat like heavy, overcast daylighting. By contrast, when a floodlight beam grazes a surface, all the shadows from any surface irregularities are long and clearly defined. Planes more nearly perpendicular to the direction of the light become either highlighted or deeply shadowed. Other planes are less bright or are rendered in degrees of shadow.

Shadows shorten as the light source is moved away from the surface, and thus become less likely to interfere with the observation of other visual elements. These softer, attenuated shadows still give the viewer a strong impression as to the nature of surface detail. A source directed upward and sideward can produce modeling effects in several planes, strengthening the dimensional quality of the architectural element.

At short viewing distances, the lighting effects of major architectural planes and elements is secondary. Construction details, namely the finish, texture, and shape of surface materials, produce the desired impressions. Highly polished surfaces such as glass, marble, glazed tile, glazed brick, porcelain enamel, and various metals can reflect the image of the light source. Depending on source location and viewer position, this image may appear to be well inside the lighted area and quite unsightly, or close to the source and much less distracting. Avoid lighting these reflective surfaces directly, and provide proper baffling so that the light source itself stays completely hidden from normal viewing angles.

Luminaire size and number can dramatically affect the results of a floodlighting project. Too few units may leave holes and neglect detail. Too many may cause unwanted brightness and add unnecessary cost. In starting a project, the number of floodlights, locations, beam spreads, and lumen outputs can be estimated in the following manner. Once these manual estimates have been completed, a computer calculation will help refine the design. See RP-33[8] for additional information on floodlighting process.

LANDSCAPE LIGHTING

Landscape lighting includes a wide variety of outdoor areas including both natural and built environments. Projects may include natural meadows or woods, parks, corporate offices, hotels, theme parks, golf courses, residential gardens or boulevards, and entry features. In every setting, lighting can add aesthetic beauty, expand the number of usable hours, improve safety, increase security, and develop a desired image. Luminaire types, sources, wattages, and lighting techniques chosen vary based on project size, usage, needs, and expectations of the owner. Considerations must be given to the requirements and appearance of plant materials in landscape lighting installations.[10] In all cases, the lighting designer's main task is to create a safe, attractive nighttime environment using an energy-efficient low-brightness system.

Design Considerations

Designs should begin with a thorough site survey. Give careful consideration to the landscape elements present. These include softscape (trees, shrubs, flowers, and other plant material), hardscape (rocks, cliffs, sidewalks, stairs, plazas, benches, planters, and other site furnishings), and water features. In every case, the designer must take into account the surroundings so that the lighting of individual elements blends with the rest of the lighting composition. Designers should then take the following steps:

- Determine the intended use of the space and the nature of the audience.
- Realize that the significant areas in daytime may not be (and are not required to be) the same as the significant nighttime areas.
- Locate major and minor focal points.

The designer's knowledge should include the characteristics of all plant material being lighted, and those not being lighted, because these factors dictate the selection and location of equipment. Information concerning plant characteristics can be obtained from the project landscape architect, agricultural extension services of local governments and universities, or the American National Standards Institute (ANSI). Plant characteristics vary with both plant type and region.[10] Consider the following characteristics:

- Overall shape, height, width, maturing, and type
- Foliage characteristics (shape, color, reflectance, texture, translucency, and density)
- Branching pattern (open, closed, dense, upright, or weeping)
- Trunk and bark condition (striped, thorny, peeling, cracked, multicolored, or flaking)
- Root depth, spread
- Growth rate (how quickly, how much)
- Evergreen or deciduous
- Seasonal changes for the location

Luminaire Types and Usage

Lighting professionals must be familiar with the luminaires and sources available for landscape and architectural feature lighting. There are eight basic luminaire types used for landscape and architectural feature lighting:

- Uplights (well lights, below-grade open recessed luminaires with a louver or grill, direct burial luminaires, sealed luminaires with the lens at grade level, bullet uplights, and grade-level adjustable accent lights)
- Downlight (typically shielded bullet-type luminaires)
- Floodlights (using reflectors with both spot and flood distributions)
- Pathway
- Decorative (sconces and lanterns)
- Bollards
- Wall packs
- Pole- or post-mounted area lights

For the purpose of this section, luminaires are combined into three basic functional categories: uplighting, downlighting, and general or area lighting.

Uplights are used to illuminate plant material, signs, sculptures, or other structures upward from their base. Because illuminated surfaces and shadowed areas are different from natural patterns generated by the sun and moon, uplighting is quite dramatic. The type of luminaire chosen should be based on its location (e.g., grass, groundcover, mulch, or concrete) and the effect desired. Well lights can be adjusted to match the height of the groundcover. Direct burial luminaires are more appropriate for concrete installations than well lights. Bullets offer better directional control than in-ground units and can be easily aimed around obstacles.

Downlights are used to illuminate plant material, objects, or walkways from above. They can be either tree or structure mounted. Illumination created by downlights facilitates pedestrian traffic and reduces safety and security concerns. Bullet luminaires with integral full shields are the tools of choice for downlighting. Well-designed, shielded bullets can minimize or eliminate light trespass concerns.

Other luminaire types are used to provide general illumination and establish borders. They are typically used in hardscape rather than softscape applications. Regardless of the application, luminaire selection is critical. Corrosion is a concern for luminaires located in areas exposed to weather. Harsh environments do not recognize the difference between residential and commercial projects. Although aluminum luminaires are low cost and can be painted a variety of colors, they are subject to corrosion. To ensure proper performance, choose luminaires constructed of low-copper aluminum alloy with either polyester powder coat or anodized finish. Although copper alloys such as brass or bronze are corrosion resistant, they are quite expensive. To achieve the corrosion resistance of copper alloys at an aluminum price, consider luminaires constructed of corrosion-proof composite materials.[10]

Sources

Lamp information (efficacy, life, and CCT) is thoroughly covered in Chapter 6, Light Sources, and earlier sections of this chapter. However, within the landscape a few generalizations apply. Cool colors (mercury vapor and some metal halide) work well on some foliage. The warmer tones of incandescent and halogen lamps (both line and low-voltage) and some metal halide lamps work well on most foliage, flowering plants, people, food, and hardscape. Compact fluorescent lamp CCTs can be matched to the object being illuminated. High-pressure sodium (HPS) and low-pressure sodium are not typically used because they do not flatter plant appearance; however, HPS is appropriate for some architectural features.

Using different sources can add depth and texture, and contrast creates areas of interest. Different colors also create different moods or feelings. Many manufacturers provide color filters to further expand the range of colors available. Remember that color is a very subjective issue; less is usually better. Scenes with multiple sources with different CCTs are difficult to photograph for publicity or advertising purposes.

Typically, low-voltage lamps and luminaires are small and easily concealed. Low voltage is appropriate for the smaller spaces and plant material often found in residential applications; however, voltages drop with the distance between the luminaires and the transformers.

Due to electrical resistance, the voltage measured at the end of a low-voltage cable is lower than voltage measured at the start of the cable (i.e., at the transformer). This difference is known as voltage drop. Luminaires closer to the transformer produce more light than those at the end of the run of the cable. To minimize the effects of voltage drop:

- Use heavier gauge cable
- Shorten cable runs
- Use lower wattage lamps
- Use fewer luminaires on each run
- Use multiple transformers

Techniques for Illuminating Trees

There are four basic approaches to illuminating trees:

- Uplighting, the most common landscape lighting technique, creates different effects depending upon luminaire placement.
- Frontlighting shows or creates shapes, highlights details and colors, and reduces or emphasizes texture, depending on how far the luminaire is from the plant(s).
- Backlighting (silhouetting) shows only form, adds depth by separating the plant(s) from the background, and creates drama by eliminating colors and details.
- Sidelighting emphasizes plant textures and creates shadows that can be used to tie areas together.[10]

Perhaps the most important uplighting effect is anchoring the tree to the landscape. If the trunk is not included when accenting the tree, the canopy appears unnaturally detached from the ground. Luminaire placement also depends on the overall shape of the tree, its branch structure, and its foliage type.[10]

- Open spreading trees. Place luminaires one-third to one-half the distance between the trunk and the edge of the canopy to highlight it from within. Flood-type distributions are appropriate for broad canopies (oaks, willows). Tilted optics and crossing beam patterns enhance both depth and texture.
- Open vertical trees. Place luminaires closer to the trunk and aim them vertically. Narrower distributions are appropriate for vertical trees (palms, poplars).
- Dense spreading trees. Luminaires should be placed outside the branch structure. Luminaires placed close to the foliage and aimed up (grazing) emphasize texture; luminaires placed farther away highlight shape.

Downlighting involves lighting areas, trees, or plant material from above. Aiming downlights through a tree's leaves and branches creates soft subtle shadow patterns on the ground. This is called "moonlighting" when using clear mercury vapor and "dappled light" when using a white light source such as incandescent or metal halide. Luminaires should always be placed as high in the tree as possible. Luminaires positioned toward the center of the tree generally create more shadows, while luminaires placed toward the edge of the tree (filtered by fewer leaves) result in higher light levels.

High levels are not required to be effective. For comparison, a full moon produces only 0.1 lux of illumination. In general, the luminance ratios between focal points and their surroundings should range from 3:1 to 5:1 or, at most, 10:1 for special effect.

Installation Guidelines

All installations should meet National Electrical Code (NEC)[11] requirements. Luminaires should be suitable for wet locations. Make sure adequate drainage is provided for areas with grade-mounted luminaires. Wiring for downlights must be shielded from mechanical damage from the ground to 2.5 m (8 ft) above grade. Never aim downlights at an angle greater than 35° from vertical, or glare is likely to be a problem.[10] Take advantage of the variety of shields offered by many manufacturers to control glare. Always use a mounting device that accommodates the growth of the tree. Plan and coordinate a maintenance and pruning schedule with the landscape architect or the landscape maintenance contractor.[10]

Design Guidelines for Water Features

Light interacts with water in three different ways: refraction, reflection, and dispersion (Figure 21-16). Light is refracted (changes direction) when passing from air into water or vice versa. This is why the apparent location of a submerged object can shift. Refraction also causes rainbows or sparkle in water droplets or in turbulent water.

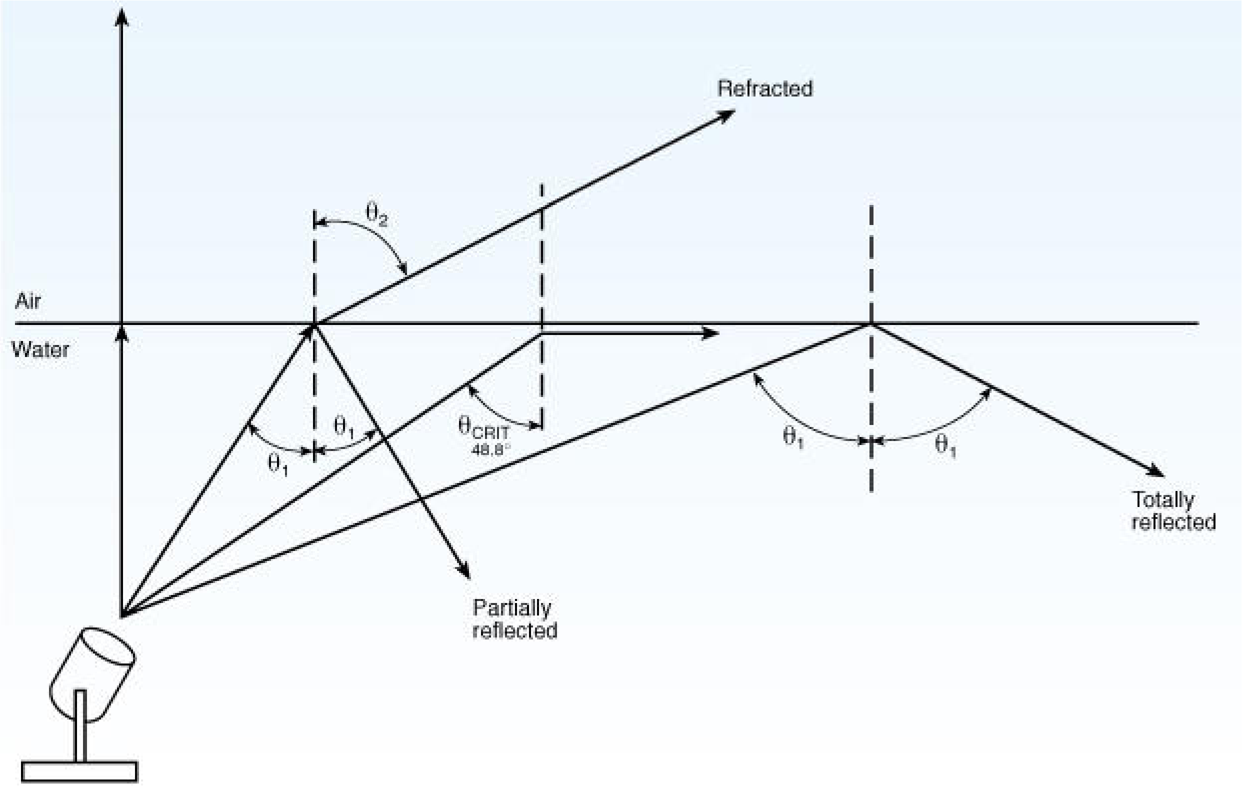


Figure 21-16. Underwater rays can be refracted or reflected depending on the incident angle with which they strike the surface of the water. Dispersion (not shown) also occurs whenever a light ray strikes a particle or air bubble in the water.

In addition to refraction, reflection also occurs when light strikes the water's surface; light is redirected back into the air or into the water in which it had been traveling. As with a mirror, the angle of incidence equals the angle of reflection. This is an important consideration for determining equipment location because it is possible to see luminaires as reflected images in a pool. Reflection can also play a role in displaying the lighted structure. When lighting objects from underwater sources in calm water, total internal reflection occurs at the water surface if the angle of incidence is greater than the critical angle (about 48°).

Depending on the particulates and air bubbles suspended in a body of water, a certain amount of light diffusion takes place. This occurs because the light traveling through the water strikes the particles or bubbles and is reflected in a different direction. This may be a help or a hindrance, depending on the desired effect. For example, if the designer is lighting ornate tile at the bottom of a fountain, diffusion may make the water appear murky, thus obscuring the tile.

Water features include both natural and built environments. Waterfalls, ponds, streams, and ocean fronts comprise a surrounding's earth features. A designer should evaluate these surroundings and determine if a specific earth feature is to be a focal point, transition area, or background element in the scene. When locating equipment, several factors should be considered, including critical angles, viewing angles, and whether the equipment is above or under water. Check local building codes carefully for any restrictions on equipment locations. When positioning equipment, make sure the luminaires are aimed so that the source cannot be seen directly or indirectly as a result of reflection and refraction angles. If placing equipment under water, the effect of light and heat on the organisms living there must be considered. All such equipment must be listed for submersible use, and all electrical codes for underwater lighting followed precisely. Fiber optics can simplify this situation because the electrical equipment is separated from the water and only requires seals to prevent water leakage out of the fountain and capillary action along the fiber. Note that all submersible equipment is about three to five times more expensive than normal wet-location outdoor equipment.

Equipment not placed under water can be installed in trees, on nearby structures, in the ground surrounding the fountain, or on the fountain structure. Maintenance and access issues should always be kept in mind. This approach may yield a less dramatic solution than that produced by submerged equipment, but the result may be far more practical and considerably less expensive. See Figure 21-17 for an example of an illuminated fountain at night.

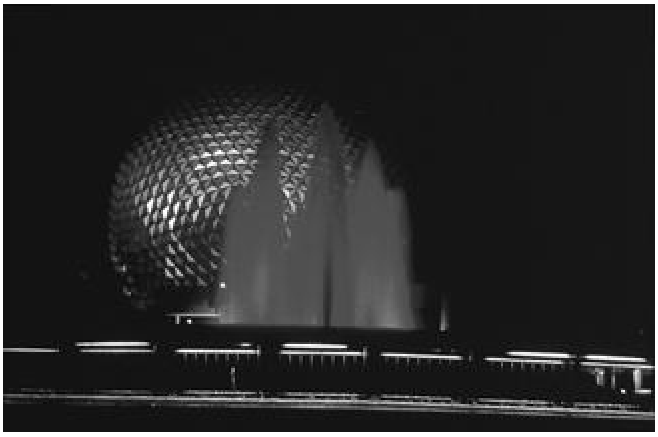


Figure 21-17. An illuminated fountain can provide nighttime theme lighting.

For general notes on equipment and source selection, refer to the lighting equipment and maintenance section. As when lighting natural-water features, all safety codes should be met as set forth by the National Electrical Code (NEC)[11] and local authorities. Underwater luminaires need strong locking mechanisms to maintain their aiming angle.

The following guidelines cover each specific water feature:

- Fountains. Determine which parts of the fountain need to be lighted, the water or the structure. Ascertain the viewing geometry and the type of lighting that will surround the fountain. If color is desired, other lighting must not overpower or wash out the colored effects.
- Waterfalls. To light a waterfall, determine the type of edge (weir) over which the water falls. If the weir is rough, the water will be agitated and aerated. Luminaires placed directly below the point where the water hits the surface allow light to travel up the falls, react with the bubbles, and give the water a glow. The water will take on the color of the light shining into it. If the weir is smooth, the water will fall in sheets. This type of waterfall should be lighted from the front with the

luminaires placed back far enough to cover the entire height of the falls.[10]

- Streams and ponds. While streams and ponds rarely represent the most important element in landscape composition, it is usually best to light them externally. Internal lighting can draw too much attention away from other areas.
- Oceanfront/Beach. The only part of the ocean that can be lighted is the foam on the surf. A great deal of light must be thrown at the ocean because most of it will be absorbed. Because oceanfront lighting could cause considerable light pollution, its use should be restricted to the occasional special event. Time control use is essential. Oceanfront lighting is not recommended near sea turtle nesting areas and requires permission from the coast guard.
- Other features. Lighting for geysers, rock faces, and other special natural features of the type often found in national parks (Figure 21-18) should be designed by a professional. All the basic design principles previously discussed should be applied. Light pollution, surround luminance, and light disturbance to the environment must also be considered.

HARDSCAPE LIGHTING

Beyond softscape and water features, the lighting designer must be concerned with illuminating a wide variety of sculptures, statues, flags, and other architectural features (hardscape). The section focuses on outdoor sculptures, vertical displays, and gazebos.

Outdoor Sculptures

A three-dimensional sculpture must be lighted from more than one direction to provide the essential highlights and shadows that reveal shape or texture (Figure 21-19). This can be accomplished by using different lamps, color filters, or beam patterns from different angles. For example, a bronze sculpture with patina may appear light blue, green, or gray, depending on the light source. Directional lighting models sculptures, expressing depth and highlighting some areas while allowing others to fall into shadow.

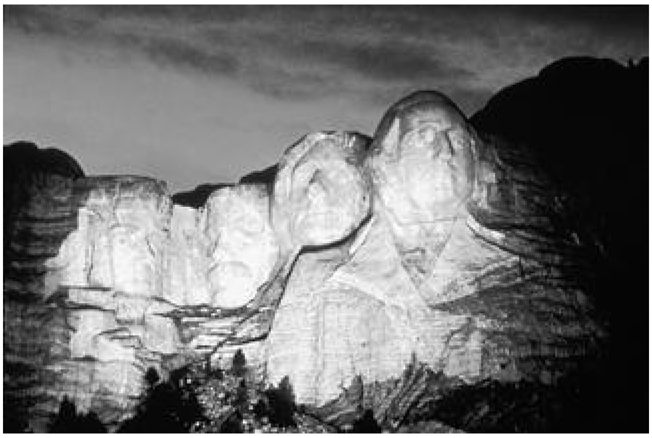


Figure 21-18. Rock face illumination should avoid hot spots or excessive spill light.

Figure 21-19. Highlight and shadow can reveal the shape and texture of outdoor sculptures, from the typical garden statue (a) to a monumental structure (b).

Shadows are indicators of surface form and texture, providing they are not so dark as to conceal important details. Highlights also give good visual clues about surface characteristics, but they should not dazzle or cause uncomfortable glare.

If a sculpture at eye level (or lower) is lighted from above on all sides, there should be few problems for the viewer. When the sculpture is tall, however, there may be glare. Listed here are some solutions:

- If lighting the sculpture from above with structure-, pole-, or tree-mounted lights, angle the luminaires sharply downward and relieve shadows with a high-reflectance pedestal.
- Keep light beams entirely within the mass of the display by using shielded luminaires and selecting lamps with the correct beam spread.
- Illuminate the sculpture from below if that does not distort its appearance.
- Combine ambient, diffuse lighting (fill light) in the space with narrow-beam lighting (key light) on important parts of the sculpture.

Vertical Displays

It is often necessary to illuminate large vertical displays uniformly. See the discussion of floodlighting earlier in this chapter.

Floodlights mounted far from a vertical surface mute a vertical display's texture; floodlights mounted close accentuate texture. Carefully select floodlight luminaires that do not create hot spots on the display (Figure 21-20). Occasionally one feature of the display may need to be highlighted. This can be accomplished with spotlighting.

Figure 21-20. Good vertical surface illuminance without hot spots

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Figure 21-21. Nighttime illumination of a gazebo showing soft lighting of the structure.

Gazebos

Usually rendered as small, raised, polygonal platforms open on the sides (Figure 21-21), gazebos typically have pitched roofs supported by perimeter columns which provide an excellent opportunity for interior lighting by mounting a centrally located pendant luminaire. This luminaire should light the ceiling so that the gazebo softly glows as seen from the outside. For larger gazebos, column- or perimeter-mounted uplights can provide additional lighting for the platform area. Wall sconces on the columns add pedestrian-level lighting if required.

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22

Roadway Lighting

ROADWAY LIGHTING DESIGN ISSUES

- Appearance of Space and Luminaires
- Direct Glare
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Light Pollution/Trespass
- Peripheral Detection
- Reflected Glare
- Shadows
- Source/Task/Eye Geometry

Fixed lighting of public ways for both vehicles and pedestrians can create a nighttime environment in which people can see comfortably and can quickly and accurately identify objects on the roadway being traveled. Roadway lighting can improve traffic safety, achieve efficient traffic movement, and promote the general use of the facility during darkness and under a wide variety of weather conditions.

As a supplement to vehicular headlight illumination, fixed lighting can enable the motorist to see details more distinctly, locate them with greater certainty, and react safely to roadway and traffic conditions present on or near the roadway facility. Pedestrians must be able to see with sufficient detail to readily negotiate the pedestrian facility and recognize the presence of other pedestrians, vehicles, and objects in their vicinity. When fixed-lighting principles and techniques are properly applied, the visibility provided on these public ways can provide economic and social benefits to the public, including:

- Reduction in nighttime accidents
- Aid to police protection
- Facilitation of traffic flow
- Promotion of business and industry during nighttime hours
- Inspiration for community spirit and growth

This chapter considers only fixed lighting for the different kinds of public roads, pedestrian walkways and bikeways of a quality considered appropriate to modern requirements for night use. See Chapter 23, Transportation Lighting, for information on vehicle headlighting.

CLASSIFICATION DEFINITIONS[1]

Roadway: Pedestrian Walkway and Bikeway Classifications

Freeway. A divided major roadway with full control of access and with no crossings at grade. This definition applies to toll as well as nontoll roads as follows:

Freeway A. Roadways with visual complexity and high traffic volumes. Usually this type of freeway is found in major metropolitan areas in or near the central core and operates through much of the early evening hours of darkness at or near design capacity.

Freeway B. All other divided roadways with full control of access where lighting is needed.

Expressway. A divided major roadway for through traffic with partial control of access and generally with interchanges at major crossroads. Expressways for noncommercial traffic within park areas are generally known as parkways.

Major. The part of the roadway system that serves as the principal network for through traffic flow. The routes connect areas of principal traffic generation and important rural highways entering the city.

Collector. The roadways serving traffic between major and local roadways. These are roadways used mainly for traffic movements within residential, commercial, and industrial areas.

Local. Roadways used primarily for direct access to residential, commercial, industrial, or other abutting property. They do not include roadways carrying through traffic. Long local roadways are generally divided into short sections by a system of collector roadway systems.

Alley. Narrow public ways within a block, generally used for vehicular access to the rear of abutting properties.

Sidewalk. Paved or otherwise improved areas for pedestrian use, located within public street rights-of-way that also contain roadways for vehicular traffic.

Pedestrian Walkway. A public walk for pedestrian traffic, not necessarily within the right-of-way for a vehicular traffic roadway. Included are skywalks (pedestrian overpasses), subwalks (pedestrian tunnels), walkways giving access to parks or block interiors, and midblock street crossings.

Isolated Interchange. A grade-separated roadway crossing that is not part of a continuously lighted system, with one or more ramp connections with the crossroad.

Isolated Intersection. The general area where two or more discontinuously lighted roadways join or cross at the same level. The intersection includes the roadway and roadside facilities for traffic movement in that area. A special type is the channelized intersection, in which traffic is directed into definite paths by islands with raised curbing.

Bikeway. Any road, street, path, or way that is specifically designated as being open to bicycle travel, regardless of whether such facilities are designed for the exclusive use of bicycles or are to be shared with other transportation modes.

Type A: Designated bicycle lane. A portion of roadway or shoulder that has been designated for use by bicyclists. It is distinguished from the portion of the roadway for motor vehicle traffic by a paint stripe, curb, or other similar device.

Type B: Bicycle trail. A separate trail or path from which motor vehicles are prohibited and which is for the exclusive use of bicyclists or the shared use of bicyclists and pedestrians. Where such a trail or path forms a part of a highway, it is separated from the roadways for motor vehicle traffic by an open space or barrier.

Area Classifications (Abutting Land Uses)

Certain land uses, such as office and industrial parks, may fit into any of the classifications below. The classification selected should be consistent with the expected night pedestrian activity.

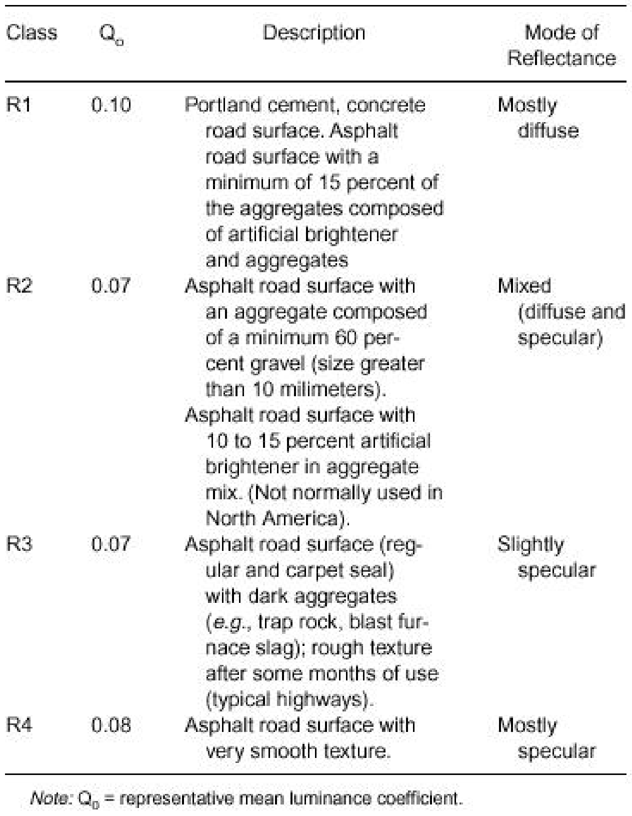
Commercial. A business area of a municipality where ordinarily there are many pedestrians during night hours. This definition applies to densely developed business areas outside, as well as within, the central part of a municipality. The area contains land use that frequently attracts a heavy volume of nighttime vehicular and pedestrian traffic.

Intermediate. Those areas of a municipality characterized by frequent moderately heavy nighttime pedestrian activity, as in blocks having libraries, community recreation centers, large apartment buildings, industrial buildings, or neighborhood retail stores.

Residential. A residential development, or a mixture of residential and small commercial establishments, characterized by few pedestrians at night. This definition includes areas with single-family homes, town houses, and small apartment buildings.

Pavement Classifications

The calculation of pavement luminance requires information about the surface reflectance characteristics of the pavement. Studies have shown that most common pavements can be grouped into a limited number of standard road surfaces having specified reflectance data given by reduced luminance coefficient tables (r tables). In this section, pavement reflectance characteristics follow the established CIE document.[2] A description of road surface classifications is given in Figure 22-1. The r tables quantifying the pavement class are shown in Figure 22-2.



Class	Q_o	Description	Mode of Reflectance
R1	0.10	Portland cement, concrete road surface. Asphalt road surface with a minimum of 15 percent of the aggregates composed of artificial brightener and aggregates	Mostly diffuse
R2	0.07	Asphalt road surface with an aggregate composed of a minimum 60 percent gravel (size greater than 10 milimeters). Asphalt road surface with 10 to 15 percent artificial brightener in aggregate mix. (Not normally used in North America).	Mixed (diffuse and specular)
R3	0.07	Asphalt road surface (regular and carpet seal) with dark aggregates (*e.g.*, trap rock, blast furnace slag); rough texture after some months of use (typical highways).	Slightly specular
R4	0.08	Asphalt road surface with very smooth texture.	Mostly specular

Note: Q_0 = representative mean luminance coefficient.

Figure 22-1. Road Surface Classifications

tan γ \ β	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655	655
0.25	619	619	619	619	610	610	610	610	610	610	610	610	610	601	601	601	601	601	601	601
0.5	539	539	539	539	539	539	521	521	521	521	521	503	503	503	503	503	503	503	503	503
0.75	431	431	431	431	431	431	431	431	431	431	395	386	371	371	371	371	371	386	395	395
1	341	341	341	341	323	323	305	296	287	287	278	269	269	269	269	269	269	278	278	278
1.25	269	269	269	260	251	242	224	207	198	189	189	180	180	180	180	180	189	198	207	224
1.5	224	224	224	215	198	180	171	162	153	148	144	144	139	139	139	144	148	153	162	180
1.75	189	189	189	171	153	139	130	121	117	112	108	103	99	99	103	108	112	121	130	139
2	162	162	157	135	117	108	99	94	90	85	85	83	84	84	86	90	94	99	103	111
2.5	121	121	117	95	79	66	60	57	54	52	51	50	51	52	54	58	61	65	69	75
3	94	94	86	66	49	41	38	36	34	33	32	31	31	33	35	38	40	43	47	51
3.5	81	80	66	46	33	28	25	23	22	22	21	21	22	22	24	27	29	31	34	38
4	71	69	55	32	23	20	18	16	15	14	14	14	15	17	19	20	22	23	25	27
4.5	63	59	43	24	17	14	13	12	12	11	11	11	12	13	14	14	16	17	19	21
5	57	52	36	19	14	12	10	9.0	9.0	8.8	8.7	8.7	9.0	10	11	13	14	15	16	16
5.5	51	47	31	15	11	9.0	8.1	7.8	7.7	7.7										
6	47	42	25	12	8.5	7.2	6.5	6.3	6.2											
6.5	43	38	22	10	6.7	5.8	5.2	5.0												
7	40	34	18	8.1	5.6	4.8	4.4	4.2												
7.5	37	31	15	6.9	4.7	4.0	3.8													
8	35	28	14	5.7	4.0	3.6	3.2													
8.5	33	25	12	4.8	3.6	3.1	2.9													
9	31	23	10	4.1	3.2	2.8														
9.5	30	22	9.0	3.7	2.8	2.5														
10	29	20	8.2	3.2	2.4	2.2														
10.5	28	18	7.3	3.0	2.2	1.9														
11	27	16	6.6	2.7	1.9	1.7														
11.5	26	15	6.1	2.4	1.7															
12	25	14	5.6	2.2	1.6															

Q_0 = 0.10; S1 = 0.25; S2 = 1.53

a

tan γ \ β	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0	390	390	390	390	390	390	390	390	390	390	390	390	390	390	390	390	390	390	390	390
0.25	411	411	411	411	411	411	411	411	411	411	379	368	357	357	346	346	346	335	335	335
0.5	411	411	411	411	403	403	384	379	370	346	325	303	281	281	271	271	271	260	260	260
0.75	379	379	379	368	357	346	325	303	281	260	238	216	206	206	206	206	208	206	206	206
1	335	335	335	325	292	291	260	238	216	195	173	152	152	152	152	152	141	141	141	141
1.25	303	303	292	271	238	206	184	152	130	119	108	100	103	106	108	108	114	114	119	119
1.5	271	271	260	227	179	152	141	119	108	93	80	76	76	80	84	87	89	91	93	95
1.75	249	238	227	195	152	124	106	91	78	67	61	52	54	58	63	67	69	71	73	74
2	227	216	195	152	117	95	80	67	61	52	45	40	41	45	49	52	54	56	57	58
2.5	195	190	146	110	74	58	48	40	35	30	27	24	26	28	30	33	35	38	40	41
3	160	155	115	67	43	33	26	21	18	17	16	16	17	17	18	21	22	24	26	27
3.5	146	131	87	41	25	18	15	13	12	11	11	11	11	11	12	14	15	17	18	21
4	132	113	67	27	15	12	10	9.4	8.7	8.2	7.9	7.6	7.9	8.7	9.6	11	12	13	15	17
4.5	118	95	50	20	12	8.9	7.4	6.6	6.3	6.1	5.7	5.6	5.8	6.3	7.1	8.4	10	12	13	14
5	106	81	38	14	8.2	6.3	5.4	5.0	4.8	4.7	4.5	4.4	4.8	5.2	6.2	7.4	8.5	9.5	10	11
5.5	96	69	29	11	6.3	5.1	4.4	4.1	3.9	3.8										
6	87	58	22	8.0	5.0	3.9	3.5	34	3.2											
6.5	78	50	17	6.1	3.8	3.1	2.8	2.7												
7	71	43	14	4.9	3.1	2.5	2.3	2.2												
7.5	67	38	12	4.1	2.6	2.1	1.9													
8	63	33	10	3.4	2.2	1.8	1.7													
8.5	58	28	8.7	2.9	1.9	1.6	1.5													
9	55	25	7.4	2.5	1.7	1.4														
9.5	52	23	6.5	2.2	1.5	1.3														
10	49	21	5.6	1.9	1.4	1.2														
l0.5	47	18	5.0	1.7	1.3	1.2														
11	44	16	4.4	1.6	1.2	1.1														
11.5	42	14	4.0	1.5	1.1															
12	41	13	3.6	1.4	1.1															

Q_0 = 0.07; S1 = 0.58; S2 = 1.80

b

Figure 22-2. *Continued.*

tan γ \ β	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294
0.25	326	326	321	321	317	312	308	308	303	298	294	280	271	262	258	253	249	244	240	240
0.5	344	344	339	339	326	317	308	298	289	276	262	235	217	204	199	199	199	199	194	194
0.75	357	353	353	339	321	303	285	267	244	222	204	176	158	149	149	149	145	136	136	140
1	362	362	352	326	276	249	226	204	181	158	140	118	104	100	100	100	100	100	100	100
1.25	357	357	348	298	244	208	176	154	136	118	104	83	73	70	71	74	77	77	77	78
1.5	353	348	326	267	217	176	145	117	100	86	78	72	60	57	58	60	60	60	61	62
1.75	339	335	303	231	172	127	104	89	79	70	62	51	45	44	45	46	45	45	46	47
2	326	321	280	190	136	100	82	71	62	54	48	39	34	34	34	35	36	36	37	38
2.5	289	280	222	127	86	65	54	44	38	34	25	23	22	23	24	24	24	24	24	25
3	253	235	163	85	53	38	31	25	23	20	18	15	15	14	15	15	16	16	17	17
3.5	217	194	122	60	35	25	22	19	16	15	13	9.9	9.0	9.0	9.9	11	11	12	12	13
4	190	163	90	43	26	20	16	14	12	9.9	9.0	7.4	7.0	7.1	7.5	8.3	8.7	9.0	9.0	9.9
4.5	163	136	73	31	20	15	12	9.9	9.0	8.3	7.7	5.4	4.8	4.9	5.4	6.1	7.0	7.7	8.3	8.5
5	145	109	60	24	16	12	9.0	8.2	7.7	6.8	6.1	4.3	3.2	3.3	3.7	4.3	5.2	6.5	6.9	7.1
5.5	127	94	47	18	14	9.9	7.7	6.9	6.1	5.7										
6	113	77	36	15	11	9.0	8.0	6.5	5.1											
6.5	104	68	30	11	8.3	6.4	5.1	4.3												
7	95	60	24	8.5	6.4	5.1	4.3	3.4												
7.5	87	53	21	7.1	5.3	4.4	3.6													
8	83	47	17	6.1	4.4	3.6	3.1													
8.5	78	42	15	5.2	3.7	3.1	2.6													
9	73	38	12	4.3	3.2	2.4														
9.5	69	34	9.9	3.8	3.5	2.2														
10	65	32	9.0	3.3	2.4	2.0														
10.5	62	29	8.0	3.0	2.1	1.9														
11	59	26	7.1	2.6	1.9	1.8														
11.5	56	24	6.3	2.4	1.8															
12	53	22	5.6	2.1	1.8															

$Q_0 = 0.07$; S1 = 1.11; S2 = 2.38

c

tan γ \ β	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0	264	264	264	264	264	264	264	264	264	264	264	264	264	264	264	264	264	264	264	264
0.25	297	317	317	317	317	310	304	290	284	277	271	244	231	224	224	218	218	211	211	211
0.5	330	343	343	343	330	310	297	284	277	264	251	218	198	185	178	172	172	165	165	165
0.75	376	383	370	350	330	304	277	251	231	211	198	165	139	132	132	125	125	125	119	119
1	396	396	396	330	290	251	218	198	185	165	145	112	86	86	86	86	86	87	87	87
1.25	403	409	370	310	251	211	178	152	132	115	103	77	66	65	65	63	65	66	67	68
1.5	409	396	356	284	218	172	139	115	100	88	79	61	50	50	50	50	52	55	55	55
1.75	409	396	343	251	178	139	108	88	75	66	59	44	37	37	37	38	40	41	42	45
2	409	383	317	224	145	106	86	71	59	53	45	33	29	29	29	30	32	33	34	37
2.5	396	356	264	152	100	73	55	45	37	32	28	21	20	20	20	21	22	24	25	26
3	370	304	211	95	63	44	30	25	21	17	16	13	12	12	13	13	15	16	17	19
3.5	343	271	165	63	40	26	19	15	13	12	11	9.8	9.1	8.8	8.8	9.4	11	12	13	15
4	317	238	132	45	24	16	13	11	9.6	9.0	8.4	7.5	7.4	7.4	7.5	7.9	8.6	9.4	11	12
4.5	297	211	106	33	17	11	9.2	7.9	7.3	6.6	6.3	6.1	6.1	6.2	6.5	6.7	7.1	7.7	8.7	9.6
5	277	185	79	24	13	8.3	7.0	6.3	5.7	5.1	5.0	5.0	5.1	5.4	5.5	5.8	6.1	6.3	6.9	7.7
5.5	257	161	59	19	9.9	7.1	5.7	5.0	4.6	4.2										
6	244	140	46	13	7.7	5.7	4.8	4.1	3.8											
6.5	231	122	37	11	5.9	4.6	3.7	3.2												
7	218	106	32	9.0	5.0	3.8	3.2	2.6												
7.5	205	94	26	7.5	4.4	3.3	2.8													
8	193	82	22	6.3	3.7	2.9	2.4													
8.5	184	74	19	5.3	3.2	2.5	2.1													
9	174	66	16	4.6	2.8	2.1														
9.5	169	59	13	4.1	2.5	2.0														
10	164	53	12	3.7	2.2	1.7														
10.5	158	49	11	3.3	2.1	1.7														
11	153	45	9.5	3.0	2.0	1.7														
11.5	149	41	8.4	2.6	1.7															
12	145	37	7.7	2.5	1.7															

$Q_0 = 0.08$; S1 = 1.55; S2 = 3.03

d

Figure 22-2e. *Continued*

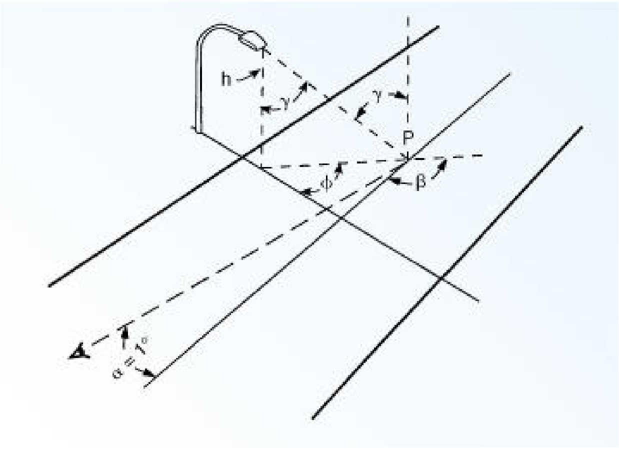


Figure 22-2. The *r*-Tables for Standard Surfaces: (a) R1, (b) R2, (c) R3, (d) R4. All values must be multiplied by 10,000. Angles are shown in (e). (Adapted from reference 2.)

Luminaire Light Distribution Classifications

Proper distribution of the light flux from luminaires is one of the essential factors in efficient roadway lighting. The light emanating from the luminaires is directionally controlled and proportioned in accordance with the roadway width, the spacing between luminaires, and the mounting locations where the luminaires are expected to be used. Therefore, there is a need for a luminaire light distribution classification system to aid the engineer or designer to narrow down the selection of luminaires that might meet the requirements specified for a given roadway system.

Several methods have been devised for showing the light distribution pattern from a luminaire (Figures 22-3 through 22-7). For practical operating reasons, the range in luminaire mounting heights may be limited. Therefore, it becomes necessary to have several different light distributions in order to light different roadway widths effectively, while using various luminaire spacing distances at a fixed luminaire mounting height. All luminaires can be classified according to their lateral and vertical distribution patterns. Different lateral distributions are available for different ratios of street width to mounting height. Different vertical distributions are available for different ratios of spacing to mounting height.

Distributions with higher vertical angles of maximum intensity emission are necessary to obtain the required uniformity of illuminance where longer luminaire spacings are used (as on residential and light-traffic roadways). These higher vertical emission angles produce a more favorable pavement luminance, which may be desired for silhouette seeing where the traffic volume is low. Distributions with lower vertical angles of maximum intensity emission are used in order to reduce system glare. This becomes more important when using high-lumen-output lamps. The lower the emission angle, the closer the luminaire spacing must be to obtain required illuminance uniformity.

Luminaire light distribution may be classified in respect to three criteria:

- Vertical light distribution
- Lateral light distribution
- Control of light distribution above maximum intensity

Classification of the light distribution should be made on the basis of an isointensity diagram which, on its rectangular coordinate grid, has superimposed a series of longitudinal roadway lines (LRL) in multiples of the mounting height (MH), and a series of transverse roadway lines (TRL), also in multiples of the MH. The relationship of LRL and TRL to an actual street and the representations are shown in Figures 22-3 through 22-7. The minimum information that should appear on such an isointensity diagram for classification is as follows:

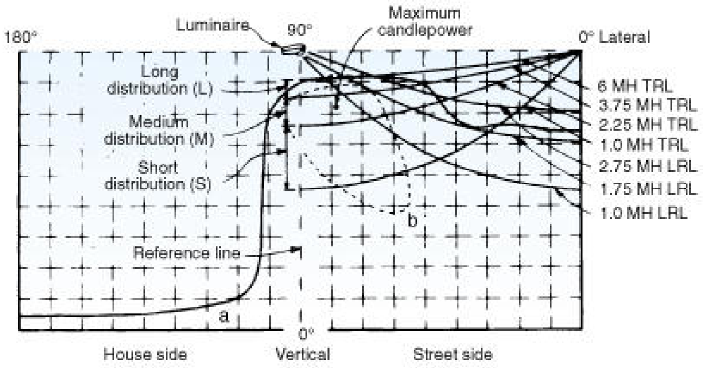


Figure 22-3. Recommended vertical light distribution boundaries on rectangular coordinate grid (representation of a sphere). Lines a and b are isointensity traces.

1. LRL lines at 1.0, 1.75, and 2.75 MH
2. TRL lines at 1.0, 2.25, 3.75, 6.0, and 8.0 MH
3. Maximum-intensity location and half-maximum-intensity trace
4. Intensity lines at the numerical values of 2.5, 5, 10, and 20% of the rated bare lamp lumens

Following are several types of luminaire light distributions. Other variations from these distributions may be useful for special applications.

Vertical Light Distributions. Vertical light distributions are divided into three groups: short (S), medium (M), and long (L) (Figures 22-3 and 22-6).

Short Distribution. A luminaire is classified as having a short light distribution when its maximum-intensity point lies in the S zone of the grid, which is from the 1.0-MH TRL up to the 2.25-MH TRL. The maximum luminaire spacing is generally less than 4.5 times the mounting height (Figures 22-3 and 22-4).

Medium Distribution. A luminaire is classified as having a medium light distribution when its maximum-intensity point lies in the M zone of the grid, which is from the 2.25-MH TRL up to the 3.75-MH TRL. The maximum luminaire spacing is less than 7.5 times the mounting height (Figures 22-3 and 22-4).

Long Distribution: A luminaire is classified as having a long light distribution when its maximum-intensity point lies in the L zone of the grid, which is from the 3.75-MH TRL up to the 6.0-MH TRL. The maximum luminaire spacing is less than 12 times the mounting height (Figures 22-3 and 22-4).

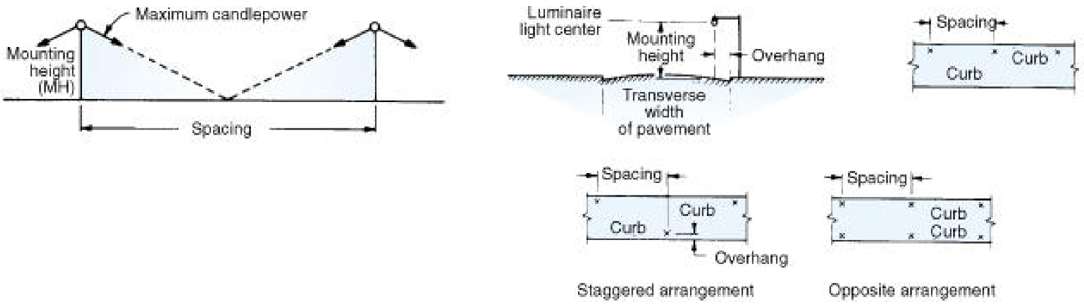


Figure 22-4. Typical lighting layouts showing spacing-to-mounting height relationships and terminology with respect to luminaire arrangement and spacing. Short Distribution--for luminaires designed to be located less than 4.5 × MH between luminaires. Medium Distribution--for luminaires designed to be located in the range of 4.5 × MH to 7.5 × MH between luminaires. Long Distribution--for luminaires designed to be located in the range of 7.5 × MH to 12 × MH between luminaires.

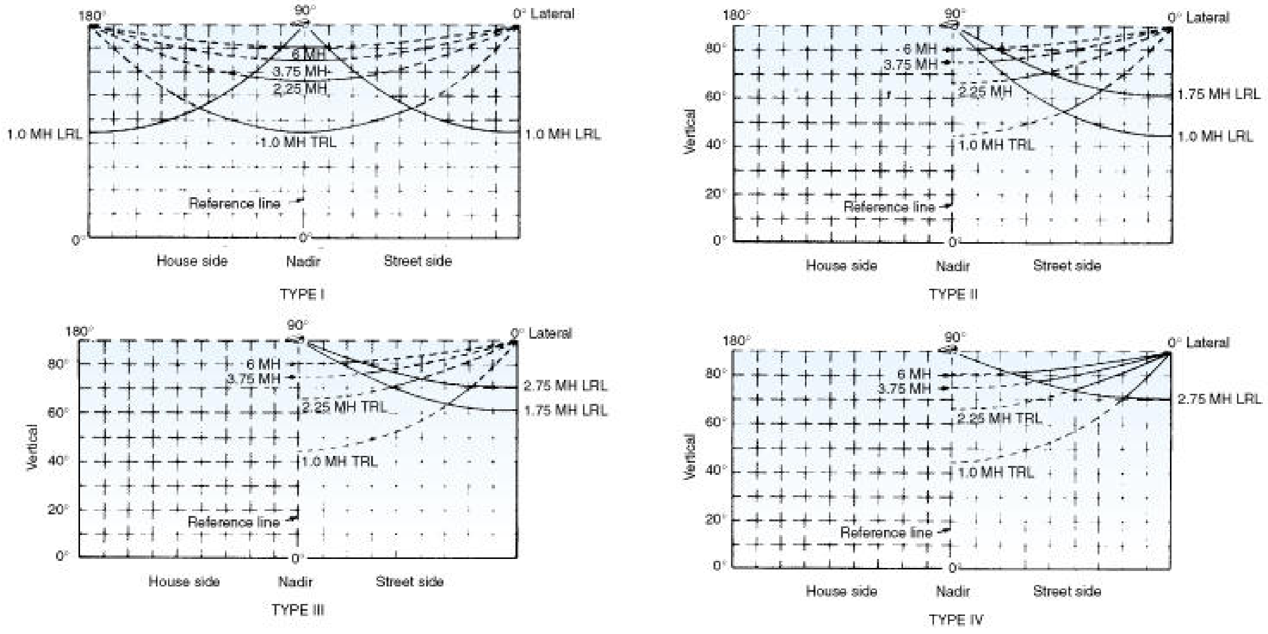


Figure 22-5. Recommended lateral light distribution boundaries on a rectangular coordinate grid (representation of a sphere). Some information omitted for clarity. See Figure 22-3 for a complete diagram.

Lateral Light Distributions. Lateral light distributions (Figures 22-5 and 22-6) are divided into two groups based on the location of the luminaire in relation to the area to be lighted. Each group may be subdivided into divisions with regard to the width of the area to be lighted in terms of the MH ratio. Only the segments of the half-maximum-intensity isointensity trace that fall within the longitudinal distribution range, as determined by the point of maximum intensity (S, M, or L), are used for establishing the luminaire distribution width classification.

Luminaires At or Near Center of Area. The group of lateral width classifications that deals with luminaires intended to be mounted at or near the center of the area to be lighted has similar light distributions on both the house side and the street side of the reference line.

Type I. A distribution is classified as Type I when its half-maximum-intensity isointensity trace lies within the Type I width range on both sides of the reference line which is bounded by 1.0-MH house side LRL and 1.0-MH street side LRL within the longitudinal distribution range (S, M, or L) where the point of maximum intensity falls (Figure 22-6a).

Type I Four-way. A distribution is classified as a Type I four-way when it has four beams of the width as defined for Type I above (Figure 22-6b).

Type V. A distribution is classified as Type V when it has circular symmetry, being essentially the same at all lateral angles around the luminaire (Figure 22-6c).

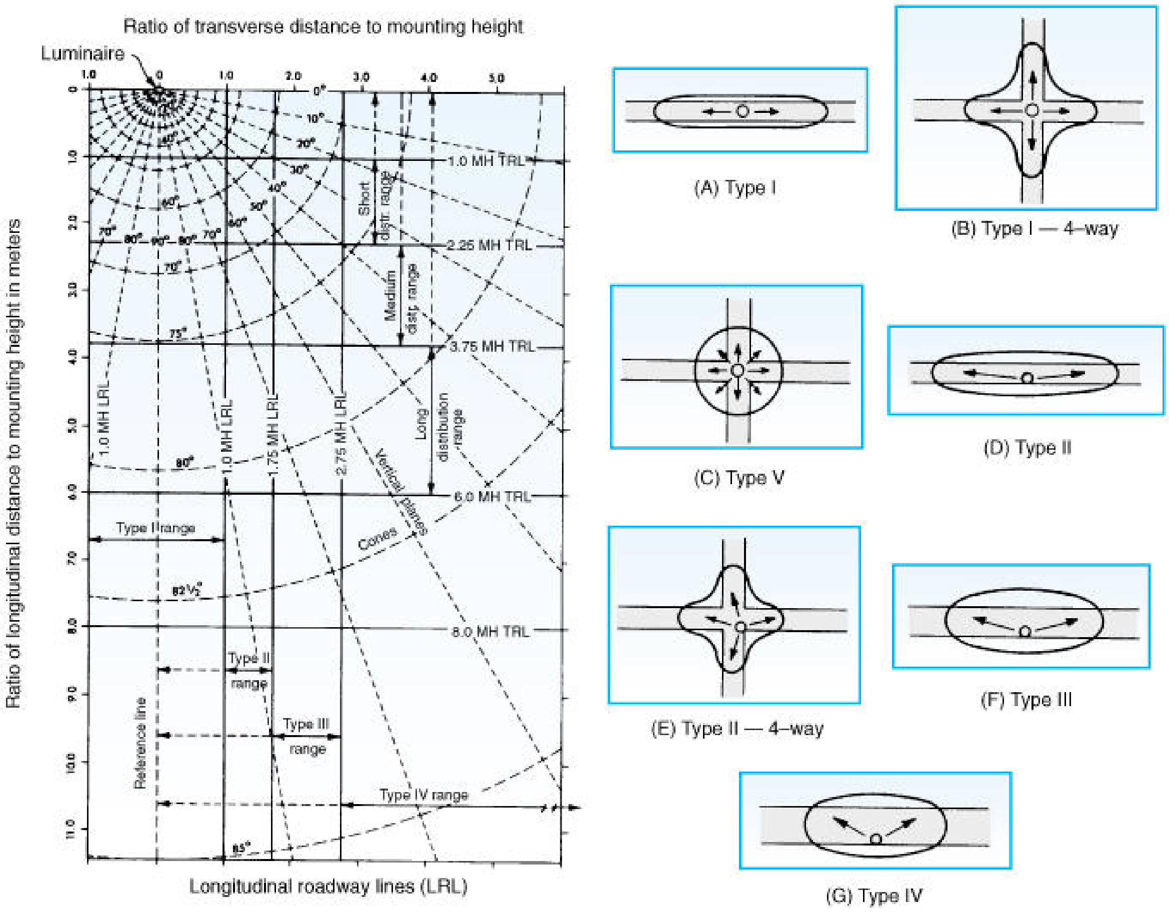
Luminaires Near Side of Area. The lateral width classifications that deal with luminaires intended to be mounted near the side of the area to be lighted vary as to the width of distribution range on the street side of the reference line. The house side segment of the half-maximum-intensity isointensity trace within the longitudinal range in which the point of maximum intensity falls (S, M, or L) may or may not cross the reference line. In general it is preferable that the half-maximum-intensity isointensity trace remain near the reference line. The variable width on the street side is as defined by the following.

Type II. A distribution is classified as Type II when the street side segment of the half-maximum-intensity isointensity trace within the longitudinal range in which the point of maximum intensity falls (S, M, or L) does not cross the 1.75-MH street side LRL (Figure 22-6d).

Type II Four-way. A distribution is classified as a Type II four-way when it has four beams, each of the width on the street side as defined for Type II above (Figure 22-6e).

Type III. A distribution is classified as Type III when the street side segment of the half-maximum-intensity isointensity trace within the longitudinal range in which the point of maximum intensity falls (S, M, or L) lies partly or entirely beyond the 1.75-MH street side LRL, but does not cross the 2.75-MH street side LRL (Figure 22-6f).

Type IV. A distribution is classified as Type IV when the street side segment of the half-maximum-intensity isointensity trace within the longitudinal range in which the point of maximum intensity falls (S, M, or L) lies partly or entirely beyond the 2.75-MH street side LRL (Figure 22-6g).



(A) Type I

(B) Type I — 4-way

(C) Type V

(D) Type II

(E) Type II — 4-way

(F) Type III

(G) Type IV

Figure 22-6. Plan view of roadway coverage for different types of luminaires.

Control of Distribution Above Maximum Intensity. Although the pavement luminance generally increases on increasing the vertical angle of light flux emission, it should be emphasized that the disability and discomfort glare also increase. However, since the rates of increase and decrease of these factors are not the same, design compromises become necessary in order to achieve balanced performance. Therefore, varying degrees of control of intensity in the upper portion of the beam above maximum intensity are required. This control of the intensity distribution is divided into three categories.

Full Cutoff. A luminaire light distribution where zero candela intensity occurs at an angle of 90° above nadir, and all greater angles from nadir. Additionally, the candela per 1000 lamp lumens does not numerically exceed 100 (10%) at an angle 80° above nadir. This applies to all lateral angles around the luminaire.

Cutoff. A luminaire light distribution is designated as cutoff when the intensity per 1000 lamp lumens does not numerically exceed 25 (2.5%) at an angle of 90° above nadir (horizontal), and 100 (10%) at a vertical angle of 80° above nadir. This applies to any lateral angle around the luminaire. (In some cases the cutoff distribution may meet the requirements of the semicutoff distribution.)

Semicutoff. A luminaire light distribution is designated as semicutoff when the intensity per 1000 lamp lumens does not numerically exceed 50 (5%) at an angle of 90° above nadir (horizontal), and 200 (20%) at a vertical angle of 80° above nadir. This applies to any lateral angle around the luminaire. (In some cases the semicutoff distribution may meet the requirements of the noncutoff distribution.)

Noncutoff. This is the category in which there is no intensity limitation in the zone above maximum intensity.

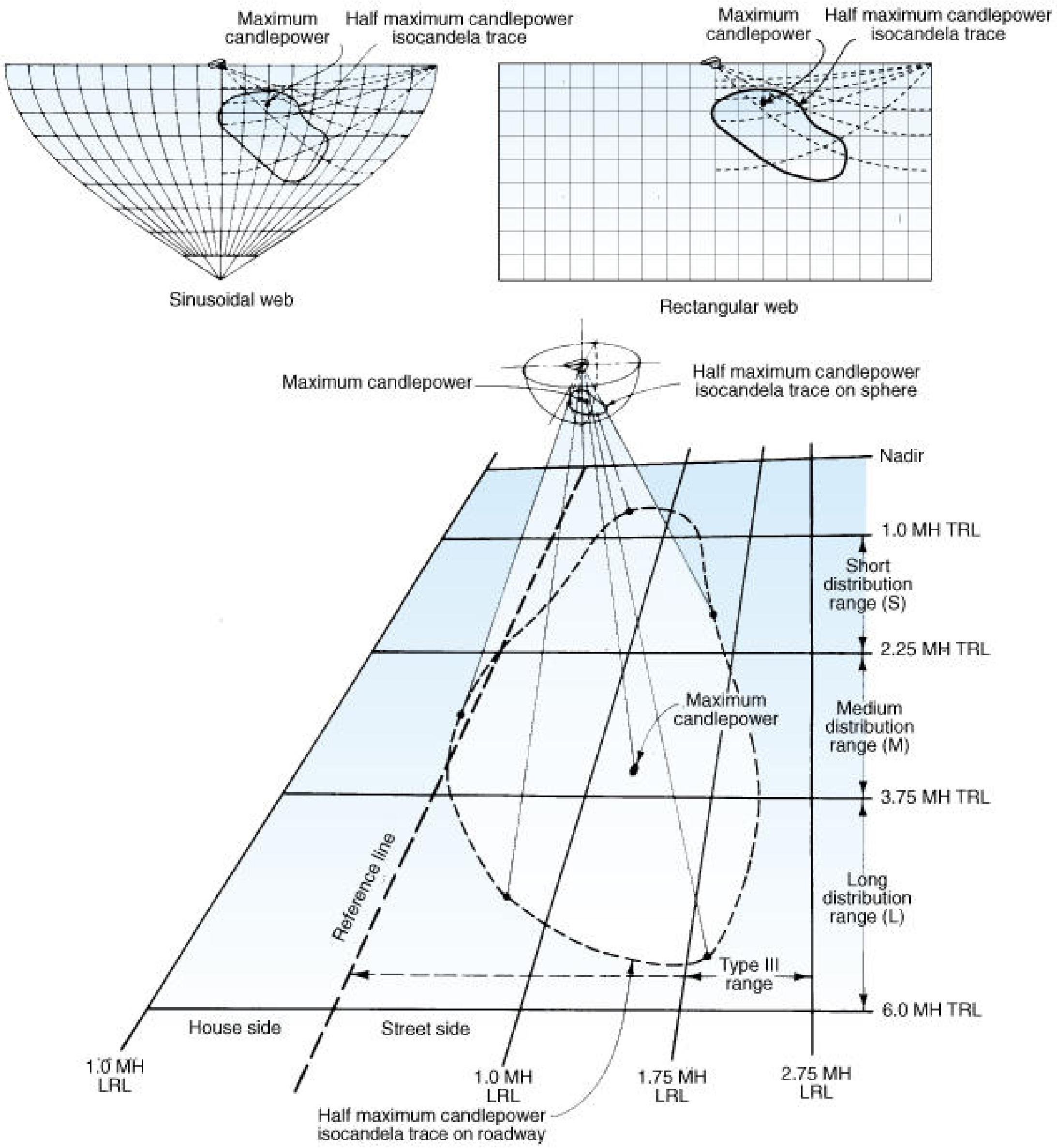


Figure 22-7. Diagram showing projection of maximum candlepower and half-maximum candlepower isocandela trace from a luminaire having a Type III--Medium distribution, on the imaginary sphere and the roadway. Sinusoidal web and rectangular web representation of sphere are also shown with maximum candlepower and half-maximum candlepower isocandela trace.

Variations. With the variations in roadway width, type of surface, luminaire mounting height, and spacing found in actual practice, there are a large number of ideal lateral distributions. For practical applications, however, a few types of lateral distribution patterns may be preferable to many complex arrangements. This simplification of distribution types is more easily understood, and consequently there is greater assurance of proper installation and more reliable maintenance.

When luminaires are tilted upward, the angle of the street side light distribution is raised. Features such as cutoff or width classification may be changed appreciably. When the tilt is planned, the output of the luminaire should be measured and the light distribution classified in the position in which it will be installed.

Type I, II, III, and IV lateral light distributions can vary across transverse roadway lines (except for the line that includes the maximum intensity) so as to provide adequate coverage of the rectangular roadway area involved. The width of the lateral angle of distribution required to adequately cover a typical width of roadway varies with the vertical angle or length of distribution as shown by the TRL. For a TRL at 4.5 MH, the lateral angle of distribution for roadway coverage is obviously narrower than that required for a TRL at 3.0 MH or 2.0 MH.

Luminaire Selection

Luminaire light distribution classification helps to determine the optical and economical suitability of a luminaire for lighting a particular roadway from the proposed mounting height and location. A wide selection of light distribution systems is available.

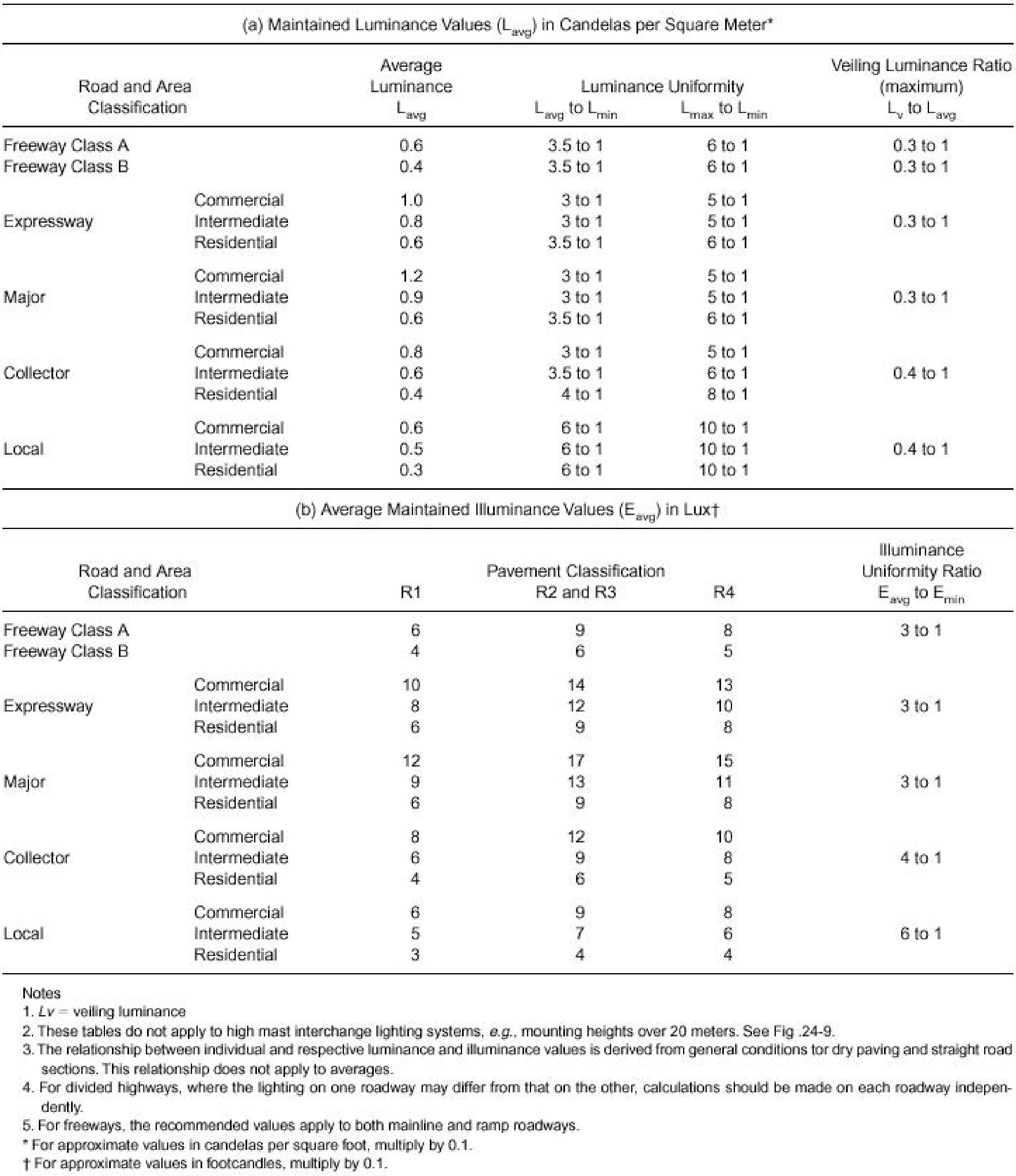
Simply because a luminaire is assigned a particular classification, there is no assurance that it produces the recommended quantity and quality of lighting for all roadway configurations and mountings shown in Figure 22-4. The relative amount and control of light in areas other than the cone of maximum intensity are equally important in producing good visibility in the final system but are not considered in the classification system.

LIGHTING DESIGN

The lighting system of a specific road section should accommodate the visual needs of night traffic (vehicular and pedestrian) and be expressed in terms clearly understandable by lighting designers, traffic engineers, and highway administrators.

The visual environmental needs along the roadway can be described in terms of pavement illuminance and luminance, uniformity, and direct glare produced by the system light sources. Figure 22-8a provides recommended luminance design requirements and uniformity. It also specifies the relationship between the average luminance L_{avg}, which is the average of all of the luminances values calculated for the section of roadway under consideration, and the veiling luminance L_v, which is defined later in this chapter.

The visual needs along the roadway can also be satisfied by the use of illuminance criteria. Figure 22-8b provides the recommended illuminance design requirements, considering the differences in roadway reflectance characteristics. The designer should not expect the lighting systems designed under the two sets of criteria to provide identical results.



(a) Maintained Luminance Values (L_{avg}) in Candelas per Square Meter*

Road and Area Classification		Average Luminance L_{avg}	Luminance Uniformity		Veiling Luminance Ratio (maximum) L_v to L_{avg}
			L_{avg} to L_{min}	L_{max} to L_{min}	
Freeway Class A		0.6	3.5 to 1	6 to 1	0.3 to 1
Freeway Class B		0.4	3.5 to 1	6 to 1	0.3 to 1
Expressway	Commercial	1.0	3 to 1	5 to 1	0.3 to 1
	Intermediate	0.8	3 to 1	5 to 1	
	Residential	0.6	3.5 to 1	6 to 1	
Major	Commercial	1.2	3 to 1	5 to 1	0.3 to 1
	Intermediate	0.9	3 to 1	5 to 1	
	Residential	0.6	3.5 to 1	6 to 1	
Collector	Commercial	0.8	3 to 1	5 to 1	0.4 to 1
	Intermediate	0.6	3.5 to 1	6 to 1	
	Residential	0.4	4 to 1	8 to 1	
Local	Commercial	0.6	6 to 1	10 to 1	0.4 to 1
	Intermediate	0.5	6 to 1	10 to 1	
	Residential	0.3	6 to 1	10 to 1	

(b) Average Maintained Illuminance Values (E_{avg}) in Lux†

Road and Area Classification		Pavement Classification			Illuminance Uniformity Ratio E_{avg} to E_{min}
		R1	R2 and R3	R4	
Freeway Class A		6	9	8	3 to 1
Freeway Class B		4	6	5	
Expressway	Commercial	10	14	13	3 to 1
	Intermediate	8	12	10	
	Residential	6	9	8	
Major	Commercial	12	17	15	3 to 1
	Intermediate	9	13	11	
	Residential	6	9	8	
Collector	Commercial	8	12	10	4 to 1
	Intermediate	6	9	8	
	Residential	4	6	5	
Local	Commercial	6	9	8	6 to 1
	Intermediate	5	7	6	
	Residential	3	4	4	

Notes
1. *Lv* = veiling luminance
2. These tables do not apply to high mast interchange lighting systems, *e.g.*, mounting heights over 20 meters. See Fig .24-9.
3. The relationship between individual and respective luminance and illuminance values is derived from general conditions for dry paving and straight road sections. This relationship does not apply to averages.
4. For divided highways, where the lighting on one roadway may differ from that on the other, calculations should be made on each roadway independently.
5. For freeways, the recommended values apply to both mainline and ramp roadways.

* For approximate values in candelas per square foot, multiply by 0.1.

† For approximate values in footcandles, multiply by 0.1.

Figure 22-8. Recommended Maintained Luminance and Illuminance Values for Roadways

The design of a roadway lighting system involves consideration of visibility, economics, aesthetics, safety, and environmental conditions, as well as appropriate material and equipment. The design process follows these major steps:

1. Determination of roadway classification and adjacent area classification along the specific road section to be lighted. There are three types of area classification: commercial, intermediate, and residential. If the pavement classification is unknown, use the R3 values of Figure 22-8.

2. (a) Selection of the level and uniformity of pavement luminance and assessment of the relationship between the veiling luminance and the average pavement luminance, as recommended in Figure 22-8a for each different area classification along the section, or

(b) Determination of the roadway pavement classification, desired average horizontal illuminance, and uniformity for design as recommended in Figure 22-8b.

3. Preliminary selection of several luminaires and light sources.

4. Preliminary selection of one or more lighting system geometries, including mounting heights and lateral luminaire positions, that may provide an acceptable design based on recommended illuminance, uniformity, and glare.

5. Calculation of either pole spacing for the various luminaire and lamp combinations under study, if for a new system, or lamp output requirements, if existing poles are to be reused, based on illuminance values. Mounting height and lateral luminaire positions can also be considered to verify meeting the requirements of Figure 22-8a or b.

6. When luminaires have been selected, borderline situations quickly become evident during the application stage. In most cases, skilled judgment must be exercised when considering luminaires for a specific system. It may not be appropriate to specify only one light distribution when it is obvious that several different luminaire light distributions provide improved performance for a specific application.

7. Selection of final decision or reentry of the design process at any step above to achieve an optimal design.

8. Selection of luminaire supports (pole and bracket) that result in an acceptable aesthetic appearance, adherence to traffic safety practice, low initial construction cost, and minimal operation and maintenance expenses.

The formation of a preliminary design involves many variables not explicitly described here. The choice of light source, the extent to which available electrical distribution facilities are used, and the types of poles, brackets, and luminaires selected are some of the factors that influence the economics of lighting. Any consideration of appearance must be resolved by professional judgment and can be justified only if the basic requirements of good visibility have first been attained. It is important that roadway lighting be planned on the basis of traffic and past accident information, which includes the factors necessary to provide for traffic safety and nighttime pedestrian security.

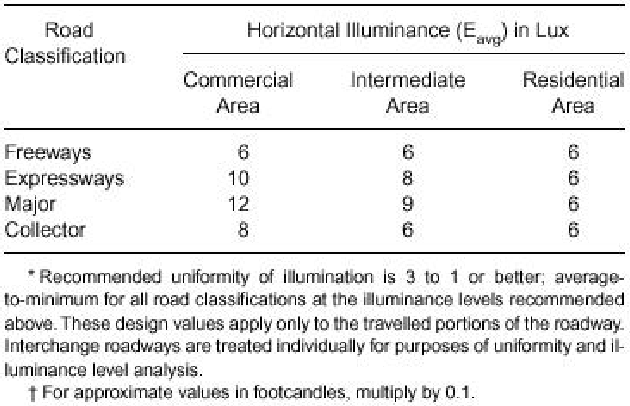
Roadway conditions may also affect the final design. These include the width of the pavement and location of curbs adjacent and within the roadway (island and medians); pavement reflectance; severe grades and curves; location and width of sidewalks and shoulders; type and location of very high volume driveways, intersections, and interchanges; underpasses and overpasses; and trees.

Lighting System Depreciation

The recommended values of Figures 22-8, 22-9, and 22-10 represent the lowest in-service luminance or illuminance values for the type of maintenance to be given to the system. Prior to beginning the design of a lighting system it is necessary to determine the expected light losses. Since luminance or illuminance values can depreciate by 50% or more between relamping and luminaire washing cycles, it is imperative to use lamp lumen depreciation (LLD) and luminaire dirt depreciation (LDD) factors that are valid and based on realistic information or judgment. See Chapter 9, Lighting Calculations, for the use of light loss factors in calculations.

Changes in Pavement Reflectance

Pavement luminance values can be changed by wear on the road surface, resulting in modifications of the reflectance coefficient. For example, asphalt tends to lighten because of exposure of aggregate, and Portland cement darkens because of carbon and oil deposits.

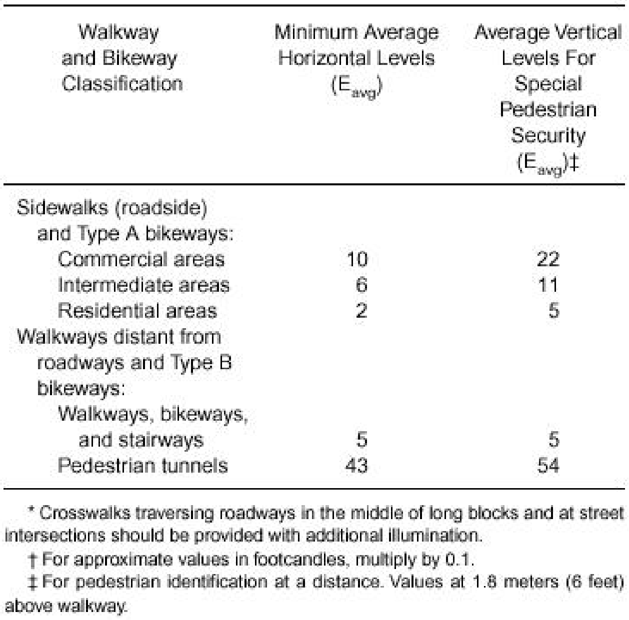


Road Classification	Horizontal Illuminance (E_{avg}) in Lux		
	Commercial Area	Intermediate Area	Residential Area
Freeways	6	6	6
Expressways	10	8	6
Major	12	9	6
Collector	8	6	6

* Recommended uniformity of illumination is 3 to 1 or better; average-to-minimum for all road classifications at the illuminance levels recommended above. These design values apply only to the travelled portions of the roadway. Interchange roadways are treated individually for purposes of uniformity and illuminance level analysis.

† For approximate values in footcandles, multiply by 0.1.

Figure 22-9. Recommended Maintained Illuminance Design Levels for High Mast Lighting* in Lux†



Walkway and Bikeway Classification	Minimum Average Horizontal Levels (E_{avg})	Average Vertical Levels For Special Pedestrian Security (E_{avg})‡
Sidewalks (roadside) and Type A bikeways:		
Commercial areas	10	22
Intermediate areas	6	11
Residential areas	2	5
Walkways distant from roadways and Type B bikeways:		
Walkways, bikeways, and stairways	5	5
Pedestrian tunnels	43	54

* Crosswalks traversing roadways in the middle of long blocks and at street intersections should be provided with additional illumination.

† For approximate values in footcandles, multiply by 0.1.

‡ For pedestrian identification at a distance. Values at 1.8 meters (6 feet) above walkway.

Figure 22-10. Recommended Average Maintained Illuminance Level for Pedestrian Ways* in Lux†

Quality

Quality lighting relates to the ability of the lighting system to provide target and obstacle contrast so that people can make decisions based on fast and accurate obstacle detection and recognition. If the quality of one lighting installation is higher than that of a second installation for the same average luminance (or illuminance) level, then visual detection of typical tasks are faster and easier under the first installation. Important lighting quality considerations for roadways are source/task/eye geometry, shadows, direct glare, reflected glare, peripheral detection, light distribution on surfaces, appearance of spaces and luminaires, light pollution/trespass, and vertical illuminance.

Uniformity

Uniformity is usually expressed in one of three ways: the average-to-minimum, minimum-to-maximum, or maximum-to-average ratio. In roadway lighting, the average-to-minimum and maximum-to-minimum ratios are usually used. The average-to-minimum point method uses the average luminance of the roadway design area between two adjacent luminaires, divided by the lowest value at any point in the area. The maximum-to-minimum point method uses the maximum and minimum values between the same adjacent luminaires.

The luminance values provided in Figure 22-8a are considered to be satisfactory only if the average-to-minimum and maximum-to-minimum uniformity ratios do not exceed the limits specified in this figure. The illuminance values given in Figure 22-8b are satisfactory if the average-to-minimum uniformity ratios are not exceeded. The luminance uniformity (average-to-minimum and maximum-to-minimum) considers the traveled portion of the roadway, except for divided highways, which may have different design requirements on each side of the roadway.

It is important in the actual design of the roadway lighting system that actual photometric data be used for the calculations rather than generic data. This assures that the lighting results achieved match the predicted values, within the normal limits of the calculations.

Luminaire Mounting Height

Mounting heights of luminaires have, in general, increased substantially during the past several decades. The advent of more efficient, higher-lumen lamps has been the primary reason. Designers have increased mounting heights in order to obtain economic and aesthetic gains in addition to increased uniformity of luminance and illuminance values when utilizing modern, high-wattage lamps. Mounting heights of 12 m (40 ft) and higher are used along roadways, and the cluster mounting of luminaires is used at interchanges. The advent of suitable servicing equipment and lowering devices has made this practical.

During this same period, there has been another trend to lower mounting heights in some cases. In general, this has been due to aesthetic considerations. An example is the use of pole top-mounted luminaires in residential areas.

When designing a system, mounting height should be considered in conjunction with spacing and lateral positioning of the luminaires as well as the luminaire type and distribution (Figure 22-11). Uniformity and levels of luminance and illuminance should be maintained as recommended regardless of the mounting height selected.

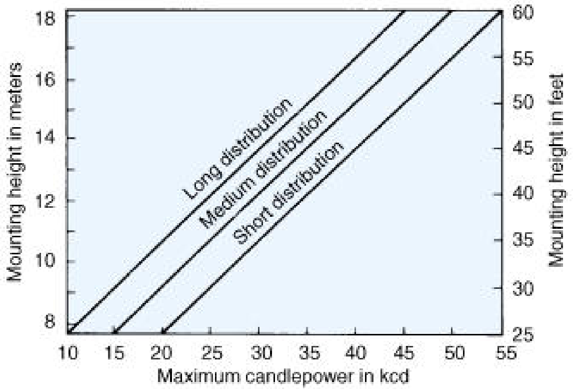


Figure 22-11. Minimum luminaire mounting heights based on current practice and veiling luminance calculations.

Increased mounting height may, but does not necessarily, reduce discomfort glare and veiling luminance. It increases the angle between the luminaires and the line of sight to the roadway; however, luminaire light distributions and intensity also are significant factors. Glare is dependent on the flux reaching the observer's eyes from all luminaires in the visual scene.

High-Mast Interchange Lighting

High-mast interchange lighting is defined as the use of a group of luminaires mounted more than 20 m (60 ft) in height. It is intended to light multiple sections of the paved roadway of an interchange.

The design levels of Figure 22-8 have not been proven to apply to high-mast interchange lighting systems. This is due to a lack of applicable experience in the design of such lighting on a luminance basis. Experience indicates that a system designed to the illuminance criteria in Figure 22-9 gives satisfactory results.

Luminaire Spacing

The spacing of luminaires is often influenced by the location of utility poles, block lengths, property lines, and roadway geometry. It is generally more economical to use lamps with high lumen output at longer intervals and higher mounting heights than to use lamps with lower lumen output at more frequent intervals with lower mounting heights. Higher mounting is usually in the interest of good lighting, provided the spacing-to-mounting-height ratio is within the range of lighting distribution for which the luminaire is designed. Terminology with respect to luminaire arrangement and spacing is shown in Figure 22-4.

Other factors to be considered are:

- Access to luminaires for servicing
- Vehicle-pole collision probabilities
- System glare aspects
- Visibility (both day and night) of traffic signs and signals
- Aesthetic appearance
- Trees
- Locations of poles at intersections to allow joint use for traffic signals

Situations Requiring Special Consideration

Roadways have many areas where the problems of vision and maneuvering of motor vehicles are complex, such as grade intersections, abrupt curves, underpasses, converging traffic lanes, diverging traffic lanes, and various types of complicated traffic interchanges. The values in Figure 22-8 are for roadway sections that are continuous and nearly level. Intersecting, merging, or diverging roadway areas require special consideration. The luminance or illuminance levels for these areas should be at least equal to the sum of the recommended values associated with each roadway that forms the intersection. Very high volume driveway connections to public streets and midblock pedestrian crosswalks should be lighted to a level at least 50% higher than the average route value.

The lighting of such areas, at first glance, appears to be a very complicated problem. It becomes apparent upon analysis, however, that all such areas consist of one of several basic types of situations or a combination of these.

Grade Intersections, Balanced Heavy Traffic. These intersections (Figure 22-12a) may have unrestricted traffic flow on both roadways, restriction by means of stop signs on one or both of the roadways, or control of the traffic by signal lights, traffic officers, or other means. Some intersections are complicated by pedestrian traffic as well as vehicular traffic. The lighting problems on all of these, however, are fundamentally the same. The luminance level in these areas should be higher than that on either intersecting road. See also the subsections on converging and diverging traffic lanes below.

Luminaires should be located so that illumination is provided on vehicles and pedestrians in the intersection area, on the pedestrian walkways, and on the adjacent roadway areas. Of particular importance here is the amount of light falling on the vertical surfaces of such objects that differentiates them from the pavement background against which they are seen.

Figure 22-12b shows a larger, more complex grade intersection. The lighting problems and techniques here are similar to those at the smaller intersections. The size, however, may make the use of more and larger luminaires mandatory.

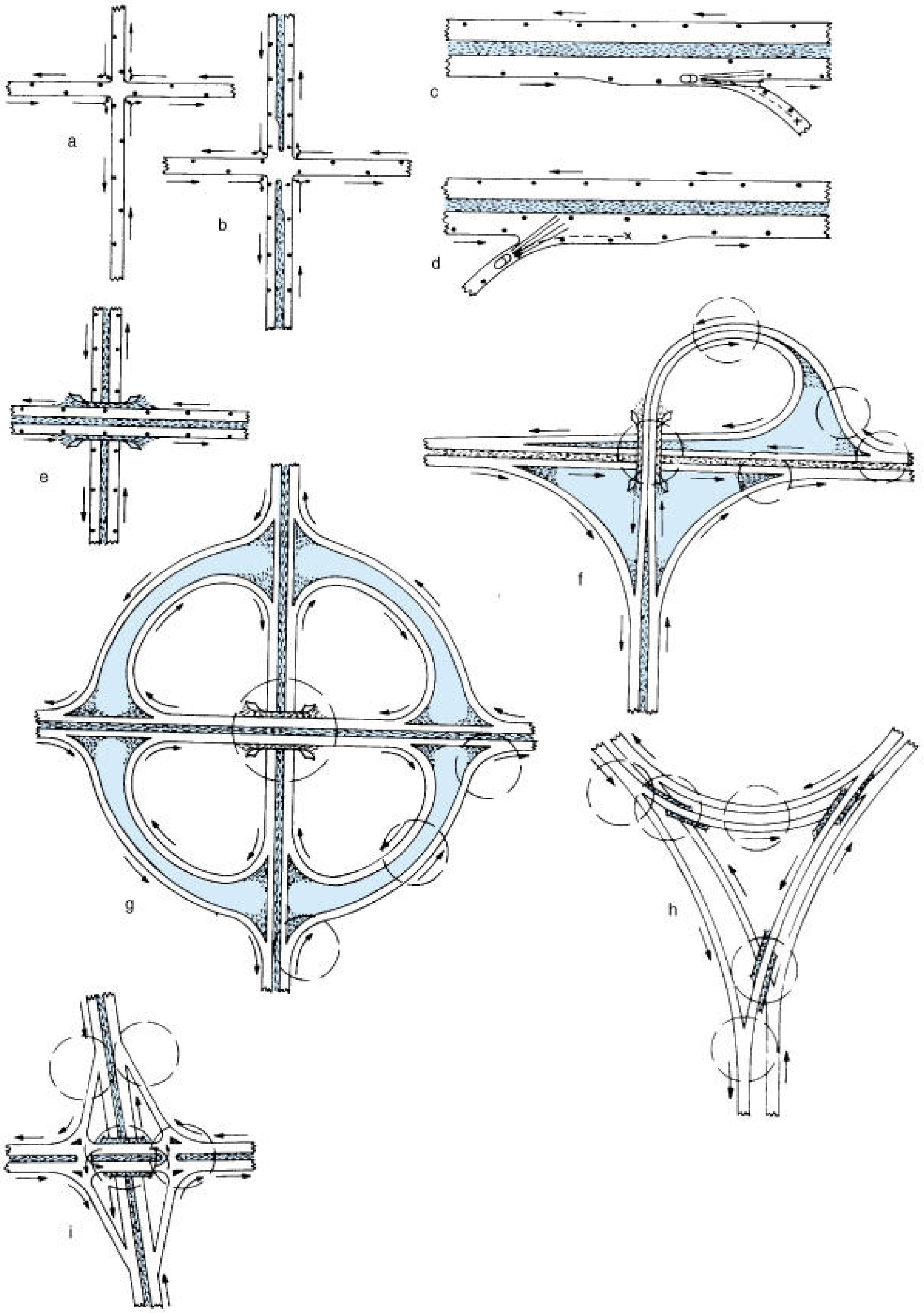


Figure 22-12. Roadway complexities. (a) Grade intersection, balanced heavy traffic. (b) Larger, more complex grade intersection. (c) Diverging traffic lanes. (d) Converging traffic lanes. (e) Underpass--overpass. (f) to (i) Traffic interchanges. Note: Arrows indicate traffic flow directions. Pole location will depend on local practice and physical conditions of the area.

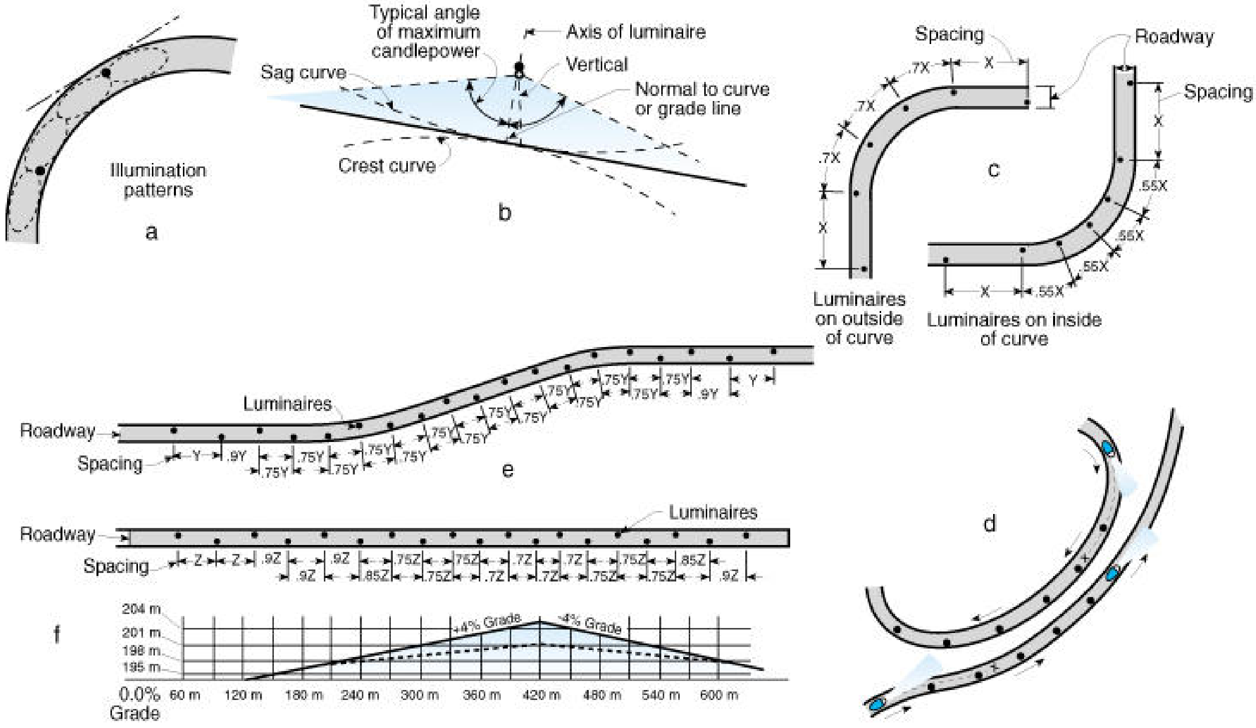


Figure 22-13. Typical lighting layouts for horizontal curves and vertical curves. (a) Luminaires oriented to place reference plane perpendicular to radius of curvature. (b) Luminaire mounting on hill (vertical curves and grade). (c) Short radius curves (horizontal). (d) Vehicle illumination will fall outside the roadway when approaching a curve. Roadway luminaires must be located to compensate for the illumination lost when this occurs. (e) Horizontal curve, radius 305 meters (1000 feet), super elevation six percent per foot. (f) 380-meter (1250-foot) vertical curve with four-percent grade and 230-meter (750 foot) sight distance. (In this illustration, 30 m = 100 ft.)

Curves and Hills. The visual problems in motor vehicle operation increase on curves and hills. In general, gradual large-radius curves, roadways with appropriate super elevation (the vertical distance between the inner and outer edges of the roadway), and gently sloping grades are lighted satisfactorily if treated like straight, level roadway surfaces (Figure 22-13). Sharper curves and steeper grades, especially at the crests of hills, warrant closer spacing of luminaires in order to provide higher pavement luminance and improved uniformities (Figure 22-13e and f).

The geometry of abrupt curves, such as those found on traffic interchanges and many roadway areas, requires careful analysis. Headlighting is not effective in these situations, and silhouette seeing (a condition where the target, or obstacle, has a lower luminance than the background) cannot be provided in some instances. Luminaires should be located to provide ample illumination on vehicles, road curbing and berms, guard rails, and so on. Poles should be located to provide adequate, safe clearance behind guardrails or any natural barriers that may exist. There is some evidence that poles are more likely to be involved in accidents if placed on the outside of curves. Many vehicle operators may be unfamiliar with these areas, and illumination on the surround greatly helps their discernment of the roadway path (Figure 22-13c and d).

Proper horizontal orientation of luminaire supports and poles on curves is important to assure balanced distribution of the light flux on the pavement (Figure 22-13a). When luminaires are located on grade inclines, it is desirable to orient the luminaire so that the light beams strike the pavement equidistant from the luminaire. This assures maximum uniformity of light distribution and keeps glare to a minimum (Figure 22-13b).

Underpass-Overpass. Short underpasses such as those encountered where a roadway goes beneath a two- or four-lane roadway generally can be lighted satisfactorily with standard luminaires if they are properly positioned (Figure 22-12e). Luminaires on the lower roadway should be positioned so that there are not large discontinuities in the pavement lighting from that on either side of the overpass and so that the recommended levels are provided. Care should be taken so that the uniformity does not fall below the minimum values recommended in Figure 22-8. These luminaires should also provide adequate vertical illumination on the supporting structures.

Longer underpasses, where such overlapping of the illumination from the street luminaires cannot be accomplished, require special treatment. Such underpasses also greatly reduce the entrance of daylight, warranting illumination during the daytime. Very high luminance levels can be justified in order to reduce the required adaptation, particularly during daylight hours. In many cases, the techniques used for tunnel lighting can be used effectively for lighting these longer underpasses.

Diverging Traffic Lanes. Diverging traffic lanes warrant extremely careful consideration because these are areas where motorists are most frequently confused. Luminaires should be placed to provide illumination on curbs, abutments, guardrails, and vehicles in the area of traffic divergence (Figure 22-12c). Poles should be located to provide adequate safety clearance for vehicles that may cross the gore area. Lighting also should be provided in the deceleration zone. Diverging roadways frequently have all the problems of abrupt curves and should be treated accordingly.

Converging Traffic Lanes. Converging traffic lanes (Figure 22-12d) frequently have all the problems of abrupt curves. Here, automobile headlighting is ineffective, and silhouette seeing cannot be provided for many of the situations. It is also essential to provide good direct side illumination on the vehicles entering the main traffic lanes.

Interchanges: High-Speed, High-Traffic-Density Roadways. Interchanges at first glance appear to be complex lighting problems. Analysis, however, shows that they are composed of one or more of the basic problems that are discussed in previous sections of this chapter and can be treated accordingly.

When designing lighting for interchanges (Figure 22-12f through i), the regular roadway lighting system usually provides sufficient surround illumination in the field of view to reveal features of the entire scene and to allow drivers to know at all times where they are and where they are going. An inadequately lighted interchange with too few luminaires may lead to confusion for the driver by giving misleading clues due to the random placement of the luminaires. (This does not apply to high-mast lighting.)

When continuous illumination for the entire interchange area cannot be provided, it may be desirable to illuminate intersections, points of access and egress, curves, hills, and similar areas of geometrical and traffic complexity. In these cases, illumination should be extended beyond the critical areas. There are two fundamental reasons for this:

- The eyes of the driver, adapted to the level of the lighted area, need about 1 s to adjust to changes in the illumination upon leaving the lighted area and must maintain vision during this period of dark adaptation. There is no evidence that a gradual reduction at the levels used in roadway lighting has any practical advantage over a sudden ending of the lighted area. This end, however, should be beyond the end of the maneuver area.
- Traffic merging into a major roadway from an access road is often slow in accelerating to the speed on the major roadway. The lighting along this area for a distance beyond the access point extends visibility and facilitates the acceleration and merging process.

The placement of luminaires should be carefully considered so as to minimize glare for the drivers and, especially, so as not to detract from sign legibility or block the view of signs.

Railroad Grade Crossings. Railroad grade crossings should be adequately lighted to allow identification of the crossing, any irregularities in the pavement surface, and the presence or absence of the train in or approaching the crossing, and to allow recognition of unlighted objects or vehicles at or near the railroad crossing. Grade crossings are normally identified by means of signs with the message on a vertical face, as well as markings on the pavement surface. The lighting direction and level should permit visual recognition of such signs and markings. Minor variation of the basic lighting layouts shown in Figure 22-14 may be desirable, depending on the exact locations of the signs or markings.

General principles to be followed in selecting and locating equipment are as follows:

- The illuminance level on a track area starting 30 m (100 ft) before the crossing and ending 30 m (100 ft) beyond it should be in accordance with Figure 22-8, but never less than a luminance of 0.8 cd/m^2 or an illuminance of 8 lx (0.8 fc) (Figure 22-14a).
- Pole location should provide uniformity (Figure 22-14b through f) as outlined above in the section "Uniformity."
- Vertical illumination of a train in a crossing is important for adequate visibility. However, care must be used in locating the luminaire so that glare is not a problem to the drivers approaching the crossing from the opposite direction.

Trees. Trees are important community assets. Careful placement of luminaires and regular tree pruning not only enhance traffic safety and pedestrian security but also preserve the character and appearance of a neighborhood. In order for the lighting designer to determine suitable overhang distances of luminaires for different mounting heights, the characteristics of the different types of trees must be known. Most tree growers or municipal arborists can provide specifications of selected trees such as shape, height, and growth circumference, which help develop a spacing pattern for street lights and trees. Large round-headed trees require more spacing between the street light and tree than a pyramidal, oval, or columnar tree. A successful result requires cooperation between the lighting designer, landscape architect, developer, and local forestry division early in the design process. In the long run, proper spacing between street lights and trees allows more light on the street and sidewalk, and the trees are allowed to grow naturally with little or no pruning. Mismatched, as well as misplaced, trees and street lights usually become a detriment to the local municipal authority, the community, and the adjacent property owner.

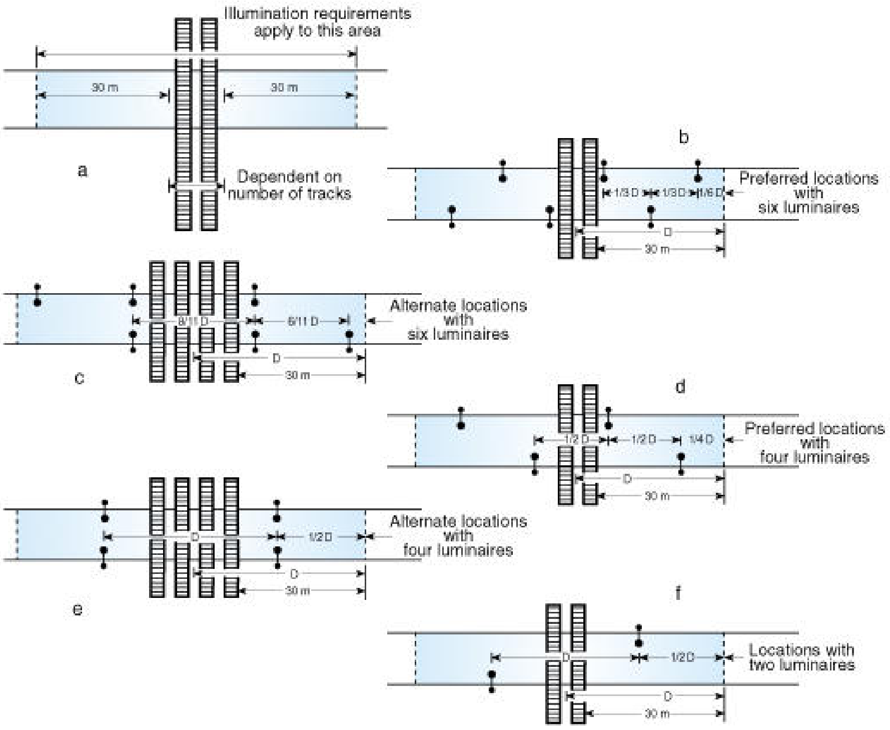


Figure 22-14. Railroad grade crossings.

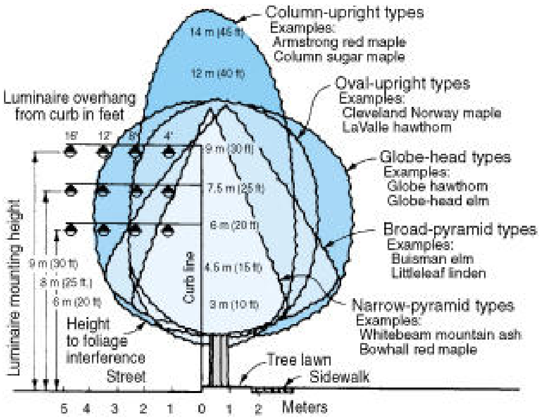


Figure 22-15. Height of foliage interference for different types of trees. Luminaire overhang must be selected to assure luminaire distribution will not be obstructed by the foliage as the tree matures. (Tree examples by E. H. Scanlon.)

Because of the recent trend to use ornamental post-top lights in urban, suburban, and subdivision designs, reasonable spacing (e.g., at least one mounting height between tree and street light) should become part of the design scheme. When using a mast-arm pole, similar concerns should be made to assure that pedestrians have adequate lighting on the sidewalk. For mast-arm designs, see Figure 22-15.

Deviations from ideal luminaire spacing may be necessary to accommodate trees. Generally, a 10 to 20% deviation in longitudinal spacing of luminaires does not seriously affect lighting uniformity, depending on the luminaire photometrics. If more than two consecutive luminaires are involved, care should be taken not to create unacceptable shadows or dark spots. Only as a last resort should deviation be permitted in the transverse overhang of the luminaires. This positioning is important for effectiveness of the lighting and appearance of the system. This latter point can be very important in regard to local residential streets.

In most cities trees are trimmed on a select basis as opposed to a formal tree trimming plan and in these cases the trimming is accomplished by the local utility. The method and manner for trimming trees should be supervised by an arborist. Most cities and large utilities have an arborist as part of the tree trimming crews.

Roadside Border Areas

Visibility for drivers can be improved if areas beyond the roadway proper are illuminated. It is desirable to widen the narrow visual field into the peripheral zone in order to reveal adjacent objects. Such conditions also improve depth perception and perspective, thereby facilitating the judgment of speed and distance. The luminance of border areas should diminish gradually and uniformly away from the road. Of course, these points must be considered in the context of local property owners; the design must eliminate objectionable light trespass.

Transition Lighting

Transition lighting is a technique intended to provide the driver with a gradual reduction in illuminance when traveling from one roadway area into another. Factors that may influence the decision to provide a transition lighting area are:

- Significant reduction in roadway cross section
- Severe horizontal or vertical curvature of the roadway
- Change from a very high lighting level to a lower level

The use of transition lighting is the option of the designer after a study of the conditions at a specific location.

Gradual decreases in pavement luminance are usually accomplished by extending the lighting system beyond the normal limits and partially interrupting the required geometric arrangement of luminaires. For example, a two-side opposite or staggered spacing arrangement could be continued to the normal lighting limits, where luminaires would be omitted from the exiting side of the roadway but continued for one to six cycles beyond the normal limits on the approach side, depending on road speed and luminaire coverage. Designer judgment should be used, and various geometric arrangements should be considered.

Alleys

A well-lighted alley increases the perception of safety and reduces criminals' opportunities to operate and hide under the cover of darkness. Alleys should be lighted to facilitate police patrolling from sidewalks and cross streets, especially in commercial areas. Generally, such lighting also meets the vehicular traffic needs in these low-traffic areas.

Pedestrian Walkways and Bikeways

Proper lighting of walkway and bikeway areas is essential to the safe and comfortable use of pedestrian areas (herein assumed to include bicyclists) at night. Many walkways and bikeways are located adjacent to lighted roadways, and no specific or separate lighting is required. Often, however, the roadway spill light is inadequate for the comfort and safety of pedestrians on the walkway or bikeway. Important lighting criteria for walkways and bikeways are source/task/eye geometry, color appearance, shadows, direct and reflected glare, peripheral detection, modeling of faces and objects, light pollution/trespass, and vertical illuminance.

It is recommended that all lighting designs conform to the illuminance requirements shown in Figure 22-10. If the roadway illumination does not provide the recommended walkway or bikeway levels, revisions or additions to the roadway lighting are necessary. The photometric data provided by the supplier of the roadway luminaires can be used for evaluating Type A or Type B sidewalk or roadway bikeway illuminance recommendations.

The recommended levels of walkway and bikeway illuminance listed in Figure 22-10 represent average maintained illuminance levels and should be considered as minimum, particularly when security and pedestrian identification at a distance is important. Visual identification of other pedestrians and objects along walkways is dependent to a great degree on vertical surface illuminance; therefore, different values are shown in the table. To provide well-lighted surroundings for such pedestrian ways as walkways and bikeways through parks, additional information is provided in Chapter 21, Exterior Lighting.

The average-to-minimum uniformity ratio in illuminating pedestrian ways where special pedestrian security is not essential should not exceed 4:1, except for residential sidewalks and Type A bikeways in residential areas, where a ratio of 10:1 is acceptable. Where increased pedestrian security is desired, the uniformity ratio should not exceed 5:1 for any walkway or bikeway.

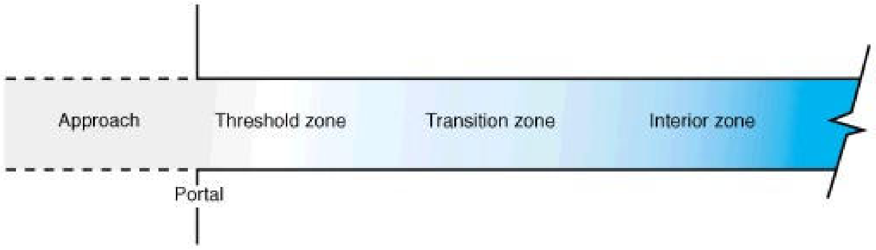
Tunnels[3,4]

Tunnel lighting should provide good visibility for drivers, both day and night. The many factors that contribute to or detract from visibility need to be identified and their specific importance determined for each tunnel. Important lighting criteria for tunnels are shadows, direct glare, reflected glare, peripheral detection, and vertical illuminance.

Physical Characteristics. For lighting purposes a tunnel is an enclosure over a roadway that restricts the normal illumination of the roadway by daylight, thus requiring an evaluation of the need for supplemental lighting. This enclosure may be created either by boring through natural materials such as earth and rock, or by construction using materials such as steel and concrete. The terminology associated with tunnels for the purpose of lighting design is described in Figure 22-16.

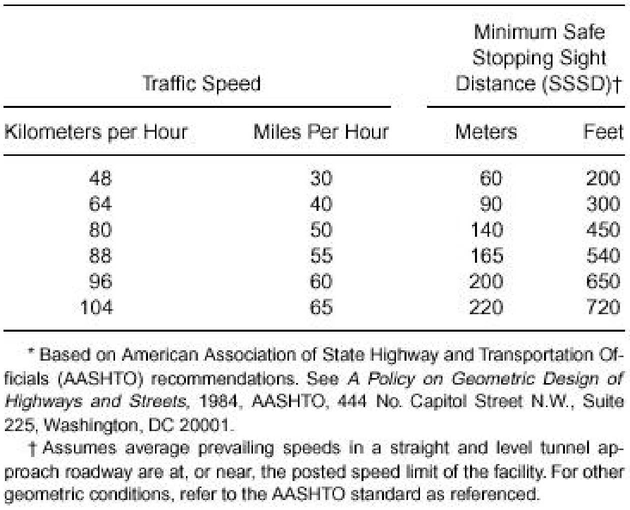
Depending on the length and the safe-stopping sight distance (SSSD), tunnels can be classified in two categories (Figure 22-17):

- Short tunnel. A tunnel having an overall length, from portal to portal along the centerline, equal to or less than the SSSD.
- Long tunnel. A tunnel with an overall length greater than the SSSD.



Approach: The external roadway area leading to the tunnel;
Portal: The plane of entrance into the tunnel;
Threshold Zone: The first part of the tunnel where, during daytime, the highest level of the lighting is provided;
Transition Zone: The area where a transition is made from the high lighting level of the threshold to the lower lighting level of the interior.
Interior Zone: The innermost part of the tunnel where the lowest level of lighting is provided.
Note: Lengths of zones will vary with the design parameters.

Figure 22-16. Descriptive terms associated with tunnel lighting.:



Traffic Speed		Minimum Safe Stopping Sight Distance (SSSD)†	
Kilometers per Hour	Miles Per Hour	Meters	Feet
48	30	60	200
64	40	90	300
80	50	140	450
88	55	165	540
96	60	200	650
104	65	220	720

* Based on American Association of State Highway and Transportation Officials (AASHTO) recommendations. See *A Policy on Geometric Design of Highways and Streets*, 1984, AASHTO, 444 No. Capitol Street N.W., Suite 225, Washington, DC 20001.

† Assumes average prevailing speeds in a straight and level tunnel approach roadway are at, or near, the posted speed limit of the facility. For other geometric conditions, refer to the AASHTO standard as referenced.

Figure 22-17. Safe Stopping Sight Distance*

The critical task facing the driver approaching the tunnel entrance portal during the daytime is to overcome the "black hole" effect created by the high ratio of external to internal luminance. The use of dark finish material on the approach road surface to the tunnel portal, and light finish material on the road surface inside the portal, for a distance at least equal to the SSSD, reduces the difference between external and internal luminances. The darkening of these external surfaces reduces the luminance level to which the eye is adapted prior to entering the tunnel, thus shortening the time to adapt to the lower luminance levels within the tunnel. For tunnels with a prominent sky background immediately above their entrance portals, objects such as plants, screens, and panels can increase the size of the darkened area above the portals.

To use daylight and supplemental electric lighting effectively, it is recommended that interior wall surfaces be of an easily maintained, high-reflectance, nonspecular finish having a reflectance of at least 50% initially. In tunnels having curved roadways or having curved approach roadways, development of high wall luminance is of great value in meeting visibility needs. Relatively narrow tunnels, where the width-to-height ratios are approximately 3 or less, normally develop good tunnel visibility as a result of reflected light from high-reflectance walls. Tunnels having greater width-to-height ratios normally require supplemental lighting of the roadway surface.

The amount and extent of daylight penetration into the tunnel entrance is largely dependent on the orientation of the tunnel with respect to the sun's path in the sky. Since the orientation of a tunnel is generally directed by criteria other than illumination considerations, the tunnel lighting system must be able to accommodate the entrance orientation conditions. In entrance portal areas, sunlight penetration can be improved by use of wall, ceiling, and roadway surface texture control.

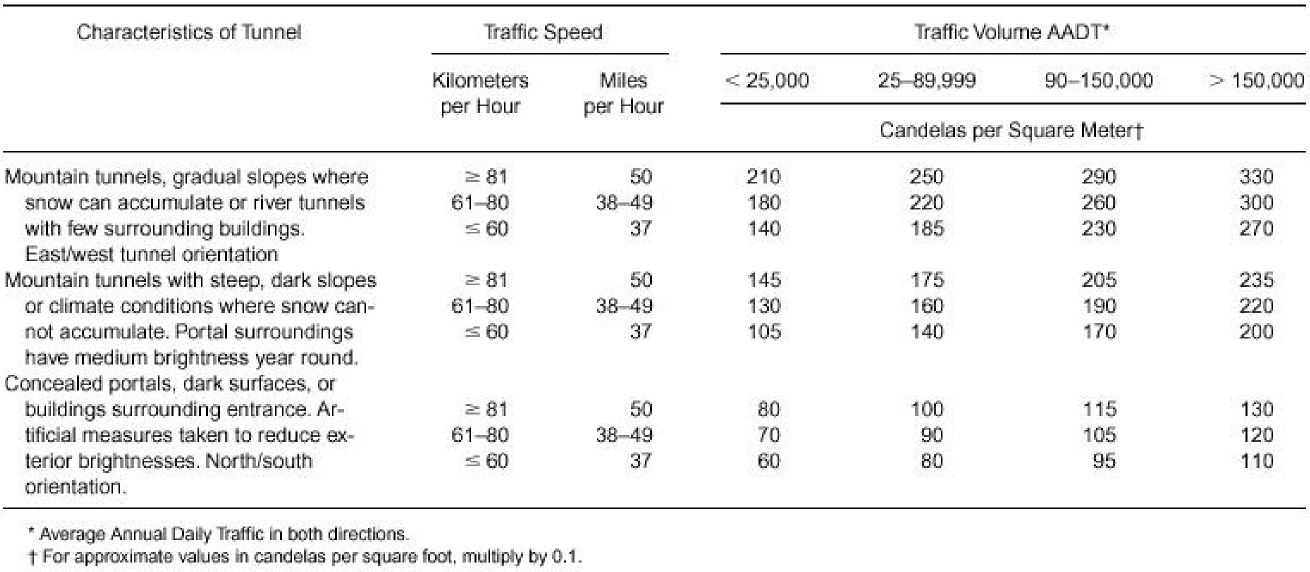
Lighting Design Considerations. Tunnel lighting design should take into account the following considerations:

- Volume and speed of traffic
- External luminance
- Tunnel classification
- Tunnel luminances during both daytime and nighttime conditions
- Lighting and electrical equipment

Volume and Speed of Traffic. Tunnels with high traffic volume and with high-speed traffic require higher luminance levels than those with lower volume and slower traffic to aid the motorist in performing more difficult driving tasks. High-volume traffic increases the probability of having to stop quickly or take evasive action. Higher speeds reduce the time available for eye adaptation and reaction to driving difficulties.

External Luminance. Since approaching drivers are looking at the tunnel entrance prior to entering the tunnel, they are adapted to the luminance of the portal area and the surrounding visual scene.

Tunnel Classification. Short tunnels, with a length of less than the SSSD and having straight, level approach alignment and a straight and level tunnel roadway, may have adequate visibility without supplemental daytime lighting. In these cases, visibility can be provided by negative contrast (silhouette), with high luminance values provided by the exit portal. In tunnels with curved roadways, where the exit portal is not visible, supplemental lighting may be required. These short tunnels should have a single lighting zone equal in luminance to the threshold zone as shown in Figure 22-18. Long tunnels require several zones of lighting.



Characteristics of Tunnel	Traffic Speed		Traffic Volume AADT*			
	Kilometers per Hour	Miles per Hour	< 25,000	25–89,999	90–150,000	> 150,000
			Candelas per Square Meter†			
Mountain tunnels, gradual slopes where snow can accumulate or river tunnels with few surrounding buildings. East/west tunnel orientation	≥ 81	50	210	250	290	330
	61–80	38–49	180	220	260	300
	≤ 60	37	140	185	230	270
Mountain tunnels with steep, dark slopes or climate conditions where snow cannot accumulate. Portal surroundings have medium brightness year round.	≥ 81	50	145	175	205	235
	61–80	38–49	130	160	190	220
	≤ 60	37	105	140	170	200
Concealed portals, dark surfaces, or buildings surrounding entrance. Artificial measures taken to reduce exterior brightnesses. North/south orientation.	≥ 81	50	80	100	115	130
	61–80	38–49	70	90	105	120
	≤ 60	37	60	80	95	110

* Average Annual Daily Traffic in both directions.

† For approximate values in candelas per square foot, multiply by 0.1.

Figure 22-18. Recommended Maintained Threshold Zone Average Payment Luminance Values for Tunnel Roadways during Daylight

Tunnel Luminance. Tunnels have several different areas with different lighting requirements. In addition, the time of day plays an important role in the lighting of tunnels. Topics discussed below include the threshold zone, the interior zone, the transition zone, nighttime tunnel lighting, uniformity rules, and maintenance considerations.

Threshold Zone. Daytime tunnel luminance in the threshold zone must be relatively high to provide visibility during eye adaptation as the motorist enters the tunnel. Figure 22-18 gives appropriate daytime threshold zone luminances. During nighttime, the motorist's eyes are adapted to the low ambient exterior luminance; therefore, a nighttime minimum luminance of 2.5 cd/m^2 is recommended for the entire length of the tunnel, including the threshold. Since the illuminance required at the tunnel threshold during nighttime hours is significantly lower than that required during daytime hours, it may be appropriate to provide for dimming or switching the tunnel lighting system to permit adjusting the threshold illuminance to provide appropriate daytime and nighttime levels. As indicated, the required luminance level is dependent on both the characteristics of the tunnel and the traffic speed and volume in the tunnel. The length of the threshold zone lighting should be 15 m (50 ft) less than the SSSD. At approximately 15 m (50 ft) before the portal, the tunnel dominates the visual scene.

Interior Zone: Daytime lighting in the interior of a long tunnel can be reduced, since the motorist's eyes will have adapted to the lower luminance of the threshold zone. Luminance of the tunnel interior zone should be a minimum of 5 cd/m^2 with a uniformity ratio below 3:1, average-to-minimum.

Transition Zone: Daytime luminance in the transition zone should taper from the threshold zone luminance to the interior zone luminance over a length equal to the SSSD. Transition zone lighting can be accomplished in various ways: greater spacing between luminaires, fewer lamps per luminaire (in the case of fluorescent lamps), lower-wattage lamps, or combinations of the above. The number of sections within the transition zone using different lighting arrangements should be such that an even transition occurs. The transition zone should first be divided into segments of equal length. The first segment after the threshold zone should have a pavement luminance of no less than 25% that of the threshold zone. Each subsequent section should have a pavement luminance no less than 33% that of the previous segment. The last segment before the interior zone should have a pavement luminance no greater than twice that of the interior zone.

Nighttime. During nighttime, the motorist's eyes are adapted to the low ambient exterior luminance; therefore, a nighttime minimum luminance of 2.5 cd/m^2 is recommended for the entire length of the tunnel.

Uniformity Ratios. Uniformity ratios within the tunnel zones should be the same as those used for general roadway lighting as shown in Figure 22-8.

Maintenance Considerations. The recommended luminance values given for tunnels in Figure 22-18 represent the lowest in-service values that should be allowed throughout the operating life of the system. Therefore, the initial luminance in the tunnel may have to be higher to compensate for lamp lumen depreciation, luminaire dirt depreciation, and tunnel surface dirt depreciation.

Lighting and Electrical Equipment. Fluorescent, HID, and low-pressure sodium lamps are the light sources used most commonly for tunnel lighting installations. Incandescent lamps are seldom used in new installations due to their low efficacy and short life.

Tunnel lighting luminaires must be ruggedly constructed to withstand the harsh environment found in most tunnels. Vibration, air turbulence caused by vehicles, vehicle exhaust fumes, road dirt, salt, and the periodic washing of tunnels with industrial detergents and high-pressure jet spray equipment are some of the conditions to which luminaires are exposed.

The power supply for tunnel lighting must be very reliable. Even a momentary loss of power cannot be tolerated, since it can lead to serious accidents if people enter complete darkness. Safety can be greatly improved by providing power from two separate sources to the entire tunnel lighting system with transfer devices that automatically switch from one power source to the other in the event of power failure. Consideration should be given to the installation of an emergency power supply to luminaires providing at least one-fifth of the design nighttime lighting level. Tunnel lighting requirements may vary during daily operation as a result of external luminances varying with weather or the position of the sun. Some installations have luminaires that can be switched or dimmed automatically with changes in the outdoor luminance or with changes in the luminaire's effective light output. Tunnel systems may also have a manned control room with closed-circuit television surveillance that allows monitoring of tunnel conditions and provides for manual override of the automatic operations.

Flicker Effect. In the interior of a lighted tunnel, where luminaires or their reflected images are in full or partial view of the vehicle occupants, the flicker effect of passing closely spaced light sources may produce undesirable behavioral sensations. The significance of this effect depends on the brightness of the source to the observer, the location of the source in the motorist's viewing field, and the frequency or rate at which successive light sources appear to be moving. The designer should avoid luminaire spacings that produce driveby frequencies of 5 to 10 Hz.[5]

Rest Areas[6]

Rest areas on limited access highways are an important feature to the motorist, and there is general agreement that for the public to obtain maximum benefits from the construction of a rest area, it must be available 24 hours a day and be considered safe to enter and stay in at least for short periods of time. To obtain this condition, these areas must be adequately lighted for nighttime use. Figure 22-19 shows a typical layout for a roadway rest area.

In designing a lighting system for a rest area, geographical location, topographical location, motorists' comfort and safety, landscaping and architectural treatment, and appearance to pedestrians must be considered. An important benefit to be derived from proper lighting is ease of policing these areas during nighttime hours. Important lighting quality criteria for rest areas include color appearance, shadows, direct glare, peripheral detection, modeling of faces and objects, points of interest, appearance of space and luminaires, and horizontal and vertical illuminances.

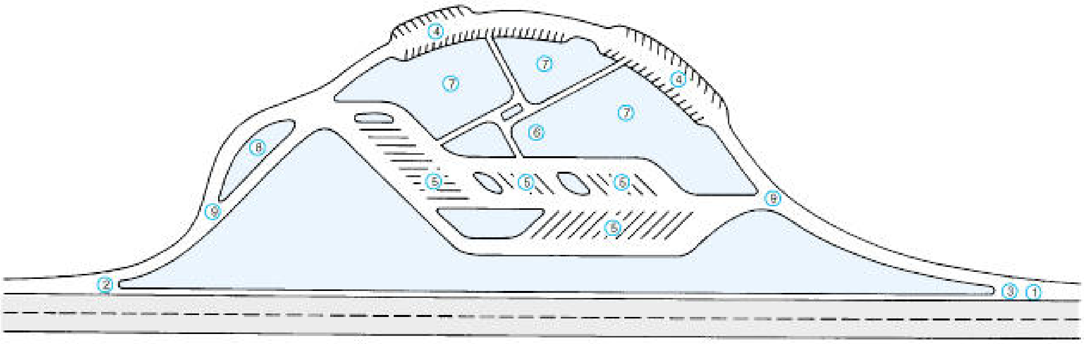


Figure 22-19. Typical layout of roadway rest area, (1) deceleration lanes; (2) acceleration lanes, (3) gore area; (4) automobile parking; (5) truck parking; (6) comfort station; (7) picnic area; (8) waste station; and (9) interior roadway.

One of the prime design considerations is the motorist's view while traveling along an unlighted main highway or in the rest area. The motorist should not be disturbed by glare or spill light from luminaires placed adjacent to the roadway within the rest areas. While traversing the entire length of the adjacent rest area, the motorist should be able to discern any vehicle leaving the rest area, as well as the traffic moving along the main roadway.

The overall design of the lighting is divided into general areas as follows:

- Entrance and exit
- Interior roadways
- Parking areas
- Activity areas

These have been defined for separate consideration because each is to be used for a different purpose. The illuminances recommended in Figure 22-20 are minimum maintained values.

Entrance and Exit. Entrance and exit areas are defined as the deceleration and acceleration lanes adjacent to the main roadway, leading to and from the gore area. These lanes should be lighted so that the driver entering or leaving the rest area can safely make the transition from the main roadway to the rest area and vice versa. At the same time, drivers electing to continue along the main roadway should be able to do so without impairment of their vision by luminaire brightness or spill light. Drivers should likewise be able to discern vehicles leaving or entering the roadway. The assumption is often made that access lanes to rest areas should be lighted in the same manner as ramps at interchanges; however, interchange ramps are usually designed for higher speeds and traffic densities. Rest area entrances and exits, with relatively low traffic density, are deceleration and acceleration lanes leading to and from low-speed roadways within the area, and thus must be designed with this purpose in mind.

It is recommended that the illuminance along the deceleration lane be allowed to vary (Figure 22-20), but the maximum illuminance should occur at the gore point between the deceleration lane and the beginning of the interior roadways. Similarly, a high illuminance level should occur at the exit gore. Illumination may decrease from this point to a point where the motorist can be considered to have merged with the through traffic. The motorist on the through lanes must be able to see an exiting vehicle, make a proper decision, and adjust to the traffic flow. The decreased illuminance is desirable for the merging motorist because it facilitates adaptation from the illuminated rest area to the unlighted roadway.

Rest Area	Illuminances**		Uniformity† Ratio
	Lux	Footcandles	
Entrance and Exit			
Access Lanes	3 to 6	.3 to .6	6:1 to 3:1
Gores	6	.6	3:1
Interior Roadways	6	.6	3:1
Parking Areas‡	11	1.0	
Activity Areas			
Major	11	1.0	3:1
Minor	5	.5	6:1

* The illuminance values recommended represent the condition just prior to cleaning and/or group relamping as calculated and planned in the design procedure.

** Average.

† Average to minimum.

‡ = 6 lux [0.6 footcandles] minimum.

Figure 22-20. Recommended Illuminance Levels for Roadway Rest Areas*

It is recommended that luminaires be used that confine the main light to the deceleration and acceleration lanes and restrict high-angle brightness. In the event that the main roadway is continuously lighted beyond the confines of the rest area, deceleration and acceleration lanes should be lighted to a level equal to that of the main roadway.

Interior Roadways. Interior roadways are those between the entrance or exit points and the parking areas. As these roadways are off the main highway, the designer may select another type of luminaire than that used on the highway. The designer should keep in mind, however, that there may be an added maintenance problem when several different types of luminaires and lamps are required within one area.

Parking Areas. Illumination of both automobile and truck parking areas should be designed so that, from the vehicle, the motorist can distinguish features of the area including pedestrians. The area should be lighted so that a motorist can read signage and be directed by it to various parts of the area. Careful attention should be paid to areas that may require special detailing, such as handicap ramps and sanitary disposal stations.

Activity Areas. Activity areas are those designed for pedestrian use. Major activity areas are those which include such structures as comfort stations and information centers, as well as the walkways between those locations and the parking area. Minor activity areas are those that include picnic tables and dog walks and their associated walkways and facilities. Generally, the illuminance in the major activity areas is higher than that in the minor areas.

Area floodlighting may be provided for architectural or other purposes. Care should be taken to ensure that stray light is not directed toward, or reflected from, the main roadway toward the passing motorist.

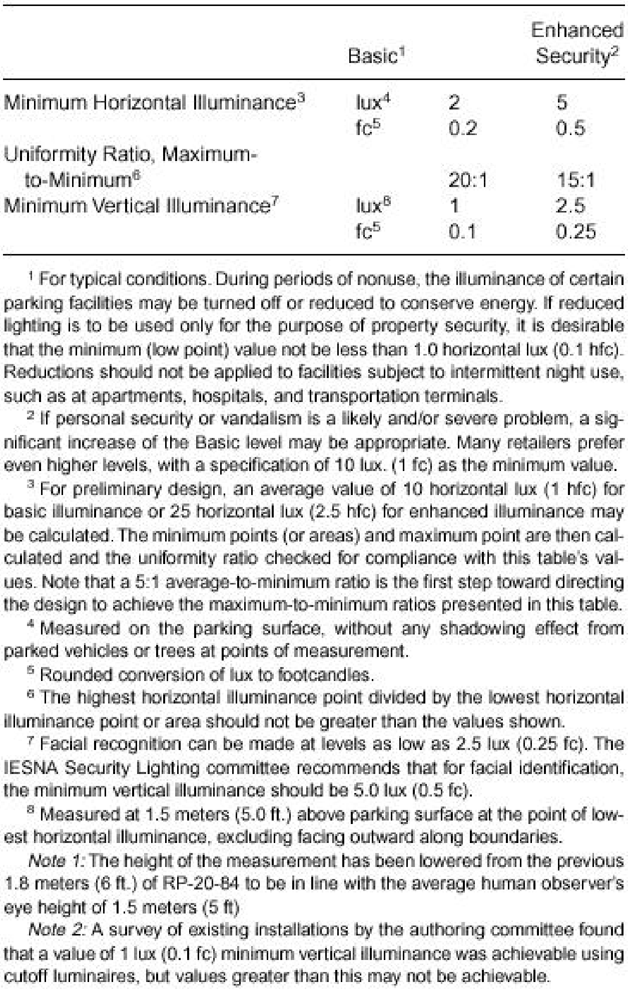
Maintenance. Rest areas are frequently in remote, isolated regions and require more rigid maintenance and supervision than facilities that can be visited more regularly by maintenance and security personnel.

Parking Facility Lighting[7]

Objectives. Parking facility lighting is important for vehicular and especially pedestrian safety, for protection against assault, theft, and vandalism; for the convenience of the user; and in some cases for business attraction. Important lighting design criteria for parking areas are source/task/eye geometry, shadows, direct and reflected glare, peripheral detection, modeling of faces and objects, light pollution and trespass, and vertical illuminance.

Types of Facilities. For lighting purposes, parking facilities can be classified as either a lot (open) or a garage (covered). Most facilities are one type or the other, but in a multilevel structure the roof is considered open while the lower levels are considered covered. Parking stalls with roofs only (open on all sides) may be treated as lots depending on the configuration of the space and the height of the spaces. The illuminance requirements for all parking facilities depend largely on pedestrian needs and perceived personal security issues.

Parking Lots. Illuminance recommendations for active lots open to the public, customers, or employees are given in Figure 22-21. The illuminance should be measured, or calculated, on a clear pavement, without any parked vehicles. The maximum and minimum values are maintained illuminances. This condition occurs just prior to lamp replacement and luminaire cleaning.



		Basic[1]	Enhanced Security[2]
Minimum Horizontal Illuminance[3]	lux[4]	2	5
	fc[5]	0.2	0.5
Uniformity Ratio, Maximum-to-Minimum[6]		20:1	15:1
Minimum Vertical Illuminance[7]	lux[8]	1	2.5
	fc[5]	0.1	0.25

[1] For typical conditions. During periods of nonuse, the illuminance of certain parking facilities may be turned off or reduced to conserve energy. If reduced lighting is to be used only for the purpose of property security, it is desirable that the minimum (low point) value not be less than 1.0 horizontal lux (0.1 hfc). Reductions should not be applied to facilities subject to intermittent night use, such as at apartments, hospitals, and transportation terminals.

[2] If personal security or vandalism is a likely and/or severe problem, a significant increase of the Basic level may be appropriate. Many retailers prefer even higher levels, with a specification of 10 lux. (1 fc) as the minimum value.

[3] For preliminary design, an average value of 10 horizontal lux (1 hfc) for basic illuminance or 25 horizontal lux (2.5 hfc) for enhanced illuminance may be calculated. The minimum points (or areas) and maximum point are then calculated and the uniformity ratio checked for compliance with this table's values. Note that a 5:1 average-to-minimum ratio is the first step toward directing the design to achieve the maximum-to-minimum ratios presented in this table.

[4] Measured on the parking surface, without any shadowing effect from parked vehicles or trees at points of measurement.

[5] Rounded conversion of lux to footcandles.

[6] The highest horizontal illuminance point divided by the lowest horizontal illuminance point or area should not be greater than the values shown.

[7] Facial recognition can be made at levels as low as 2.5 lux (0.25 fc). The IESNA Security Lighting committee recommends that for facial identification, the minimum vertical illuminance should be 5.0 lux (0.5 fc).

[8] Measured at 1.5 meters (5.0 ft.) above parking surface at the point of lowest horizontal illuminance, excluding facing outward along boundaries.

Note 1: The height of the measurement has been lowered from the previous 1.8 meters (6 ft.) of RP-20-84 to be in line with the average human observer's eye height of 1.5 meters (5 ft)

Note 2: A survey of existing installations by the authoring committee found that a value of 1 lux (0.1 fc) minimum vertical illuminance was achievable using cutoff luminaires, but values greater than this may not be achievable.

Figure 22-21. Recommended Maintained Illuminance Values for Parking Lots

Basic lighting requirements tend to be similar for most types of land uses. Typical or average security needs are equally as great in a parking lot serving an apartment building, a regional shopping center, or a sports complex.

Exits, entrances, gate access, internal connecting roadways or ring roads, and cross-aisles should be given special consideration to permit ready identification and to enhance safety. Generally, higher illuminance should be placed along these routes by using appropriate locations of luminaires, larger light sources, and additional luminaires. Illuminance of the driveway access to streets should at least match any local public lighting. For high-volume driveways, such as those at community or regional shopping centers, an increase of 50% in the average public road lighting level is desirable; however, this value should be compatible with local conditions. If the street has no lighting, the basic values in Figure 22-21 can be used and are applicable to the curb line.

For good visibility of objects such as curbs, poles, fire hydrants, and pedestrians, vertical illuminance is important. The values in Figure 22-21 obviously do not apply to a direction facing outward along a boundary, because this would require lighting equipment beyond the property line. Similarly, they do not apply to a direction facing inward between an outer line of luminaires and the boundary line. The values are for a location 1.5 m (5 ft) above the pavement.

The shadow effects of trees and fixed objects such as large signs or building walls also should be examined. It is sometimes practical to adjust luminaire locations to minimize or even eliminate such shadows.

Lighting for parking lots should provide not only the recommended minimum illuminance levels but also good color rendition, uniformity, and minimal glare.

Shielding lamps, reflectors, or lenses minimize glare and enhance visibility. Undesirable sky glow should be minimized by limiting the upward component of the luminaire light distribution. Spill light extending beyond the boundary of the parking lot may be undesirable if it falls onto a different land use. Spill light is unwelcome by residential owners and is sometimes prohibited by local ordinances.

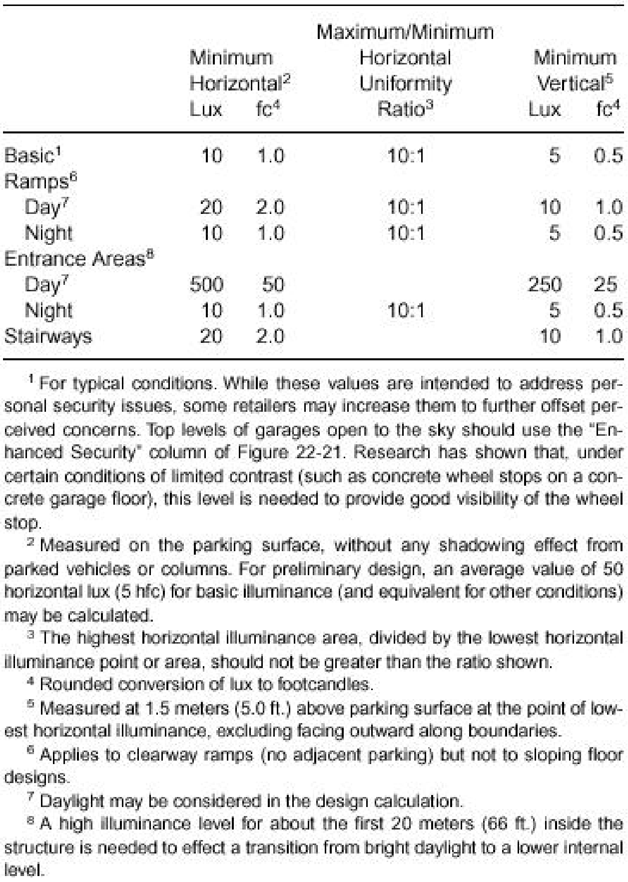
Lamps typically used in parking lots include HID and some types of low-pressure sodium. The advantages and disadvantages of various lamp types are available in Chapter 6, Light Sources, and Appendix Table A-2 of IESNA RP-20.[7]

A variety of luminaires is used in parking lots, including floodlighting, area lighting, architectural, post-top, wall-mounted, high-mast, and roadway-lighting luminaires. Of these types, the floodlighting and roadway lighting luminaires are most commonly used (see Chapter 7, Luminaires).

All lighting installations depreciate with time and require a continuing maintenance program in order to provide the design illuminance. The designer must consider and assume the degree and frequency of maintenance. Vandalism can generally be reduced by mounting luminaires at least 3 m above ground level. High-impact materials such as tempered glass, acrylic, and polycarbonate, when incorporated into the design of shields, lenses, refractors or globes, are extremely useful for damage reduction.

Poles should be placed so as to reduce collision with automobiles. Poles should be set on pillars to minimize direct contact with an automobile.

Parking Garages. Illumination recommendations for parking garages are given in Figure 22-22. These apply to covered and enclosed facilities intended for use by the general public, and those used by residents, customers, and employees of apartment buildings or commercial developments. They are not intended to apply to garages used exclusively for repair or storage of commercial vehicles, or where vehicles are parked by attendants.



	Minimum Horizontal[2]		Maximum/Minimum Horizontal Uniformity Ratio[3]	Minimum Vertical[5]	
	Lux	fc[4]		Lux	fc[4]
Basic[1]	10	1.0	10:1	5	0.5
Ramps[6]					
Day[7]	20	2.0	10:1	10	1.0
Night	10	1.0	10:1	5	0.5
Entrance Areas[8]					
Day[7]	500	50		250	25
Night	10	1.0	10:1	5	0.5
Stairways	20	2.0		10	1.0

[1] For typical conditions. While these values are intended to address personal security issues, some retailers may increase them to further offset perceived concerns. Top levels of garages open to the sky should use the "Enhanced Security" column of Figure 22-21. Research has shown that, under certain conditions of limited contrast (such as concrete wheel stops on a concrete garage floor), this level is needed to provide good visibility of the wheel stop.

[2] Measured on the parking surface, without any shadowing effect from parked vehicles or columns. For preliminary design, an average value of 50 horizontal lux (5 hfc) for basic illuminance (and equivalent for other conditions) may be calculated.

[3] The highest horizontal illuminance area, divided by the lowest horizontal illuminance point or area, should not be greater than the ratio shown.

[4] Rounded conversion of lux to footcandles.

[5] Measured at 1.5 meters (5.0 ft.) above parking surface at the point of lowest horizontal illuminance, excluding facing outward along boundaries.

[6] Applies to clearway ramps (no adjacent parking) but not to sloping floor designs.

[7] Daylight may be considered in the design calculation.

[8] A high illuminance level for about the first 20 meters (66 ft.) inside the structure is needed to effect a transition from bright daylight to a lower internal level.

Figure 22-22. Recommended Maintained Illuminance for Parking Garages

From a security standpoint, and to reduce personal apprehension, garages need higher illuminances than open parking facilities. Good lighting uniformity should be provided to enhance pedestrian safety since access aisles are used by pedestrians for walking between cars and stairways or elevators. While Figure 22-22 specifies that the minimum vertical illumination be at least 50% of the minimum the horizontal illuminance, a higher percentage is desirable in garages to enhance visibility and security.

Driving ramps can be contained entirely within the structure or mounted along the perimeter. The latter are usually open to the sky and may require little or no daytime lighting. Ramps with parking along one or both sides are called sloping floor designs and require basic garage illumination.

The entrance area is defined as the drive aisle and any adjacent parking stalls, from the portal or physical building line to 20 m (60 ft) inside the structure. Where parking is not provided next to the drive lane, the width of entrance area should be defined by the adjacent walls, if any, but should not exceed 15 m (50 ft). Elevated illuminances during the day are needed for the transition from full daylight to the relatively low interior illuminances. Ordinarily, entry to a garage involves a turn from a street or service road. Designs that involve a straight entry run of some distance (50 m [160 ft] or more) allow drivers to enter at higher speeds and may require correspondingly longer transition areas. In such cases, the illuminances can be stepped down in successive stages beyond the first 15 m (50 ft).

Light sources typically used today are metal halide and HPS. Luminaires for above-ground garages require many of the photometric and environmental considerations used in the design of lighting for parking lots. Open-wall structures are exposed to the same temperatures as open lots. Luminaires should be of a type designed for use in impact and corrosion- and emission-prone hostile outdoor environments requiring weather-proof, vandal-resistant construction. Luminaires for garages are categorized as cutoff and noncutoff. The cutoff type usually has a flat lens or enclosure to provide a shielded light source with resultant low brightness and glare. The noncutoff type is most commonly available with a dropped luminous diffusing lens or refractor allowing wider spacings. However, because of the typically low mounting heights, control of glare is essential, either by luminaire selection or placement. A lamp and luminaire maintenance program should be considered as part of the lighting design, including written instructions for maintenance personnel.

Emergency lighting units should be located in strategic positions to provide lighting in case of an interruption to the normal power supply. In general, they should provide approximately 10% of the lighting levels of Figure 22-22, with a minimum of 10 lx for pedestrian egress, or meet applicable local code requirements.

Special Considerations. Lighting of access roads to all types of parking facilities should match the local highway lighting as much as possible. The average maintained illuminance should be compatible with local conditions. The average-to-minimum illuminance uniformity ratio should not exceed 3:1.

In all parking facilities, consideration should be given to color rendition. Users sometimes have trouble identifying their cars under light sources with poor color rendering characteristics.

In many parking facilities, closed-circuit television is necessary. The illuminance, the light source, the photometric distribution, and the pattern of luminaires as well as the camera position must be considered to ensure effective results.

Special Considerations for Open Facilities. In open parking facilities, exits, entrances, loading zones, pedestrian crossings, and collector lanes should be given special priority to ensure safety and security. Outdoor pedestrian stairways require luminaires to illuminate changes in step elevation. Parking facilities for rest or scenic areas adjacent to roadways generally employ lower illuminances. See the section on "Rest Areas" earlier in this chapter for more information.

Special Consideration for Covered Facilities. In covered parking facilities, vertical illuminances of objects such as columns and walls should be equal to the horizontal values given in Figure 22-22. These vertical values should be for a location 1.8 m (6 ft) above the pavement.

In covered parking facilities the design should be arranged so that some lighting can be left on for security reasons. The low level from Figure 22-21 for open parking facilities can be used for this purpose.

Illuminated Roadway Signs[8]

Motorists may stop or reduce speed at roadway signs that are difficult to read, and thus create a hazardous condition. Proper sign lighting can aid rapid and accurate recognition of the sign shape, color, and message.

Lighting for roadway signs becomes more significant as the volume of traffic increases, the complexity of highway design increases, the likelihood of adverse weather increases, and ambient luminance increases. Important lighting design criteria for roadway signs are source/task/eye geometry, reflected glare, light distribution on surfaces, modeling of faces and objects, points of interest, surface characteristics of objects, appearance of area and luminaires, and vertical illuminance.

Ambient Luminance. The background luminance against which a sign is viewed by a motorist is called its ambient luminance. Three categories of ambient luminance (high, medium, and low) can be identified:

- High: Areas with high street lighting levels and brightly lighted advertising signs
- Medium: Areas with small commercial developments and lighted roadways and interchanges
- Low: Rural areas without lighting or areas with very low levels of lighting

High levels of ambient luminance can make sign lighting mandatory in order to ensure sign legibility for decisive driver action.

Light Source Selection. Energy consumption is a major consideration that must be balanced by other factors, such as color rendering, ambient temperature, and maintenance. Selection should be based on lamp efficacy and life in addition to its color rendering properties. Lighting must maintain the color rendering as close as practical to that seen under daylight conditions.

Illumination Recommendations. There are three types of lighted signs: externally lighted signs, internally lighted signs, and luminous source message signs (where the message is formed by lamps).

Externally Lighted Signs. Recommended illuminances for externally lighted signs are shown in Figure 22-23. A maximum-to-minimum illuminance uniformity ratio of 6:1 should not be exceeded for acceptable appearance of the sign face. Lower ratios will produce a more legible sign.

Ambient Light Level	Sign Illuminance		Sign Luminance* Candelas per square meter
	lux	footcandles	
Low	100–200	10–20	22–44
Medium	200–400	20–40	44–89
High	400–800	40–80	89–178

* Based on maintained reflectance of 70 percent for white sign letters.

Figure 22-23. Recommended Maintained Levels for Externally Lighted Roadway Signs

	Ambient light level		
	Low	Medium	High
Candelas per square meter	240	520	1000
Candelas per square foot	24	52	100

Figure 22-24. Recommended Maintained Luminance for Internally Lighted Roadway Signs

Internally Lighted Signs. Recommended luminances for internally lighted signs are shown in Figure 22-24. These luminance values are for a white translucent material forming the legend and the border. For colors other than white, higher luminance values may be required to obtain the same contrast with the background.

The maximum-to-minimum luminance ratio of the sign background should not exceed 6:1, and no adjacent areas 0.3 by 0.3 m (1 by 1 ft) should have a luminance difference greater than 20%. The maximum-to-minimum luminance ratio for the entire sign legend should not exceed 6:1. Lastly, the average luminance contrast between legend and background should be greater than 10:1.

Luminous Source Message Signs. Recommended levels have been established only for a variable message sign composed of a matrix of luminous sources that can be selectively lighted. These levels are the same as those given in Figure 22-24.

COMPUTATIONAL METHODS

The basic computations that follow apply to conventional roadway lighting systems mounted alongside the street or highway at heights of 5 to 20 m (15 to 60 ft) above the pavement. The data and techniques can also be applied to adjacent walkways, median strips, and other areas. Illuminance, light loss factors, and luminance are important in roadway lighting, but because of their general nature, illuminance calculations and light loss factors are discussed in Chapter 9, Lighting Calculations. Roadway luminance calculations, because of their unique r tables and roadway coordinate system, are included in this chapter. Special computations relating to area lighting with high-mast equipment over 20 m (60 ft) above the pavement, to walkways and bikeways, and to veiling luminance are also covered in this chapter.

The recommended design values, as well as uniformity ratios, are given in Figures 22-8, 22-9, and 22-10. These represent the lowest maintained values that are currently considered appropriate for the kinds of roadways or walkways in various areas. Numerous installations have been made at higher levels. Furthermore, the recommendations assume the use of applicable types of luminaire light distribution, lamp size, mounting heights, spacing, and transverse locations. These figures do not represent initial readings but should be the lowest in-service values of systems designed with the proper light loss factors. The tables indicate whether the values are averages or minimal for each area.

Light Loss Factors

Once design values for illuminance or luminance are established and a preliminary choice of a luminaire is made, light loss factors (LLF) can be evaluated. Several of these factors are affected by time-dependent depreciation effects. Others exist initially and continue through the life of the installation. However, all factors should be studied, and attempts should be made to improve LLFs wherever possible. Consult Chapter 9, Lighting Calculations, for details on LLFs that are not included in this chapter. The following LLFs are applicable to roadway lighting:

Lamp Lumen Depreciation. Consult the manufacturer.

Luminaire Dirt Depreciation. The accumulation of dirt on luminaires results in a loss in light output. This loss is known as the luminaire dirt depreciation (LDD) factor and is estimated by dirt category (very clean, clean, moderate, dirty, or very dirty) from definitions given in Figure 22-25. The LDD is found from the appropriate dirt category curve in Figure 22-25 and the proper elapsed time in years of the planned cleaning cycle.

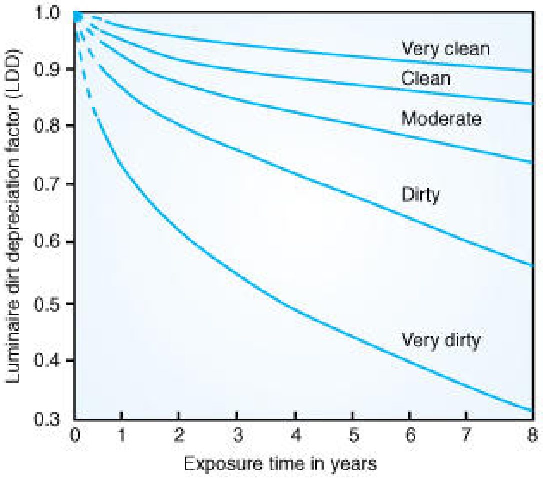


Figure 22-25. Chart for estimating roadway luminaire dirt depreciation factor for enclosed and gasketed luminaires.

Luminaire Ambient Temperature. Consult the manufacturer.

Voltage to Luminaire. Consult the utility.

Ballast and Lamp Factor.[9,10] Consult the manufacturer.

Luminaire Surface Depreciation. Experience is the best predictor; no factors are available at present.

Burnouts. Routine maintenance is required.

Total Light Loss Factor. The total light loss factor is simply the product of all the contributing factors described above. Where factors are not applicable, they are omitted. If, at this point, it is found that the total light loss factor is excessive, it may be desirable to reselect the luminaire or lamp or to modify the cleaning and maintenance schedule.

Another factor that must be considered in the calculation is the change in the performance of individual components as a result of operation with a range of different associated luminaire components. For example, a lamp does not always have the same lumen output when used with ballasts of different manufacturers or when installed in luminaires of different design or manufacturer. This should be taken into account in the calculations for luminance or illuminance. The factor used for calculations can be in the range of 5 to 15%.

Determination of Average and Point Illuminance

The average illuminance over a large pavement area may be calculated by means of an average-footcandle calculation, a utilization curve (which is almost never used today), an isoilluminance (isofootcandle) curve, or by computing the illuminance at a large number of points and averaging the values found.

Average-Lux (Average-Footcandle) Computation. The formulas for determination of average horizontal illuminance in roadway lighting are the same ones used for average illuminance for parking lots in Chapter 9, Lighting Calculations.

Utilization Curves. Utilization curves, available for various types of luminaires, afford a practical method for the determination of average illuminance over the roadway surface where lamp size, mounting height, width of roadway, overhang, and spacing between luminaires are known or assumed. Conversely, the desired spacing or any other unknown factor may readily be determined if the other factors are given.

A coefficient of utilization is derived from the utilization curve and is the percentage of rated lamp lumens that falls on either of two striplike areas of infinite length, one extending in front of the luminaire (street side) and the other behind the luminaire (house side), when the luminaire is level and oriented over the roadway in a manner equivalent to that in which it was tested. Since the roadway width is expressed in terms of a ratio of luminaire mounting height to roadway width, the term has no dimensions.

Isoilluminance (Isofootcandle) Diagram. An isoilluminance diagram is a graphical representation of points of equal illuminance connected by a continuous line. Such diagrams are convenient for making point illuminance determinations and are provided by the manufacturer of the luminaire under consideration. They have become less common since the introduction of powerful computer programs that can quickly and easily make point-by-point roadway lighting calculations.

Point-by-Point Calculation Method. For a complete description of the classical point-by-point calculation method and an example of its application, see Chapter 9, Lighting Calculations.

Determination of Luminance

Luminance values at a point may be calculated from photometric data obtained and provided by most manufacturers for luminaires associated with roadways. Parameters of position are important determinations that should be consistently applied for both luminance calculations and measurements.

The luminance of a point *P* (Figure 22-2e) can be written as a sum of contributions from all *n* luminaires:

$$L_P = \sum_{i=1}^{n} \frac{r(\beta_i, \gamma_i)\, I(\phi_i, \gamma_i)}{10{,}000 h^2} \qquad (22\text{-}1)$$

where all symbols, except luminous intensity (*I*), are defined in Figure 22-2. The factor 10,000 appears in the denominator because the values in Figure 22-2 should have been multiplied by 10,000. (If the values are taken directly from Figure 22-2 without multiplying by 10,000, the factor 10,000 in the denominator of Equation 22-1 should be omitted.) The value of *I* must be depreciated by the light loss factor times any equipment factors.

Calculation and Measurement Parameters (Figures 22-2 and 22-26).

- Observer eye height: 1.45 m (4.75 ft) above grade
- Line of sight of observer: downward 1° below horizontal over a distance of 83 m (272 ft); parallel to edge of roadway along lines 1/4 of the roadway line width from edges of each lane (two lines per lane)
- Lighting system to be measured: smooth and level, at least 10 mounting heights long
- Number of points per line: at least 10, not more than 5 m (16.5 ft) apart
- Area covered by measurement and calculations: all points between two luminaires on one side of roadway (Figure 22-26)
- Calculation-point location with respect to contributing luminaires: at least one luminaire behind, and at least three ahead of the calculation point *P*
- Luminaire light distribution data: based on initial installed values using actual lamp-luminaire performance
- Luminance values: to be calculated using the r tables in Figure 22-2
- Horizontal illuminance *Eh*: to be printed and recorded at the same points as the luminance values, as a reference
- Luminance *L*: to be printed and recorded at the same points as the horizontal illuminance values
- Average luminance L_{avg}: to be determined by averaging all values of the evaluated roadway section
- Longitudinal luminance uniformity: lane uniformity *LL* to be determined as the ratio of the maximum to the minimum luminance in any 1/4-lane line, taking the worst (highest) ratio as the rating for the roadway
- Average luminance uniformity: to be determined by rating the average luminance L_{avg} to the minimum found in any of the lines within the roadway
- Maximum luminance uniformity: to be determined by rating the maximum luminance found in any of the lines to the minimum found in any of the lines within the roadway

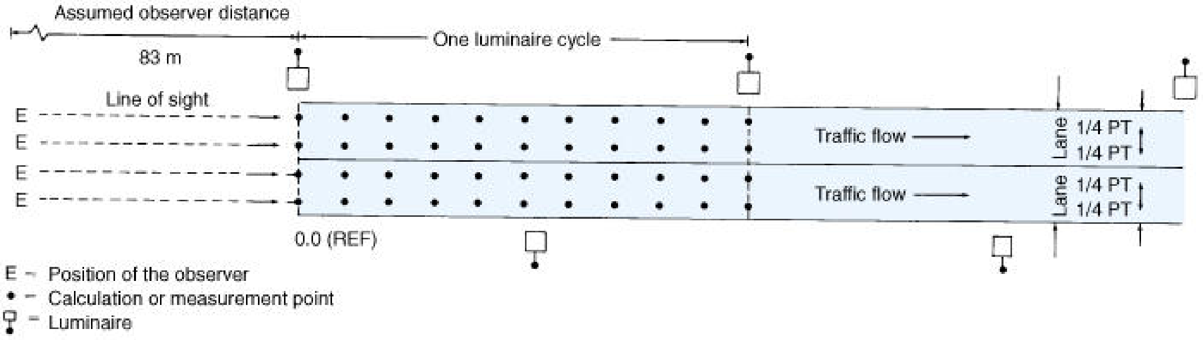


Figure 22-26. Luminance calculation points.

Veiling Luminance

The L_v (expressed in cd/m^2) of a roadway lighting system can be determined from the observer's position by using the following empirically derived formula[11] to calculate the L_v contributed by each luminaire separately, and then summing the individual L values:

$$L_v = \frac{10\,E_v}{\theta^2 + 1.5\theta} \qquad (22\text{-}2)$$

where

E_v = vertical illuminance in the plane of the pupil of the observer's eye,
θ = angle between the line of sight and the luminaire in degrees.

Note that the line of sight is a line parallel to the curb line of the roadway and located away from the edge of the roadway in one of the quarter-lane planes, at an eye height of 1.45 m (4.75 ft) above the road (Figure 22-27).

The number of luminaire cycles is to be the same as that for determining the pavement luminance. The L_v for an entire system of n luminaires is therefore

$$L_v = \sum_{i=1}^{n} \frac{10\,E_{vi}}{\theta^2 + 1.5\theta} \qquad (22\text{-}3)$$

Walkway and Bikeway Lighting

The procedure to determine the horizontal illuminance values on pedestrian ways for safe and comfortable use is similar to that followed for roadways. Because the design of roadway lighting places greater emphasis on achieving proper illuminance on the roadway, it is customary for the lighting system to be initially selected to suit the needs of the roadway. Then, the system is checked to determine if the sidewalk illuminance levels and uniformity are adequate. If not, the designer may modify the luminaire type or spacing, may provide supplemental lighting primarily for the sidewalk area, or may do both in order to achieve proper illuminance on both roadway and sidewalk. See Chapter 21, Exterior Lighting, for additional walkway and bikeway lighting recommendations.

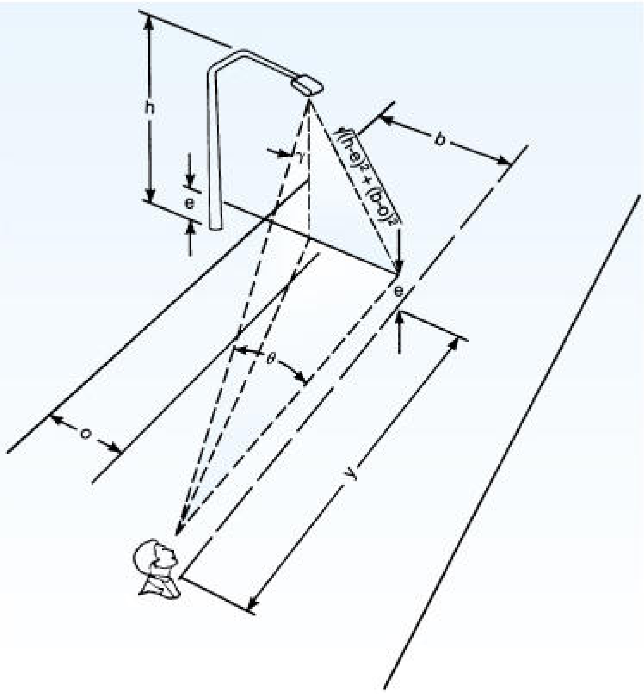


Figure 22-27. Angular relationships for calculating *Lv* (Veiling Luminance) from a single luminaire. Angle γ in

this figure equals Angle γ in Figure 22-2.
Note:

$$\gamma \text{ arc tan } \frac{\sqrt{y^2 + (b - o)^2}}{h - e}$$

$$\times\ \theta \text{ arc tan } \frac{\sqrt{(h - e)^2 + (b - o)^2}}{y}$$

where

h = mounting height of luminaire above the road surface in meters.
e = eye above the road surface in meters.

In some areas where personal security is a problem and identification of another pedestrian at a distance is important, the recommended levels in the right column of Figure 22-10 apply. These recommendations are stated in terms of the average vertical illuminance reaching a plane surface 1.8 m (6 ft) above the walkway and perpendicular to the centerline of the walkway.

Crosswalks traversing roadways in the middle of long blocks and at street intersections should have specific illumination. Average vertical illuminance levels for special pedestrian security should be maintained (Figure 22-10). An example of the calculation procedure for vertical illuminance can be found in Chapter 9, Lighting Calculations.

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23

Transportation Lighting

TRANSPORTATION LIGHTING DESIGN ISSUES

- Color Appearance (and Color Contrast)
- Direct Glare
- Flicker (and Strobe)
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Modeling of Faces or Objects
- Reflected Glare
- Shadows
- Source/Task/Eye Geometry

The principles established for good interior and exterior lighting apply also to the transportation field; however, the characteristics of the electric power supply make illumination for transportation vehicles more difficult. Both alternating and direct-current power supplies are available, and a wide variety of voltages and frequencies are involved. One of the principal problems is to adapt lamps and lighting equipment to the available power. Also, the tremendous length of roadways and railways, the fact that they are used intermittently, and their exposure to a wide variety of weather conditions are transportation factors that complicate the lighting design.

AUTOMOBILE LIGHTING

Automobile lighting is generally restricted by two related factors. First, automobiles commonly use low voltage, generally 12-V systems. Some transportation vehicles, such as aircraft and buses, use 24-V storage systems because of their length. Second, automotive electrical systems have limited power capacity. It takes ten times the current to power a 100-W device at 12 V than at 120 V. For this reason, many of the lighting devices are chosen for luminous efficiency rather than availability or low cost.

Exterior Lighting

Exterior lighting is divided into two categories: "forward illumination" and "signaling and marking." Forward lighting includes headlights, fog lights, auxiliary driving, and auxiliary passing lamps. Signal lighting includes stop and tail lamps, turn signal lamps, four-way emergency lamps, cornering lamps, sidemarker lamps, and license plate illumination lamps.

Headlighting. Headlighting has always presented a dichotomous situation for the lighting designer. On one hand, the luminous intensity directed down the road is very important to the driver for maintaining lane control, detecting roadway obstacles, and giving the driver a feeling of well-being behind the wheel of the vehicle. On the other hand, glare to oncoming drivers in meeting and following (rearview mirror) situations places a restriction on how much light can be delivered to some locations on the roadway. Generally speaking, glare zones and roadway markers or roadway obstacles can be separated by only a few centimeters to a meter (1/2 to 3/4 ° of visual angle at distances of 5 to 100 m [15 to 300 ft]).

As a result, headlighting beam distributions have always been an optimization between forward visibility and minimized glare. The different specifications for the European Union (EU) and for the United States (the Society of Automotive Engineers [SAE] and the Federal Motor Vehicle Safety Standard [FMVSS108]), however, give testimony to the strong differences of opinion over the relative importance of glare and forward visibility. Progress is being made toward a harmonized specification that will be accepted in both Europe and the United States.

Headlighting regulations throughout the world have developed along different lines. The United States adopted a "sealed-beam" PAR lamp standard. The concept of sealing a pressed glass parabolic reflector and lens envelope around a precisely located filament and filling the hermetic assembly with an inert gas was invented in the United States.[1] The

PAR lamp technology retained most of the lamp's initial lumen output throughout life and was easy and inexpensive to replace. The filament was positioned horizontally across the parabolic axis (C6 filament) by high-speed equipment developed for mass production of other low-voltage automotive lamps. This technology set the U.S. headlamp beam pattern standards.

In Europe, a different headlighting technology was developing. They settled on a replaceable bulb located along the parabolic axis. The axial (C8) filament orientation produces a good beam pattern with a very sharp horizontal cutoff, using simple lens optics. In general, U.S. standards and regulations for headlamps allow more glare, both rearview mirror and opposing, than do the comparable EU regulations. There is also a test voltage disparity (about 12.0 V for ECE, or 12.8 V for SAE) that unrealistically amplifies the apparent differences. The biggest disagreement has been over the aim method and the controlled left cutoff used in Europe for visually aiming headlamps. A single technology for headlamp design has not yet been adopted worldwide, as the relative benefits of competing philosophies continues to be debated.

In recent years, different forms of headlamps have become widely used. Many newer vehicles in the United States now use replaceable quartz-halogen bulbs instead of the traditional sealed beam types. An important trend is developing, particularly in Europe, in the use of high-intensity discharge (HID) headlamps. These use a combination of metal halides for high lumen output and xenon for fast warmup. They are driven by an electronic ballast and ignitor. HID headlamps are typically designed with a broader beam pattern than quartz-halogen systems.

Headlamp Designs. Headlight systems are based on many optical configurations. The simplest optical configuration, at least in theory, is the parabolic reflector system (Figure 23-1a). A light source, usually a single or double filament lamp, is located at or near the focal point of a three-dimensional parabolic reflector. Light is reflected from the parabolic surface and directed forward in roughly the desired beam shape. Optical elements on the lens further refine the beam pattern to meet the driver's visual needs and the pertinent lighting specification. Parabolic systems are very efficient collimators of light and can be optimized for some flexibility in making beam pattern accommodations for a variety of user needs. Tooling for injection molding or glass pressing is relatively inexpensive and easy to modify. However, the attainable beam shapes with parabolic systems are somewhat limited.

Figure 23-1. Headlight systems. (a) Parabolic reflector system, and (b) non-parabolic reflector system.

Non-parabolic reflector systems can have smooth surface shapes like parabolic systems, but they are not parabolic in the mathematical sense. Non-parabolic reflectors can also be segmented. Because the reflector surface is not parabolic, the optical design has more control over the beam shape. In this way the need for an optically active lens is reduced or eliminated, which is desirable for design and styling reasons (Figure 23-1b). Tooling for non-parabolic reflectors is expensive and difficult to change.

Fog Lighting. Fog beam patterns tend to be very wide, generally out to 20 or 30° on each side of the beam pattern. They are designed to be aimed downward so as to illuminate the roadway immediately in front of the vehicle (where the driver supposedly is trying to find his path through the fog). The veiling effects of fog are difficult to overcome. High photometric intensity levels that aid in lane keeping or obstacle detection are also responsible for the veiling effects of fog. Light striking fog droplets is reflected on the front surface and via retroreflection from the back surface of the droplet. It is probable that the high-angle light (at 5, 10, 20°) is the main culprit. Most fog lamps and fog beam specifications recognize this and limit luminous intensity at high angles to much lower levels than headlamps. Some analytical work has been done that sheds new light on fog lighting.[2] It shows that in fog, high-angle glare light (8 to 50° up) creates much more veiling luminance than the low-angle (1 to 2° up) light. Fog illuminated by vehicle lamps approximately doubles the threshold luminance as it reduces the retinal image contrast between an illuminated obstacle and the surrounding veiling luminance.

Whatever the mechanism of veiling by fog may be, fog lamps themselves tend to be relatively low wattage (30 to 55

W), and small and compact (in order to fit in small vehicle recesses and under bumpers), and they generally have less optical precision and sophistication in their design than do headlamps. The device's short duration and infrequent duty cycle, coupled with the variable and transitory nature of fog, have not encouraged technical understanding of the fog application nor the device specification to address it. The SAE standards in place as of this writing can be traced back to SAE standards in force in 1938.

Auxiliary Lighting. In the automotive context, auxiliary lighting refers to auxiliary driving (upper beam) and auxiliary passing (lower beam) lamps. Generally these lamps produce beams that are similar in shape and light distribution to the respective beams that the lamps were created to augment. It is easy to rationalize that this is proper for the upper-beam driving situation. However, some would argue that the auxiliary low beam or passing lamp should provide light where the typical lower beam output is known to be weak, on the immediate left and in the extreme lateral areas. This probably explains why fog lamps, with their broad high-intensity zone (HIZ) and extremely wide spread, are frequently used to augment lower-beam headlamps.

Signal and Marking Lighting. This lighting classification generally includes stop and high-mounted stop lamps; tail lamps; back-up lamps; side, rear marker, and clearance lamps; front and side turn signal lamps; four-way flasher lamps; front and rear cornering lamps; and even license plate lamps. A recent addition to the variety of signal lamps is the center-high-mounted-stop-lamp (CHMSL). It was mandated in the federal regulation covering automotive lighting, 49 CFR, Part 571.108.[3]

The purpose of most signal and marking lighting devices is to help a vehicle be seen. (Cornering lamps are the notable exceptions since they enable the driver to see the curb.) All of the other devices are used to signal others of:

- The vehicle's presence in the lane of travel
- The driver's application of the vehicle's brakes
- The driver's intention to change the position of his vehicle in the lane
- The presence of a stopped or slow-moving vehicle in the lane of travel

Signal and marking lighting devices typically use incandescent lamps with one or two filaments. Recently, some vehicles have been equipped with light-emitting diodes (LEDs) for the red functions. Equipment has also been produced that uses neon tubing in various colors. Both LED and neon have the advantages of reduced power usage because of high efficacy and a faster on time for the light output.

Signal Lamp Colors. For automotive (and tractor-trailer) use, three colors are available: red, white, and yellow. Blue is reserved for emergency vehicles. In the United States, red is allowed only on the rear or rear-side of automobiles and trucks. Yellow is used on the back, front, or side, as is white. Green has never been used to any extent. The appropriate ranges of signal colors are specified by Society of Automotive Engineers (SAE) in SAE J578, Color Specification.[4]

The main signal colors are yellow and red. Yellow has historically signaled that "caution" is appropriate, whereas red indicated that a vehicle may be slowing or stopped and that there is a potential hazard in approaching at too high a speed. Yellow is used on the front or rear of a vehicle to signal an intention to turn. Red can be used only on the back of a vehicle as a marker light or to signal braking and turning. School buses use flashing yellow and red for slowing and stopping/loading situations, respectively.

Uncolored light is generally for signaling presence or for guidance in cornering and backup applications. Emergency vehicles can use blue in addition to red and white for warning and hazard signals.

For commercial tractors and trailers over 2032 mm (80 in.) in width, marker lamp and signal lamp colors and locations are specified in the Code of Federal Regulation (CFR) and SAE standards. Red is generally used for the rear and rear sides of trailers, and yellow is used for the front of the tractor and for the middle and front sides of the trailer.

Intensity of Signal Light. Brake light minimum luminous intensity specifications (80.0 cd) require 40 times the luminous intensity of a tail lamp (at 2.0 cd).

Light Patterns. The pattern to which signal lights are designed or to which they must comply can be generally characterized as "wide" rather than "high." Geometric and application considerations are also taken into account. For instance, in braking situations the following driver is most likely located to the rear of the stopping vehicle and not generally to the side. For this reason stop light patterns are specified to only 20° to each side (and 10° up or down). On the other hand, side marker lamps must be viewed from a variety of angles. The specification for side marker or clearance lamps covers angles of 45° to each side (and 10° up and down). Why stop lamps are required to spread light only to 20° should be obvious in the context of automotive power conservation and voltage losses over extended electrical runs. Conservation of light energy and maximization of the maximum beam intensity (MBI) is of course the goal for stop lamps, and this drives a trade-off of beam width for beam intensity. Specific intensity distributions can be found in 49CFR[3] and SAE HS-34, Ground Vehicle Lighting Standards Manual.[5]

Display Methods. The method of display for signal lamps is consistent with the intended message. In critical and potentially dangerous situations, hazard warnings are displayed as flashing signals. The flash rate is specified to fall between 60 and 120 flashes per minute. Turn signals similarly are flashed in order to distinguish them from intermittent brake signals. Brake lamps remain on during the brake application period. There have been proposals (and patents issued, not necessarily in that order) to specify a variable brake signal flash rate depending on the rate of deceleration. The standards and regulatory bodies have resisted such overtures in order to maintain the distinction between emergency or turning signals and braking signals.

Specifications for Exterior Lighting of Motor Vehicles

United States Standards. The mass production methods characteristic of the automotive industry encourage extensive standardization, and through the cooperation of the Society of Automotive Engineers (SAE), the Illuminating Engineering Society of North America (IESNA), safety engineers, and state motor vehicle administrators, standards have been developed that cover the characteristics and procedures for testing automotive lighting equipment. The U.S. Department of Transportation has issued standards for automotive lighting equipment, in general following the SAE standards with some variations and additions. The SAE standards are published annually in the SAE Handbook[6] and are reviewed at least once every five years and continued or revised. The standards outline specifications and tests for the various lighting devices, covering such details as photometry, color, vibration, moisture, dust, and corrosion.

Original and replacement lamps for vehicular lighting are regulated in the United States by the Federal Motor Vehicle Safety Standard (FMVSS) No. 108. These regulations, established by the National Highway Traffic Safety Association (NHTSA), cover headlighting, signaling and marking lamps, reflective devices, and assorted equipment necessary for the safe operation of vehicles after darkness and under other conditions of reduced visibility. Since NHTSA regulations change from time to time, that agency should be contacted for the latest information before proceeding with new designs. The NHTSA frequently specifies an older SAE standard (as indicated by an earlier suffix letter) than that published in the latest SAE Handbook.

Devices such as fog lamps and auxiliary driving lamps are regulated by the individual states. The American Association of Motor Vehicle Administration coordinates most regulations of the states and maintains a listing of recognized lighting devices not covered by Federal Motor Vehicle Safety Standard No. 108.

Canada Standards. Transport Canada uses ECE, SAE, and FMVSS 108 standards to augment the Canadian regulation, Canadian Motor Vehicle Safety Standard (CMVSS) 108, as necessary. Where other needs exist, Canadian rule writers develop new laws for their own needs. This happened when Canada made use of Daytime Running Lights (DRLs) mandatory on all new vehicles. Daytime running lamps, first used in the Scandinavian countries, operate any time the engine is running. Canada allows fog lamps, running lamps, low- or high-beam lamps (at reduced voltage), or specifically designed DRL lamps to be used for DRL purposes. In other cases, Canada allows versions of ECE or SAE lighting devices. Headlamps are a good example of a situation where both ECE and SAE specifications are allowed. In Canada, regulation of device performance is by audit as it is in the United States, but the audited samples are taken from the vehicle assembly factory floor rather than purchased from repair or aftermarket sources.

Mexico Standards. Mexico is similar to many developing countries in that it does not have a formal automotive standard for headlighting. Presently Mexico accepts lighting built to either the ECE or SAE standards. Aftermarket products are available that are not necessarily designed to either standard. Many countries that do not have their own automotive lighting standards adopt the ISO versions. These are generally similar to ECE. Mexico has not adopted the ISO version as this book goes to press.

Interior Lighting

Interior lighting in vehicles takes two forms: the lighting of the instruments and controls, and the general lighting for the driver and passengers. Lighting for the instruments and controls should be designed to make their location and status immediately apparent, during the day and at night. To ensure good visibility during the day, the instrument panel should be designed so that no direct illumination from the sun or sky is reflected towards the driver or passengers. To ensure good visibility at night, both the instrument panel and the controls should be illuminated. Provision for dimming this lighting is desirable to avoid excessive brightness at night, such brightness having the potential to interfere with the driver's view of the road. Illumination of instrument panels and controls can be provided in many different ways using incandescent lamps, LEDs, electroluminescent sources, and ultraviolet sources/fluorescent materials, with the light being delivered directly or through filters, waveguides, or fiber optics (Figure 23-2).

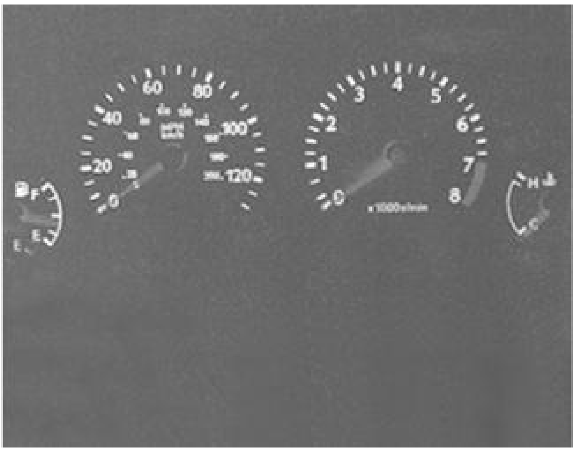


Figure 23-2. Typical automobile instrument panel.

General interior lighting for vehicles is designed to help with safe entry and exit of the vehicle, and to allow drivers and passengers to read maps and other material, without interfering with the safe operation of the vehicle. Broadly, there are two forms of general interior lighting: diffuse lighting and very focused lighting. The diffuse lighting is used to light footwells, the glove box, the area outside the car door when the door is open, the trunk, the engine compartment, and so on. The very focused lighting is used as a reading light, aimed specifically at the driver and/or passenger seats, with the light being restricted to a circle of about 300 mm diameter located where someone sitting in the seat would hold a map. Desirable illuminances for the diffuse lighting applications are in the range of 5 to 10 lx. For the focused reading light, illuminances in the range of 50 to 80 lx are required. Care should be taken with the placement and light distribution of general interior lighting luminaires so as to keep the luminaires outside the field of view of the driver and passenger, to ensure that the luminaires are not reflected from the windshield and to minimize the amount of light falling on the windshield, front fascia, and instrument panel of vehicle.

Reflex Devices in Transportation Lighting

Retroreflecting devices, or reflex reflectors, are important in transportation lighting and signaling and for directional guides. Other applications include reflector flares for highway emergency markers; railway switch signals; clearance markers for commercial vehicles; luminous warnings and direction signs; delineators of highway contours; marine buoys; contact markers for airplane landing strips; bicycle front, rear, and side markers; belts and markers for traffic officers; luminous paving strips; and luminous advertising display signs.

Principles of Operation. A reflex reflector is a device that turns light back toward its source. There are several specific types of these devices; however, the principle of operation--the production of brightness in the direction of the source (Figure 23-3)--is the same for all types. The greater the accuracy of the design of the reflex reflector, the narrower the cone of reflected visual brightness and the brighter the signal. Two optical systems in use are the triple reflector (corner of a cube) and the lens-mirror device. The triple reflector is most commonly used in automotive devices.

Triple Reflectors. The triple reflector makes use of the principle of reflection from plane surfaces where the angle of incidence is such that total reflection takes place. Three optically flat surfaces arranged mutually at right angles, as the inside corner of a cube, form a system so that any ray of light that has been successively internally reflected from the three surfaces is reflected back upon the source.

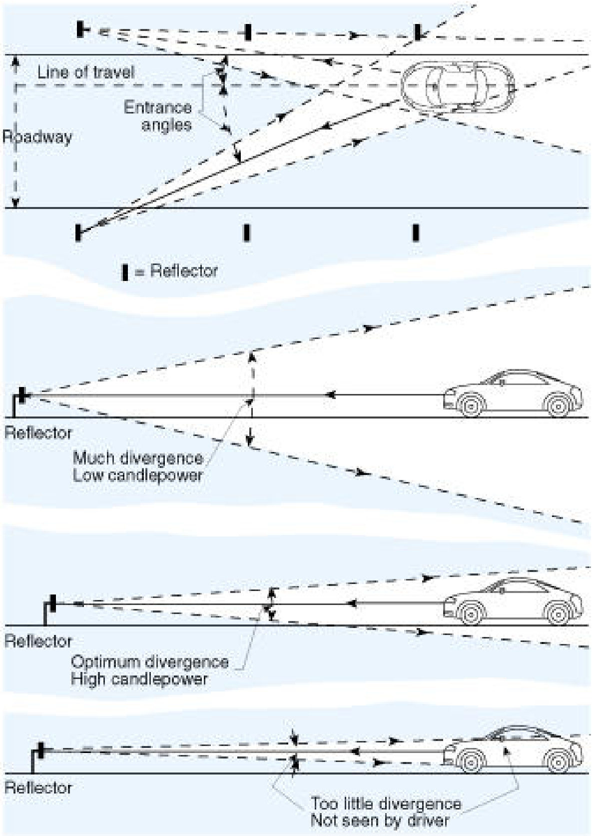


Figure 23-3. Effect of the divergence of reflex devices on their angular coverage and intensity.

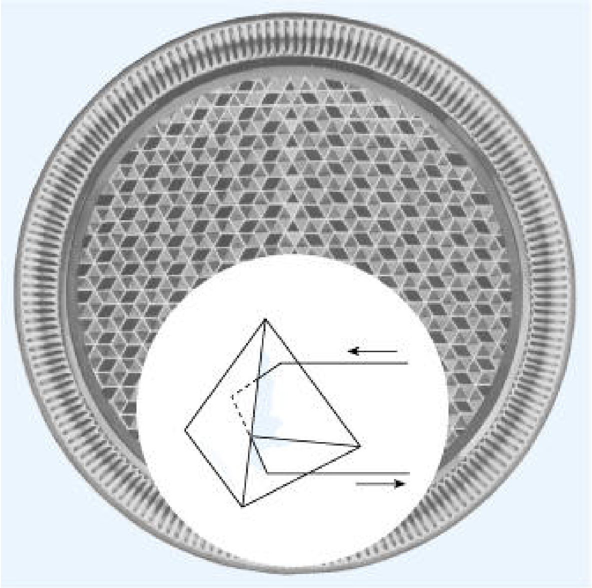


Figure 23-4. Triple mirror reflectors comprise aggregates of concave cube corners.

A plaque of transparent glass or plastic with a continuous pattern of small adjacent cube corners molded into the back, as shown in Figure 23-4, is a commonly used form of reflex reflector. Acrylic or polycarbonate plastics are the most commonly used plastics and are more adaptable than glass to accurate shaping of the prisms, resulting in greater intensity of the return beam. Economy of manufacture, lightness, and shatter resistance are other advantages of plastic. A 76-mm (3-in.) plastic reflex reflector can be seen from up to 300 m (1000 ft) from an automobile using highbeam headlights.

Lens-Mirror Reflex. The lens-mirror button consists of a short-focal-length lens-and-mirror combination designed, to some extent with regard to chromatic and spherical aberration, so that the lens focuses the light source upon the mirror, the mirror and lens returning the reflection in the direction of the source (Figure 23-5). An aggregate of small lenses pressed into a plaque with a mirrored backing formed into concave surfaces, properly designed, produces a very satisfactory reflex reflector.

Another device that produces a wide spread of light, but lower luminance, is a spherical transparent glass bead embedded in a diffuse reflecting material such as white or aluminum paint. This type of reflex reflector is used largely in signboards and in center stripes on highway pavements.

Maintenance and Construction. For good maintenance, all the reflecting and transmitting surfaces should be kept clean and, where possible, free from moisture. The construction should be such that the rear surfaces are either sealed and waterproofed integrally, or open to a sealed compartment, as when the reflector forms part of a lamp lens. Moisture on a totally reflecting surface lessens the reflection. If moisture should accumulate on a dusty surface, optical contact takes place and light passes through the surface rather than being reflected. Any roughening or etching of the transmitting surface also tends to reduce the efficiency.

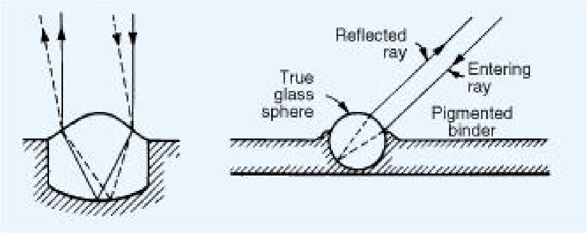


Figure 23-5. Light paths in button and spherical ball lens-mirror reflexes.

PUBLIC CONVEYANCE LIGHTING FOR ROAD AND RAIL

The general principles established for lighting of fixed interiors covered in other chapters of this Handbook can be applied to the lighting of public conveyance interiors. This has been made possible through the development of solidstate devices and the availability of new light sources and luminaires.

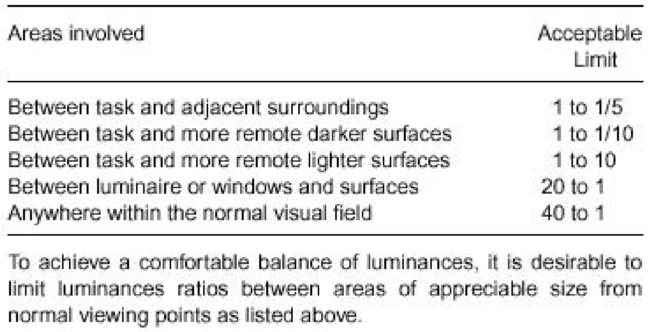
Illuminance

In modern road and rail conveyances, passenger seeing tasks can vary widely, including ordinary tasks such as boarding and exiting, depositing fares or having them collected, finding one's seat, reading and writing, and viewing advertising cards, as well as residential-type tasks on intercity trains such as are found in dining cars, lounges, and washrooms. Illuminances for the special tasks found in road and rail conveyances listed in Chapter 10, Quality of the Visual Environment, represent values that have been found to be satisfactory in practice. In general, they are consistent with similar tasks in other land applications and have been tempered only to recognize the factors of adaptation and comfort where the exterior surround is in darkness and when passengers must move from lighted to unlighted areas.

The illuminance values given previously in the Handbook are maintained values that are to be provided on the visual tasks regardless of their location or viewing plane. To ensure these values, the original lighting design should make allowance for the decrease in light output caused by luminaire dirt accumulations and depreciation of other interior surfaces such as walls, ceilings, floors, and upholstery and by lamp lumen depreciation.

Quality of Illumination

Luminaires and windows of high luminance and high luminance ratios between these elements and their immediate surrounds produce uncomfortable seeing conditions (Figure 23-6), and prolonged exposure generally results in eye fatigue. To avoid discomfort from high luminances that reach the eyes directly or indirectly through reflections from shiny surfaces or from improperly shielded light sources, lighting equipment should be located as far from the line of sight as possible. Glossy reflecting surfaces should be covered or modified to reduce glare, and luminaires and windows should have proper brightness control. This is obviously difficult to accomplish in a vehicle whose use requires good sight lines to ensure proper operation of the vehicle.

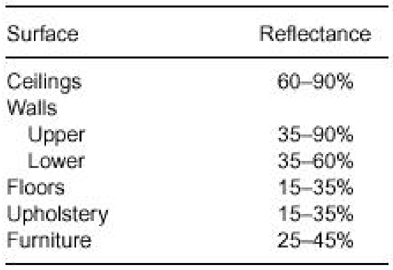


Areas involved	Acceptable Limit
Between task and adjacent surroundings	1 to 1/5
Between task and more remote darker surfaces	1 to 1/10
Between task and more remote lighter surfaces	1 to 10
Between luminaire or windows and surfaces	20 to 1
Anywhere within the normal visual field	40 to 1

To achieve a comfortable balance of luminances, it is desirable to limit luminances ratios between areas of appreciable size from normal viewing points as listed above.

Figure 23-6. Recommended Luminance Ratios for Public Conveyances

In passenger spaces, the average luminaire luminance should not exceed 1700 cd/m^2. The luminance of the brightest 645 mm^2 (1 in.^{2}) area of the luminaire diffuser should not exceed twice the average value. The luminance ratio between the luminaire and the ceiling should not be more than 20:1, as shown in Figure 23-6. Luminances within the remainder of the environment also should be balanced in accordance with Figure 23-6. The use of matte finishes of reflectances recommended in Figure 23-7 helps to achieve this balance.



Surface	Reflectance
Ceilings	60–90%
Walls	
Upper	35–90%
Lower	35–60%
Floors	15–35%
Upholstery	15–35%
Furniture	25–45%

Figure 23-7. Suggested Reflectance Values for Surfaces in Public Conveyance Interiors

Colors of objects appear to change with the surface finish of the object. It should be noted that matte finishes reflect diffuse light and give an object a more consistent color appearance, while glossy surfaces can lose their color when viewed in a direction near the specular angle. Finishes such as velvet and deep-pile carpeting appear darker than smoothsurface materials such as vinyl or plastic laminate of the same color.

For public conveyance vehicle lighting, the most important lighting quality factors are:

- Luminances of room surfaces
- Direct glare
- Safety and security
- Source/task/eye geometry
- Horizontal illuminance
- Vertical illuminance (at fare boxes)

For more information on these quality factors, refer to Chapter 10, Quality of the Visual Environment. Achieving the quality factors is discussed further in this chapter.

Choice of Light Source

Incandescent and fluorescent lamps are normally used in the lighting of public conveyance interiors. Incandescent lamps are usually considered where (1) operating hours are short, (2) a high degree of light control is necessary, (3) interior surfaces are warm in color, and (4) general illuminance values are low. Fluorescent lamps are considered where (1) operating hours are long, (2) general illuminance values are higher, (3) the linear shape is desired, and (4) surface colors are cool.

Road Conveyances: City, Intercity, and School

General lighting is provided for passenger movement along aisles and for seat selection. City buses often leave general lighting on at all times because of the frequent movement of passengers when boarding and exiting the bus. Intercity buses usually turn general lighting off when on the road to allow the driver's eyes to adjust to the outside brightness. For school bus lighting, the general principles and requirements are the same as those for city buses and intercity buses;

however, higher levels of general lighting are provided for surveillance of active children, whether the bus is moving or stopped, being boarded or exited. Lighting should be directed or shielded in such a way that the driver's vision is not impaired by reflected or direct glare in the field of view.

Boarding and Exiting. The seeing tasks are on the steps and the ground or platform area. Both the steps and an area extending not less than 1.2 m (4 ft) outside the door should be illuminated to allow passengers to see the base of the steps and the curb or platform area. The plane of the task is horizontal and on steps, curbs, or platforms. Lighting fixtures located low, outside and on either side of the door aid in illuminating the ground at the point of exiting. Illumination should be provided at the center of each step and not less than 450 mm (18 in.) from the bottom step on the ground, centered on the doorway.

Fare Collection. The seeing task is one of identifying money or tickets and depositing fares, and therefore the fare box and the immediate area around the box should be illuminated. The plane of the task can be horizontal or vertical and at the top of the fare box or along the vertical surface of the box on the driver's side. Illumination should be provided at all locations where seeing is important for the task.

Aisle Lighting. The task is one of observing the floor area for obstacles and the seat area for accommodation, generally while the vehicle is moving. The plane of the task for walking is at floor level, and for seat selection at the back of seats. Illumination should be provided on a horizontal plane at the centerline of the aisle floor and, for seat selection, on a horizontal plane at the top center of each seat back.

Advertising Cards. The seeing task is viewing opaque or backlighted translucent advertising cards placed at the top of side walls. The plane of the task is vertical to approximately 45°.

Illumination on opaque cards should be provided on the face of the card. Luminance values of backlighted advertising cards should be measured at the face of the luminaire without the card over the diffuser. Within the diffuser area, the maximum luminance should not exceed twice the average.

Reading. The seeing task is generally one of reading newspapers, magazines, and books and is generally the most difficult seeing task encountered in conveyances. The task plane, which is at 45°, should be as free from reflection as possible.

For a seated passenger, the illumination should be provided on a plane 430 mm (17 in.) above the front edge of the seat on a 45° angle. For the standing passenger, the measurement should be taken 1420 mm (56 in.) above the floor on a 45° plane at the edge of the aisle seat as if a passenger were reading facing the seat.

Typical Lighting Methods

City Buses. For boarding and exiting, luminaires should be designed, located, and arranged so as to minimize shadows, prevent glare for both passenger and driver, maintain a uniform illuminance, and remain permanently in adjustment. Typical luminaire locations are on the ceiling, over the steps, and at the side of the step well. Figure 23-8 illustrates one approach to general lighting for aisle seat selection and reading.

For fare collection, luminaires can be ceiling mounted, or local lighting can be used. The use of automatic fare boxes requires adequate lighting, both quantity and location, to permit the operator to see the fare at the time of paying and as the coins, bills, and tickets are displayed in the fare box.

Transportation of handicapped persons has been facilitated by small paratransit vehicles that can easily travel city streets, especially those in residential areas. This type of bus is designed for fewer passengers (approximately twelve) and can accommodate several wheelchairs. It is equipped with a lift and seat belts. Lighting is provided by ceiling-mounted fluorescent luminaires (Figure 23-9).

Intercity Buses. For boarding and exiting, the lighting of step wells and the outside ground area is the same as for city buses. Figure 23-10 is an example of luminaires located for reading. Illumination for fare collection, aisle lights, and seat selection can be provided by an indirect system. A low-level night light system is often desirable so that passengers can move throughout the vehicle safely while the driver's night vision is not impaired. Special luminaires are often provided for the baggage racks above the seats.

Figure 23-8. Articulated city bus. Fluorescent luminaires mounted end to end over the passenger seats provide diffuse semidirect illumination. Dome lights are incandescent.

Figure 23-9. Interior of twelve-passenger paratransit vehicle, equiped with a lift to accomodate wheelchairs. Ceiling-mounted fluorescent luminaires provide diffuse semidirect illumination.

Figure 23-10. Intercity bus. Individually controlled beam-type incandescent lights are mounted over the seats to provide each passenger with a reading light.

Lighting for Rapid Transit

"Rapid transit" refers to intracity rail service such as subway or surface railways. It is generally characterized by fast trips ranging from a few minutes to an hour. Standing passengers are a normal condition of this service. The seeing tasks and their lighting are the same as those described above in the section "Road Conveyances: City, Intercity, and School," except that the illumination for boarding and exiting should be provided on the tread of the entrance and platform areas.

To attract riders, an inviting image of comfort, pleasantness, cleanliness, and security must be provided for rapid transit facilities. The lighting criteria presented here guide the component design, equipment selection, and photometric performance needed to produce the desired environment.

These criteria cover normal, emergency, and security systems for the proper illumination of passenger stations underground, at grade, and on elevated structures. Additional information on emergency and security lighting is contained in Chapter 29, Emergency, Safety, and Security Lighting. Also discussed is lighting for bus loading areas, car repair shops, car storage yards, parking lots, and other special structures. Consideration also should be given to the arrangement and location of lighting circuits and panel configurations to accommodate automated energy control devices.

Typical Lighting Methods. For boarding and exiting, provisions should be made for illumination of the threshold and the steps of the car. In addition, car illumination should supplement platform illumination for at least 1.2 m (4 ft) from the car body at the location of the doors. In general, fare collection is made before entering the boarding platform; however, where rapid transit cars have fare collection facilities, it is necessary to provide illumination by an internal light in the fare box or a ceiling light similar to those on city buses.

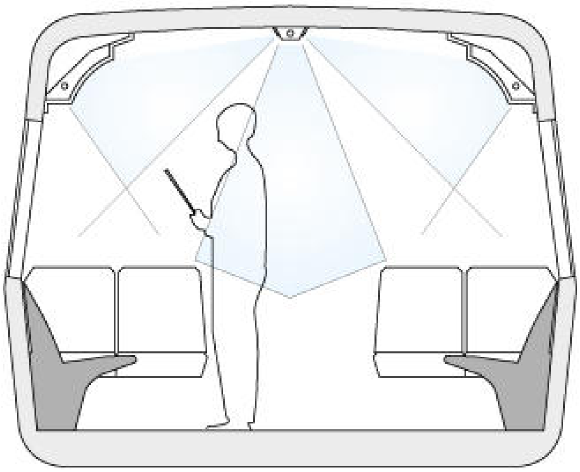


Figure 23-11. Backlighted car-card luminaires with supplementary center strip lighting.

Figure 23-12. Continuous rows of linear fluorescent luminaires with prismatic diffusers light the car and opaque advertising cards over the car windows.

Generally, fluorescent luminaires are employed due to their efficacy, long life, and general diffuse illumination. Commonly, a row of luminaires is installed down the center of a car, or two rows of luminaires on both sides of the car center, or in a cornice on sides of the car. In some cars a third row of fluorescent luminaires is added between the outside rows, often with an air distributor combined for an integrated ceiling.

Where transverse seats are installed in the car, transverse luminaires can be used. They can be mounted above selected rows of seats provided that they do not interfere with the car structural elements and air distribution system.

Some luminaires for backlighted advertising cards are designed to provide adequate lighting for both standees and seated passengers (Figure 23-11). Supplementary center strip luminaires are needed. In cars using opaque cards, illumination can be supplied from rows of continuous fluorescent luminaires over the passenger seats as in Figure 23-12.

Classification of Areas

For the purpose of organizing visual tasks, five specific areas are identified: station sites, parking lots, platforms, track tunnels, and ancillary spaces.

Station sites. Station sites for rapid transit systems can be below grade (subway stations); on grade, such as interchanges with bus and light rail vehicle (LRV) or trolley car systems; and above grade on elevated structures. For bus, trolley, or cable car stops see Chapter 22, Roadway Lighting.

Parking Lots. Both open and enclosed parking lots[7] are covered in Chapter 22, Roadway Lighting.

Platforms. Platforms are the areas adjacent to the bus lane or track, from which the passenger boards the vehicle. Platforms may require special treatment when located below grade. Absence of daylight coupled with restrictive entrance and exit paths can increase the hazard potential. Grade and elevated platforms give the perception of openness, while below grade platforms can cause a feeling of confinement (Figure 23-13).

Tunnels. Railway tunnel lighting is usually of interest only to transit authority employees. Experience with track fires, power failures, derailments, and faulty equipment has shown, however, that extensive safety requirements beyond those previously considered under the terms of "accessible to qualified personnel only" must be established and met for the safe egress from the tunnel of all people, employees, and passengers.

Ancillary Spaces. All other spaces mentioned in the Glossary, plus any other specialized areas, both public and non-public, are considered to be ancillary spaces.

Figure 23-13. Well-lighted underground rail station platforms add to passenger comfort and safety. It is important that the car entrance and exit areas have good lighting.

Figure 23-14. This train is lighted with luminaires that have baffles to cut down on glare. The luminaires have been designed with passenger safety in mind.

Lighting Recommendations

Illuminance recommendations are given in Chapter 10, Quality of the Visual Environment, for all rapid transit areas classified herein. The method for calculating these levels is outlined in Chapter 9, Lighting Calculations. These recommendations should help ensure a safe and pleasing environment for the passengers as well as an efficient workplace for employees. The illuminance recommendations found in Chapter 10, Quality of the Visual Environment, are the minimum recommended maintained levels consistent with the seeing tasks involved.

For public transportation terminal and station lighting, the most important lighting design factors are:

- Appearance of spaces and luminaires

- Direct glare
- Reflected glare
- Safety and security
- Source/task/eye geometry
- Horizontal illuminance
- Vertical illuminance (at fare boxes)
- Daylighting integration and control

General. These criteria are a guide to minimum illuminance values considered acceptable for passenger safety and convenience. After thorough evaluation by the designer, a standardized luminaire arrangement might be adopted, because of architectural and economic considerations, which would produce illuminance recommendations above those given in Chapters 9, Lighting Calculations, or Chapter 10, Quality of the Visual Environment. However, a minimum lighting level must be maintained to protect passengers from tripping hazards, particularly during quick transfers to and from trains, and from criminal activity (Figure 23-14).

Outdoors. For information on parking lots, see Chapter 22, Roadway Lighting and IESNA RP-20-98.[7] Lighting should provide for a comfortable transition from street to station area. The designer can use imagination in the creation of a distinctive style for each station or can employ one style for an entire system. However, the chosen style should clearly identify the structure or entrance as "the subway," "the metro," or whatever name has been chosen by the operating authority. Also, depending on the location, the lighting must not intrude on any nearby neighborhood. See the recommendations in this chapter and Chapter 21, Exterior Lighting, for information on light trespass (Figure 23-15).

Indoors. Chapter 14, Lighting for Public Places and Institutions, gives recommended illuminances for indoor public spaces. Station light levels may need to be increased during daylight hours to minimize the otherwise abrupt changes from outdoor to indoor brightness levels. Station design should incorporate daylighting, to the greatest extent practicable, to minimize the use of electric light. A brightly lighted station with no dark corners or narrow circuitous passageways facilitates police surveillance and tends to discourage petty crime. Adequate lighting is particularly important to encourage public transportation use by visually impaired and elderly passengers.

Figure 23-15. Rail stations can be well lighted for after-dark operation so that the lights do not trespass onto neighboring property. Note that the overhead lighting is directed toward the station. Adequate lighting and aesthetic elements such as the distinctive wall design contribute to passenger comfort, safety, and appeal.

Figure 23-16. Car shop lighting. (a) Linear fluorescent luminaires in suitable environmental housings provide light to the underside of rail cars to allow maintenance work to be done with speed and accuracy. (b) Wide-distribution fluorescent luminaires provide good general lighting and vertical illuminance to facilitate cleaning

and maintenance. Luminaire housings must meet the environmental requirements.

Security Lighting. Personal security is an important aspect of the design of rapid transit facilities. If the public does not feel safe, they will not use these systems. Also, the considerable investment in property and equipment required to operate a modern rapid transit system mandates a prudent security program. Properly designed lighting is an important element in such a program. Since security systems are now heavily dependent on closed-circuit TV, it is critical that the requirements of the TV camera be understood and that the lighting system provides the necessary illuminance, both horizontal and vertical, with the proper distribution. For more information on this subject, see the illuminance recommendations in Chapter 10, Quality of the Visual Environment, and Chapter 29, Emergency, Safety, and Security Lighting.

Emergency Lighting. All underground stations and tunnels must be provided with emergency lighting installed according to the National Electric Code (NFPA 70).[8] The power shall be supplied from an independent source such as batteries or standby generators. In all cases the lighting must comply with code and the regulations of the appropriate authority having jurisdiction. The emergency system should provide for a minimum of three hours' operation at a voltage suitable to maintain proper operation of the lighting, but in no case less than 80% of rated system voltage. Emergency lighting (including all lighted exit signs and other essential signs) in track tunnels should be located close to the top of the rail or emergency walkway and a meter or more (several feet) below the tunnel crown. This minimizes the possibility that stratified smoke obscure the sign during a tunnel fire. Refer to Chapter 29, Emergency, Safety, and Security Lighting, for further recommendations on safety lighting.

Car Shops and Yards. Recent trends towards more automation in transit systems and the resultant increase in the cost of equipment have greatly influenced the design of car shops and maintenance facilities. The old methods of servicing heavy-duty railroad type equipment are giving way to "aircraft-style" maintenance concepts, which support quick change-out of the sophisticated modular components.

These new maintenance concepts have greatly influenced shop design, in particular the use of overhead cranes. The following items should be thoroughly investigated in the planning of shop lighting for new rapid transit car maintenance facilities.

- Much of the floor area now consists of large open pits with short columns supporting the rails in lieu of the traditional single pit-and-ledge concept. This allows for the use of linear fluorescent sources below the rails to provide shadowless illumination on the underside of the cars (Figure 23-16).
- Large storage areas are required for spare inventory to support the remove-and-replace maintenance concept.
- Some of the tasks performed in the main shop that require a combination of ambient/task lighting are: dropping of car trucks; disassembly and reassembly of car trucks; wheel pressing; wheel turning, removal, and replacement of car subassemblies; and washing and cleaning cars.
- Some typical tasks performed in component repair facilities are: rewind traction motors; repair of electrical and electronic controls; and overhaul car heating, ventilation, and air-conditioning (HVAC) units.
- Incandescent, fluorescent, and high-intensity discharge (HID) light sources are suitable for shop installations. Selection of lamp types depends on the importance of color-coded wiring harnesses and other tasks where color is used for identification. In these cases, high-pressure sodium is not a suitable choice.
- Component repair should be handled as a separate activity and thus a separate facility can be provided (remote if necessary) from the main shop. This facility should include a "clean room" for the repair of complex electronic apparatus (see Chapter 26, Energy Management). Component repair shops are usually of low-bay (under 18 ft) construction, and therefore fluorescent area luminaires, either recessed or surface-mounted, together with supplemental task lights, are appropriate. See Chapter 19, Industrial Lighting, and ANSI/IES RP-7,[9] Recommended Practice for Industrial Lighting, for more detailed discussions of these areas.
- The lighting for car and bus storage yards is primarily for security. Special trackwork in yard areas may require higher light levels.

Rail Conveyances: Intercity and Commuter

Seeing tasks on intercity and commuter trains are much the same as on other public conveyances. The only differences are those additional tasks in the facilities provided for passenger comfort during long-distance travel, such as food preparation areas, diners, and washrooms. Some tasks described here do not apply to commuter trains.

Boarding and Exiting. Vestibule and platform lighting should be designed so that passengers board and detrain safely. The seeing tasks are on the platform, steps, and vestibule floor, and all are horizontal at floor level. The viewing angle is practically vertical for the person to observe the condition of the tread surface and platform alignment with the car floor. Illumination should be provided at the center of the vestibule floor and at the longitudinal centerline of the steps. Both track and vestibule levels are generally provided with a luminaire over each trapdoor, illuminating vestibule and step areas. Supplementary lighting can be provided by step lights located in the step well to increase illumination over steps, and a leading light located adjacent to steps can be directed to give increased illumination in front of the steps (Figure 23-17).

Fare or Ticket Collection. There are no special lighting requirements for fare or ticket collection, since this normally takes place while passengers are seated (see the section on "Intercity Buses" above).

Figure 23-17. Downlights illuminate the platform and car door area. Horizontal illuminance is important since the viewing task is at the platform and entrance tread. Color should be selected to properly render the color of painted hazard markings.

Figure 23-18. Linear luminaires with well-designed diffusers distribute light uniformly throughout the car and control glare from the luminaires. Light-colored, matte interior finishes would have been effective in glare control in the car pictured.

Advertising Cards. The seeing task is the same as for road conveyances except that some cards can be placed on bulkheads at the end of passenger compartments.

Aisle Lighting and Seat Selection. The seeing task is one of observing the floor area for obstacles and the seat area for accommodations. The plane of the task is at floor level for walking and at the top center of each seat back for seat selection. General lighting can be provided indirectly by luminaires mounted in the extreme corner of the baggage rack and the outer wall of the car, by ceiling-mounted luminaires that direct the light to the desired areas as in Figure 23-18, and by luminous ceilings. Individual reading lights are desirable, as shown in the figure, because the baggage rack casts shadows on the window seats.

Illumination should be provided on a horizontal plane at the centerline of the floor. For seat selection, illuminance should be measured on a horizontal plane at the top center of each seat back.

Reading. The task is one of reading magazines, newspapers, books, or business correspondence for an extended period of time. The plane of the task and measurement of illuminances are the same as those for road conveyances. Laptop computers are being used with increasing frequency. These generally have liquid crystal displays (LCDs), which can be adjusted to reduce reflected glare. Illumination for reading, writing, and laptop computer applications can be accomplished by adjustable controlled reading lights, mounted either in the aisle edge of the baggage rack or at the line of the baggage rack and the outer wall of the car. In the case of the closed type of baggage rack, these lights are mounted directly above the seats.

Food Preparation. The work performed is preparing foods and beverages and cleaning the area. The task plane is horizontal on work counters 910 mm (36 in.) from the floor. Illumination should be provided on the work counters from the front to the back edge. Higher illuminances are given in these areas for the utmost efficiency of operating personnel and to ensure good appearance of food and its proper inspection. Quality of lighting is important, especially in regard to color. In addition to general lighting, usually supplied by ceiling-mounted luminaires, supplementary lighting should be provided over all work areas. The service window between the kitchen and pantry should be well lighted to facilitate food inspection. Refrigeration cabinets should have at least one lamp per compartment, operated by automatic door switches. For more information see Chapter 13, Hospitality Facilities and Entertainment Lighting.

Dining Area Lighting. The functions of the lighting system in dining areas are to enhance the appeal of the interior decorations, table settings, and food and to assist in providing a comfortable, pleasant atmosphere for the diners. Passengers need light for eating and drinking and for reading menus and checks. The task plane is horizontal to 45° from the horizontal, 200 mm (8 in.) in from the front edge of the table at each seat position. Illumination should be provided on a plane 45° up facing the seated diner, 200 mm (8 in.) from the front edge of the table or counter. Quality and color of light under these circumstances are more important than quantity, however. The design of the lighting system should be governed by the overall decor of the car and the effects desired. Direct incandescent downlighting on a table provides sparkle to the silverware and glassware that cannot be obtained from diffuse illumination, and is an important aid to eye appeal (Figure 23-19).

Figure 23-19. Well-controlled, diffuse lighting provides a comfortable, relaxing environment for dining. Low-glare incandescent point sources directed onto the table would add sparkle to enhance the visual environment.

Lounge. General illumination should be such as to meet the requirements for relaxing and conversing and to provide sufficient illumination to the upper walls and ceiling for the elimination of high luminance ratios. In addition to relaxing and conversing, there are seeing tasks such as reading and card playing. For reading, the task plane is the same as for road conveyances. For card playing the task is horizontal at the playing surface. Supplementary luminaires can be required to furnish a higher level for prolonged reading and typing or processing business forms. General illumination should be provided on a horizontal plane 760 mm (30 in.) from the floor.

Sleeping Car (Pullman). The bedroom compartment can be considered the passenger's traveling apartment. Lighting should add to the comfort, convenience, and beauty of the accommodations. As in any good lighting installation, the ability to perform the visual task is the primary consideration. The visual tasks in sleeping accommodations are similar to those in the home.

The arrangement of berths and provisions for upper storage in the daytime severely limits the ceiling area available for luminaires. Structural members, air ducts, and conduit runs also limit the usable ceiling area. In general, the location and maximum size of a luminaire in the ceiling are fixed by the space available. Figure 23-20 shows a typical sleeping car with supplementary downlights for reading.

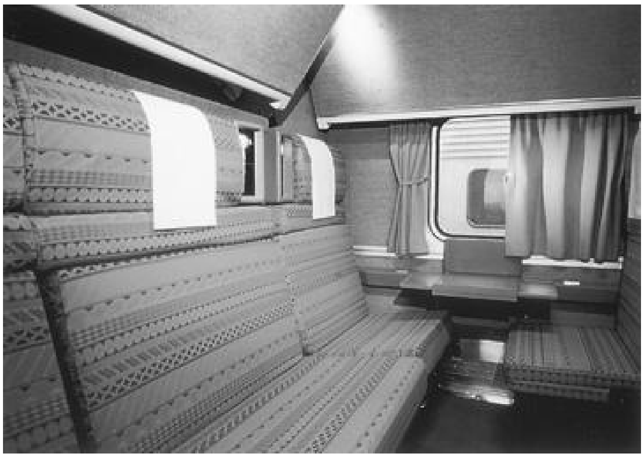


Figure 23-20. Sleeping car illuminated with a ceiling-mounted luminaire for general lighting and individually controlled beam-type lights for reading.

Berth lighting units should be designed to provide suitable illumination for reading in bed. Here again, as in the case of the ceiling luminaires, freedom of design and optimum use of materials are limited by the physical characteristics of the application. Berth lighting units should be designed to provide a concentrated beam of light for the reading task and a component for general illumination to reduce excessive luminance ratios.

Washrooms and Toilet Sections. The lighting design should provide general illumination and mirror lighting from luminaires on the ceiling, side walls, or both. A luminaire, generally located in the ceiling, should be provided in the toilet section. The most demanding tasks usually are shaving and applying makeup. Because the apparent distance of the face or figure as viewed in the mirror is twice its actual distance from the mirror, and because the details to be seen in shaving and critical inspection are usually small and of low contrast with the background, the visual task can be a difficult one. The task area in a standing position consists of two 150 by 220 mm (6 by 8 1/2 in.) planes at right angles to each other, converging at a point 410 mm (16 in.) out from the mirror, and centered vertically 1550 mm (61 in.) above the floor (see Chapter 18, Residential Lighting). They represent the front and sides of the face. A third plane 300 mm (12 in.) square, its front edge also 410 mm (16 in.) out from the mirror, is tilted up 25° above the horizontal and represents the top of the head. Recommended illuminances should be provided 1550 mm (61 in.) above the floor and 410 mm (16 in.) from the mirror, with the plane facing in the direction of the light source.

Lamps and Electric Power Systems for Transportation Lighting

Lamps. Both incandescent and fluorescent lamps are used for public conveyance lighting, but there is a trend toward more fluorescent lighting. The high efficacy, linear shape, and low luminance of the fluorescent lamp make it well suited to vehicular lighting. However, few public conveyances have the normal 60-Hz, 120-V alternating current for which most fluorescent lamps and accessories are designed. Consequently, special electrical systems have been devised to facilitate the use of fluorescent lamps in this field. Multiple incandescent filament lamps suitable for transportation are described in Chapter 6, Light Sources.

Electric Systems for Operating Fluorescent Lamps in Public Conveyances

Fluorescent lamps were primarily developed for ac operation and are generally more efficient and satisfactory when operated on ac, but a dc power supply for lighting has been the accepted standard in the transportation field until recent years. Certain sizes of fluorescent lamps can be operated directly on the dc power available on the vehicle, or ac can be generated from the dc supply by means of various types of conversion units.[10]

With dc operation of fluorescent lamps, a resistance-type ballast is used to control the current. Ballast loss should be included when determining the total power required for the lighting. Also, in lamps over 600 mm (24 in.) in length, the direction of the current flow through the lamps should be periodically reversed to prevent the reduction in light output at the positive end of the lamp caused by the gradual drift of the mercury to the negative end. The useful lamp life on dc burning is reduced to approximately 80% of that on ac burning. Also, special provisions are needed to ensure dependable lamp starting at low line voltage and at lower ambient temperatures.

The use of power conversion equipment to convert from dc to ac is common practice (Figure 23-21). The conversion can be to 60 Hz; however, the trend is toward higher frequencies in order to gain overall efficiency and reduced weight in the auxiliary equipment.

Two common methods of conversion in use to produce ac from the dc power source are available. They are described in the following paragraphs.

Rotary Machines. Devices such as rotary converters,[11] motor alternators, and booster inverters are being used on dc voltages to generate various ac output voltages. Gasoline-electric or diesel-electric equipment are available for mounting beneath a car and for a "head-end" ac power system.

Inverter Systems. These systems produce ac power, usually of a high frequency ranging from 400 Hz to 25 kHz. The lower frequencies are sometimes used in applications where the noise of the vehicle overcomes the resulting hum. High frequencies are quieter and provide minimum equipment size and maximum system efficacy. High-frequency power can improve the efficacy of any fluorescent lamp; however, the ballast and all component equipment should be designed for good lamp performance, taking into consideration ample open circuit voltage and correct operating watts for the fluorescent lamp involved.

Railway Guidance Systems

Railway train operating personnel receive guidance through three main categories of luminaires:

- Exterior lights on the train, including headlights and marker lights
- Interior cab signals
- Wayside signals

Voice communications by electrical communication systems serve various crew coordinating functions and yard movements; however, actual train movement into any main line segment of the rail system is normally directed by a signal light indication.

Exterior Lights on Trains. Locomotive headlights are classified either as road service, giving 240-m (800-ft) object visibility, or as switching service, giving 90-m (300-ft) object visibility, as governed by the regulations of the Federal Railroad Administration, Department of Transportation. Headlight equipment consists of two all-glass sealed-beam approximately 200-W PAR-56 lamps mounted in a single housing, each lamp projecting a 5 to 10° beam with a center-beam intensity of approximately 250,000 to 300,000 cd. The pair of lamps exceeds the performance and reliability of the old single-reflector headlight. Shielding is provided to minimize veiling glare from stray light illuminating atmospheric particles in the line of sight. In addition to lighting possible obstructions on the right of way, the headlight also serves to retroreflect colored markers at switch locations (Figure 23-22).

A recent addition to the forward lighting on railroad locomotives is the "ditch light." Two lights have been added for the purpose of increasing the visibility of the locomotive for drivers approaching railroad crossings. The lamps are mounted at about eye levels for automobile drivers and are located on either side of the front of the locomotive. The lights can burn continually or flash alternately. While no regulations exist at the time of this writing for ditch lights, a common lamp used for this purpose is a PAR-56 75-V incandescent "spot" lamp with approximately 6000 lumen output. The lamps must be carefully aimed to ensure that they are visible for the intended purpose but do not create dangerous glare for drivers or oncoming train crews.

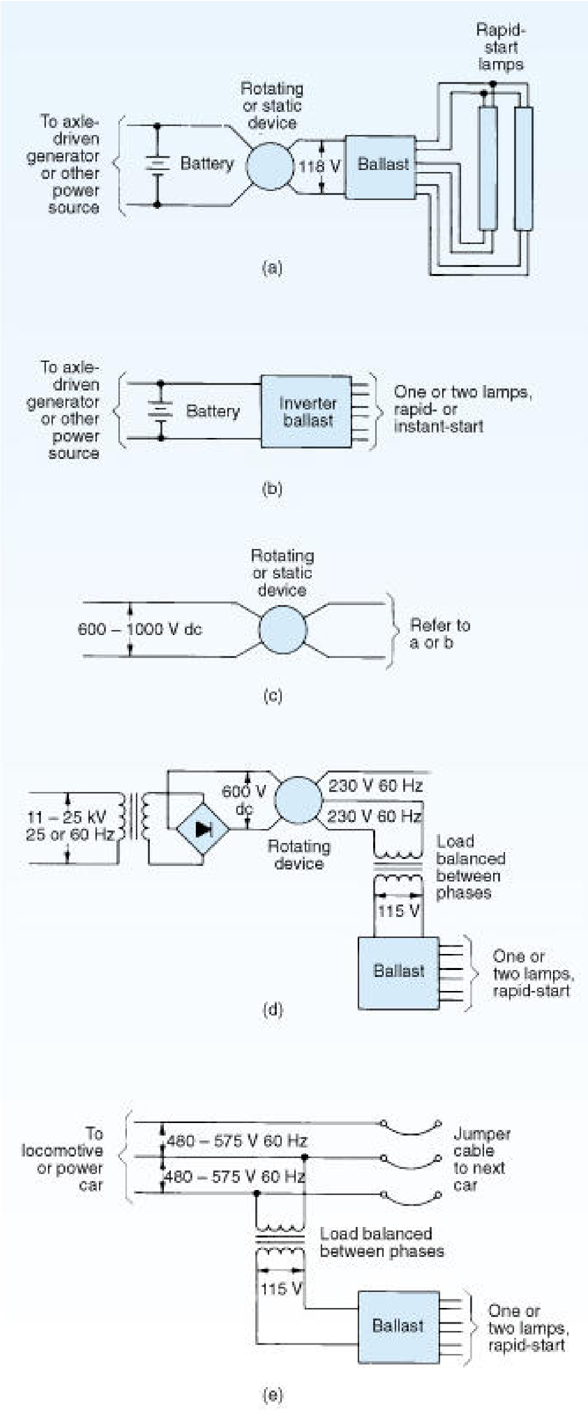


Figure 23-21. Typical circuits for operating fluorescent lamps in the transportation field: (a) circuit for converting available dc to 60-Hz ac; (b) circuit using available dc; (c) circuit for converting high-voltage dc; (d) circuit for converting high-voltage ac; and (e) circuit used with power from locomotive.

Figure 23-22. Rail car headlights are mounted as far from the operator's line of sight as possible to reduce reflected glare. The pairs of lights provide lighting superior to previously used single-lamp headlights.

Locomotive Cab Signals. With suitable track circuits and electric receiving equipment, automatic signal lights inside the cab can be made to show signal aspects corresponding to those of the wayside signals. This is useful in times of poor visibility due to atmospheric conditions or other obstructions. Changes of wayside signals ahead of the train can be displayed promptly in the cab, thus expediting response to the change. When cab signals are supplemented with speed control, the engineer is required to limit the train speed to that prescribed by the cab signal to prevent automatic brake application.

Rapid Transit Cab Signals. In rapid transit systems, speed commands are continuously transmitted, through the rails, precisely and exclusively to the train intended. Onboard, the cab signal displays the commands, and the overspeed control system compares the actual train speed with the maximum speed allowed by the cab signal (Figure 23-23). If the actual speed exceeds the limit displayed, the system warns the motor operator, audibly, that a brake application is required. If the operator fails to take action immediately, the control system automatically stops the train.

Wayside Signals. The movement and speed of trains into each segment of track is permitted only by the adjacent signal indication, with some advance information provided by the range of the signal beam and the preceding signal.

Wayside Signal Range. The beam intensity and range considerations for a lighted signal are based on the estimated safe visual range by day in clear weather. For red and green signals it is common to use the formula

$$D=\sqrt{186\,I} \qquad (23\text{-}1)$$

where

D = range in m,
I = intensity in cd;

or

$$D=\sqrt{2000\,I} \qquad (23\text{-}2)$$

where

D = range in ft,
I = intensity in cd of the same type of signal when equipped with colorless optical parts.

Yellow and lunar white lenses provide a somewhat longer range, but blue ones provide only about one-third the distance D.

By the use of these formulas and the candlepower distribution curve of a signal beam, it is possible to lay out a chart or plan that shows the ground area over which a particular signal will be within visible range in clear weather. This signal range plan can be superimposed on a track plan to see whether the signal will have visibility over a particular track approach (Figure 23-24). Signal manufacturing companies have prepared range charts for their various signal units embodying the large variety of horizontal beam-spreading and beam-deflecting auxiliary lenses available.

Figure 23-23. In this type of rapid transit cab signal, lighted segments on the speedometer show the highest speed permitted. The six windows below the speedometer light to show yellow, green, and red aspects and speed limits.

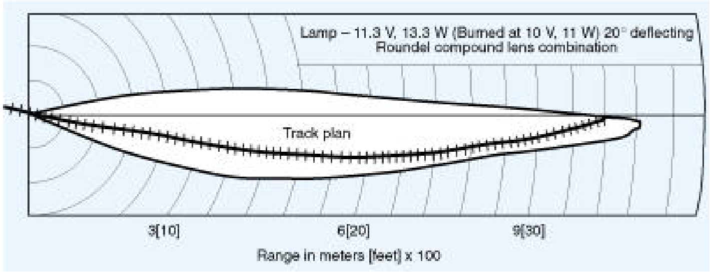


Figure 23-24. Range chart for searchlight-type signal unit with part of a track plan superimposed to show the range of useful coverage.

A horizontal deflecting or spreading prismatic element can be chosen to provide visibility along a curved track approach. A vertical deflecting prismatic element is necessary to enable an engineer to see a signal at very close range high overhead or to see a signal close to the ground.

External Light Interference. By making the front surface of lenses and roundels convex rather than flat, it is possible to redirect most of the reflected ambient light away from the direction of the beam, thus improving signal visibility. Together with hoods or visors, which are always used, this ensures that daylight produces negligible interference with the signal under most conditions. Occasionally, flat auxiliary roundels are inclined at selected angles.

The incorporation of reflectors in the optics of a signal involves particularly careful analysis to prevent reflected external light. A typical deep parabolic reflector, as used in ordinary spotlights, could flash false indications from external light if used in signals.

Color.[12-14] Train operating personnel are selected to have normal color vision. The colors used by railways in North America are, with very few exceptions, governed by the Signal Manual of the Association of American Railroads (Figure 23-25). These color specifications contain basic definitions for the colors to be displayed in service and the tolerances for color-limit filters to be used to inspect signal glassware. The primary standard filters controlling these inspection filters are maintained by the National Institute of Standards and Technology (NIST) in Washington, D.C.

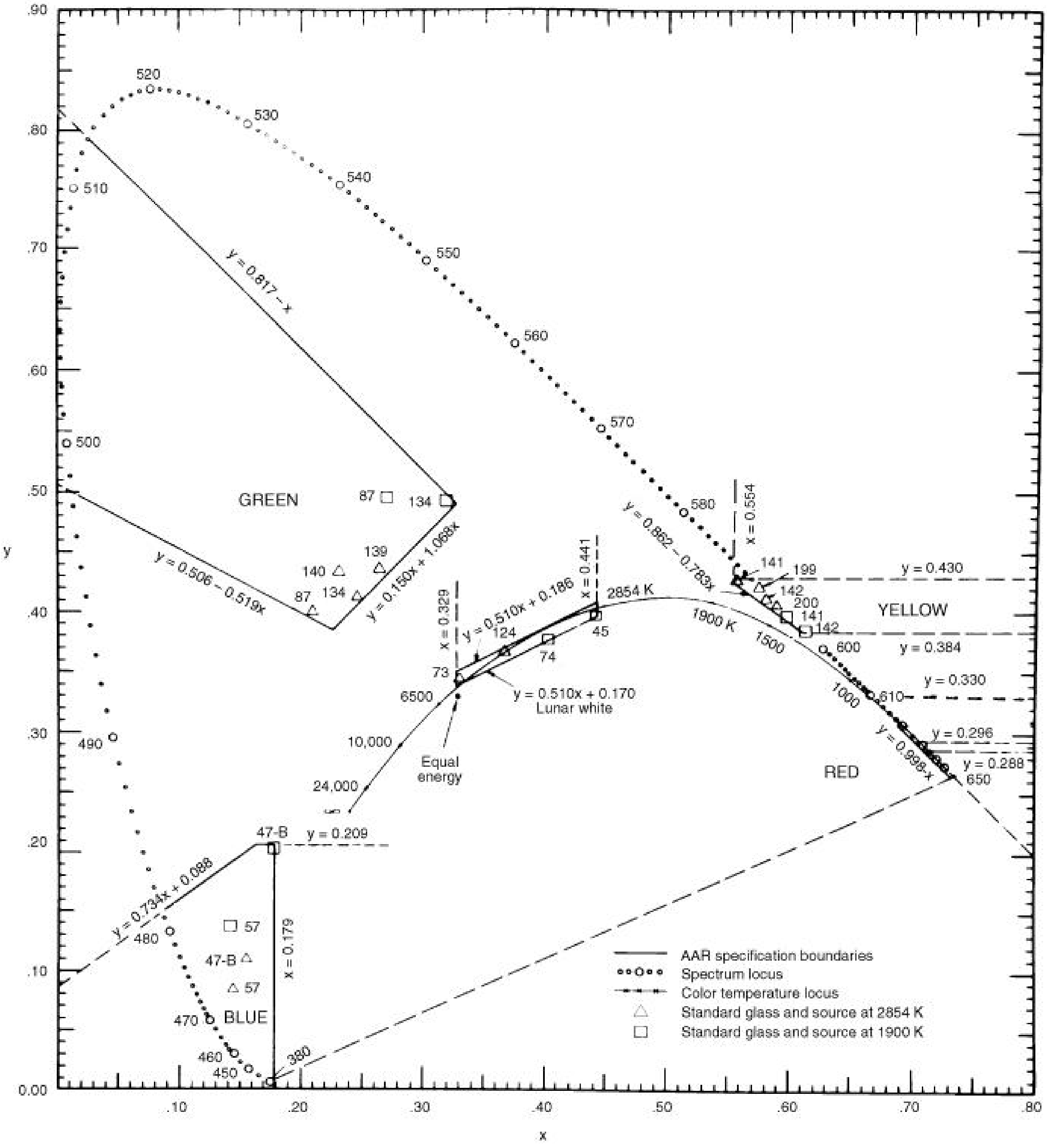


Figure 23-25. Railway signal color specifications plotted on a CIE chromaticity diagram.

The Association of American Railroads currently specifies five colors: red, yellow, green, blue, and lunar white; however, only red, yellow, and green are used for long-range color signals. Both the red and the yellow are somewhat more saturated than those used in street traffic signals. Blue signals are not used frequently because of the very low short-wavelength emission of incandescent signal lamps and the low transmission of light, about 2%, by blue glass. Lunar white is the term applied to white light, as filtered by a bluish glass, that raises the apparent color temperature, or "whiteness." The lunar white aspect from an incandescent signal lamp will appear about 4000 to 5000 K, and from a kerosene lamp about 3000 to 4000 K. Purple is no longer recommended as a signal color because the filter has low transmission and because the color makes different impressions upon different observers.

As is commonly understood, red is associated with the most restrictive signal indications, green with the least restrictive, and yellow intermediate. For the specific meaning of the signal aspects, many of which involve two or more lights shown together, see American Railway Signaling Principles and Practices, Chapter II, published by the Association of American Railroads.[12]

Wayside Signal Types. Modern signal units and their arrangement on a mast all have some feature suggestive of the early semaphore unit, which had a blade for day viewing and associated color disks that swung in front of a lamp for night viewing. The three types of signals that depend entirely on light are described below as position-light signal, color-light signal, and color-position-light signal (Figure 23-26). All utilize large targets or black backgrounds to permit low-wattage lamps to show up without blending into the sky. Lamps are usually of 18 to 25 W with very small filaments that must be precisely located at the focal point by a prefocus base. Every signal unit is accurately aimed using a sighting device during installation or is adjusted according to radio instructions from a viewer down the track.

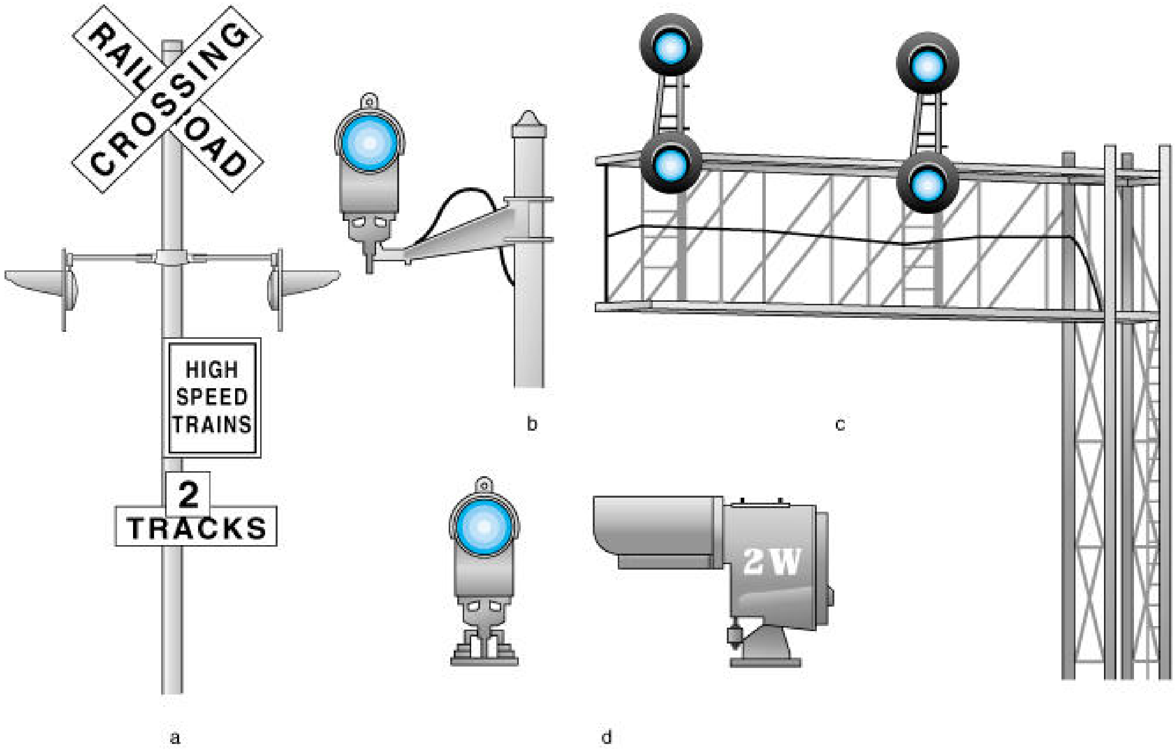


Figure 23-26. (a) Grade crossing lights; (b) color-light signal on a mast; (c) searchlight-type color-light signals; and (d) color-position-light signal.

Color-Light Signal. A color-light signal can involve separate lights with colored lenses for each color, or else the signal lighting units can have internal mechanisms and movable filters to change the color within each unit. This latter movable filter unit is called a searchlight signal and permits three units on a mast to display the widest variety of color combinations, for instance, "red over yellow over yellow," "green over yellow over red," and so on.

Position-Light Signal. The position-light signal is a type of wayside signal that does not depend on color discrimination by the engineer. In this type, a number of lamps (maximum nine) are mounted on a circular target, with eight lights arranged in a circle and one light at the center. By operating three lamps at a time, the aspect of the signal can be a vertical, horizontal, or diagonal row. Each of the target lights is aligned by its own projector system in the direction of the approaching train. Yellow lenses are normally used to achieve distinctiveness from other, nonsignal lights.

Color-Position-Light Signal. The color-position-light signal utilizes a combination of the principles of the color-light and the position-light systems. Here also there are several lights on a target. These can be lighted in pairs: vertical pair (green), horizontal pair (red), and right and left diagonal pairs (yellow and lunar white, respectively).

Power Sources for Signals. The lighted aspect displayed is controlled by relays at the signal actuated by coded impulses in the track circuit; however, for complete dependability, power for the lamp comes from storage batteries at the location. The batteries can be used alone or as standby for ac service. To provide long lamp life and reduce the probability of a dark signal, lamps are usually burned at 90% of rated voltage.

Control Panels for Signal Systems

The movement of trains and the sections of track thus occupied are represented on control panels at interlocking or at centralized traffic control centers. On such a panel the operator is presented with push buttons that operate relays for switches and signals along a portion of the rail line that can be a local yard or several hundred kilometers (several hundred miles) of track. Lights indicate the response of the switches and signals.

A track diagram for the territory is studded with indicator lights that show when a train occupies certain sections of track along the line or what route has been established.

Railway-Highway Grade Crossing Lights

Warnings for highway traffic at grade crossings are provided by train-actuated flashing red lights. Generally four pairs of horizontally spaced alternately flashing red lights of 18 to 25 W are used. Track circuits that sense the presence of an approaching train control the lights. The light beam width is usually 30° and provides usable visibility of 300 m (1000 ft). The lights normally operate from ac with dc standby. Recent advances in LED lamp technology have made railway-highway grade crossing signals using these lamps practical. The 10-volt LEDs provide long life and relatively trouble-free operation. Use of multiple LEDs in a red signal light improves the reliability and visibility of the signal and effects a substantial reduction in the operating power of the signal lights.

MARINE LIGHTING

Introduction

General. This section provides lighting recommendations for the principal living, dining, recreational, and work areas found in ships and small craft. The tasks and areas considered include both exterior and interior lighting applications as well as those devoted to navigational and operating functions necessary for the safe and effective operation of vessels. Guidance for the installation of emergency lighting essential to the safety of life and property, in the event of failure of the normal electric power supply, is also included.

Marine Lighting Practice. In the past, marine lighting practice has been limited by the quantity and characteristics of the available electric power supply. Recent developments in solid-state devices, efficient light sources, and lighting equipment design have substantially reduced those limitations. It is therefore possible to utilize techniques for marine applications that are similar to those used for lighting ashore.

Visual Tasks. A ship's visual tasks are similar to those encountered ashore. Accordingly, marine lighting design requirements are the same as those found for the corresponding tasks in residential, hotel, commercial, and industrial areas. Additionally, there are special requirements which are not encountered ashore that must be considered in the design of marine lighting systems. They include electric shock hazards, corrosion, shock and vibration, temperature and humidity extremes, fire resistance, and space weight limitations. There is also concern for radio frequency interference from ballasted light sources. Considerations for the selection of light sources are found in Chapter 6, Light Sources. Lighting equipment is discussed in this chapter and in Chapter 7, Luminaires.

Regulatory Body Requirements and Other Standards

U.S. Vessels. The lighting requirements for life safety for ships of United States registry are established by the U.S. Coast Guard. Regulations regarding ships' electrical plants and lighting are contained in the U.S. Coast Guard Electrical Engineering Regulations.[15] The lighting regulations reflect the lighting requirements published by the International Conference on the Safety of Life at Sea.

For U.S. Naval vessels, the lighting specification for a ship is derived from either the General Specifications for Ships of the U.S. Navy[16] or the General Specifications for T-Ships of the U.S. Navy.[17] Design guidance is contained in Lighting on Naval Ships.[18] The military specification that covers shipboard lighting fixtures is Fixtures, Navy Shipboard Lighting, General Specifications for Shipboard Use of Lighting Fixtures and Associated Parts.[19] All of the documents are published by the Naval Sea Systems Command of the U.S. Navy.

Navigation. Lighting requirements for navigation are contained in the Rules of the Road,[20] which is published by the U.S. Coast Guard. Complete details for the design and application of lighting equipment for aids to marine navigation are contained in the latest edition of the U.S. Coast Guard Ocean Engineering Report Number 37 (CG25037), Visual Signaling: Theory and Application to Aids to Navigation.[21]

The Committee on Marine Transportation of the Institute of Electrical and Electronics Engineers (IEEE) has published the Recommended Practice for Electric Installations on Shipboard, IEEE Std 45.[22] It serves as a guide for the installation of electric equipment on merchant vessels having an electric plant system.

Navy Lighting Equipment. Lighting equipment installed aboard U.S. Navy ships is manufactured to the General Specifications for Fixtures, Navy Shipboard Lighting,[19] and to end-item specifications that are identified in Lighting on Naval Ships[18] as well as suitable Commercial Item Descriptions approved by the Naval Sea Systems Command.

Luminaires. Detailed guidance for the construction of luminaires for marine applications are contained in UL 595, Standard for Marine-type Electric Lighting Fixtures,[23] and UL 844, Standards for Electrical Lighting Fixtures for Use in Hazardous Locations.[24] Both documents are published by Underwriters Laboratories. In Canada, the Canadian Standards Association (CSA),[25] which may have different requirements, should be consulted. Typical hazardous locations include pump rooms, product barges, offshore platforms, and within 3.0 meters (10 feet) of vents and pumping stations.

Underwriters Laboratories Service Label. The Underwriters Laboratories Service Label is provided for most luminaires with the exception of utilitarian desk and bulkhead luminaires. Labeled luminaires are identified by the Underwriters Laboratories service mark together with the designation "Marine-type Electric Fixture" or "Marine-type Recessed Electric Fixture." The labels also include other applicable luminaire information such as "Inside-type," "Inside Drip-proof-type," "Outside-type (Salt Water)," or "Outside-type (Fresh Water)."

Underwriters Laboratories Re-examination Service. The Underwriters Laboratories Re-examination Service is used for unwired general utilitarian-type luminaires for deck and bulkhead mounting where exposed to the weather or other wet or damp locations. Such luminaires are not labeled, rather they are listed by catalog number in the Electrical Construction Materials List[26] published by Underwriters Laboratories. Listed luminaires are characterized by features including junction boxes, protective glassware, and often protective guards.

The U.S. Coast Guard has reviewed and approved procedures for miscellaneous items of electrical equipment that are built to alternative design standards. Because most luminaires in UL 595 are utilitarian in nature, this approach has been used to evaluate interior decorative luminaires used on passenger vessels. Luminaires, which are designed to a recognized electrical standard such as what is cited in References 27-32, can be reviewed for conformance to the general marine requirements of UL 595. These luminaires should include vibration clamps for fluorescent lamps longer than 102 cm [40 in.], secure mounting of glassware, and rigid mounting of luminaires (chain suspension and loose glass globes are unacceptable).

Objectives of Shipboard Lighting

The objective of marine lighting is to provide adequate lighting for the safety and well-being of passengers and crew as well as for the various tasks encountered aboard ships and other vessels. Illuminance recommendations for the tasks and spaces normally encountered in marine applications are found in Chapter 10, Quality of the Visual Environment. The illuminance levels are based on the need for safety and on functional and decorative characteristics of the areas concerned. Values listed represent minimum maintained illuminance as averaged across the task area, measured without daylight, and include all lighting units normally contributing to the general and task illuminance such as wall brackets, floor lamps, and table lamps.

The Standard Practice for Human Engineering Design for Marine Systems, Equipment and Facilities[33] establishes general human engineering design criteria for marine vessels, systems, and subsystems. In general, the recommendations in ASTM F1166 are derived from those published by the IESNA but they lag behind the current guidance by several years.

General Lighting. For most applications, the general lighting provides a substantially uniform level of illuminance throughout the space. Some variation can be intentionally introduced by the designer. Examples include the delineation of preferred traffic routes, the separation of task or functional areas, and the definition of a transition between spaces of significantly different luminances. The general illuminance system meets the requirements for safe trafficking as well as task illuminance requirements, which cover all or substantially all of the space. When the general illuminance system must meet multiple task requirements, consideration should be given to special switching and control systems.

Task and Supplementary Lighting. Task lighting is provided to meet the illuminance requirements of a specific task. Typical locations for task lighting include instrumentation, controls, mirrors, berths, and desks (Figure 23-27). Care should be taken to avoid direct and reflected glare, overly high luminance (brightness) in the field of view, and shadows. This is particularly true in marine lighting applications because illuminance levels are kept to the minimum acceptable levels due to the limited capacity of the electrical distribution system.

Supplementary lighting is that which is provided in addition to the general illuminance to meet a task illuminance requirement. Energy conservation ashore and the limited electrical resources at sea dictate that supplementary illuminance be installed in visual task areas rather than installing a general illuminance system that provides the high illuminance levels required by only a fraction of the space. The two terms are sometimes used interchangeably; however, task lighting refers to the total requirement and supplementary lighting refers to the increased illuminance to meet the task requirement over that provided by the general lighting system.

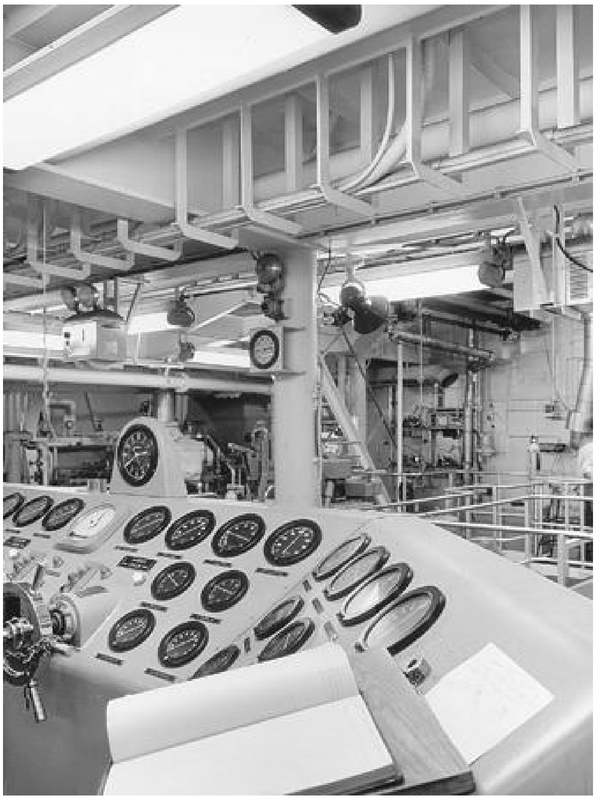
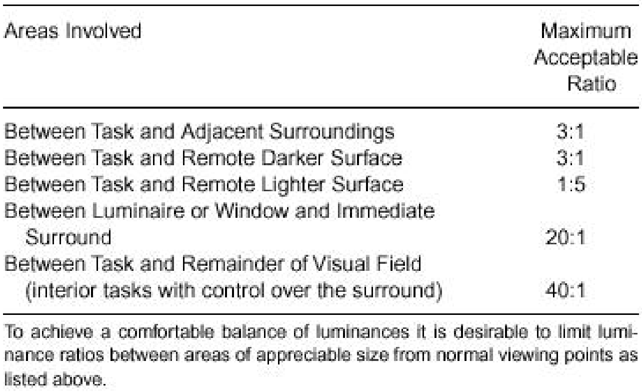


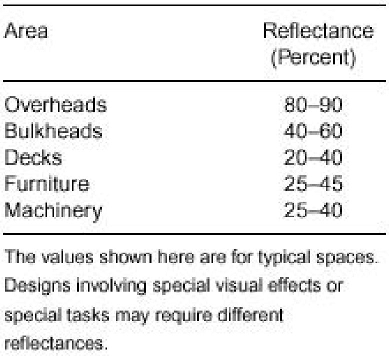
Figure 23-27. Lighting for the engineering control console is provided by fluorescent luminaires. Care should be taken to avoid glare and veiling reflections.



Areas Involved	Maximum Acceptable Ratio
Between Task and Adjacent Surroundings	3:1
Between Task and Remote Darker Surface	3:1
Between Task and Remote Lighter Surface	1:5
Between Luminaire or Window and Immediate Surround	20:1
Between Task and Remainder of Visual Field (interior tasks with control over the surround)	40:1

To achieve a comfortable balance of luminances it is desirable to limit luminance ratios between areas of appreciable size from normal viewing points as listed above.

Figure 23-28. Recommended Luminance Ratios



Area	Reflectance (Percent)
Overheads	80–90
Bulkheads	40–60
Decks	20–40
Furniture	25–45
Machinery	25–40

The values shown here are for typical spaces. Designs involving special visual effects or special tasks may require different reflectances.

Figure 23-29. Recommended Reflectance Values

Ambient Lighting. Lighting also contributes to a comfortable, livable environment. Similarly in shop and machinery spaces, the environment must support productivity and safety. Attention must be paid to the reflectance of finishes, the effect of the light source upon the color and texture of surfaces, the overall design of the space, and minimizing undesirable luminance ratios. The reader is directed to Chapter 10, Quality of the Visual Environment, for the latest recommendations regarding design factors important in marine lighting.

Also levels of illuminance or luminance should not change abruptly between the interior of a ship and the exterior at exit locations. Figure 23-28 provides recommended luminance ratios. In order to meet the criteria, care must be taken in the selection of materials to meet the recommended reflectance values of Figure 23-29 and in the selection and placement of luminaires to minimize glare and veiling luminances.

Adaptation. Many marine lighting tasks are performed on deck at night under dark-adapted conditions. The eyes require time to adjust to changes in luminance. The adaptation state of the eye is based on the average brightness of the visual field. In general the eye adapts quickly to increasing task and surround luminances. Adaptation to very low luminances takes longer. Up to one half hour is required for the eye to adapt to night vision conditions from normal interior illuminance levels. This is due to the slow regeneration time for the rods that are saturated at high luminances. Neutral-density filter material to provide low-level white lighting for interior illuminance at night has been considered optimal for task performance while maintaining dark adaptation.[34]

Illuminance Recommendations. Recommendations for illuminance levels in marine applications are provided in Chapter 10, Quality of the Visual Environment.

Light Sources and Luminaires

For marine lighting applications, incandescent, fluorescent, and high-intensity discharge (HID) are used most often. For special applications light-emitting diodes (LEDs), electroluminescent panels, cold-cathode, and lasers can be used (see Chapter 6, Light Sources). Selection depends on the particular requirements of the visual task (Figure 23-30), the installation being considered, the system economics or efficiencies, the personal preferences of the ship's owner, and the objectives of the designer.

Figure 23-30. Low light levels in the combat information center of the U.S.S. Shiloh permit the viewing of visual displays and radar screens.

Incandescent. Incandescent lamps are the principal light source for navigation lights. Special "rough service" lamps are required in some marine applications. In living spaces, they can be used to meet aesthetic criteria for areas that require low illuminance levels. For interior applications or with fixtures mounted directly to bulkheads or overheads, the adequate dissipation of heat must be ensured. Because of their higher efficacy, fluorescent lamps are replacing less efficient incandescent sources for general service applications (area and task lighting).

Fluorescent and Cold Cathode. Fluorescent lamps have longer lamp life and reduced energy costs. Efficacy is particularly important in marine applications where the cost to produce a kilowatt-hour of electrical energy is two to four times the cost of generating electric energy ashore. Fluorescent luminaires are best applied for general illuminance of weather-deck areas where mounting heights are relatively low (<2 m [<6.6 ft.]).

Marine applications involve more vibration and shock than comparable applications ashore. Accordingly, short lamp lengths and compact fluorescent lamps are preferred for marine applications. Similarly, because of storage and handling problems, fluorescent lamps exceeding 122 cm (48 in.) are not recommended for marine lighting. Socket clamps are available to retain linear fluorescent lamps in the lamp sockets where they can be jarred loose due to vibration during normal operations.

Compact fluorescent lamps (CFLs) are ideally suited to marine applications. Their small profile makes them more resilient to shock and vibration. For lamps greater than 13 W, appropriate restraints should be incorporated into the luminaire design. The smaller-wattage CFLs (regardless of base type) are also ideal replacements for general-service incandescent lamps.

Fluorescent lamp ballasts for marine applications must incorporate more complex circuitry to protect the lamps and correct the power factor. Ballasts must be rated for the specific electric distribution system on the vessel. Particular care should be paid to ungrounded (floating neutral) systems in which both conductors are at a potential above ground. For naval and other industrial marine applications (such as oil drilling platforms), ballasts should meet the electric power supply requirements of MIL-STD-1399, Section 300.[35] It should also be noted that the use of mercury and mercury compounds found in fluorescent (and HID lamps) is restricted in naval shipboard spaces as per MIL-STD-2036.[36]

High-Intensity Discharge Low-Pressure Sodium. The family of high-intensity discharge lamps, metal halide, and high-pressure sodium lamps, as well as low-pressure sodium, is used when a high lumen package is required. As on shore, these lamps are used primarily for exterior applications. As a general rule, all HID lamps used in marine applications should be installed in fully enclosed luminaires. This will contain the hot fragments should the lamp break while in operation. Where eye safety is a key concern, self-extinguishing lamps are available for applications where the lamp must be extinguished when the outer bulb is broken. Marine environments are particularly sensitive to mercury contamination because of its corrosive action on aluminum components and because of potential health hazards in confined space. Consequently, HID lamps are subject to MIL-STD-2036[36] as for fluorescent lamps.

Luminaires. Luminaires can be open, drip-proof, watertight, or explosion-proof with optical assemblies to direct, diffuse, or modify the illuminance from a light source. Open or drip-proof types are generally used in dry interior spaces such as general lighting in state rooms, toilets, messrooms, passages, stairs, and public spaces. Watertight luminaires are used in corrosive, damp, or wet exterior locations such as weather decks, cleaning gear lockers, galleys, and in machinery spaces. Where explosive vapors or gases can be expected to accumulate, luminaires should be located outside the compartment or must be explosion-proof. The U.S. Coast Guard Electrical Engineering Regulations[15] and the Recommended Practice for Electric Installations on Shipboard, IEEE Standard 45[22] should be consulted for specific areas where either watertight or explosion-proof luminaires may be required.

Other Considerations. Particular consideration should be given to the weight, size, and energy consumption of the lighting equipment. Care should be used to minimize corrosion and electrolytic action caused by contact of dissimilar metals. Copper-free aluminum (99% pure) should be used in salt water environments. The materials used should also be suitable to meet requirements as to mounting location and cargo type. Fluorescent luminaires should have devices incorporated to prevent accidental lamp release. The incorporation of radio filters or suppressors should be considered; however, grounded capacitive/inductive filters should not be used because they can create erroneous ground faults.

Luminaire Selection. Because vessels are in motion on the water, they are subject to shock and vibration loads. Luminaires must withstand those loads and protect the lamps and auxiliary components mounted within. The design and selection of optical and decorative components must consider the potential loads due to a vessel's motion.

Marine Electric Distribution Systems for Lighting

General. Marine electric distribution systems are governed by codes approved by regulatory bodies. The guidance in this section is intended to provide a reference for the lighting designer.

Passenger Ships. The lighting on board passenger ships consists of general lighting, temporary emergency lighting, and final emergency lighting systems.

- The general lighting system is supplied from the ship's electric distribution system and furnishes power to the major sources of illumination.
- The temporary emergency lighting system is supplied from storage batteries and comes on instantly when power to the general lighting system fails. It must provide adequate lighting for safety, escape, and preventing panic during the period between failure of the general lighting power supply and energizing of the final emergency supply. Under normal conditions the system is supplied from the ship's electric distribution system and forms a part of the general lighting.
- The final emergency lighting system is supplied from an emergency generator that starts and comes on line automatically. It replaces the battery power for the temporary emergency lighting system. Under normal conditions, circuits on this system are supplied from the ship's normal electric distribution system and form part of the general lighting. An automatic bus transfer switch or bus tie breaker links the emergency lighting panel to the vessel's main generator and the emergency generator. It operates automatically when main power is lost to shift the load to the emergency generator. When main power is restored, the load is manually or automatically shifted back to the main distribution bus.

Cargo, Miscellaneous Ships, and Tankers. The lighting onboard cargo, miscellaneous vessels, and tankers (not classified as passenger vessels) consists of general lighting and emergency lighting.

- The general lighting system is supplied from the ship's electric distribution system and furnishes power to the major sources of illumination.
- The emergency lighting system is supplied from either storage batteries or an emergency generator. It can be put into operation either automatically or manually when electric power to the general lighting system fails. Under normal conditions the emergency system is energized from the ship's power supply and forms part of the general lighting system.

Naval Vessels. There are three lighting systems on naval vessels: general, emergency, and battle lighting.

- The general lighting system is supplied from the ship's electric distribution system and furnishes power to the major sources of illumination.
- The emergency lighting system is fed from the emergency switchboard. Under normal circumstances, the emergency switchboard is fed from the ship's service generators. When the ship's service generator is lost, an emergency generator automatically comes on line and feeds the emergency switchboard. Emergency fluorescent lighting is designed to operate for five hours using an internal power source when power is lost.
- The battery-powered battle lanterns are automatically energized when normal and emergency power are lost. They illuminate key watch stations, weapons control stations, safety equipment, escape routes, operation of vital services, and controls required to facilitate restoration of power to the electric distribution system. In many new-construction ships and retrofit applications, fixed battle lantern installations are being replaced by fluorescent luminaires with integral battery packs. When a ship's power is lost, one lamp remains energized with luminaire output reduced by about 80%. The luminaires meet MIL-DTL-16377.[19]

Offshore Platforms. Offshore platforms require electric distribution systems that are comparable to industrial facilities ashore (Figure 23-31). Electric power is normally supplied by alternating current generators. Because of the critical nature of many of the processes involved, continuity of electric power supplies is essential. Accordingly normal and emergency systems are provided. For the lighting system, a battery back-up system is recommended as is found on naval ships.

Figure 23-31. Nighttime illuminance permits offshore oil rigs, such as these North Sea production platforms, to operate around the clock. Care must be taken to avoid masking obstruction and navigation lights.

Pleasure Craft. Pleasure craft can range from small cruisers to ocean-going yachts. General lighting is provided by a system powered by the vessel's electric distribution system. When a ship's service generator is not installed, battery power is used. On smaller vessels, the generator is powered by the main engines and charges the batteries. Lighting systems generally are not differentiated by function as is the case on larger vessels.

Voltages and Distribution. The standard generator and distribution bus voltages in use today are 60 Hz alternating current in the following three configurations:

- 120 V, three-phase, ungrounded, delta connected
- 208Y/120 V, three-phase, four wire, grounded neutral, wye connected
- 480 or 450 V, three-phase, ungrounded, delta connected.

On smaller vessels and some older ships, power and lighting circuits are supplied from direct current generators and batteries. Common lighting circuit voltages include 12, 24, and 120 V.

Grounding. There are several shipboard lighting design considerations related to grounding. Many systems are ungrounded or have a system neutral that is at a different potential from the hull of the vessel. Accordingly, the safety ground (green conductor) and the equipment housing must be isolated from both the line and the neutral conductors. This is necessary for safety considerations and for preventing unintentional ground faults. Amplification of this guidance can be found in References 15, 18, 22, 35, and 36.

Certain ballasts must be supplied from grounded electrical systems to operate satisfactorily; accordingly, they must not be installed on ungrounded marine electric distribution systems. Ballasts having an open-circuit voltage of more than 700 V are not permitted by the U.S. Coast Guard.

Receptacles of the proper type and configuration should be provided throughout the vessel for the use of portable luminaires or other lighting equipment connected to the electrical system. Where required by regulations or good practice, ground fault circuit interrupting devices must be applied.

Switching. Lighting in large public spaces, weather deck locations, machinery spaces, and cargo holds should be controlled directly from the lighting distribution panels. General lighting in staterooms, baths, messrooms, crew and officer recreation rooms, and other smaller spaces should be controlled by two-pole switches located at each door. Switches can also be provided at beds and desks for crew and passenger convenience. The selection of switch type (watertight, non-watertight, or explosion-proof) should be based on location. In general, where luminaires are of watertight construction, watertight switches should be utilized. Typical locations include weather decks and machinery spaces. Switches, which must be located where explosive gases, vapors, or dust are expected to accumulate, should be of the explosion-proof type. Navigation lights, all exterior lights forward of the wheel-house, and all lifeboat floodlights should be controlled from the wheel-house.

Lighting System Design

Application Guidance

Living, Office, and Public Spaces. Stateroom, dining, recreation, office, and medical spaces for passengers, officers, and crew should have general as well as local lighting. Spaces in which supplementary illuminance are indicated include reading, serving, dressing, and makeup areas. Controls for general lighting should be placed at principal entrances. Controls for supplementary lighting should be located conveniently to the task. Figures 23-32 and 23-33 show lighting for a stateroom and lounge. Minimum requirements are provided in the International Convention for Safety of Life at Sea.[37,38]

Passageways, stair foyers, and stairs should be uniformly illuminated such that they do not pose a hazard. Care should be taken to light the entire width of passageways and stairs as well as compartment numbers and other signage. Average illuminance is not the only metric recommended for these spaces; the average-to-minimum illuminance ratio should not exceed 6:1. Minimum illuminance levels for safety should be provided by luminaires connected to the emergency power system or battery backup.

Dining rooms for passengers and officers, the wardroom, the crew's mess, lounges, libraries, and recreational spaces are all public spaces. The same principles and techniques utilized ashore apply. Special consideration should be given to the emergency lighting requirements as shipboard spaces are more restricted or obstructed than similar spaces ashore.

Navigation Spaces. During nighttime operations, the pilot house, bridge, and navigation areas must be in complete darkness, with the exception of instrument lights and the chart table. Low-level white lighting should be provided for performing the seeing tasks. Dimming controls are recommended.[34] General lighting in the chart room should be provided by ceiling luminaires. For night operation, neutral-density filters or separate task sources should be provided. The task luminaire for the chart table should be fed from the emergency power system or a battery backup. Task lights can be installed to illuminate the chronometer and ship's clock, which are controlled by a momentary contact switch.

High-level white lighting, as required for cleaning and maintenance, should also be provided.

Figure 23-32. One of the M/Y Lady Tiffany's contemporary staterooms showing the use of fluorescent and incandescent luminaires installed for sea service.

Figure 23-33. Lounge space aboard the M/Y Lady Tiffany showing a combination of recessed, cove, wall mounted, and torchiere luminaires.

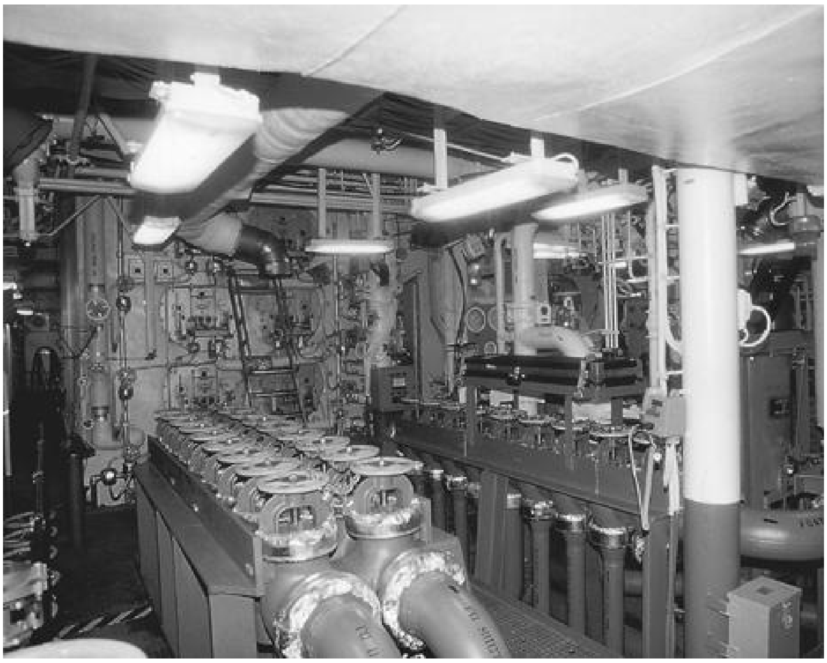


Figure 23-34. General illuminance for machinery in the engine room is provided by water-tight fluorescent luminaires on vibration mountings. These luminaires are installed so as to avoid piping and other obstructions. Care should be taken to illuminate gauges, controls, and rotating machinery components.

Lighting in passageways and spaces adjacent to the pilot house and bridge should be equipped with controls that extinguish the lights when doors to those areas are opened at night. As an alternative, light traps can be provided.

Operating and Service Spaces. Machinery spaces, including steering gear, auxiliary, and other operating spaces, should be provided with overhead-mounted general illuminance with supplementary and task lighting installed to illuminate obscured areas, control and gauge panels, and other task surfaces having specific visual tasks. Lighting should be designed to prevent veiling luminances on instrument and control surfaces. Figure 23-34 illustrates machinery room lighting. Emergency lighting should be provided for instruments and controls as well as for emergency egress. Vapor-proof and waterproof luminaires are typically required, and hazardous-location luminaires can also be required in spaces where hazardous cargo and fuel are handled. Protective guards or impact-resistant lenses are recommended.

Exterior Lighting

Special Considerations. Lighting is required when the vessel is in port and underway. Exterior lighting in port is used for cargo handling, passenger boarding, security, and maintenance (Figure 23-35). Decorative lighting can also be provided for entertainment or advertising. Luminaires should be waterproof and located for ease of maintenance. During underway periods, many similar activities can be undertaken; however, care must be exercised to prevent excessive stray light from being directed at the bridge or in a manner that interferes with the recognition of navigation lights by other vessels. Light sources should be selected for long life and stability under expected electrical system operating conditions.

General Topside Lighting. The outside lighting of decks should utilize watertight deck and bulkhead luminaires. Protective guards or lenses should be provided. Light levels should be held to the minimum required for safe passage. Tug boats require illumination that permits working on deck with minimal impact upon night vision or interference with navigation and running lights; this is typically provided by the use of amber lenses on luminaires.

Cargo Handling. Ships are usually fitted with permanent lighting in cargo holds. Receptacles are placed adjacent to hatches for the installation of temporary/portable lighting equipment. Floodlighting is recommended in the vicinity of cargo hatches. Fixed lighting for this purpose can be mounted on the superstructure, masts, or booms. Tankers should have lighting of valves, piping, and gauges. Figure 23-36 illustrates topside lighting.

Aircraft and Night Operations Underway. Many vessels are engaged in special operations at night. They include fishing boats, military vessels, dredges, and research ships. Both military and commercial vessels operate aircraft at night. Fixed-wing operations are limited to aircraft carriers with airport lighting procedures being adapted to the marine environment (Figure 23-37). Helicopter operations are common on fishing boats, offshore platforms, passenger vessels, private yachts, and Coast Guard cutters. Lighting for helicopter operations should conform to aviation lighting practice. Guidance for the lighting of helicopter landing platforms can be found in References 15, 39, and 40 and in the section

"Heliports" later in this chapter.

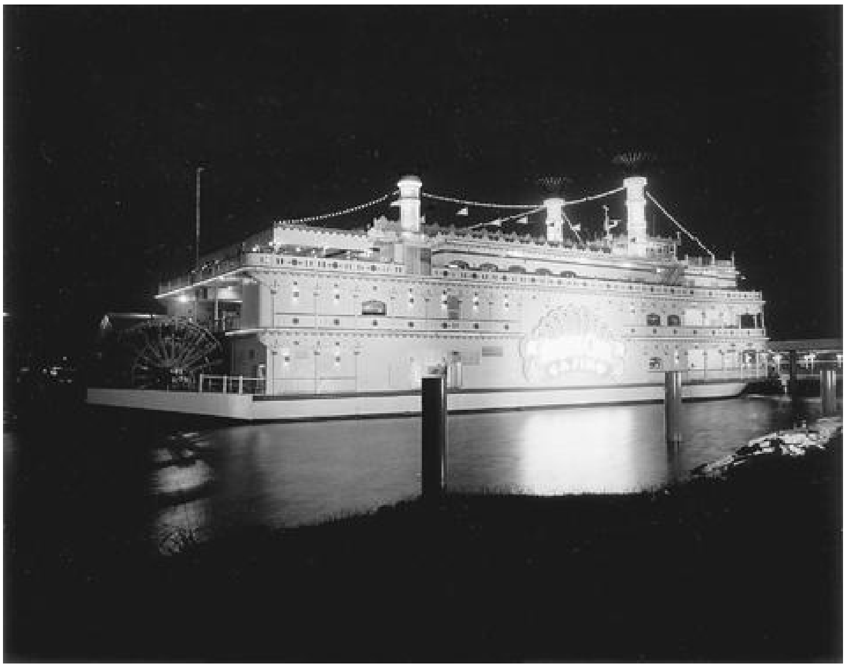


Figure 23-35. The M/V Treasure Chest, a modern riverboat casino, provides an example of in-port topside lighting.

Figure 23-36. Deck illuminance on a tanker is provided by high-tower floodlights using HID lamps.

Figure 23-37. Careful use of fixed lighting permits the launch and recovery of aircraft at night from an aircraft carrier. Care must be taken to protect the night vision of aviators and flight deck personnel.

Care should be taken to avoid blinding or misleading the pilot with stray light. For fishing vessels, illuminance should cover the entire fantail and nets in the vicinity of the hull. Such operations are inherently dangerous, and illuminance should provide clear visual cues. Generally, a blending of high-pressure sodium vapor and tungsten-halogen luminaires is used to provide the best compromise between required light levels and system efficiency.

Underway Refueling and Replenishment. Specific requirements for underway refueling and replenishment during periods of darkness are contained in Reference 18. General practices include the use of red filters on floodlights illuminating underway replenishment stations. Luminaires should be placed to minimize glare for personnel manning the stations. Illuminance should be uniform throughout the work area with added illuminance in the landing areas, connection points for refueling hoses, and attachment points for the underway replenishment lines. Obstruction lights are placed at the edge of the deck where life lines are removed to bring material aboard and on stanchions at either end of the landing area. Lights are also mounted on the phone/distance line to indicate the spacing between ships. Portable lights with various colored filters are used for signaling; an illuminated station marking box is mounted during night operations to identify each station.

Lifeboat and Life Raft Launching. Floodlights should be provided at each lifeboat or life raft launching station. A set of fixed lights should be installed to illuminate the boat during all steps of launching and recovery. For safety, redundancy is required; lighting should be provided by at least two luminaires. Horizontal illuminance levels should be checked at each deck level and at the waterline to verify the adequacy of the lighting for all positions of the life boats. An adjustable floodlight should be provided to facilitate the recovery of boats at night. Power should be provided from the emergency system with battery backup. Minimum requirements are provided in the International Convention for Safety of Life at Sea.[37,38] Sometimes the life vests are equipped with rescue lights (Figure 23-38).

Figure 23-38. Rescue light mounted to a life vest. The light illuminates on impact with salt water.

Stack Lighting. Where stack lighting is desired, floodlights equipped with shielding and focusing capability are recommended. The luminaires should uniformly illuminate the stack area and minimize spill light. Luminaires exposed to exhaust gases must be able to resist corrosive attack from dilute solutions of sulfuric and nitric acids.

Searchlights. Where a navigational searchlight is desired, it should be located above the pilothouse and be remotely operable from within the pilothouse. Portable searchlights for signaling should be provided for operation from either bridge wing. They should be energized from either the ship's emergency system or be battery-operated. Signaling can be effected by keying the power to the light with a momentary contact switch or through the use of shutters fitted to the luminaire. The latter is the preferred method to maximize lamp life.

Security Lighting. While a ship is in port, security lighting can be required at the waterline to prevent unauthorized access or criminal activity. Portable floodlights are installed to ensure complete coverage of the waterline. Additional guidance is provided in Reference 18.

Navigation Lights. Requirements for running, anchor, and signal lights are delineated in Rules of the Road.[20] Such lights should be installed to conform to the specific rules governing the waters in which the vessel is expected to navigate. A running light indicator panel, equipped with both visible and audible indications of lamp failure, should be provided for the masthead, range, side, stern, and special occupation lights. All navigation and other special purpose lights used for navigation purposes should be powered from the emergency system. Dual filament lamps, switchable from the navigating light control panel, can be used to ensure that a light is available at all times and during all weather conditions. This allows lamp replacement to be performed under good conditions.

Portable Lighting. Maintenance and emergency situations often require the use of portable lighting equipment. Battery-powered equipment must be kept available for situations in which the ship's power is not available. For routine maintenance, portable lighting fed from the ship's distribution circuits is generally used. Luminaires manufactured for shore applications are typically unsafe aboard ship due to grounding and waterproofing requirements. Portable luminaires intended for naval shipboard use should meet the requirements of MIL-DTL-16377.[19]

Specialty Lighting. In places such as the Suez and Panama Canals, specialized lighting can be required. The Suez Canal requires a unique lantern (which can be leased) to be mounted on the bow of the vessel, port and starboard bridge-wing searchlights (to illuminate the banks of the canal), and stack lighting to assist in identifying the vessel. The Panama Canal Commission requires that the Pilot Ladder be illuminated by a forward shining light over the side of the vessel. Additionally, for vessels over 100 m (300 ft) a blue steering or rate-of-turn indicator light, which is separately controlled and visible along the centerline in the pilothouse, is required on the bow of the vessel.

Naval, Coast Guard, and Other Military Vessels. All of the considerations just discussed apply equally to vessels constructed for military service or for supporting military operations. There are, however, additional concerns that must be taken into account when designing and specifying lighting for military vessels.

In addition to conventional illumination, red, yellow, and blue light sources are used for general lighting in areas having specialized tasks. The need for topside operations at night dictates that much of a military vessel have darkening capability that permits the access and passage of personnel without a loss of night vision adaptation.

Aids to Marine Navigation. The operation and maintenance of marine aids to navigation in U.S. waters is the responsibility of the U.S. Coast Guard. There are over 16,000 lighthouses, buoys, and beacons in U.S. navigable waters. Other visual aids to navigation are maintained by state and local agencies on lakes and rivers used for recreational boating. A discussion of navigation aids is presented in the IESNA Recommended Practice for Marine Lighting, RP-12[41] and CG-250-37.[21]

Lighting System Maintenance

General. A system of regularly scheduled maintenance should be established for the lighting system. It will ensure that luminaires and compartment surfaces are kept clean and in proper operating condition. The marine environment is more severe than is encountered in the typical installation ashore.

Mechanical. Because marine lighting equipment is subjected to extreme environments, regular inspection and repair of mountings, brackets, and shock restraints should be performed. Similarly, the gaskets and seals of waterproof luminaires and controls should be maintained. Mechanical inspections can be combined with other maintenance actions like group relamping. However, each luminaire should be visually examined annually and after any high shock loadings that might impose damage. Shock and mechanical vibration are major causes of mechanical failures.

Electrical. Because many marine lighting systems use ungrounded electric distribution systems, and because there is a high risk of electrical shock in a marine environment, lighting feeders should be tested for ground faults quarterly and after any maintenance involving the lighting system's electrical components.

Field Measurements

A marine lighting survey is conducted to document the performance of a lighting system for comparison to the design criteria or to evaluate a suspected performance problem. In surveying a lighting installation in the field, consideration should be given to documenting both the quality and quantity of light delivered to the space. Details for performing such a survey can be found in the IESNA Recommended Practice for Marine Lighting, RP-12.[41]

Marina Lighting

Architectural lighting in and around a marina should not conflict with the navigation equipment lights and markings. All equipment must be chosen and installed to help guide the boats and simplify docking. Docks and walkways adjacent to bodies of water should be lighted to create enough contrast to enhance the visibility of small objects, ropes, and cleats on docks that could cause tripping and accidental falls.

The final installation should avoid the use of beacons, or red and green lights, which could be mistaken for navigational lights. Marina or dock lighting must be visible from distances of at least one nautical mile. The lighting design should not produce glare and light pollution, which limit the visibility of the navigation equipment, or cause reflected glare from the water, preventing a safe approach to the marina and dock for an incoming boat.

Agencies such as the U.S. Coast Guard and the U.S. Army Corps of Engineers can provide additional information on navigational lights. See the reference section of this chapter.

AVIATION

Aviation lighting falls into two principal descriptions: aircraft lighting and airport lighting. Aircraft lighting has three components: exterior lighting of the aircraft, crew station or cockpit lighting, and, in commercial aircraft, passenger interior lighting. These subcategories cover a spectrum of lighting equipment ranging from lighting for visual collision avoidance, to instrument and panel lighting, to decorative lighting in the passenger cabins. Airport lighting can be divided into two parts: lighting used for signaling and lighting used for illumination. Signaling lighting includes taxiway and runway edge lights, runway threshold lights, approach lighting, runway end illuminator lights, and signage. Illumination lighting is used to illuminate wind cones, aprons, and parking areas.

The intent of this chapter is to provide an overview of basic aircraft and airport lighting requirements. Because regulations controlling these lighting requirements often change, current detailed specifications and guidelines should be obtained from the appropriate agency listed at the end of this chapter.

Airport lighting language has its own acronyms. A listing of the more common acronyms associated with aviation lighting is included at the end of this chapter.

Standardization

In both aircraft lighting and airport lighting, standardization is essential. The interstate and international scope of operations by aircraft make the establishment of color and intensity standards imperative for all of the visual aid systems necessary to operate aircraft safely. These regulations and standards are originated by the Federal Aviation Administration (FAA) and the military agencies within the United States. Outside the United States, organizations such as the International Civil Aviation Organization (ICAO), Transport Canada, and the North Atlantic Treaty Organization (NATO) establish these regulations. When it is pertinent in this section, the relevant regulations or regulating body has been mentioned. Before planning new or modified aviation lighting or visual aids, the appropriate agencies or standards must be consulted.

Aircraft Lighting

The exterior lighting on an aircraft must perform satisfactorily over a wide range of environmental conditions. The environment in which this aircraft lighting equipment operates during flight is extremely harsh, and includes such conditions as extremely high or subzero temperatures, pressures induced by aerodynamics, and vibration and shock. These conditions are not normally found in most lighting applications. Further, the luminaires on the exterior of an aircraft perform a specific function and are installed in specific locations on a given type of aircraft. All airplanes are equipped with position/navigation lights. Usually these lights are designed to fit within the wing, wing tip area, or tail assembly (empennage), thus requiring different types of luminaires for each type of aircraft. Each type of aircraft, and even similar aircraft for different owners, may have completely different cockpit or crew station arrangements, and the lighting is designed specifically for that type aircraft or modification. Nevertheless, many of the small luminaires and lamps can be standard types. In commercial passenger aircraft, the luminaires used within the cabin for reading light and no-smoking and exit signs are always designed specifically for the type of aircraft in which they are to be installed.

Aircraft Grouping. There are three broad groupings of aircraft. They are general aviation, commercial, and military.

General Aviation Grouping. General aviation aircraft range from the very small, private, single-engine airplanes up through the single-engine piston and twin-engine turbo-prop or jet aircraft, commonly termed "bizjets." The minimum lighting requirements for these aircraft are found in Part 23 of the United States Federal Aviation Regulations (FAR)[42] for fixed-wing airplanes, and in Part 27[43] for helicopters. Part 91[44] (Operating Requirements) requires the use of position/navigation lights and anticollision lights for all night operations. Position/navigation lights (consisting of red and green wing tip lights and white tail lights) are so named because they are intended to indicate to an observer, and to other pilots, the position of the aircraft.

Commercial Grouping. Commercial or airline aircraft must include luminaires meeting FAR Part 25[45] for fixed-wing aircraft and FAR Part 29[46] for transport-type helicopters. Operating requirements for airline operations are found in Part 121[47] of the FAR. These include minimum lighting requirements for use of position/navigation lights, anticollision lights, landing, instrument and indicator lights, wing ice, floodlights, and signage (emergency egress, no-smoking, and fasten-seat-belt signs).

Military Grouping. Military aircraft also include a wide variety of types, ranging from small trainers to high-performance fighters, bombers, large transport aircraft, tankers, helicopters, and others. While military aircraft have many of the same lighting requirements as general or commercial aviation, they frequently require special luminaires for military functions such as formation flying, in-flight refueling, and approach to aircraft carrier decks. In the United States all aircraft exterior lighting must meet the minimum requirements of the FARs. However, in many cases the Navy, Air Force, and Army specifications exceed these requirements. Navy exterior aircraft lighting requirements are generally covered in Specification MIL-L-006730;[48] Navy interior lighting requirements are in Specification MIL-L-18276.[49] Requirements for lighting of Air Force and Army airplanes are described in specification MIL-L-6503.[50] These specifications often reference other documents that have been issued for various detailed lighting requirements.

Aircraft Electrical Systems. New aircraft are now equipped with either 28-V dc or 120/208-V, 400-Hz, three-phase electrical power systems. In the past, most small single-engine and some twin-engine aircraft were equipped with 14-V dc systems. In some cases the luminaires can be used with appropriate lamps to produce the same lighting performance on either 14- or 28-V electrical systems. In many cases, lamps for aircraft using 400-Hz systems can be lower voltage (6 to 10 V) and operated from individual transformers. Low-voltage incandescent filament lamps have greater strength and resistance to shock and vibration, are a more compact size than higher-voltage types, and can result in improved optical performance.

Exterior Lighting Of Aircraft. The exterior lighting systems on aircraft include position lighting systems to aid in the location and flight direction of aircraft after dark, lighting to help prevent mid-air collisions, lighting to be used during the final approach and landing of aircraft, lighting for use during ground operations of the aircraft, and other miscellaneous systems.

Position Lights. For many years aircraft have been equipped with a system of position/navigation lights consisting of red lights on the left wing tip, green lights on the right wing tip, and white lights on the tail or, in some cases in larger aircraft, on the trailing edge of each wing tip. These lights are required for all systems and on all aircraft operating at night. Intensities of red and green position lights projected in the forward direction are required to be a minimum of 40 cd by the FAR. However, on many of the larger aircraft, such as airliners, they produce more than 300 cd. Commercial aircraft are commonly equipped with dual position lights for redundancy, which increases reliability. Having white tail lights on the trailing edge of the wing tips makes maintenance easier and provides a better assessment of altitude when the aircraft is viewed from the rear.

Anticollision Lights. The FAA specifications state that anticollision lights can be either red or white. Current FARs require that these lights produce a minimum of 400 cd of effective intensity near the horizontal plane and 20 cd at vertical angles of 75° up or down. This produces a pattern around the airplane somewhat like a doughnut. Condenser discharge flash tubes (strobes) are commonly used for white anticollision lights. They are also used in some red anticollision lights, but since a strobe does not contain much long-wavelength radiation, it is not the best of sources for red. Strobe lights are operated at energy levels of 15 to 100 joules per flash and flash rates of 45 to 50 flashes per minute. Effective light intensities range from 100 to more than 4000 cd. Exceeding the FAA requirements of 400 cd on larger aircraft, such as airliners, increases the chance of being seen by other aircraft and also compensates for the loss in light output as the strobe lights age. Locating the white high-intensity strobe lights on the wing tip reduces the problems caused by reflections or backscatter, which can interfere with the crew's vision from the cockpit. Many aircraft are equipped with both red and white anticollision light systems. The red anticollision light system is located on the top and bottom of the fuselage and the white anticollision light systems on the wing tips. This arrangement is now common on airliners.

While the aircraft is on the ground, it has become accepted practice to operate the low-intensity red anticollision lights to indicate that aircraft engines are operating and to turn the white strobe lights on only when the pilot prepares for takeoff.

Landing Lights. Landing lights often use 400-W to 1000-W PAR-46 sealed-beam lamps. Large aircraft are commonly equipped with four of these lamps in a landing light system, with one in each outboard wing section in retractable luminaires and one in a fixed unit in each inboard wing root. On some aircraft, fixed landing lights are located on the nose landing gear struts (Figure 23-39). Landing lights are used to improve the visibility of the aircraft, particularly when aircraft are within 16 km (10 mi) of a tower-controlled airport or lower than 3000 m (10,000 ft). To avoid having to extend landing gear prematurely, some airplanes are now equipped with fixed recognition lights in the wing tips or wing leading edges. These lights usually produce a relatively narrow beam with an intensity of approximately 70,000 cd. Helicopters are equipped with search and landing lights controlled in both elevation and azimuth by operating a four-way switch located on the collective pitch control.

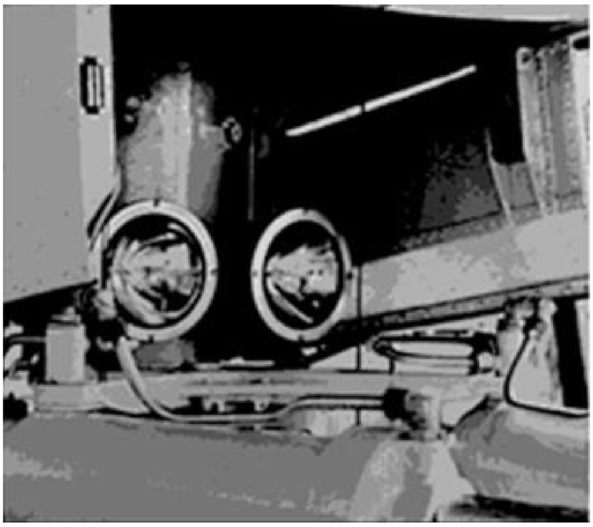


Figure 23-39. Landing/taxi light mounted on nose wheel strut.

Taxi Lights. Taxi lights mounted on the aircraft normally have a wide horizontal and a narrow vertical beam and are commonly mounted on landing gear struts. In some cases, they are mounted on the movable section of a nose wheel strut as shown in Figure 23-39. Dual-filament, sealed-beam lamps are used, where operation of one or both filaments provides a specified taxi or landing light pattern. In other cases there are fixed taxi lights located in wing root cavities to illuminate areas outboard and ahead of the aircraft so as to identify taxiway turnoff areas.

Auxiliary Lights. Many aircraft, civilian and military, are equipped with auxiliary lights of all types. "Wing de-ice lights" are located in the fuselage and shine out along the leading edge of the wing so that the pilot can view the wing leading edge at night for ice build-up. "Logo lights" are often located on the upper side of the horizontal stabilizer to shine up and illuminate the vertical fin. Logo lights can also be located on the trailing edge of the wings aimed at the vertical fin.

Navy carrier-based aircraft are equipped with red, green, and amber lights that can be seen day or night during landing operations by the landing signal officer (LSO) aboard the aircraft carrier. These lights indicate to the LSO the approach attitude of the aircraft.

Crew Station Lighting. Modern aircraft have evolved a sophisticated crew station that is called the "glass cockpit" (Figure 23-40). Self-luminous devices, such as cathode ray tubes or flat panels, provide most of the meaningful data to the pilot. In most multiengine aircraft, the lighting is an integral part of the instrument or the device providing data to the pilot. Switch panels are normally plastic panels about 5 mm (0.19 in.) thick that are lighted with small embedded subminiature lamps or electroluminescent material. New aircraft, such as the Boeing 777, utilize LEDs in the control light plates (Figure 23-41). Since practically all new aircraft, military and commercial, now use cathode-ray tubes or flat-panels in the glass cockpit, red illumination of cockpits has been dropped.

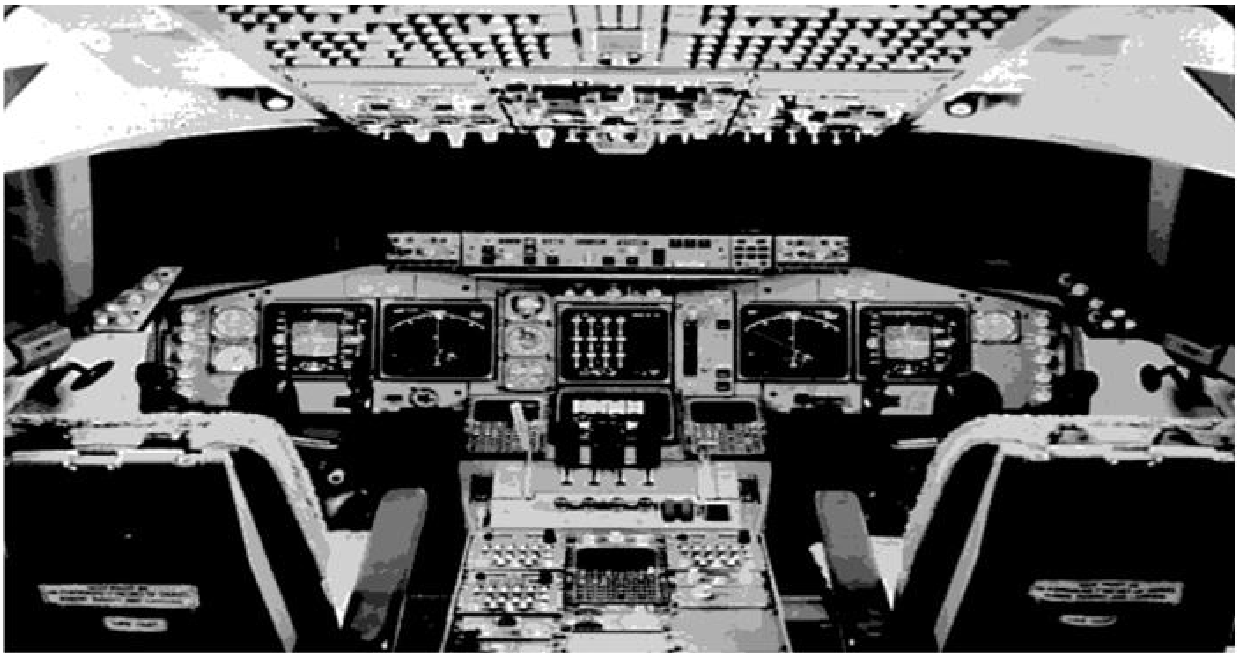


Figure 23-40. Boeing 747 glass cockpit.

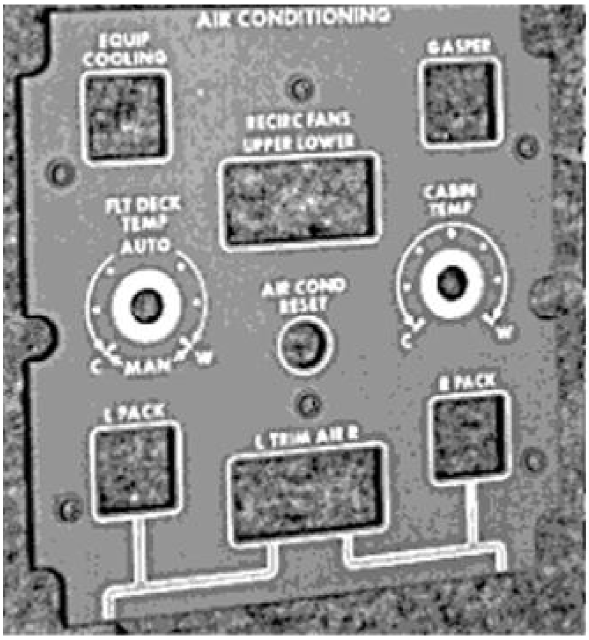


Figure 23-41. Edge-lighted panel utilizing LEDs.

Most aircraft are also equipped with instrument floodlighting systems in addition to integral instrument and panel lighting. This system provides low-level background lighting in order to avoid any autokinetic effect that can be produced when lighted markings are viewed against a perfectly black background. Aircraft are commonly equipped with "thunderstorm" floodlights capable of providing about 1000 1x (100 fc). These lights ensure the continued visibility of instruments in case dark adaptation is suddenly destroyed by bright light such as a lightning flash. Annunciator and indicator lights within the crew stations should be readable in bright sunlight producing incident illumination of 100 klx (10,000 fc).

Most airplanes are also equipped with map lights. These are easily controlled by the cockpit crew to provide a desired level of illumination on navigational charts.

Passenger Interior Lighting. Since considerable use is made of lighting in conjunction with the decorative designs in the cabin, passenger interior lighting varies from one aircraft to another depending on the specific airline's interior preferences.

Individually controlled passenger reading lights are an important part of the cabin lighting system. These luminaires provide a level of 250 to 300 lx (25 to 30 fc) on the reading plane and must produce well-controlled beam patterns to avoid interference with adjacent passengers. The distance between the luminaires and the reading plane can be less than 760 mm (30 in.) or as much as 2 m (80 in.).

A variety of lighted signs is used in the passenger interiors of airplanes. These include "no-smoking," "fasten-seat-belts," and "return-to-seat" signs. In some cases, large signs are located on the forward bulkheads of compartments; in others, smaller signs are located in passenger service units for each row of seats. Frequently, the design of the sign is part of the decorative scheme in the airplane interior. Sign symbols have become quite common and should conform to international standards where such standards are available.

Passenger cabins are usually equipped with fluorescent or incandescent lighting. Valance lights over windows on either side of the cabin are very common. Also, many airplanes are equipped with striplights that illuminate the ceilings of the cabins from locations above the bag racks. The general-lighting luminaires are concealed to improve aesthetics and eliminate glare.

Other than signs and luminaires for reading, cabin lights are dimmable by the cabin crew either continuously or in steps. Both hot- and cold-cathode fluorescent lamps can be used.

Emergency Egress Lighting. The FAA specifies minimum lighting requirements for area lighting as well as the size, luminance, and contrast of signs directing passengers to marked exits. Luminaires are installed in the ceiling of the passenger compartment of the aircraft to provide an illuminance of at least 0.5 lx (0.05 fc) at seat armrest level measured on the centerline of the main passenger aisle.[69] Other luminaires are installed to illuminate the exit areas. FAA regulations require floor-proximity emergency escape path marking. All airliners today have markings that provide emergency evacuation guidance for passengers when all sources of illumination more than 1.2 m (4 ft) above the cabin aisle floor are totally obscured. These systems consist of small lamps, low on the sides of aisle seats. There are also plastic extruded strips, which include wiring and small lamps, on about 500 mm (20 in.) centers installed on the floor along one side or both sides of the aisle next to the seats. Colored lamps in these strips, usually red, indicate exit locations. Small exit signs are located at floor level, adjacent to all exits. Electroluminescent strips are used in some cases on the floor covering across the galley from the aisle to the exit. Escape slides and over the wing exit paths on the outside of the airplane are also illuminated. All safety luminaires and signs are powered by batteries and are activated automatically or manually on failure of the aircraft electrical power system.

Airport Lighting[51]

Airport lighting encompasses a wide range of lighting systems. These include those systems required for operation of both aircraft and ground vehicles (air-side lighting), parking and roadway areas around the airport (land-side lighting), and lighting of obstructions surrounding the airport.

Air-side lighting requirements contained in this chapter are patterned after the requirements of the U.S. Federal Aviation Administration (FAA). Requirements in other countries may vary somewhat from the FAA requirements, but the International Civil Aviation Organization (ICAO) requires similar airport lighting in member countries to promote safe operations throughout the world.

Runway Classification. Ground lighting and other visual aids required at an airport are usually based on the visibility conditions under which operations are conducted and the electronic navigational aids available at the airport to support such operations. It is necessary to know and understand these conditions to provide the proper navigation lighting systems for air-side operations.

Depending on the types of navigational aids available, runways are classified as visual or instrument. A visual runway is one intended only for the operation of aircraft using visual flight rules (VFRs). Low-intensity runway and taxiway edge lights (LIRLs and LITLs) are required for runways and taxiways designated for VFR operations. An instrument runway is one suitable for an instrument approach under instrument flight rules (IFRs) utilizing electronic and visual navigation facilities. If these facilities provide only horizontal guidance or area navigational information, such as very high frequency omnidirectional range (VOR), nondirectional radio beacon (NDB), simplified direction finder (SDF), localizer (LOC), airport surveillance radar (ASR), landing distance available (LDA) or global positioning systems (GPSs), the runway is called a nonprecision instrument runway. If the facilities also provide vertical guidance in addition to the horizontal guidance, as with instrument landing systems (ILSs), microwave landing systems (MLSs), or precision approach radar (PAR), the runway is call a precision instrument runway.[52]

Nonprecision approach instrument runways have medium-intensity edge lights (MIRLs), runway end identifier lights (REILs), or precision approach path indicator (PAPIs) systems. They are not required to have an approach lighting system (ALS), but such a system is recommended. The ALS for nonprecision approach runways can be a medium-intensity approach lighting system (MALS), medium-intensity approach lighting system with sequenced flashers

(MALSF), or an omnidirectional approach lighting system (ODALS). These systems enhance the pilot's ability to complete a landing but do not reduce approach minima.[51,52]

Precision approach instrument runways are required to have both electronic and navigational lighting systems. A precision approach runway is categorized (I through III) by the runway visual range (RVR) and decision height (DH). RVR is the distance, reported in hundreds of feet, a pilot will see a high-intensity light source down the runway from the approach end. It is based on the sighting of either high-intensity runway lights or on the visual contact of other targets, whichever yields the greater visual range. RVR is the horizontal range and not the slant range. The DH is the height above the runway at which a missed approach is initiated if the required visual reference has not been established. The RVR and DH for runway categories are contained in Figure 23-42. Precision approach Category I runways having an RVR of 750 m (2400 ft) or more require only high-intensity runway edge lights. All other category I, II, or III runways require HIRL edge lights, touchdown zone lights (TDZLs), and centerline lights (CLs). Category III runways must have all of the visual aids noted here plus increasing degrees of electronic instrumentation (which is beyond the scope of this Handbook). The added electronic instrumentation determines whether the runway is Category IIIA, B, or C.

Precision Approach Instrument Runway Category	Runway Visual Range		Decision Height		Runway and Approach Lighting	
	m	(ft)	m	(ft)	Runway	Approach
I	750	(2400)	60	(200)	HIRL	MALSR
	550	(1800)			TDZL, CL, HIRL	MALSF
II	370	(1200)	30	(100)	TDZL, CL, HIRL	ALSF-2
IIIA	210	(700)	0	(0)	TDZL, CL, HIRL	ALSF-2
IIIB	45	(150)	0	(0)	TDZL, CL, HIRL	ALSF-2
IIIC	0	(0)	0	(0)	TDZL, CL, HIRL	ALSF-2

Figure 23-42. Runway Visibility Condition Categories

Figure 23-42 indicates FAA visibility and lighting requirements for precision instrument runways. Reduction in runway Category I approach minima can be achieved by upgrading from a MALSR to MALSF approach lighting systems. All other categories of precision approach runways require a high-intensity approach light system with sequenced flashers (ALSF-2).[53]

Runway and Taxiway Lighting Guidance Systems.[52-64] Runway and taxiway lighting guidance systems are installed to provide visual aid to pilots during both takeoffs and landings. These visual aids consist of reflectors, signs, and painted markings as well as approach lights, runway lights, and taxiway lights.

Approach Lighting Systems. There are several levels of approach lighting systems (ALSs) available, depending on the classification of the airport and runways and the conditions under which airport operations are conducted. The most comprehensive ALSs are installed on precision approach runways conducting operations under most weather conditions and serving commercial and military aircraft. Less sophisticated ALSs are used for general aviation airports. Airports operating only during fair weather and VFR conditions are not required to have an ALS.

An ALS is comprised of white and colored steady-burning lights, white sequentially flashing lights, or a combination of both. Steady-burning lights are unidirectional and have variable-intensity controls for all categories to permit adjusting the ALS intensity to suit visibility conditions at the airport. The sequentially flashing lights are unidirectional and are also variable-intensity (usually three levels). Flashing follows a sequence, starting at the furthest luminaire from the threshold and moving toward the threshold. Each sequenced flasher operates at two flashes per second. All systems incorporate frangible mountings, or low-mass structures, designed to minimize damage to landing aircraft in the event the structures are hit. These structures hold the individual luminaires in proper orientation.[54] ALSs are selected based on the runway category. Most ALSs for precision approach runways in the United States are designed and installed by the FAA. See Figure 23-42 for a summary of ALSs and runway lighting systems for the various categories of precision approach instrument runways.

1. Approach Lights for Nonprecision Approach Runways. Of the three ALS systems in this group--Medium-Intensity Approach Light Systems (MALSs), Medium-Intensity Approach Light Systems with Sequenced Flashers (MALSFs), and Omnidirectional Approach Light Systems (ODALSs)--two systems, the MALS and MALSF, are versions of the Medium-intensity Approach Light System with runaway alignment indicator lights (MALSR). The other system, the ODALS, uses only omnidirectional sequenced flashers.[53]

a. Medium-Intensity Approach Light System (MALS). The MALS is identical to the MALSR shown in Figure 23-43 for the first 420 m (1400 ft), and MALS can be considered a building block of a MALSR for phased development.

b. Medium-Intensity Approach Light System with Sequenced Flashers (MALSF). The MALSF consists of a MALS with three sequenced flashers at the three outer light bar locations as depicted in Figure 23-43. These flashers are added to the MALS at locations where high ambient background lighting or other conditions require these lights to assist pilots in making an early identification of the ALS. These lights flash in sequence toward the threshold at a rate of twice per second and are the same as the flashers used in the MALSR.

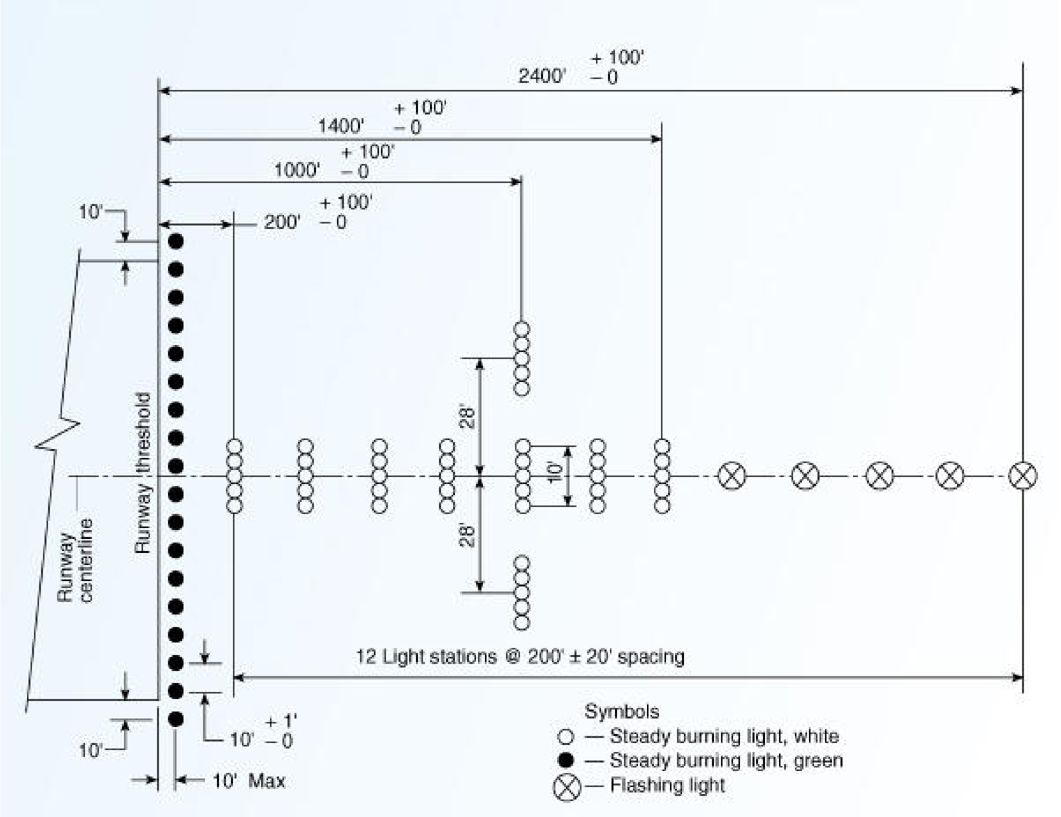
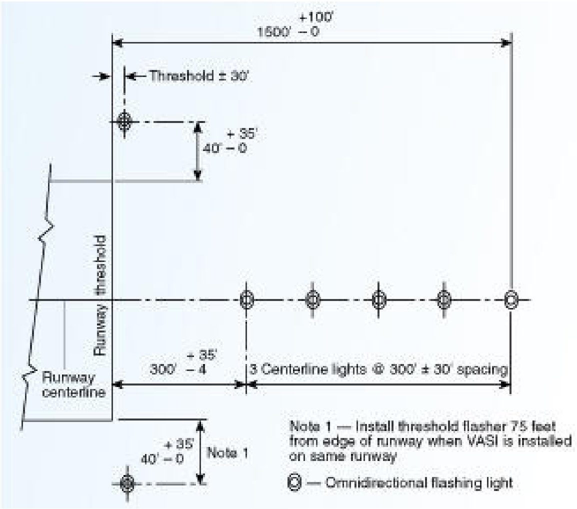


Figure 23-43. MALS (without flashers) or MALSF (with flashers). The MALS is identical to the MALSR for the first 420 m (1400 ft).



Note 1 — Install threshold flasher 75 feet from edge of runway when VASI is installed on same runway

Figure 23-44. ODALS.

c. Omnidirectional Approach Light System (ODALS). This approach light system consists of seven white omnidirectional flashing lights of variable intensity with a flash rate of one flash per second sequenced toward the runway threshold. The two lights on the threshold flash in unison. The layout is shown in Figure 23-44.

2. Approach Light Systems for Category I Precision Approach Runways. Within North America the recognized ALS for Category I runways is the MALSR.[53] The Calvert (or Modified Calvert) system and an Alpha system (ALSF-1) have been used in the past but generally are not recommended now. If information on these systems is required, the reader is referred to the appropriate regulatory agencies.

The MALSR uses steady-burning, unidirectional white lights and unidirectional white sequenced flashers. All lights are of variable intensity. Figure 23-43 shows the MALSR layout.

3. Approach Light System for Category II and III Precision Approach Runways. Category II and III operations require a high-intensity approach light system with sequenced flashers (ALSF-2). The system layout is shown in Figure 23-45. This system uses white, red, and green unidirectional, steady-burning lights and white unidirectional sequenced flashers, all of variable intensity. A flash rate of twice per second in the direction of approach to the runway is used.

Land requirements for ALS systems require a site 125 m (400 ft) wide extending from the runway threshold to a point 60 m (200 ft) beyond the outermost light of the ALS. A clear line of sight from the approaching aircraft to all of the lights in the ALS is required.

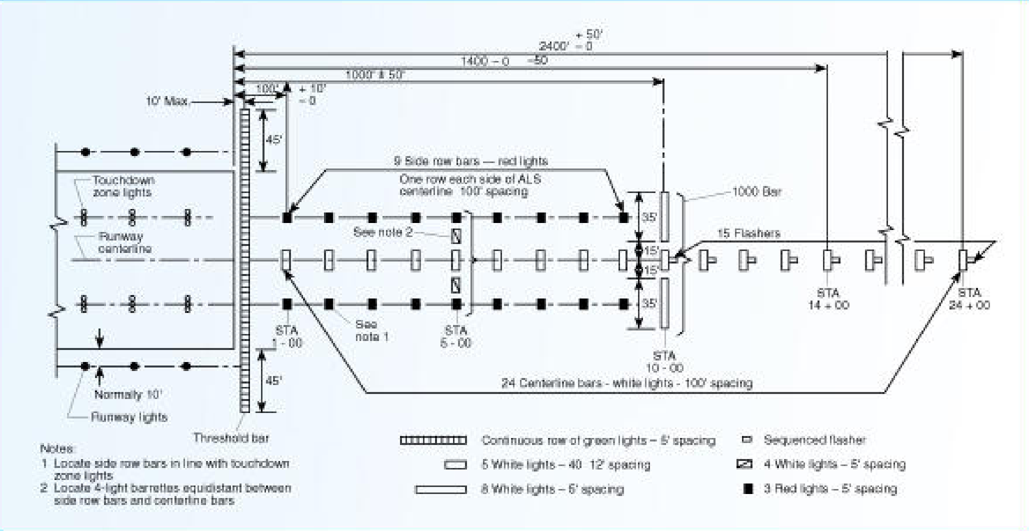


Figure 23-45. ALSF-2

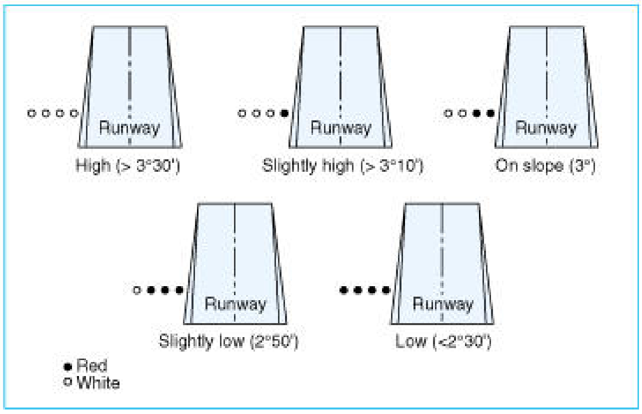


Figure 23-46. PAPI system visual presentation.

4. Precision Approach Path Indicator (PAPI).[52] The PAPI is the standard accepted glide slope indicator under the ICAO recommendations. The PAPI has replaced the visual approach slope indicator (VASI) as the most widely accepted system in the world today. The PAPI presents a red and white format. The system is installed in a single bar configuration made up of two or four projector housings. These housings project

a white-over-red signal. The desired approach path is defined by two red and two white signals for a four-box PAPI System as shown in Figure 23-46. In the basic four-box system, the projectors are set at different vertical angles with the unit nearest the runway set 30 minutes of arc above the nominal glide path, the second unit 10 minutes of arc above the nominal glide path, and the third and fourth projectors aimed 10 minutes of arc and 30 minutes of arc, respectively, below the nominal glide path. Longitudinal location of the PAPI boxes is established to give the required runway threshold crossing height (TCH). The required TCH is based on the aircraft with the greatest cockpit-to-wheel height using the runway.

5. Lead-in Lighting Systems (LDINs). Lead-in lights consist of at least three flashing lights installed at or near ground level to define the desired course to an ALS or runway threshold. An LDIN is designed to overcome such problems as hazardous terrain, obstructions, and noise-sensitive areas. They can be curved, straight, or a combination of both. The lights are placed on the desired approach path, beginning at a point within visual range of the final approach. Generally, the lights are spaced at 900 m (3000 ft) intervals. Each LDIN system design is unique. Sufficient land to permit installation and operation of the lights is required together with the right to keep the lights visible to approaching aircraft. A clear line of sight from the approaching aircraft to the next light ahead in the system is required.

6. Runway End Identifier Lights (REILs).[53] REILs are located near the threshold of a runway. They provide rapid and positive identification of the approach end of a runway. REILs are usually most effective in identifying runways surrounded by a preponderance of other lighting or lacking contrast with surrounding terrain. They are usually installed on visual or instrument runways other than Categories I, II, or III. Runway end identifier lights are two synchronized, flashing white unidirectional lights. Intensity is not variable.

Runway Delineation

1. Runway Edge Lights.[55] A runway edge light system is used to outline the lateral and longitudinal limits of usable runway landing or take-off areas during periods of darkness and restricted daytime visibility. The selection of a lighting system is based on the type of operations conducted on the particular runway:

a. Low-intensity runway lights (LIRLs) are installed on runways at VFR airports with no planned approach procedures.

b. Medium-intensity runway lights (MIRLs) are installed on runways having a nonprecision IFR procedure for either circling or straight-in approaches.

c. High-intensity runway lights (HIRLs) are installed on runways having precision approach procedures and for runways utilizing RVR instrumentation.

Runway edge lights are steady-burning white lights having variable intensity. For an instrument approach runway, yellow lights are used for 600 m (2000 ft), or one-half of the runway length, whichever is less, at the opposite end of the runway from which an instrument approach is made. In the case of a displaced threshold, the edge lights are continued to the end of the displaced runway where the displaced portion of the runway is still available for aircraft rollout, taxiing, and takeoff. The edge lights between the displaced end of the runway and the displaced threshold are red to aircraft approaching from the displaced end of the runway, and white to aircraft approaching from the opposite end of the runway, except for the last 610 m (2000 ft), or one-half of the useable runway length, whichever is less, where the lights are yellow.

2. Runway Threshold and End Lights.[55] Runway threshold lights are fixed green unidirectional lights in the direction of approach to the runway. The intensity and beam spread of the lights are designed for the visual and ambient light conditions for which the runway is intended.

Runway end lights are fixed red unidirectional lights in the direction of the active runway. The intensity and beam spread of the lights are designed for the visual and ambient light conditions for which the runway is intended. The runway threshold and end lights, except where a displaced threshold might exist, are usually combined into one luminaire.

3. Runway Centerline Lights.[56] Runway centerline lights are intended to facilitate landing under adverse visual conditions. Runway centerline lights are recommended on Category I instrument approach runways; they are required on Category II and III instrument runways and on runways where visibility distances are less than 550 m (1800 ft) RVR. Runway centerline lights are steady-burning, variable-intensity white lights, except within the last 900 m (3000 ft) of the runway end. Alternate red and white lights are used between 900 m (3000 ft) and 300 m (1000 ft) from the runway end. From 300 m (1000 ft) to the runway

end, only red lights are used. For displaced threshold portions of a runway that are over 215 m (700 ft) long, runway centerline lights should be interlocked with a MALS to prevent both systems being on at the same time. If the runway approach is from the displaced end of the runway and the runway has a high-intensity ALS, such as ALSF-2, it is not necessary to circuit the centerline lights separately because the high-intensity ALS washes out the centerline lights in the displaced area of the runway.

4. Runway Touchdown Zone Lights (TDZLs).[56] TDZLs are landing aids used with some precision approach runways to indicate the touchdown zone under adverse visual conditions. These steady-burning, variable-intensity white lights are located in the runway touchdown zone of instrument runways.

Runway Pavement Markings.[57] All runways have some or all of the following markings:

- threshold
- centerline
- edge
- touchdown zone
- taxiway lead-off
- lead-on
- land and hold short
- displaced threshold

All of these markings can have runway lighting and reflectors associated with them. The most likely lighting markings to be required are centerline, edge, lead-off and lead-on, and displaced threshold. The runway lighting system must be coordinated with the runway marking requirements for every runway on the airfield to ensure the lights and markings occur where required in the finished installation.

Note: At the time of publication, the FAA in the United States is in the process of revising the required lighting for land and hold short operation locations at selected commercial and general aviation airports. Refer to the latest revisions of the applicable FAA Advisory Circulars for current requirements.

Taxiway Guidance Systems. To enhance taxiing capabilities in low visibility conditions and to reduce the risk of runway incursions, taxiway lighting, signage, and markings are used. In addition to these improvements, FAA Advisory Circular (AC) 120-57, Surface Movement Guidance and Control System (SMGCS),[58] requires a low visibility taxi plan for any airport that has takeoff or landing operations with visibility minima below 365 m (1200 ft) RVR. Taxi routes to and from the SMGCS runway must be designated and displayed on a SMGCS low visibility taxi route chart. Progressive taxiway lighting systems, taxiway markings, and geographical position markers are used to guide pilots and confirm aircraft location to controllers. The SMGCS is typically used at high-density commercial airports where complex ground taxiing routes and distances from the control tower are such that an automated SMGCS enhances ground movement safety. Taxiway lighting guidance systems that can be included in the airport SMGCS low visibility taxi route include edge lights, centerline lights, runway guard lights, stop bars, clearance bars, reflectors, and illuminated guidance signs.

Taxiway Lighting. Taxiway lighting includes edge, centerline, runway guard, stop bar, and clearance bar systems. Edge lighting systems are used to outline the edges of taxiways during periods of darkness and restricted visibility. Taxiway centerline lighting provides guidance for the pilot and facilitates ground traffic movement under low visibility conditions. Runway guard lights (RGLs), stop bars, and clearance bars provide information to the pilot allowing an aircraft to be safely operated on the airport taxiways without infringing on other aircraft operations. These systems all facilitate taxiing during low visibility conditions. Airports served by scheduled air carriers authorized to operate when the visibility is less than 365 m (1200 ft) RVR should have the necessary low-visibility lighting systems.[58]

1. Taxiway Edge Lighting.[55] Low-intensity taxiway lights (LITLs) are for use at airports where LIRLs are used. Medium-intensity taxiway lights (MITLs) are used at airports where either MIRLs or HIRLs are used. At most major airports these lights have variable-intensity settings, which can be adjusted by air traffic controllers at the request of the pilots.

Taxiway edge lighting is provided along taxiways intended for use at night and along taxiways not provided with centerline lights. Taxiway edge lighting luminaires are required for airline nighttime operations. For low-activity airports, elevated reflectors can be used instead of edge lights.

All taxiway edge lights are continuously operating blue lights. These luminaires provide guidance to pilots taxiing in either direction. Optional adjustable baffles can be installed to minimize the "sea-of-blue" effect created by edge lights from several taxiways. Circuiting of the taxiway edge lights to allow only those lights required for current operation to be energized is also effective. Intensity control should be used to match visibility conditions and prolong lamp life.

2. Taxiway Centerline Lighting.[59] This lighting serves primarily as a ground traffic aid and as a supplement to taxiway pavement markings and other taxiway guidance elements under low visibility conditions. Taxiway centerline lighting is also recommended for all airports with runways having precision approach procedures, particularly at high-traffic-density airports. These systems are provided on taxiways intended for use during periods of low visibility, operational confusion, new construction and retrofitting, or in conditions where the RVR is at or below 365 m (1200 ft).

Taxiway centerline lighting systems consist of single, uni- or bidirectional, in-pavement, steady-burning lights. They are installed alongside the taxiway centerline markings in a straight line on straight portions, on the centerline of curved portions, and along designated taxiing paths in portions of runways, ramps, and apron areas.

Taxiway centerline lights that cross a runway are alternate green and yellow from the runway centerline to the runway holding position or the ILS/MLS critical area holding position, whichever is the more critical. The first light beyond the critical area marking is yellow.[59] All other taxiway centerline lights are green.

For acute-angled exits, taxiway centerline "lead-off" lights begin 60 m (200 ft) prior to the point of curvature of the designated taxiway path. For other taxiway exits, which lie on low-visibility taxi routes, centerline lead-off lights begin at the point of curvature on the runway, if the runway has approach or departure minima below 183 m (600 ft) RVR.

Taxiway centerline "lead-on" lights extend from the taxiway to the runway centerline if the runway has departure minima below 183 m (600 ft) RVR. Where controlled stop bars are installed, the lead-on lights can be controlled automatically by taxiway and runway imbedded sensors activated by aircraft movements.[59]

Lead-off and lead-on lights are recommended for runways with RVR of less than 365 m (1200 ft). On taxiways crossing another taxiway, centerline lighting continues across the intersection.[51,57,59] System control and circuit routing should be designed to permit activation of various taxiway sections by control tower operators.

3. Runway Guard Lights, Stop Bars, and Clearance Bars.[59] Runway guard lights (RGLs) are installed at taxiway and runway intersections to provide a distinctive warning to anyone approaching a runway holding position. In-pavement RGLs consist of a row of alternately illuminated, unidirectional yellow lights across the taxiway. The center luminaire is in line with the taxiway centerline lights. The RGLs are located ahead of the hold line marking on the taxiway. RGLs need not be operating when the associated runway is closed to landing and takeoff operations. RGLs can be either in-pavement or elevated luminaires, and generally both types are not installed on the same taxiway. Elevated RGLs consist of two alternately illuminated yellow lights located on either side of the taxiway.

Stop bars provide a distinctive "stop" signal to anyone approaching an active, low-visibility runway. "Controlled" stop bars are used to permit access to the active runway on low-visibility taxi routes; uncontrolled stop bars protect an active runway at taxiway and runway intersections that are not part of the low-visibility taxi route. Controlled stop bars and taxiway lead-on lights can be controlled automatically by taxiway and runway imbedded sensors with the lights being automatically activated by the aircraft movements.[59] Stop bars are required for operations below 183 m (600 ft) RVR at illuminated taxiways that provide access to the active runway. Stop bars consist of a row of red in-pavement, unidirectional lights visible to aircraft approaching the intersection or taxiway holding position. They are spaced across the entire width of the taxiway with an elevated red light installed on both sides of the taxiway. In-pavement stop bar lights are located longitudinally parallel to the holding side of the runway holding position marking.[57] The beam of the in-pavement stop bar lights should be perpendicular to the holding position marking. In cases where the taxiway is not perpendicular to the runway intersected, a twelve-hole base should be used for the stop bar lights to allow the light to be rotated to align the stop bar light beam as closely as possible to the taxiway centerline. Elevated stop bar luminaires are located in line with the in-pavement stop bar lights. Where snow removal is performed at the airport, the elevated stop bar lights should be located no closer to the taxiway than the taxiway edge lights. To avoid conflicts with other lights in the same area, the elevated stop bar lights can be moved farther from the runway. The intensity and beam patterns of the stop bar lights should not be less than that of the taxiway lights.

Combination in-pavement RGLs and stop bar lights[58] can be installed where permitted by the FAA.[59] The controls should be so designed that the stop bar lights and RGLs cannot operate at the same time. Combination lights are installed at the same location and with the same orientation as the in-pavement stop bar lights.

Clearance bars are installed at locations where aircraft and surface vehicles may conflict. A clearance bar consists of a row of three in-pavement yellow lights. The luminaires can be uni- or bidirectional, depending on whether the taxiway is to be used in one or two directions. Clearance bar lights are installed with the center light of the clearance bar in line with the taxiway centerline lights.

4. Runway and Taxiway Guidance Signs.[60-62] A runway and taxiway guidance sign system is an essential part of a successful SMGCS and is necessary for the safe and efficient operation of an airport under both normal and restricted visibility conditions. These systems identify the runway or taxiway on which the aircraft is located, routes toward a desired destination on the airport, mandatory holding positions and boundaries for approach areas, ILS critical areas, runway safety areas, and obstacle-free zones.

Runway and taxiway guidance signs are generally illuminated by means of an exterior or interior light source. Most recent sign systems, particularly at major airports handling commercial airline service, utilize interior sign lighting.

Runway and taxiway guidance sign planning should be in accordance with the requirements of the FAA or other authority having jurisdiction. Guidance signs include the following types of information:

- Runway distance remaining signs
- Mandatory instruction signs
- Destination signs
- Location signs
- Direction signs
- Information signs

Taxiway Pavement Markings.[57] All taxiways will have some or all of the following markings:

- centerline
- edge
- runway guard bar
- hold bar
- stop bar
- clearance bar
- ILS/MLS hold
- Location

All of these markings can have taxiway lighting and reflectors associated with them. The taxiway lighting system must be coordinated with the taxiway markings for every taxiway.

Electrical Circuits for Airfield Lighting. Power source requirements and lighting electrical circuits are outside the scope of this Handbook. This information is available from the FAA Advisory Circulars and other sources.

Control Systems. Lighting controls vary according to airfield operations. Those with an air traffic control tower (ATCT) control airfield and approach lighting from the tower. Qualified and trained personnel operate a lighting control panel that identifies, displays pictorially and monitors airfield lighting functions and output characteristics.

Control system design must be simple and clear to permit quick operator response in an emergency. Redundant controls are provided in electrical vaults so air-side safety is assured.

Close of operations for an airfield with ATCT could be at any time determined by the airport owner. At this time, lighting control is transferred to radio control. An approaching pilot activates airfield lighting by depressing the microphone switch of the aircraft's radio a predetermined number of times (usually 3, 5, or 7 times) within five seconds. A 15-minute lighting "ON" cycle is initiated, which turns on selected navigational lighting systems and permits the pilot to confirm airport identification, complete the landing, and taxi to parking.

Airport Beacons. An airport beacon is installed on or adjacent to the airport to aid the pilot in locating the airport after dark or under adverse visual conditions. Rotating beacons show alternating white and color flashes spaced 180° apart for lighted civil airports and two white flashes for unlighted civil airports. For heliports, the flashes are spaced to accommodate the three colors, white, green, and yellow. The light from the beacon shows at all angles of azimuth. The beacon beam characteristics are regulated and can be obtained from the documents of the agency having jurisdiction.[63]

Beacons should not interfere with the pilot or ATCT. Beacons should be located within 1500 m (5000 ft) of a runway except in cases where surrounding terrain unduly restricts the visibility of the beacon. The distance can then be increased to a maximum of 3.2 km (2 mi) from the usable landing area as long as the airport itself is readily identifiable from the beacon location. Refer to the applicable regulations for the required beacon location and lighting requirements.

Heliports. Heliport lighting and markings provide guidance to helicopter pilots for landing and takeoff. Heliports consist of one or more helipads and may or may not be associated with an airport. If the heliport is to be used at night, it should have, as a minimum, helipad markings, a lighted wind indicator, perimeter lights, and a heliport beacon.[63]

The basic heliport marking is a large, white letter "H" located at the center of the helipad or landing and takeoff area. The marking for a hospital helipad is a large, red H at the center of a white cross. The boundaries of the landing area are outlined with a white stripe that can be continuous or segmented.

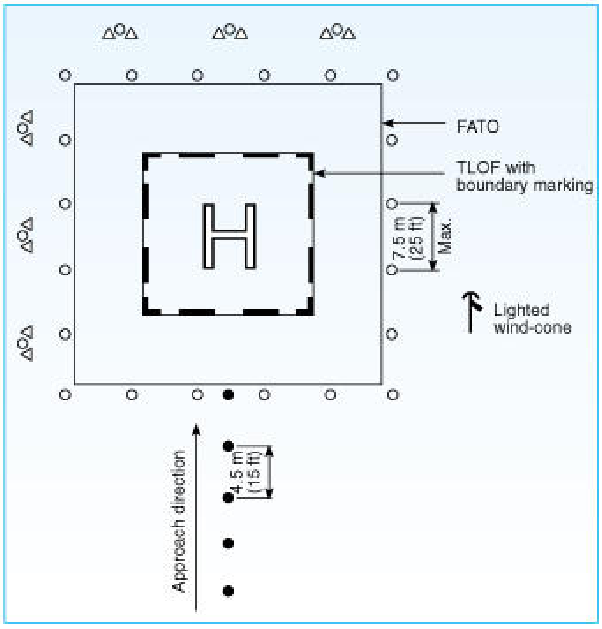


Figure 23-47. Typical heliport lighting and marking.

Public General Aviation Heliports.[65] Heliports usually consist of two areas, a Final Approach and Takeoff Area (FATO) and a Touchdown and Lift-off Area (TLOF). For nighttime operation, the FATO or the TLOF, but not both, need to be lighted. Omnidirectional perimeter lights define the limits of the FATO or TLOF. Flush-mounted green lights usually identify taxiway centerlines, and blue omnidirectional lights or reflectors define the taxiway edge. Omnidirectional yellow landing direction lights are optional where it is desirable to indicate the landing direction(s). A typical layout is shown in Figure 23-47.

Perimeter lights around the FATO or TLOF form a square, rectangle, or circle made up of evenly spaced lights, either elevated or flush mounted. For squares or rectangles, one luminaire is installed at each corner, and at least two additional lights, evenly spaced not more than 7.5 m (25 ft) apart, are installed on every side. A circular area has a minimum of eight lights spaced uniformly around the circumference at not more than 7.5 m (25 ft) on center. Perimeter lights are often provided with intensity control. Current requirements are for yellow lights of the intensity and distribution specified in the regulatory documents. Aviation officials are reviewing a switch to another color, such as green, to differentiate heliport perimeter from general area lighting, which is often provided by sodium lamps. Refer to current regulatory documents. Flush-mounted luminaires can be located on the edge, or within 0.3 m (1 ft) of the edge, of the TLOF. Raised luminaires, modified to be no more than 20 cm (8 in.) high, should be located 3 m (10 ft) out from the edge of the TLOF and should not penetrate a horizontal plane at the TLOF elevation by more than 5 cm (2 in.). On raised TLOF platforms the perimeter lights can be placed up to 1.5 m (5 ft) from the edge of the platform where snow removal equipment can damage the lights.

Landing direction lights consist of five omnidirectional yellow luminaires in a straight line starting at the location of the perimeter lights and extending out in the direction of the preferred approach or take-off, spaced 4.5 m (15 ft) apart. While there can be more than one set of landing direction lights, only one is illuminated at any given time. The landing direction lights have the same photometric characteristics as the perimeter lights.

Taxiway centerlines employ flush, unidirectional green lights. The lights are spaced at 15 m (50 ft) intervals on straight sections and not more than 7.5 m (25 ft) intervals on curves with a minimum of four lights on a curved section. Approved green retroreflectors can be used instead of green lights.

Taxi route edges that do not contain a paved taxiway are defined by raised blue lights or reflectors modified to be no more than 20 cm (8 in.) high. Spacing is identical to that for taxiways. Helicopter taxiing routes are marked with large, "yellow-green-yellow" horizontal signs for air taxiing centerlines or vertical, cylindrical "yellow-green-yellow" markers for hover taxi route edges. More information on the luminaires suitable for heliport lighting can be obtained from the appropriate regulatory agency documents.[65]

Beacons are used to identify heliport locations. The beacon is located within 0.8 km (0.5 mi) of the helipad. A heliport beacon is not required for heliports located on a lighted airport. Visual glide slope indicators,[66] such as heliport approach path indicators (HAPIs) or PAPIs can also be installed to provide pilots with visual course and descent cues.

Helipad floodlighting is used to illuminate the helipad landing area, aid in pilot depth perception, and improve the helipad conspicuity. Helipad floodlights are white with a wide beam spread and no intensity above the horizontal plane. Floodlights can be mounted on adjacent buildings to reduce the congestion created by multiple poles. Illuminance on the helipad should be a minimum of 32 lx (3 fc). Floodlights that could interfere with pilot vision should be capable of being turned off during landing and take-off.

The requirements for hospital heliports are similar to those for general aviation heliports with the exception that hospital pads are often located on the roof of one of the hospital buildings. These pads are often elevated and must provide adequate clearance from building parts to allow safe approach and landing. Elevated pads are provided with a safety net around the perimeter of the pad if they are more than 75 cm (30 in.) above the surrounding roof. Where snow is likely, the perimeter lights can be located at the edge of the safety net, up to 1.5 m (5 ft) from the pad perimeter. Nonprecision instrument approach or precision instrument approach systems can be installed to improved visibility.[65]

wire marking and lighting. Unmarked electric and telephone wires in the heliport area can be difficult to see. It is recommended that wires located within 150 m (500 ft) of the FATO, as well as those within 1 km (0.5 mile) that are beneath and up to 30 m (100 ft) to the side of an approach or takeoff path, be marked to make them more conspicuous.[65,67]

Vehicle Access and Parking Areas. Area lighting recommendations are available in Chapter 22, Roadway Lighting, and in IESNA RP-20-98,[7] Recommended Practice for Parking Facilities. Parking and roadway lighting around an airport should not interfere with the visibility of the control tower operators or pilots.

All airport roadway and parking area luminaires must satisfy federal aviation regulations (FAR) Part 77 height limitations and should not have any light distribution above the horizontal plane. The illuminance on the control tower windows from all sources should be no more than 1 lx (0.1 fc). This includes reflected light from horizontal surfaces and direct high-angle light from nearby luminaires. In areas of regular snowfall, reflected light from horizontal surfaces can be a significant factor. Special attention should be given to the selection and placement of area and roadway lighting equipment so as not to obstruct the direct view of runways and taxiways from the tower.

Obstruction Identification. Objects that lie outside the boundaries set by FAR Part 77[68] may have to be marked or lighted so that the obstruction is conspicuous both day and night. An aeronautical study should be conducted to determine which obstructions must be lighted.

Two types of markings are used:

- Painting. Objects with essentially unbroken surfaces are painted an alternating pattern of aviation orange and aviation white.
- Markers. Markers should be used to mark obstructions where it is impractical to mark such obstructions by painting. Two types of markers are used: spherical markers not less than 500 mm (20 in.) in diameter, colored aviation orange, and flags of a checkerboard pattern in white and aviation orange.

The purpose of lighting a structure is to warn of its presence during both day and night conditions.

Three obstruction lighting systems are commonly used:

- Aviation red obstruction lights, consisting of flashing beacons and steady-burning lights, are used for night operations and during periods of limited visibility during the day.
- Medium-intensity flashing white obstruction lights can be used for both day and night marking. When operated

continuously for structures 153 m (500 ft) or less in height, other methods of marking are not required. For structures exceeding 153 m (500 ft), daytime marking is always required.

- High-intensity white obstruction lights, consisting of variable-intensity, flashing white lights, are used for both day and night operations. When these lights are operated continuously, other types of marking and lighting are not needed.

Dual lighting consists of aviation red obstruction lights for night operations and high-intensity white lights for day operations. The failure mode for dual systems shall ensure that both systems (the red and white lights) are not operating simultaneously.

All aviation obstruction lighting systems should include control devices that will monitor operations and force the system into a prescribed fail-safe mode in the event of a problem. Remote monitoring of the obstruction lights and the controls should be provided for all systems.

Figure 23-48 contains standards for dual lighting an obstruction higher than 60 m (200 ft). Figure 23-48, one of several obstruction lighting recommendations available from the FAA, illustrates lighting requirements for an antenna more than 12 m (40 ft) above the top of the obstruction. The figure is divided into six segments (F-1 through F-6), each representing a range of obstruction heights. For each segment of the table, there are several lights required at points along the height of the obstruction. For instance, within the F-4 segment, which covers obstructions between 320 m (1050 ft) and 427 m (1400 ft), lights are required at eight equally spaced heights. If the antenna was 366 m (1200 ft), eight sets of lights would be spaced every 46 m (150 ft) vertically on the obstruction. The character of the luminaires is indicated by the lines in the figure. For example, at the —34— height point (275 m or 900 ft above the ground level), a solid line is indicated in the figure. At this level, L-856 (white) and L-864 (red) luminaires are required. The L-8xx series refers to standard FAA luminaires from approved manufacturers having the characteristics shown in Figures 23-49 and 23-50. Detailed marking requirements are contained in the FAA Advisory Circular "Obstruction Marking and Lighting."[67]

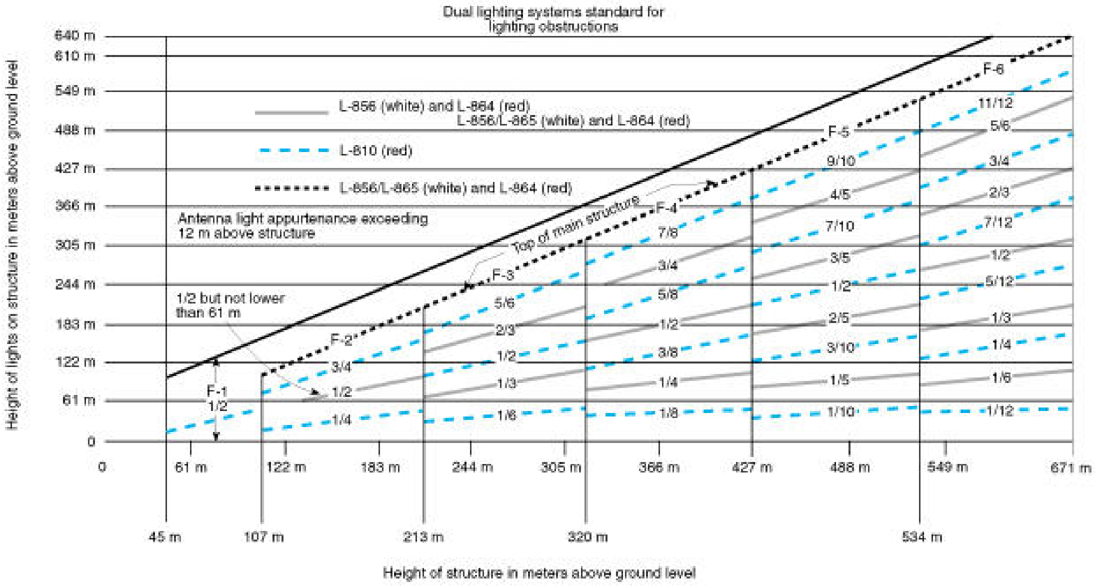
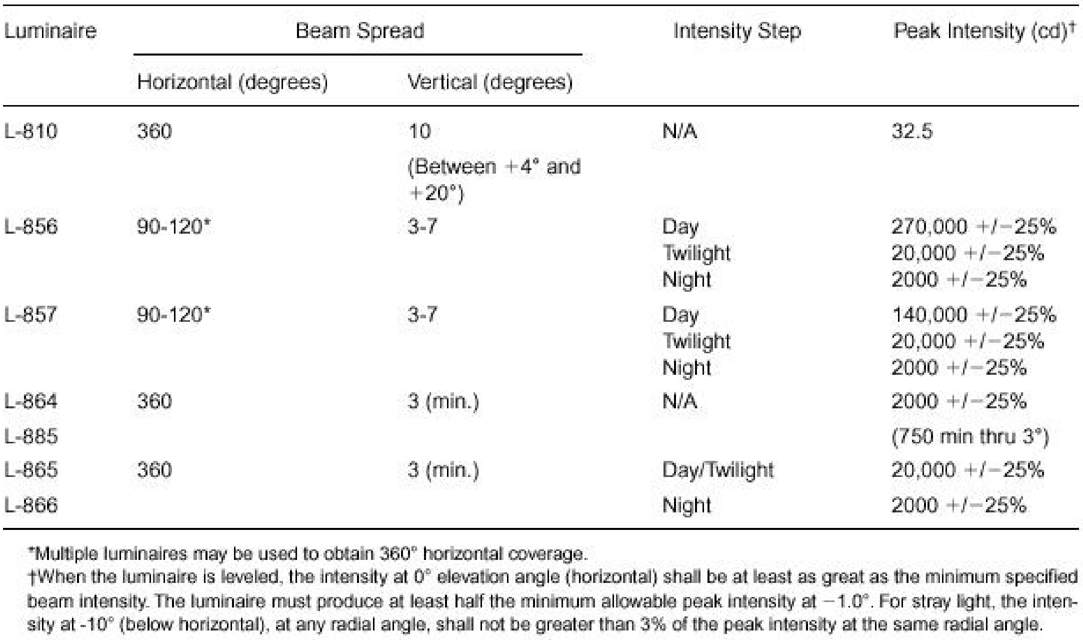


Figure 23-48. Typical standards for lighting obstructions. See text for explanation and example.



Luminaire	Beam Spread		Intensity Step	Peak Intensity (cd)†
	Horizontal (degrees)	Vertical (degrees)		
L-810	360	10 (Between +4° and +20°)	N/A	32.5
L-856	90-120*	3-7	Day Twilight Night	270,000 +/−25% 20,000 +/−25% 2000 +/−25%
L-857	90-120*	3-7	Day Twilight Night	140,000 +/−25% 20,000 +/−25% 2000 +/−25%
L-864	360	3 (min.)	N/A	2000 +/−25%
L-885				(750 min thru 3°)
L-865	360	3 (min.)	Day/Twilight	20,000 +/−25%
L-866			Night	2000 +/−25%

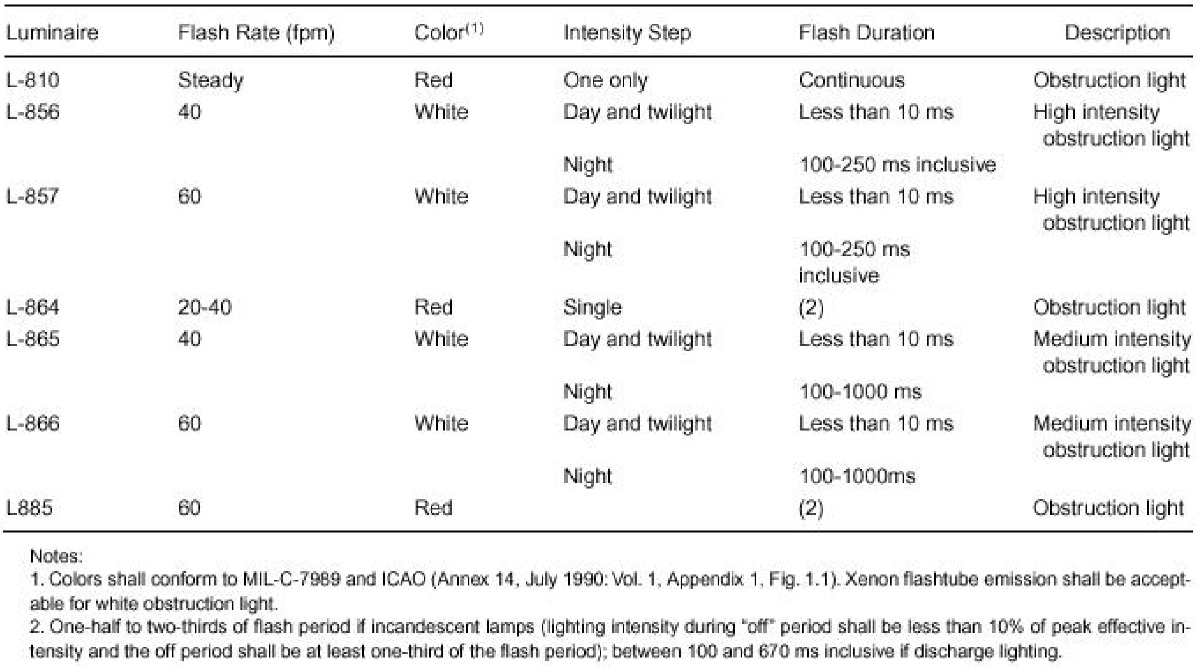
*Multiple luminaires may be used to obtain 360° horizontal coverage.
†When the luminaire is leveled, the intensity at 0° elevation angle (horizontal) shall be at least as great as the minimum specified beam intensity. The luminaire must produce at least half the minimum allowable peak intensity at −1.0°. For stray light, the intensity at -10° (below horizontal), at any radial angle, shall not be greater than 3% of the peak intensity at the same radial angle.

Figure 23-49. Obstruction Light Beam Spread and Intensity Requirements

Lighting System Maintenance. Airport lighting must have a high degree of reliability. Airport lighting systems should be inspected every night. Inoperative lights should be noted and repairs made the following day while the system is not in use. Scheduled maintenance for the lighting systems will minimize unexpected outages. Inspections of electrical systems are made by qualified personnel using a regular inspection routine.

Where an airport's SMGCS plan has been implemented, the air-side lighting required for low-visibility operations should be activated prior to implementation of the plan and visually checked for proper operation. Program requirements to ensure operational readiness are contained in FAA Advisory Circulars.[55,56,59] The lights should be checked every two to four hours after turn-on as long as the SMGCS plan is in effect. If the operation of the lighting system falls below acceptable standards during operation, an alternative operational plan should be activated. During normal operations, the runway and taxiway lighting systems should be checked one hour before sunset and at other times as suggested by the responsible authority.[52-59]

LIGHTING TERMS AND ACRONYMS USED WITH AIRPORT LIGHTING



Luminaire	Flash Rate (fpm)	Color(1)	Intensity Step	Flash Duration	Description
L-810	Steady	Red	One only	Continuous	Obstruction light
L-856	40	White	Day and twilight	Less than 10 ms	High intensity obstruction light
			Night	100-250 ms inclusive	
L-857	60	White	Day and twilight	Less than 10 ms	High intensity obstruction light
			Night	100-250 ms inclusive	
L-864	20-40	Red	Single	(2)	Obstruction light
L-865	40	White	Day and twilight	Less than 10 ms	Medium intensity obstruction light
			Night	100-1000 ms	
L-866	60	White	Day and twilight	Less than 10 ms	Medium intensity obstruction light
			Night	100-1000ms	
L885	60	Red		(2)	Obstruction light

Notes:
1. Colors shall conform to MIL-C-7989 and ICAO (Annex 14, July 1990: Vol. 1, Appendix 1, Fig. 1.1). Xenon flashtube emission shall be acceptable for white obstruction light.
2. One-half to two-thirds of flash period if incandescent lamps (lighting intensity during "off" period shall be less than 10% of peak effective intensity and the off period shall be at least one-third of the flash period); between 100 and 670 ms inclusive if discharge lighting.

Figure 23-50. Obstruction Lighting Characteristics

Airport lighting consists of many specialized terms and acronyms. The following lists the most common.

ALSF - High-intensity approach light system with sequenced flashers
ATCT - Air traffic control tower
CCR - Constant current regulator
CTAF - Common traffic advisory frequency
CL - Centerline
DH - Decision height
DME - Distance measuring equipment
FAR - Federal aviation regulation
FBO - Fixed base operator
FARA - Final approach reference area
FATO - Final approach and touchdown area
GPS - Global positioning system
HIRL - High-intensity runway light
IFR - Instrument flight rules
ILS - Instrument landing system
LIRL - Low-intensity runway light
LDIN - Lead-in approach lighting system
LITL - Low-intensity taxiway light
LORAN - Low-frequency omnidirectional area navigation
MALS - Medium-intensity approach lighting system
MALSF - MALS with sequenced flashers
MALSR - MALS with runway alignment indicator light
MIRL - Medium-intensity runway light
MITL - Medium-intensity taxiway light
MLS - Microwave landing system
NDB - Nondirectional radio beacon
NPIA - Nonprecision instrument approach
ODALS - Omnidirectional approach light system
OFZ - Obstacle free zone
PAPI - Precision approach path indicator
PAR - Precision approach radar
PIA - Precision instrument approach
PLASI - Pulse light approach slope indicator
RAIL - Runway alignment indicator light
REIL - Runway end identifier light
RVR - Runway visual range
SDF - Simplified direction finder
TCH - Threshold crossing height
TDZ - Touchdown zone
TDZL - Touchdown zone light
TLOF - Touchdown and lift off area
VASI - Visual approach slope indicator
VFR - Visual flight rule
VOR - Very high frequency omnidirectional range

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24

Underwater Lighting

Over the last decade the utilization of the sea for recreational, industrial, and military purposes has increased. In this context, the fabrication and use of underwater imaging systems has played a central role.[1-5] For daylight operation in shallow waters, natural light may provide adequate visibility; however, for deeper operations where natural light is limited, the use of electric lighting systems is mandatory. Water also affects color appearance, looking yellow, yellow-green, or green in bays or coastal areas, and blue-green in deep, clear ocean water.

One important aspect of the propagation of light in water is that suspended particles severely attenuate and scatter the light. The external pressure of water at great depths and the corrosive effects of seawater also provide unusual challenges to the designer of lighting equipment for underwater applications.

TERMS AND DEFINITIONS

Many of the terms and definitions given here are peculiar to underwater lighting. Generally they follow the recommendations of the Committee on Ocean Optics of the International Association for the Physical Sciences of the Ocean (IAPSO).[6] Definitions of terms used in this chapter are listed below.

It should be noted that in the past some authors have used terms such as "absorption" or "extinction" to mean "beam attenuation" as it is defined here. To further confuse matters, both "extinction coefficient" and "vertical extinction coefficient" have sometimes been used for the term "diffuse attenuation coefficient." Caution must be exercised when reading reports in the literature about the propagation of light underwater.

Absorption Coefficient. The ratio of the radiant flux lost through absorption (dF_a), in an infinitesimally thin layer of medium normal to the beam, to the incident flux F, divided by the thickness of the layer (dx):

$$a = -\frac{1}{F}\frac{dF_a}{dx} \qquad (24\text{-}1)$$

The unit for a is m^{-1}.

The symbol F for radiant flux is an IAPSO standard. The corresponding IESNA symbol for radiant flux is Φ.

Volume Scattering Function. The radiant intensity $dI(\theta)$from a volume element dV in a given direction θ, per unit of irradiance E of a beam incident on the volume, per unit volume (θ is ordinarily measured from the forward direction):

$$\beta(\theta) = \frac{1}{E}\frac{dI(\theta)}{dV} \qquad (24\text{-}2)$$

The unit for $\beta(\theta)$ is m^{-1}.

(Total) Scattering Coefficient. The ratio of radiant flux lost through scattering in an infinitesimally thin layer of the medium normal to the beam (dF_s) to the incident flux F, divided by the thickness of the layer (dx); equivalent to the integral of the volume scattering function over all directions:

$$b = -\frac{1}{F}\frac{dF_s}{dx} = \int_0^{4\pi} \beta(\theta)\, d\omega = 2\pi \int_0^{\pi} \beta(\theta) \sin\theta\, d\theta \tag{24-3}$$

The unit for b is m^{-1}.

Beam Attenuation Coefficient. The sum of the absorption coefficient a and the scattering coefficient b:

$$c = a + b \tag{24-4}$$

The unit for c is m^{-1}. Note that sometimes the symbol a is used instead of c. This is an older type of notation that is not currently in use.

Attenuation Length. The reciprocal of the beam attenuation coefficient c:

$$\text{attenuation length} = \frac{1}{c} \tag{24-5}$$

The unit for attenuation length is m. This value gives the distance in which the intensity of a beam of light is reduced to 1/e (approximately 37%) of its initial value. It is analogous to the mean free path in physics and the time constant in electronics.

Diffuse Attenuation Coefficient for Irradiance. The ratio of irradiance lost through absorption and scattering in an infinitesimally thin horizontal layer of the medium (dE) to the incident irradiance E, divided by the thickness of the layer (dz).

$$K = -\frac{1}{E}\frac{dE}{dz} \tag{24-6}$$

For an extended explanation of these equations with some additional information, see Reference 7.

FILTERING PROPERTIES OF WATER[8]

The spectral absorption of water varies for different locations. Some typical spectral transmittance curves for different types of water are shown in Figure 24-1.[9] Although absorption accounts for most of these differences, scattering is also important. Deep ocean water is classified as Case I with minimal absorption near 480 nm, giving this water a blue-green appearance. Coastal water is classified as Case II and has minimum absorption near 532 nm, giving a green or yellow appearance.[4,10]

Highly purified or distilled water is the most transparent water. The absorption coefficient of distilled water can approach 0.02 m^{-1} at a wavelength of 480 nm.[8] Some very clear lakes approach this value, but it is quite rare for sea water to have an absorption coefficient much lower than 0.04 m^{-1}.

The absorption curves for most bodies of water differ greatly from those of distilled water due to the presence of silt, pollution, and plant and animal material. Plankton absorbs short wavelengths much more than long wavelengths. Therefore, the peak of the transmission curve in ocean water that includes plankton moves from 480 to between 510 and 570 nm, depending on plankton density.

The curve in Figure 24-1 for Morrison Springs, Florida is essentially the same as for distilled water and has a transmittance of over 90% at 480 nm. The main difference between the samples from Morrison Springs and the Gulf of Mexico is the latter's lower short-wavelength transmittance, presumably a result of plankton. The Long Island Sound water shows lower transmittance throughout the spectrum, with the greatest loss in the short wavelengths. Water in polluted areas such as the Thames River in Connecticut[9] transmits very little light.

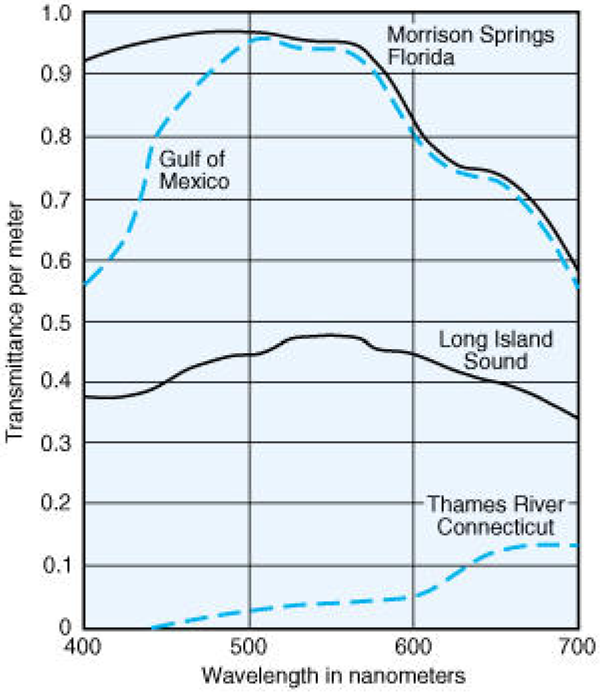
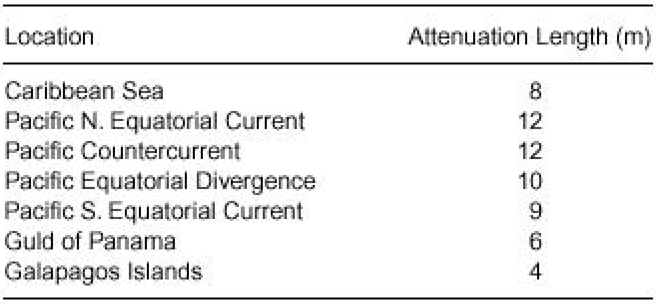


Figure 24-1. Spectral transmittance of 1 m of various bodies of water.

VIEWING DISTANCES IN WATER

Since light transmittance in water is related to distance by an exponential function, the spectral absorption becomes extreme as the distance the light travels increases. Therefore, the relative visibility of different colors varies considerably in different types of water and at different distances.

Underwater imaging systems that use electric light sources can be arranged in a variety of ways, depending on the goals of the imaging system (e.g., whether maximum forward viewing is desired or whether the light source(s) illuminate only objects in close proximity). Since water quality varies substantially in different regions, a convenient means of describing the performance of an underwater imaging system uses the number of attenuation lengths at which the system can form suitable images. Typical values of the attenuation length for several bodies of water are given in Figure 24-2.[11]



Location	Attenuation Length (m)
Caribbean Sea	8
Pacific N. Equatorial Current	12
Pacific Countercurrent	12
Pacific Equatorial Divergence	10
Pacific S. Equatorial Current	9
Guld of Panama	6
Galapagos Islands	4

Figure 24-2. Values of One Attenuation Length for Several Bodies of Water

Using the attenuation length to calculate the illuminance on an underwater surface may result in errors from the actual illuminance. Some light that is scattered underwater may still illuminate the surface of interest or be rescattered into the beam. Computer modeling can be used to predict the propagation of light if the absorbing and scattering characteristics of the water are known.[12]

Conventional imaging systems, which employ a simple arrangement of cameras, light sources, and the object to be lighted, can work reasonably well at close distances. Proximity of the light to the camera creates backscattered light, which veils objects, particularly at substantial distances. One can separate the camera and light sources to increase performance, but to obtain greater imaging distances, special techniques such as laser-range gating or synchronous scanning systems can be used. Both of these techniques aim to reduce backscatter.[13]

Laser-range gated systems[14,15] use a short pulse of collimated light from a laser to obtain the image of interest. They are quite successful at reducing backscatter because of the collimation. Imaging ranges greater than those achieved with conventional light sources can be obtained. At very long ranges, however, the intensity required to obtain good images may be impractical. Some systems use repeated brief pulses of laser light to capture several images, which can then be combined into a single image.

Synchronous scanning systems consist of a laser beam scanned across the target coupled with a receiver that follows the backscattered light from the system. These systems attempt to minimize the volume of water that is simultaneously illuminated by the laser and imaged by the receiver. Such systems can achieve good imaging performance at ranges of up to five attenuation lengths.[16]

For those with more modest budgets, several simple techniques can be used to reduce the backscatter from the intersection of the volume of water shared by the camera and the lights:

1. A light shield (septum) can be used to shield most of the line of sight from the direct field of the lamp or the optical control (reflector or refractor).

2. The light source can be offset to one side of the sensor. Then no part of the line of sight is close to the lamps; therefore, the inverse-square law and attenuation by absorption and scattering operate to avoid intense lighting of the water close to the sensor.

3. A technique using crossed polarizers can be used. The lamp and the sensor must have orthogonally oriented polarizers, and the object must depolarize the light upon reflection in order for it to be visible. Each polarizer absorbs about half the light, so either the light source intensity must be increased or the camera must have longer integration times, faster lens speed, or greater sensitivity.

Imaging self-luminous objects underwater avoids many of the problems associated with backscatter described above. In this case the geometry of the sensor is less critical; the attenuation of light through water is the only serious limiting factor.

SENSOR CHARACTERISTICS

A wide variety of sensors is available for underwater use. The choice of sensor type depends on the overall system requirements and has a bearing on the characteristics required of the associated underwater lighting equipment.

These sensors may be divided into several categories: electronic imaging, as in the case of video or still-frame cameras; conventional cameras that use film; or a type of photon detector, such as a photomultiplier tube (PMT) or photodiode.

Photographic Films

Black-and-white films used in underwater photography have International Organization for Standardization (ISO) ratings between 12 and 400; with special development, ISO ratings up to 3200 can be obtained. Negative and positive color films are available with ISO ratings from 25 to 400, and again, special processing can push these film speeds even higher. It is best to discuss the application with the film manufacturer to determine the best film for use in a given application. The spectral responses of typical films are shown in Figure 24-3.

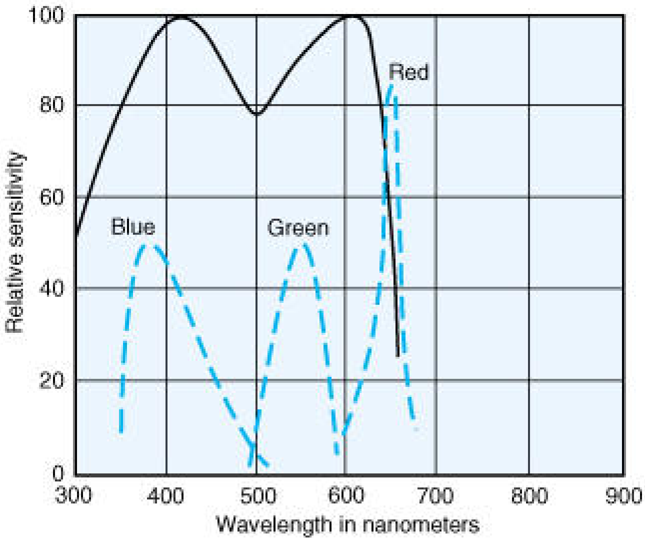


Figure 24-3. Spectral responses of black-and-white panchromatic negative film (solid line) and of a typical color-reversal film (dashed line).

Television Sensors

Over the past several years the devices used to obtain television pictures have changed dramatically. The devices of the past, such as vidicons, image orthicons, and isocons, are rarely used today. They suffer from high lag time (the time required between images, resulting from the persistence of the previous image), low sensitivity, and high power requirements. Consequently they have been replaced with newer technology.

The secondary-electron conduction (SEC) camera tube is of moderate size and sensitivity. It has a low lag time (10% or less) and is not affected much by relative scene motion.

The electron-bombarded silicon target and silicon intensified target (SIT) tubes are still used in security and military applications. They have extremely high sensitivity and operate in ambient light environments such as moonlight or starlight. They are highly burn-resistant diode array targets. These tubes are intermediate in size and provide a higher signal-to-noise ratio than older devices.

Charge-coupled devices (CCDs) have become the most common imaging devices. They are sensitive and operate at reduced power levels. They also have the advantage of being able to acquire a "snapshot" image in a variable time frame and have the equivalent of shutter speeds in the range of 0.001 s. The image cannot be downloaded to the video electronic package as quickly, but it can be stored in digital buffer memory for later transmission as a video signal timed to produce a picture in the standard 1/60-s interlacing video system common to the industry. The ability to acquire information at such a high speed allows the CCD imaging device to stop action and produce very clear, high-speed pictures.

Recent CCD imaging cameras span a range of price and performance regimes, allowing for a fairly broad number of options for underwater imaging. Commercial-grade video CCD cameras have limited sensitivity but provide excellent color images at short ranges. For longer range imaging, video CCD cameras with greater sensitivities and reduced background noise must be used, but they can be expensive. CCD cameras for still-frame underwater imaging are currently rare.

Nonimaging Sensors

Photodiodes and photomultipliers available for use in underwater instrumentation generally employ semitransparent photocathodes with a spectral response similar to those shown in Figure 24-4. Characteristics of other types of photosensitive devices are described in Chapter 2, Measurement of Light and Other Radiant Energy. Because of the extreme variations possible in the spectral transmittance of water, it is often necessary to match the sensor spectral response to the system application or to make a number of narrow-band measurements.

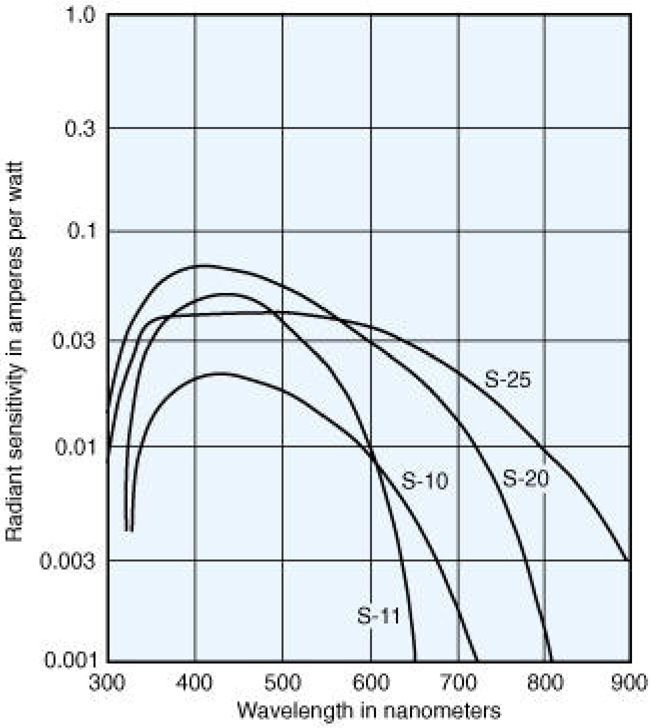


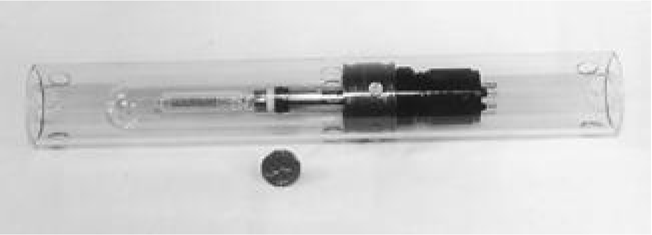
Figure 24-4. Absolute spectral response of some semitransparent photocathodes.

LIGHT SOURCES FOR UNDERWATER USE

Many kinds of light sources are used in underwater lighting systems in a wide range of wattages for television and photography as well as for visual inspection. Incandescent sources are used where instantaneous starting, simplicity, and small size are requirements. Arc discharge sources are used when higher efficacy is required. Some typical underwater lighting units are shown in Figure 24-5.

Color Balance and Extended Range Imaging

In choosing light sources for underwater applications, one should consider the filtering properties of the water. Theoretically it should be possible to maximize the color rendering of any underwater scene by proper choice of a light source. In clear ocean water, for example, a tungsten lamp with high output in the long wavelengths might be used to replace the wavelengths absorbed by the water. In turbid water, on the other hand, a mercury source with its preponderance of short- and middle-wavelength light could bring a better color balance. In all practicality, however, the balance may have to be achieved on a trial-and-error basis, since waters vary so much and the exponential absorption of light with both lighting and viewing distances makes the actual underwater ranges very important.


a


b


c


d

e

Figure 24-5. Typical underwater lighting units. (a) All-purpose, multidirectional incandescent light, 1000 W maximum, rated to 1000 m. (b) 400-W arc light, rated to 6000 m. (c) 1200-W arc light, rated to 6000 m. (d) All-purpose incandescent light, 325 W maximum, rated to 6000 m. (e) 1200-W arc light, rated to 6000 m.

Although not commonly available in underwater lighting equipment, other light sources applicable to underwater systems include scandium sodium metal halide, mercury short-arc, and xenon short-arc lamps. These have been found to be effective for visual, photographic, and television uses. As described above, lasers are increasingly being used in underwater imaging systems.[17]

Electrical characteristics and power supplies for the various light sources are discussed in Chapter 6, Light Sources. Also, underwater lighting equipment manufacturers can provide auxiliary circuits that are especially designed for the unusual requirements of various underwater lighting applications. Information pertaining to the design of pressure housings for underwater light sources is available.[18]

UNDERWATER LIGHTING CALCULATIONS

The amount of light needed for an underwater task is a function of many variables: environmental conditions; the camera light geometry; the spectral characteristics and power of an underwater light source, including the beam patterns of the lights; and the sensitivity of the camera. In principle, these factors can all be incorporated into a computer model that permits both the accurate prediction of the light seen by the camera and the resultant image quality. The latest generation of personal computers performs this computation without much difficulty.[19]

Computer models can be very accurate, especially when scattering in water is low. Scattering leads to a blurring of images. This blurring is difficult to quantify, although several researchers have developed models to estimate this effect.[20,21]

Electric Lighting Calculations[11,13,22-26]

When monochromatic sources such as lasers are used, the assumption that the useful light is monochromatic is certainly valid. However, most underwater lighting systems use sources that provide broadband illumination. Tabulated values[27] allow the user to correct for the wavelength-dependent absorption and scattering in water of different types.

INTERPRETATION OF UNDERWATER LIGHT SOURCE PHOTOMETRIC INFORMATION

The performance of underwater light sources is almost always specified in terms of their performance in air. These data are usually supplied on product information sheets, but they can be misleading because of the significant and spectrally dependent differences in absorption between water and air. There are no established methods of instrumentation to evaluate a light source in the water environment. A number of research programs by light source manufacturers are underway, but standardization will take some time to develop.

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Lighting Economics

THE ROLE OF ECONOMIC ANALYSIS IN LIGHTING[1-5]

Lighting must be responsive to all the needs of the user, including economic needs. In fact, economic needs often drive the decision-making process when lighting systems are designed and purchased. Unfortunately, economic concerns are often considered the antagonist of aesthetic and visual concerns. The lighting professional tends to draw up a list of those criteria and needs that are considered essential, and then begins the complicated process of identifying priorities and determining those that can be accommodated by the budget.

Rather than considering economic analysis as the antithesis of engineering analysis or aesthetic design, it should be viewed as a framework within which all of the needs of the various clientele can be taken properly into account. For example, when a worker's vision is impaired by disability glare, reduced productivity is an economic consequence. A decision to improve the lighting could be based on the economic needs of the owner. When the lighting of an office building atrium fails to complement the architecture of the space, the rental value fails to achieve its potential. Again, a decision to improve the lighting is an economic decision. Thus, correctly taking care of economic needs can ensure that the other lighting needs are properly considered.

A comprehensive lighting economic analysis for new or existing systems should:

- Compare alternative systems
- Evaluate maintenance techniques and procedures
- Evaluate energy management technologies and strategies
- Determine the effect of lighting on other building systems
- Plan budget and cash flow
- Simplify lighting system characteristics to a cost measure
- Determine the benefit of lighting relative to its cost (cost-benefit analysis)

LIGHTING COST COMPARISONS

Many metrics and techniques have been proposed over the years for comparing the cost of one lighting system with that of another. These methods can be classified into two categories: first-level and second-level analysis methods (Figure 25-1). The distinction between the two groups is that the first-level methods do not consider the time value of money. The term "time value of money" refers to the fact that one dollar today is not equivalent to the promise of one dollar at a specified time in the future.

The Cost of Light

The simplest economic analysis consists of one rule: the initial costs are compared and the least expensive is chosen. Thus, if lamp A costs $1.20 and lamp B costs $1.00, lamp B is selected. If the lamps are identical in performance, this may be a sufficient analysis. However, if lamp A produces 1000 lumens (lm) and lamp B produces only 800 lm, then one might choose A based on a comparison of the cost per lumen (A, 0.12 cents/lm; B, 0.125 cents/lm). On the other hand, lamp A might have a rated life of 1000 h as compared with 1100 h for lamp B, so a further refinement of the calculation would be necessary.

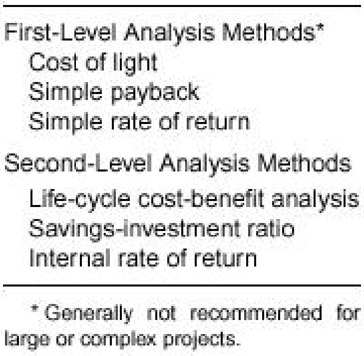
Both costs and benefits must enter the analysis in order to obtain a meaningful result. The process of providing the desired lighting involves the expenditure of money for a number of products (e.g., lamps, luminaires, and wire, and services such as labor and electricity) to obtain certain benefits, namely light. This was recognized early in the history of electrical lighting, and basic measures of lighting value have been developed based on the idea of cost per unit of lighting delivered. This is the traditional "cost of light" and would logically be expressed in dollars per lumen hour. Because the cost per lumen hour of a typical general lighting system is very small, the unit of dollars per million lumen hours is usually used instead.

The cost of light can be expressed by the following equation:

$$U = \frac{10}{Q}\left(\frac{P+h}{L} + WR\right) \qquad (25\text{-}1)$$

where

U = unit cost of light for a lamp (dollars/10^6 lm×h),
Q = mean lamp flux (lumens),
P = lamp price (cents),
h = labor cost to replace one lamp (cents),
L = average rated lamp life (thousands of hours),
W = mean input power per lamp (lamp and losses) (watts),
R = energy cost (cents/kilowatt-hour).



First-Level Analysis Methods*
- Cost of light
- Simple payback
- Simple rate of return

Second-Level Analysis Methods
- Life-cycle cost-benefit analysis
- Savings-investment ratio
- Internal rate of return

* Generally not recommended for large or complex projects.

Figure 25-1. Lighting Cost Compairson Methods

The cost of light is calculated by multiplying the average light output in lumens by the life of the lamps and dividing the result into the total owning and operating costs for the same time period. Equation 25-1 shows the simplest formulation. The cost-of-light method can be used to compare two competing lamps for use in the same lighting system or to evaluate a retrofit lamp such as a compact fluorescent lamp as an alternative to an existing incandescent lamp.

Note that this equation contains no information about the luminaire in which the lamp is housed. Care must be exercised in extending its use to choices between systems containing different luminaires. Suppose, for example, a manufacturer introduces a new lamp as an efficient replacement for metal halide lamps. By performing the calculation of Equation 25-1 twice, once for a metal halide lamp and once for the new lamp, one could determine approximately the cost to produce one million lumen hours with each of the two lamps individually. However, if the lamps differed appreciably in physical characteristics such as size, shape, and operating temperature, the luminaires that house them might also differ appreciably in efficiency, cleaning requirements, intensity distribution, or maintenance characteristics. Each of these differences could affect the cost of owning and using the system.

Another weakness of the cost-of-light method is that it does not consider the time value of money. However, when the life of the project is short (say, two years or less), as occurs in seasonal or other temporary lighting, interest rates have little effect on the analysis, and a method that ignores them can still be useful. Also, if interest rates are very low or are considered separately (as in a project involving an expense rather than a capital expenditure), then ignoring the time value of money may be appropriate.

Simple Payback

Simple payback is a first-level method commonly used in the lighting industry today for comparing and evaluating a lighting project or proposal. Payback offers information about the amount of time required for an investment or initial outlay to be paid off. It is defined as the initial cost of a system divided by the annual cash flow or saving that the system engenders. Simple payback is calculated by the following formula:

$$P = \frac{I}{A} \qquad (25\text{-}2)$$

where

P = payback period (years),
I = incremental investment (dollars),
A = incremental annual cash flow.

The term "incremental" in the above definitions for *I* and *A* indicates a comparison of one system to another. Two types of comparisons are possible: comparing a proposed replacement system to an existing system, or comparing design alternatives for a new space in which there is no existing system. The former is the more common use of the concept in lighting.

Frequently, questions arise concerning the desirability of replacing existing lighting with a new technology. Will a system pay for itself and how long will it take to do so are the most commonly asked questions. For example, the owner of an office building may estimate that a certain lighting modification saves about $2000 in energy costs annually. The expense associated with purchasing and installing the modification is estimated at $11,000. Thus the simple payback period would be

$$\boldsymbol{P = \$11{,}000/\$2000 = 5.5\ \text{yr}}$$

Those who like the simple payback method argue that it is easy to use and a simple way to determine the profitability of a proposed action. In fact, however, it is actually a risk assessment tool posing as a profitability metric. This is seen by examining the question the method answers. It does not answer the question, is a certain investment profitable? Rather, it responds to the concerns of the person who is unsure about the future and hopes to recoup the investment as soon as possible. If getting money back is the primary concern, then there is no reason to make the investment at all. If no investment is made, then that money is available immediately, and the payback is zero years, the ideal result of a simple payback calculation.

Another problem with this method is that it fails to consider what happens after the investment is paid back. For example, if the savings from system A (which has a shorter payback than system B) decline sharply each year after the payback period, but the savings of system B remain steady, the payback method has led to the choice of an inferior alternative. A similar situation is encountered if the systems have different lengths of economic life. Therefore the payback method cannot be used when the alternatives have nonuniform cash flows, nor is it appropriate for assessing options having different lives.

As with all first-level methods, simple payback does not consider the time value of money. Therefore, like the cost-of-light method, simple payback is best suited for short-lived projects for which interest rates have little importance. Simple payback can also be helpful as an initial screening method for projects of longer duration: if a system pays back within some specified short period (typically one or two years), then it is extremely likely to be profitable and can be accepted with no further analysis. However, a project that does not pass such a test should not be rejected, since it may still be profitable. Instead, the project should be subjected to more rigorous analysis based on a second-level method.

Simple Rate of Return

The simple rate of return is simply the reciprocal of the payback:

$$\mathrm{ROR} = \frac{A}{I} \qquad (25\text{-}3)$$

where

ROR = rate of return,
A = incremental annual cash flow,
I = incremental investment.

Thus if a system saves $20,000/yr and requires an initial investment of $100,000, its simple rate of return is $20,000/$100,000, or 20%, equivalent to a 5-yr payback. The advantages and disadvantages of this method are identical to those of the payback method. It is simple to apply and understand, but it cannot deal with nonuniform savings streams or unequal lives.

Life-Cycle Cost-Benefit Analysis (LCCBA)

The first-level methods are attractive due to their simplicity. However, they may lead to serious errors, and thus they are generally not recommended for large or complex projects. Of the second-level methods, life-cycle cost-benefit analysis (LCCBA) has emerged as the most robust method and is approved by experts in managerial economics from all industries.[6-8] Therefore, LCCBA is presented here as the economic analysis method recommended by IESNA.[9]

LCCBA uses a differential cost to give a direct comparison of systems under consideration. As with all second-level methods, the time value of money is considered. An outline of this method for comparing new interior lighting systems is illustrated by the worksheet in Figure 25-2. Within the format of that figure, two lighting system alternatives (systems 1 and 2) are compared. Both systems must be assumed to provide equal functional benefits or to fulfill all functional requirements, and any additional benefits either system provides have no economic value to the owner. The method is easily expanded using the same format if comparison of additional options is desired.

The first step in the LCCBA process is to complete the worksheet in Figure 25-2 for each system under consideration. The notes give estimates and default values to be used only as a last resort for values that are not available by any other means. Since initial costs and annual power and maintenance costs occur at different times, they cannot be directly compared. The second step, then, is to put all terms into their time equivalents to allow comparison. The following equations are used to take into consideration the time value of money.

The single present-worth factor is calculated by

$$P = F \times \frac{1}{(1+i)^y} \qquad (25\text{-}4)$$

where

P = present worth, or the equivalent value at present (dollars),
F = future worth, or the amount in the future (dollars),
y = number of years,
i = opportunity or interest rate as a decimal fraction (5% equals 0.05).

The single present-worth factor finds a value today, *P*, which is equivalent to a value in the future, *F*. In other words, one is equally willing to be paid *P* dollars today as to pay *F* dollars at a time *y* years in the future.

The uniform present-worth factor is determined by the following equation:

$$P = A \times \frac{(1 + i)^y - 1}{i\,(1 + i)^y} \qquad (25\text{-}5)$$

where

P = present worth, or the amount at present (dollars),
A = amount of an annual payment (dollars),
y = number of years,
i = opportunity or interest rate as a decimal fraction.

This equation converts a stream of equal annual amounts into a single present value. These is no cost difference between making annual payments of *A* dollars for the next *y* years and paying *P* dollars today.

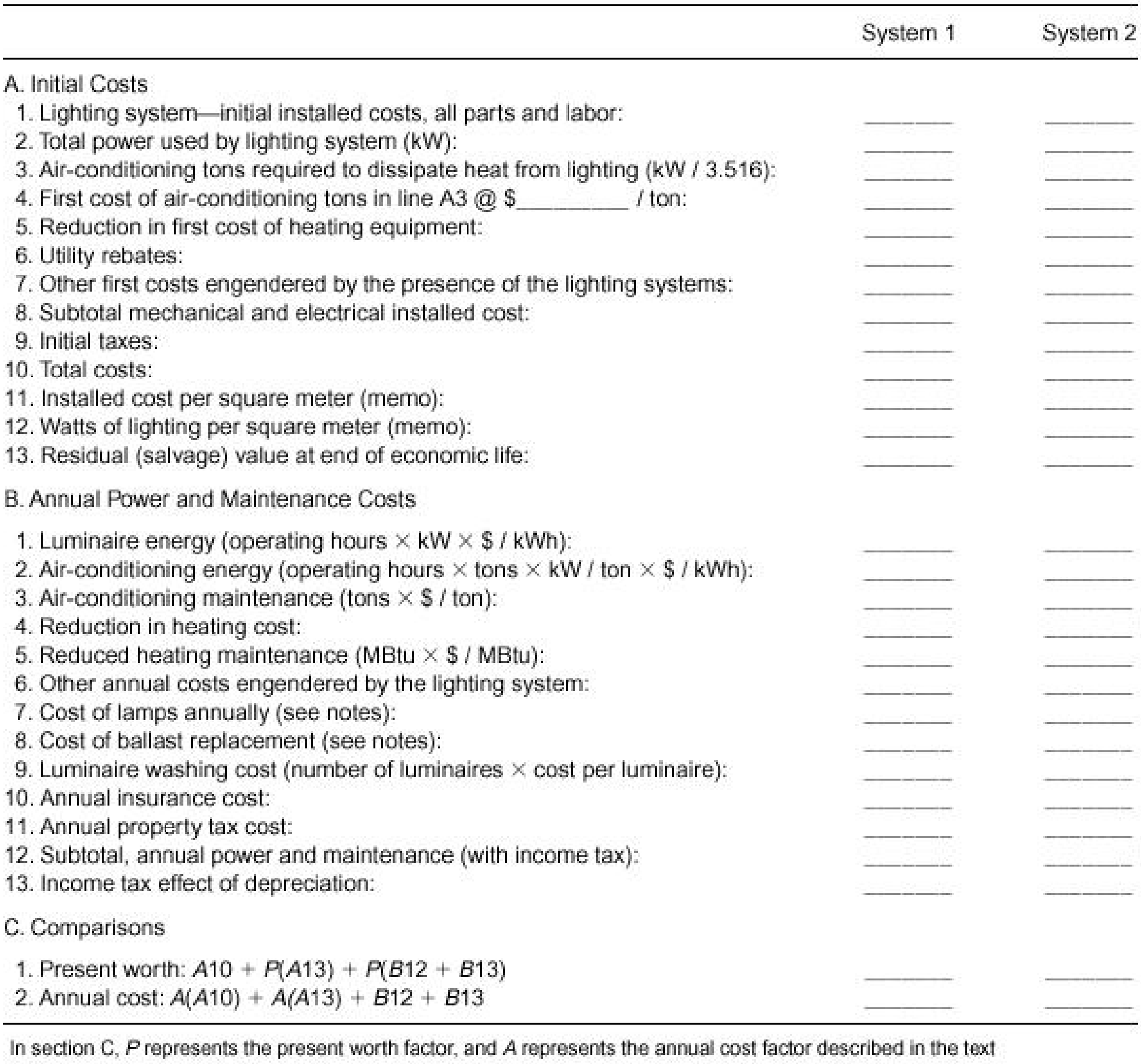
The uniform capital recovery factor is

$$A = P \times \frac{i\,(1 + i)^y}{(1 + i)^y - 1} \qquad (25\text{-}6)$$

where

A = amount of an annual payment (dollars),
P = present worth, or amount at present (dollars),
y = number of years,
i = opportunity or interest rate as a decimal fraction.

The reciprocal of the uniform present-worth factor, the uniform capital recovery factor, is the annual amount which, in a uniform stream, is equivalent to *P* dollars today.



	System 1	System 2
A. Initial Costs		
1. Lighting system—initial installed costs, all parts and labor:	______	______
2. Total power used by lighting system (kW):	______	______
3. Air-conditioning tons required to dissipate heat from lighting (kW / 3.516):	______	______
4. First cost of air-conditioning tons in line A3 @ $________ / ton:	______	______
5. Reduction in first cost of heating equipment:	______	______
6. Utility rebates:	______	______
7. Other first costs engendered by the presence of the lighting systems:	______	______
8. Subtotal mechanical and electrical installed cost:	______	______
9. Initial taxes:	______	______
10. Total costs:	______	______
11. Installed cost per square meter (memo):	______	______
12. Watts of lighting per square meter (memo):	______	______
13. Residual (salvage) value at end of economic life:	______	______
B. Annual Power and Maintenance Costs		
1. Luminaire energy (operating hours × kW × $ / kWh):	______	______
2. Air-conditioning energy (operating hours × tons × kW / ton × $ / kWh):	______	______
3. Air-conditioning maintenance (tons × $ / ton):	______	______
4. Reduction in heating cost:	______	______
5. Reduced heating maintenance (MBtu × $ / MBtu):	______	______
6. Other annual costs engendered by the lighting system:	______	______
7. Cost of lamps annually (see notes):	______	______
8. Cost of ballast replacement (see notes):	______	______
9. Luminaire washing cost (number of luminaires × cost per luminaire):	______	______
10. Annual insurance cost:	______	______
11. Annual property tax cost:	______	______
12. Subtotal, annual power and maintenance (with income tax):	______	______
13. Income tax effect of depreciation:	______	______
C. Comparisons		
1. Present worth: $A10 + P(A13) + P(B12 + B13)$	______	______
2. Annual cost: $A(A10) + A(A13) + B12 + B13$	______	______

In section C, *P* represents the present worth factor, and *A* represents the annual cost factor described in the text

Figure 25-2. Worksheet for LCCBA

The uniform sinking fund factor is determined by

$$A = F \times \frac{i}{(1 + i)^y - 1} \qquad (25\text{-}7)$$

where

F = future worth, or amount in the future (dollars),
A = amount of an annual payment (dollars),
y = number of years,
i = opportunity or interest rate as a decimal fraction.

This equation finds an equal stream of annual amounts that is equivalent to some specified amount at a specific time in the future. Again, there is no cost difference between the offer of *F* dollars *y* years from now and the offer of *A* dollars each year for *y* years.

The present worth of an escalating annual cost can be determined by one of several formulas. The general form is

$$P = \sum_{k=1}^{y} A \frac{(1+r)^k}{(1+i)^k} \qquad (25\text{-}8a)$$

where

P = present worth, or amount at present (dollars),
A = initial annual payment (dollars),
y = number of years,
i = opportunity or interest rate,
r = rate of escalation, or percentage by which the annual payment increases each year, as a decimal fraction (5% equals 0.05).

If the interest rate *i* and the rate of escalation *r* are the same, the above equation becomes

$$P = A\,y \qquad (25\text{-}8b)$$

If i and r are different, Equation 25-8a becomes

$$P = A \times \frac{(1+r)[(1+i)^y - (1+r)^y]}{(1-r)(1+i)^y} \qquad (25\text{-}8c)$$

The systems can now be compared in either of two ways. Either the residual value (line A13 from Figure 25-2) and annual costs (lines B12 and B13) can be converted to their present values using Equations 25-4 and 25-5, respectively, or the total initial cost (line A10 from Figure 25-2) and the residual value (line A13) can be converted to annualized amounts using Equations 25-6 and 25-7, respectively. Once all costs for a system have been converted to either annual equivalents or present-worth equivalents, they can be summed to obtain a single value for each system. Systems can now be compared on the basis of a single number. These approaches are summarized in section C of Figure 25-2.

An additional subtlety can be injected if an estimate is available for the expected rate of cost increase over time for any of the costs (for example, if it is predicted that the cost of energy will increase 5% each year over the planning horizon). Using Equation 25-8a, b, or c, escalation rates of this type can be applied to the annual costs of lines B1 through B11 of Figure 25-2.

Notes on the Use of Equations 25-4 through 25-8. Equations 25-4 through 25-8 serve to make explicit the notion that one dollar today is not equal in value to one dollar a year from now. This is easily seen from the example of \$100 deposited in an account that bears 5% annual interest. At the end of one year, the amount has grown to \$100 plus 5%, or \$105. Thus it can be said that \$100 today is in some sense equivalent to \$105 one year from today. In terms of Equation 25-4,

$$P = F \times \frac{1}{(1+i)^y}$$

$$\$100 = \$105 \times \frac{1}{(1+0.05)^1}$$

If it is desired to know how much would need to be deposited in this account today in order to yield \$100,000 in 20 years, Equation 25-4 can again be applied:

$$P = \$100{,}000 \times \frac{1}{(1 + 0.05)^{20}}$$

$$P = \$37{,}689$$

Again, $37,689 today and $100,000 in 20 years are considered equivalent at an interest rate of 5%. This equivalence holds for any 20-year investment at 5% interest, including lighting systems.

Similarly, time equivalents can be computed for streams of equal annual payments or receipts. For example, if the depositor in the previous example does not have $37,689 today to deposit in an account, it might be desirable to know how much money must be set aside each year over the next 20 years in order to have $100,000 on hand at the end of that period. Equation 25-7 is used:

$$A = F \times \frac{i}{(1 + i)^{y} - 1}$$

$$A = \$100{,}000 \times \frac{0.05}{(1 + 0.05)^{20} - 1}$$

$$A = \$3024$$

Twenty annual payments of $3024 are equivalent to $100,000, 20 years from now, if the interest rate is 5%. One might be willing to pay $3024 annually in maintenance costs to avoid the need to replace a lighting system at a cost of $100,000 after 20 years.

To illustrate the use of Equation 25-5, consider a lighting retrofit that saves $10,000 per year in energy costs each year over the next 10 years. How much should one be willing to pay for this retrofit today if the interest rate is 6%?

$$P = A \times \frac{(1 + i)^{y} - 1}{i\,(1 + i)^{y}}$$

$$P = \$10{,}000 \times \frac{(1 + 0.06)^{10} - 1}{0.06(1 + 0.06)^{10}}$$

$$P = \$73{,}601$$

So $73,601 today is equivalent to a stream of equal payments (or receipts) of $10,000 annually for 10 years at 6% interest.

NOTES ON THE LCCBA WORKSHEET

This section contains some explanatory information for using the LCCBA worksheet in Figure 25-2. Since the analysis of lighting system economics is predominantly the analysis of costs, the convention used is costs are positive, and revenues, savings, and benefits are negative. Estimates and default values listed should be used only as a last resort if actual figures are not available.

This worksheet procedure can be used to analyze new construction as well as lighting retrofits. For lighting retrofits, the existing system can be identified as System 1, and each line item should reflect the associated cost. Most of the initial costs for the existing system are zero, unless maintenance to the existing lighting system is considered. Costs for the proposed replacement system should account for reused equipment (e.g., most of the existing electrical wiring). Input values should reflect the combined performance and cost characteristics of the lamp/ballast/luminaire combination.

Section A

1. An estimate is prepared for material and labor of the installation. This amount is in dollars.

2. Enter the connected load of the lighting system, including ballasts and transformers, if any. This line should be in kilowatts.

3. Each lighting system introduces heat into the building, which must be dissipated by the air-conditioning system. One ton of air conditioning can dissipate the heat generated by 3.516 kW of lighting (equivalent to 12,000 Btu/h). If the lighting system choice alters the size of the air-conditioning equipment, the appropriate equipment sizes should be entered so that the difference in refrigeration tonnage is considered between alternate lighting conditions. If the air-conditioning equipment does not change, enter a zero on this line.

   Note: If a daylighting system is being analyzed, the air conditioning loads are likely to be affected by the glazing conditions and by the interior and exterior shading devices employed.[10]

4. Enter the first cost of the air-conditioning equipment in line A3, which is between $1000 and $2000 per ton. Use the same value for each system. If the cooling requirements of the systems differ only by a few tons, the same nominal-size cooling plant can be used for both. For example, if one system requires 62 tons of cooling and another requires 64, then both designs might call for a 65-ton unit, and no first-cost differential would be realized. A similar caveat applies to item A5. The value on this line should be in dollars.

5. The heat generated by each lighting system can reduce the heating load on the building. This means that the heating plant can be smaller, and thus the first cost of the heating plant is reduced. Enter on line A5 the amount of that reduction for each lighting system as a negative number. Heating equipment costs range from approximately $15 to $25 for each kBtu it consumes. Each kilowatt of lighting reduces the heating needed by about 3.4 kBtu/h. This line should be in dollars. Note that in the analysis of a daylighting system, the effect on the cooling and heating loads should be addressed through a detailed analysis.[11]

6. In order to reduce peak demand, electric utility companies in the United States may offer incentives for end users who retrofit or install energy-efficient lighting equipment in their buildings. Enter a financial incentive as a negative number, in dollars.

7. Include any other differential costs, such as insulation, solar power, or tax credits, in dollars.

8. The subtotal is the sum of lines A1, A4, A5, A6, and A7, taking proper note of signs.

9. Usually 6 to 8% of the first cost (line A8). Enter as a dollar amount.

10. The sum of lines A8 and A9.

11. The installed cost per square meter can be included as a memo; it does not enter into the LCCBA calculation.

12. The power density can be included as a memo; it does not enter into the LCCBA calculation.

13. The amount the system will be worth at the end of its economic life (as scrap, for example). Use the same life for each system under comparison. Note that this value is negative if money is received for the salvage; it is positive if a cost is incurred to dispose of the system at the end of its life. This amount is in dollars.

Section B

1. The number of operating hours and cost per kilowatt-hour depends on occupancy schedules and local power rates. Ten hours a day, five days a week, 52 weeks per year represents 2600 h. In the United States, the average energy cost for commercial, institutional, and industrial customers is on the order of $0.08 to $0.09 per kWh. The impact of demand charges should be included in the kWh rate if the lighting system is expected to operate at the time of peak building demand. If the system is operated exclusively at off-peak hours, only the energy charge should be considered. This line is in dollars.

2. The number of tons of air conditioning should come from line A3. The number of kilowatts per ton for a central plant is approximately 1.25. The value in this line is in dollars.

3. This value can be approximated by $150/ton times the air-conditioning tons from line A3, in dollars.

4. This is the reduction in the annual cost of fuel for heating equipment due to increased heat obtained from the lighting system. The number of heating hours can be obtained by the formula

$$\text{heating hours} = (\text{lighting hours}) \times 0.85 - (\text{cooling hours})$$

The heat from the lighting system in MBtu is given by this formula:

$$\begin{aligned}\text{heat from lighting system} = {} & (\text{kW of lighting}) \\ & \times (3.413\ \text{MBtu/kWh}) \\ & \times (\text{heating hours})\end{aligned}$$

To convert costs of typical fuels to dollars per MBtu, multiply the cost of fuel (such as $0.80/gal for fuel oil) by the corresponding value in column 4 of Figure 25-3 (such as 10 gal/MBtu). For example, if the price of electricity is $0.10/kWh, the cost per MBtu is ($0.10/kWh) × (293 kWh/MBtu) = $29.30/MBtu. If the price of fuel oil is $0.80/gal, the cost per MBtu is ($0.80/gal) × (10 gal/MBtu) = $8.00/MBtu. Thus

$$\text{annual reduction in heating energy costs} = (\text{MBtu of heat from lighting}) \times (\text{fuel cost per MBtu})$$

This value should be in dollars. Note that if daylighting is used, the effects of shading devices on air-conditioning costs should also be considered.[10]

5. Heating maintenance costs can be approximated by $2/MBtu. Multiply by the number of MBtu of heat from lighting to get a dollar amount.

6. Other costs may include costs, in dollars, for inspection of the lighting system.

7. The cost of lamps per year depends on the relamping strategy. If spot relamping is used, then the lamp cost per year is figured from this formula:

$$\text{lamp cost per year} = \frac{(\text{cost for spot replacement of one lamp}) \times (\text{number of lamps in the system})}{(\text{lamp life}) / (\text{annual burning hours})}$$

For group relamping, use

$$\text{lamp cost per year} = (\text{number of lamps replaced per year}) \times (\text{cost per lamp of group relamping})$$

Either way, the number on this line should be a dollar amount.

8. To annualize ballast costs, use

$$\text{ballast cost per year} = \frac{(\text{cost to replace one ballast}) \times (\text{number of ballasts in the system})}{(\text{ballast life}) / (\text{annual burning hours})}$$

   This amount is in dollars.

9. Multiply the number of luminaires by the cost to clean a single luminaire to obtain the annual cost in dollars.

10. Approximately 1 to 1.5% of first cost.

11. Approximately 4 to 6% of first cost.

12. The annual expenses of lines B1 through B11 serve to reduce the owner's income tax liability based on the income tax rate (ITR). The net cost of these items is entered as

$$(\mathrm{B1} + \mathrm{B2} + \mathrm{B3} + \mathrm{B4} + \mathrm{B5} + \mathrm{B6} + \mathrm{B7} + \mathrm{B8} + \mathrm{B9} + \mathrm{B10} + \mathrm{B11}) \times (1 - \mathrm{ITR})$$

13. Depreciation reduces the owner's income tax liability. Assuming the asset is depreciated by the same amount each year (straight-line depreciation), the annual depreciation amount is given by

$$D = \frac{\text{initial cost from line A10}}{\text{economic life of system}}$$

If the owner's income tax rate (ITR) is expressed as a decimal fraction, then the tax effect is $T = D \times \mathrm{ITR}$. This should be entered as a negative dollar amount, since it is a benefit or saving.

Section C

1. A present-worth comparison is done by finding "time zero" equivalents of all future costs and adding those to the initial costs of line A10. Equation 25-5 is used to convert the annual values in B12 and B13 to their equivalents at time zero. Use Equation 25-1 to convert the residual value (A13).

2. An annual-cost comparison requires that all one-time costs (initial costs and residual values) be converted to annual equivalents. These are then added to the annual energy and maintenance costs. Use Equation 25-6 to convert the initial cost of line A10 to its annual equivalent. The residual value (line A13) is converted to an annual value using Equation 25-7.

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26

Energy Management

Energy management has become increasingly important since the early 1970s, stimulated by the escalation of energy costs, the depletion of certain energy sources, and the concern for the protection of our environment. The responsible use of energy has become a general public concern and consequently has motivated development of new legislation, codes, and standards designed to establish minimum levels of energy efficiency. As a result, the way buildings are constructed, lighted, heated, and cooled is closely examined. Criteria for new building design and for existing buildings have been developed to ensure that energy resources are used efficiently. This chapter provides an overview of lighting energy management, describes important influences on lighting energy use, and provides references to other sections for more detail on specific lighting issues.

Electric lighting consumes a significant amount of energy. About 20 to 25% of all electricity used in buildings and about 5% of total energy consumption in the United States is used for lighting. Lighting also produces additional heat in buildings, which is sometimes beneficial in cold climates but generally represents a significant load on air conditioning systems. The heat from lighting typically accounts for 15 to 20% of a building's cooling load.

Over the last decade, energy management has become a fundamental element of mainstream lighting design. There have been many significant factors contributing to this trend. These factors include utility programs for promoting demand side management (DSM), the development and promulgation of energy codes and standards designed to minimize building energy waste, and ongoing technological development of lighting equipment to improve system efficacies and utilization efficiencies. This chapter provides an overview of current activity in all of these areas and shows how they relate to design and application issues.

LIGHTING SYSTEM DESIGN FOR ENERGY EFFICIENCY

The key elements of lighting design for energy efficiency are outlined schematically in Figure 26-1.

Lighting Needs

First and foremost, the lighting needs of a space must be defined to optimize proper allocation and management of energy. Lighting needs may range from simple orientation to complex visual tasks. Important considerations for prolonged visual tasks associated with work environments include adequate illuminance on the task surface, a proper balance of luminance between the task surface and surrounding surfaces, control of direct and reflected glare, and acceptable color rendering of task elements and surrounds. Other considerations also apply, depending on the details of the specific visual task being performed.

When the nature and location of visual tasks can be identified, it is usually possible to reduce surrounding ambient illuminances and corresponding energy consumption by providing light more selectively where and when it is needed. When specific tasks and their locations cannot be identified, a more uniform pattern of ambient illumination is generally provided, along with provisions for task lighting and local control. In applications where there are no prolonged visual tasks, lighting for emphasis, aesthetics, and safety are prime considerations.

Lighting needs for specific applications can be found in Chapter 10, Quality of the Visual Environment, and the relevant application chapters. In addition, there are numerous IESNA publications that provide guidance in identifying and addressing lighting needs.[1-3] The ASHRAE/IESNA Standard 90.1[4] and its compliance manual can be consulted for guidelines in determining lighting energy allocations for specific applications.

Space Design and Utilization. Space design and utilization characteristics are often determined before the lighting system is considered. However, it is necessary to coordinate the design of lighting and control systems with these characteristics in order to maximize the energy efficiency potential. For larger interior spaces, surface reflectances should be 0.7 or higher. This increases the brightness within the space and reduces the amount of electric lighting needed to produce a given illuminance. The design and utilization of a space should also facilitate effective use of daylight.

Applications that involve similar visual tasks should be grouped together when possible to optimize the energy used for lighting. Using a base level of ambient illumination with "layers" of task-specific luminaires provides an additional degree of flexibility and economy by allowing luminaires to be easily relocated when the design or function of a space changes.

Occupancy schedules of a space should be planned to optimize the effectiveness of lighting controls. Traffic patterns should be predetermined so that logical applications for occupancy sensors can be identified. This usually requires coordination among members of the project design team.

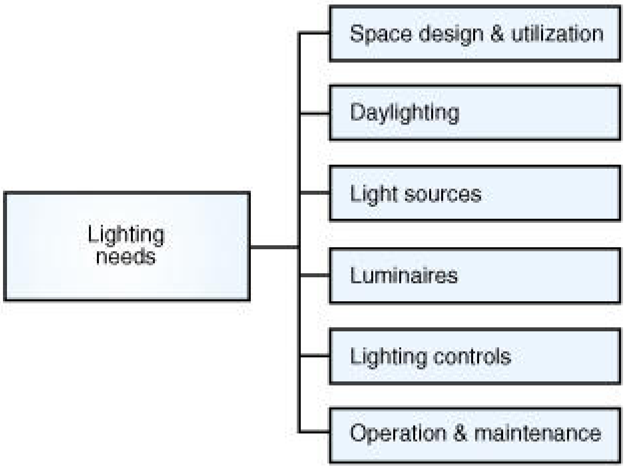


Figure 26-1. Key elements of lighting energy management.

Daylighting. Daylight can be an excellent source of ambient illumination. The potential for daylight utilization should be evaluated early in the design development of a space. Architectural features such as overhangs, light shelves, and window treatments may be incorporated into the design to enhance daylight utilization and control. For effective use of daylight in energy management, the levels and hours of daylight availability must be determined. Also, the manner in which daylight is distributed in the space is important. Glare from fenestration should be controlled to the same degree as glare from luminaires (Figure 26-2). The best daylighting designs maximize daylight penetration into the space while minimizing the negative effects of direct sun.

The heat gain or loss through fenestration must be coordinated with the building envelope and HVAC systems. The use of exterior sun control devices and high-performance heat-reflecting and insulating glass in windows should also be considered to minimize solar heat gain in the summer and heat loss in the winter without obstructing views of the exterior. Daylighting reduces energy consumption primarily if electric lighting can be reduced. The electric lighting design should be coordinated with available daylight so that illuminance and distribution are integrated. Automatic and manual dimming controls should be considered for continuous adjustment of electric lighting levels to achieve maximum energy savings and occupant acceptance.[5,6]

Chapter 8, Daylighting, can provide useful information on the availability of daylight, daylight control systems, and design and evaluation methods. Recently published data from manufacturers of fenestration materials and controls should also be consulted.

Figure 26-2. Effective utilization of daylight is important. Glare from fenestration should be controlled to the same degree as glare from luminaires.

Light Sources. Electric light sources should be selected to maintain the highest efficacy while providing proper color qualities, physical and optical size, and long-life operating characteristics (e.g., warm-up time, restrike time, and dimming). These attributes are related to decisions on luminaire types, lighting controls, and the general operation and maintenance after installation.

The relative efficacy ranges of commonly used light sources, including ballast losses, are shown in Figure 26-3. Within a lamp type, the higher-wattage sources are generally more efficacious than the lower-wattage sources. High-pressure sodium, metal halide, and fluorescent lamps are the most efficient white light sources; mercury vapor and standard incandescent lamps are the least efficacious. Except for incandescent lamps, including halogen lamps, light sources require a specific ballast. Ballast efficiencies vary and can have a large effect on the total lighting system efficacy. Also, fluorescent lamp electronic ballasts are more efficient than magnetic ballasts and generally improve lighting quality by reducing lamp flicker and ballast hum.

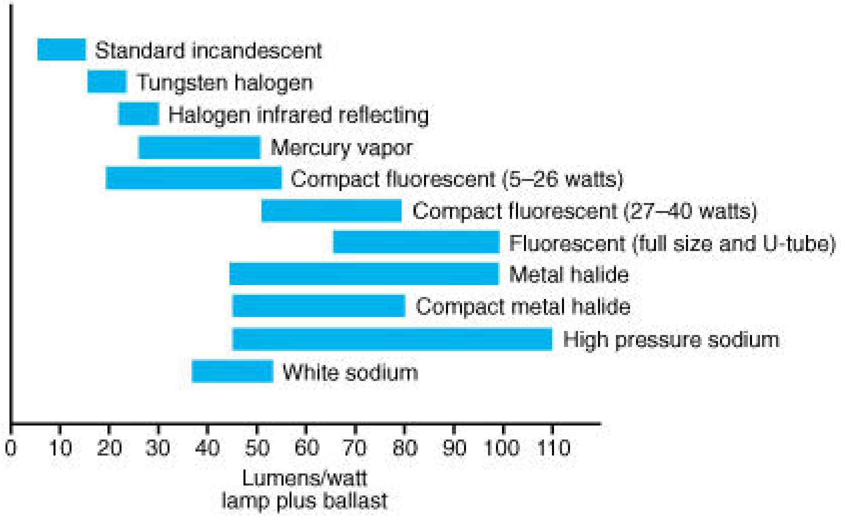


Figure 26-3. Light source efficacies.

There are other key issues that must be considered when selecting a ballast. One of these is ballast factor, which represents the percentage of rated lamp lumens that is produced by a ballast relative to those produced by a reference ballast. Low-output ballasts have a low ballast factor and require proportionally lower power. A method for comparing the efficacy of lamp/ballast systems on a normalized basis is the calculation of Ballast Efficacy Factor (BEF). BEF is defined as ballast factor (BF) in percent, divided by the total ballast input power in watts.[7]

$$\mathrm{BEF} = \frac{\mathrm{BF} \times 100}{\text{ballast input watts}}$$

A higher BEF value indicates a more efficacious lamp-ballast system. Since BEF is a comparative expression for a given lamp-ballast combination, only two-lamp ballast systems should be compared with each other, three-lamp ballast systems with each other, and so on. See the section "Equipment Regulations" later in this chapter for U.S. regulation of BEF. Also, see Chapter 6, Light Sources, for more information about ballasts.

Chapter 6, Light Sources, provides detailed information pertaining to the operation and performance of various lamp types. Lamp manufacturers' published data provide specific information relative to lumen output, efficacy, life expectancy, lumen maintenance, and costs.

Luminaires. A luminaire is an assembly of individual components including lamps, ballasts, sockets, wiring, and optical media such as reflectors, louvers, and lenses. The efficiency of the luminaire is affected by the performance of these individual components. Typically, luminaire configurations are constructed to perform specific functions for specific applications (Figure 26-4). Application constraints such as ambient temperature, color requirements, accessibility, and glare control needs may require the use of certain components or preclude the use of others. The efficiency of a luminaire must be evaluated relative to specific application criteria.

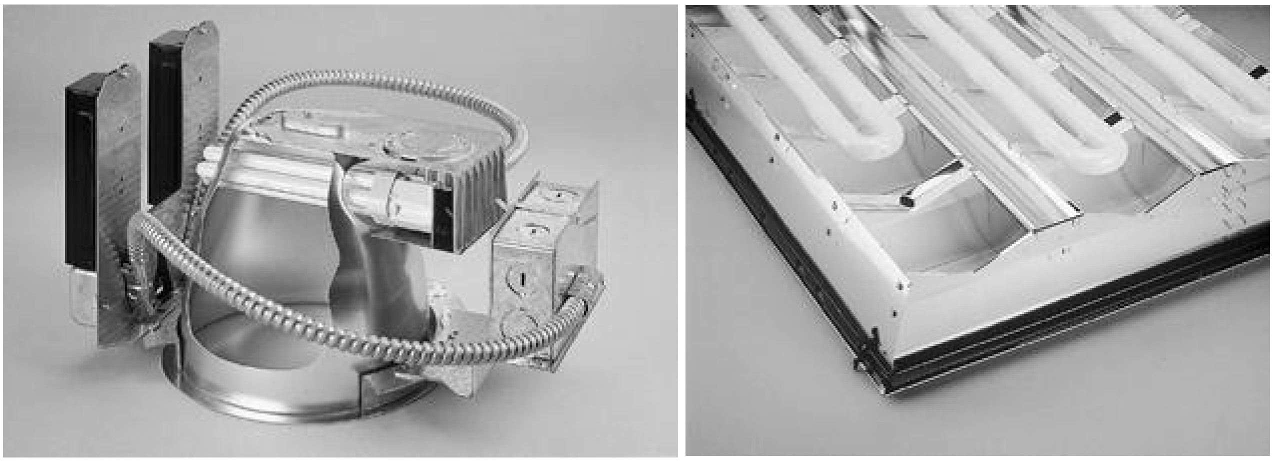


Figure 26-4. The performance of luminaires is a function of source efficacy, geometry (downlight vs. linear luminaire), the optical system for controling distribution and shielding, and the ability of the luminaire to manage and dissipate heat created by components.

In spaces that contain important visual tasks, a primary objective of the lighting system is to illuminate the task effectively. In addition, the system must effectively illuminate the ambient space to balance luminances and create a comfortable visual environment. The system that provides task illuminance may be independent of the system that provides ambient illuminance, or else the same system may provide both (Figure 26-5). In either case, it is important that the luminaires perform their functions efficiently and that the designer understand their optical performance and impact on the overall environment.

Luminaires that can be cleaned easily and those with low dirt accumulation maintain greater efficiency and reduce maintenance costs over system life. When possible, luminaires with heat-transfer capabilities should be considered for interior applications so that heat generated by the lighting system can be effectively utilized or removed from a space and coordinated with the overall building HVAC design.

Data from luminaire manufacturers are useful for determining how efficiently luminaires meet lighting needs. The efficiency of a luminaire is the percentage of lamp lumens produced that actually exits the luminaire. Efficiency does not provide any indication of lighting quality and should not be the determining factor in luminaire selection. Chapter 7, Luminaires, should be consulted for further information about luminaires.

Figure 26-5. An ambient lighting system that also provides wall and task lighting.

Lighting Controls. The most efficient luminaires and light sources can be utilized even more effectively by integrating them with lighting controls that make the lighting more responsive to changing requirements. Lighting control strategies should be implemented either centrally, over an entire building, or locally, in individual areas. Various combinations of these two levels of control are also common.

Central lighting control systems allow for lighting load scheduling to reduce peak demand as well as provide the ability to monitor and control total energy use. Central lighting control systems can be interfaced with overall building management systems (BMS). Most energy codes require that a discrete space be provided with some means of controlling the lighting within that space (Figure 26-6).

A building also can be divided into areas that have different lighting needs and require different control strategies. For example, perimeter zones consisting mainly of private offices should be differentiated from core zones utilizing an open-plan landscape. Private offices are good candidates for manual and automatic lighting control because they have unpredictable occupancy schedules, they are typically low-traffic areas requiring task-level illumination only when occupied, and they often utilize a significant daylight contribution.[5]

Lighting control strategies are closely related to space utilization. It is essential to understand and coordinate space utilization in order to optimize the effectiveness of lighting controls for energy management (refer to the section "Space Design and Utilization" above). Lighting controls must eliminate or reduce lighting during off hours. The system must be flexible so that luminaires are used only where and when the relatively few people working late at night or on weekends are present. Off-hours operation should not defeat shut-off controls and thereby allow lighting to operate all night or all weekend.

Chapter 27, Lighting Controls, should be consulted for a more detailed discussion of lighting controls. Information from manufacturers should also be consulted for performance data and application assistance on various control technologies.

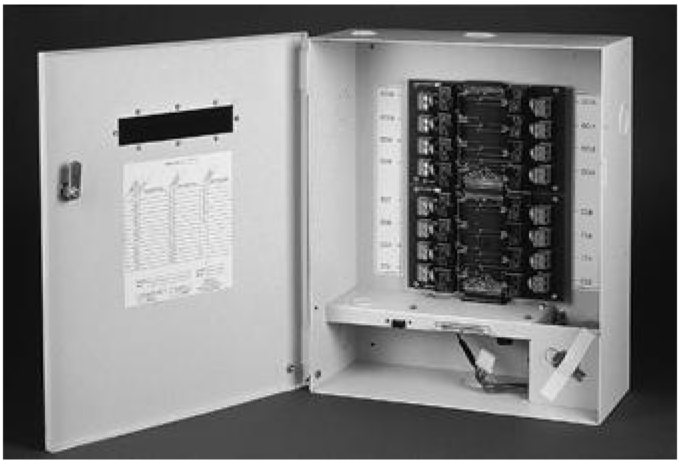


Figure 26-6. An example of a central lighting control system based on programmable time-of-day operation of relays and low-voltage switching.

Operation and Maintenance. All lighting systems require maintenance after installation. A planned maintenance program augments the ability of a lighting system to meet design objectives effectively and efficiently throughout its life. Scheduled maintenance should include procedures for lamps, ballasts, luminaires, controls, fenestration, and room surfaces. Group relamping and a regular cleaning program are recommended for maximum maintained efficiency.

A planned systematic maintenance schedule saves energy and operating costs over time. If the commitment to implement scheduled maintenance is made in the initial stage of design, a significant capital cost saving is also possible because less equipment is required. Refer to Chapter 28, Lighting

Maintenance, for a more detailed discussion relative to efficient operation and maintenance of lighting systems.

ENERGY EFFICIENCY FOR EXISTING BUILDINGS

Existing buildings should comply with the same lighting energy recommendations as new buildings. Improved energy utilization options include modifying or replacing lighting systems, using reduced-wattage sources in spaces that provide higher illuminance than currently recommended, and modifying the operating hours of the lighting equipment.

Specifying lighting system changes for existing spaces can be more accurate than it is for new construction because the space and its use can be surveyed. An existing building is evaluated from the standpoint of power and energy by two methods: a building survey and the determination of the lighting power allowances.

Building Survey

A building's lighting systems can be assessed to determine the existing lighting condition, current lighting needs, the connected electrical load, hours of operation, and the controls system. The electrical load, including lamp watts, ballast watts, and losses (including those introduced by dimming devices), should be documented. The power for portable and supplementary lighting devices should be included in the total. Factors related to occupancy, daylighting, and controls should be included. Specific information on surface finishes and reflectances should also be recorded. Sampling procedures can be used to avoid measuring every feature of the space.

Lighting Power Allowance Determination

Local energy codes and ASHRAE/IESNA 90.1-1999 provide the total lighting power allowance (TLPA), which consists of exterior lighting power allowance (ELPA) and interior lighting power allowance (ILPA), as well as procedures for calculating them and control requirements for interior and exterior illumination systems.[4]

The actual current energy use for the facility is determined and compared with the energy limit. The difference is the energy saving from the retrofits. The resulting revised energy use estimate can be compared with the recommended energy limit. If it exceeds the limit, the lighting systems should be reevaluated. Spaces or strategies that are inefficient should be identified and modified to reduce the estimated energy below the calculated limit. Reference 8 contains the full procedure and energy management forms to estimate and evaluate lighting energy use for buildings.

LIGHTING EFFICIENCY STANDARDS, REGULATIONS, CODES

Lighting efficiency standards are designed to establish maximum energy levels for a building. The overall goal is to minimize energy consumed by a lighting system without compromising the quality of the lighting design. Generally, one of two approaches is taken: setting minimum efficiency for specific components or limiting the available power for lighting. The latter approach is commonly known as an application standard, whereas the former is known as equipment regulations. Over the last decade, both application standards and equipment regulations have been enacted into building energy codes by federal, state, and provincial governments in North America. Both of these approaches address lighting power, but it should be remembered that energy savings (kilowatt-hours) can be achieved by reducing the connected load power for the lighting system or the time the lighting system is operated.

Applications Standards/Codes

Lighting application standards can encourage good lighting principles and do not prescribe the use of specific technologies, because inexpensive equipment is not necessarily the most energy efficient or cost effective. Life-cycle cost models are very effective for justifying the economic merits of increased equipment efficiency (see Chapter 25, Lighting Economics).

Current ASHRAE/IESNA Standards. The industry benchmark of energy application standards for buildings is the ASHRAE/IESNA series. As a combined effort of the Illuminating Engineering Society of North America (IESNA) and the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), the first building energy standard was published in 1975. This standard, 90.1: "Energy Conservation in New Building Design," was developed as a national voluntary consensus standard. The 1980 version of this standard was approved as an ANSI standard. During the 1980s, many states and provinces in North America enacted regulations based directly or indirectly on this standard. The standard has been updated three times; the current version is ASHRAE/IESNA 90.1-1999 Energy Standard for Buildings Except Low-Rise Residential Buildings.[4]

The purposes of the standard are to:

- Set minimum requirements for the energy-efficient design of new buildings so that they may be constructed, operated, and maintained in a manner that minimizes the use of energy without constraining the building function or the comfort or productivity of the occupants.
- Provide criteria for energy-efficient design and methods for determining compliance with these criteria.
- Provide sound guidance for energy-efficient design.

The organization of ASHRAE/IESNA 90.1-1999 is shown in Figure 26-7. All buildings must meet the basic requirements. The basic requirements with respect to lighting, relative to the above purposes, include minimum criteria for lighting controls, power allowance for internal building lighting, and power allowance for external building lighting. For internal building power allowances, Standard 90.1 offers a choice of three different methods for determining compliance: energy cost budget, prescriptive path for a building (Building-Area Method) or prescriptive path for spaces in a building (Space-by-Space Method).

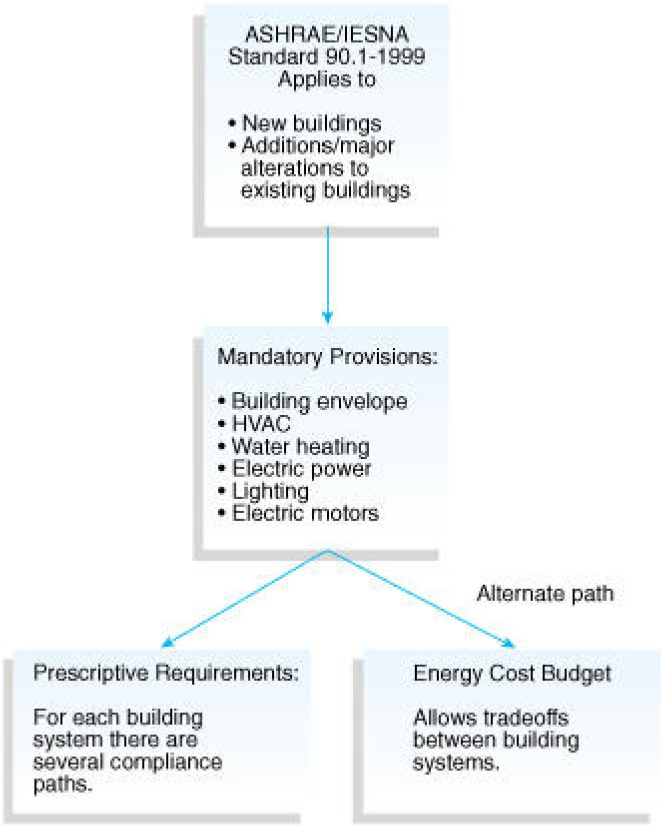


Figure 26-7. The structure of ASHRAE / IES Standard 90.1-1999.

The energy cost budget approach is the most encompassing and complex method of assessing compliance. A whole-building energy model must be used to predict energy use. It allows the designer to trade off lighting energy with other energy systems (e.g., the HVAC system). Although the method is flexible, it requires sophisticated analysis tools and is time consuming.

The Building Area Method addresses the need for a quick and simple process for calculating the prescriptive interior lighting power allowance (ILPA) for whole building types. This method does not address unique project requirements and is intended primarily for generic building types, core and shell buildings, or during the preliminary design phase. The ILPA is calculated by selecting the lighting power density from a table in the standard, multiplied by the gross lighted floor area (square feet or square meters) of the building. The actual design is measured against the value determined with this method.

The Space-by-Space Method provides a more accurate and detailed calculation procedure to determine the ILPA than the prescriptive method. The ILPA is calculated room by room and is task specific. Lighting power densities for each space are listed in a table in the standard. The ILPA for the building is the sum of lighting power allowances of all spaces. Similarly, the exterior lighting power allowance is the sum of lighting power allowances for all applicable exterior applications permitted.

While ASHRAE/IESNA 90.1-1999[4] applies to new buildings, ASHRAE/IESNA Standard 100[9] applies to existing buildings. It provides requirements for retrofit lighting modifications. In general, the required changes can be done easily by maintenance personnel. When major renovations are made to existing buildings, for example, when the entire lighting system is replaced, it is recommended that the designer meet the requirements for new construction even though compliance may not be required.

Compliance with Standard 90.1-1999[4] or Standard 100[9] does not ensure good lighting. The purpose of these standards is to set limits on the amount of power that can be used for lighting. While it is the consensus of experts that good lighting can be achieved within the limits set by Standard 90.1, it is the responsibility of the designer to achieve it.

U.S. State Energy Codes. State legislation governing lighting energy consumption varies from state to state. The federal Energy Policy Act of 1992 (EPACT),[10] requires all states to adopt a building energy code that meets or exceeds the requirements of ASHRAE/IES 90.1-1989. The Model Energy Code (MEC)[11] contains a codified version of Standard 90.1-1989 and is used by many states to meet the EPACT requirement. The MEC has been developed by the Council of American Building Officials (CABO) with participation of other building code officials.

Canadian Application Standards/Codes. The Canadian Standing Committee on Energy Conservation in Buildings (a subcommittee of the Canadian Commission on Buildings and Fire Codes) is in the process of developing a National Energy Code for commercial buildings and for homes. Once finalized, the regulation of buildings in Canada will be the responsibility of provincial and territorial governments. Provinces will have the option of adopting all or part of the National Energy Code.

Mexican Energy Codes. Mexico has no formal energy standards or code requirements at the state or federal level.

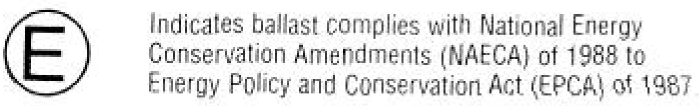
Equipment Regulations

In both the United States and Canada, the government has been playing an increasing role in regulating the conservation of lighting energy through standards on lighting components. The primary institutions responsible for national standards are the U.S. Department of Energy (DOE) and Natural Resources Canada (NRC). Harmonization of standards is necessary so that (1) lower efficiency products are not dumped from a country with regulations to one without, (2) manufacturers can design products according to one standard instead of several, and (3) the regulatory burden is decreased.

U.S. Regulations. Two laws specifically mandate the use of efficient lighting components: the National Appliance Energy Conservation Amendments of 1988 (NAECA)[12] and the Energy Policy Act of 1992 (EPACT).[10] NAECA regulates the sale of inefficient ballasts for fluorescent lamps. Ballasts sold for use in commercial or industrial lighting installations were required to meet or exceed minimum BEF values, discussed earlier in this chapter.

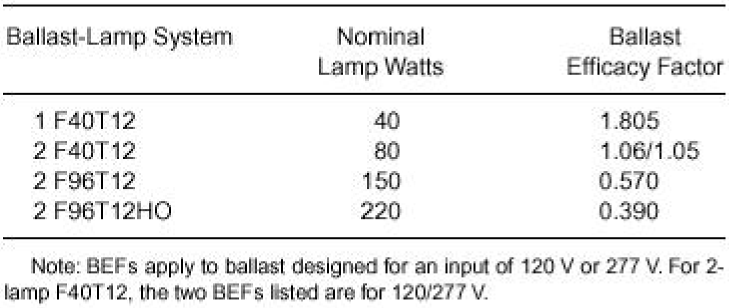
The impact of this regulation was that common magnetic ballasts did not comply, but more energy-efficient magnetic ballasts and efficient electronic ballast did. The law exempted dimming ballasts and those for use at ambient temperatures of −18°C (0°F) or less, and ballasts with low power factor (less than 0.90) for residential use. Ballasts that meet the efficiency criteria are identified by a circle E symbol on the label (Figure 26-8).

EPACT mandated energy-efficiency standards for common lamps used in the United States. Minimum efficacy standards were developed for popular lamp types within the categories of incandescent R and PAR and linear fluorescent lamps (see Figures 26-9, 26-10, and 26-11 and Chapter 6, Light Sources). These standards were phased in during 1994 and 1995. The impact was that halogen PAR lamps complied, whereas the standard and reduced-wattage PAR lamps and many R lamps did not. For 4-foot and 2-foot U-tube, 8-foot slimline, and 8-foot high-output fluorescent lamps, the standard established minimum requirements for both efficacy and color rendering index (CRI). Effectively, reduced-wattage T-12 halophosphor fluorescent lamps complied, as did T-8 and T-12 fluorescent lamps coated with rare earth phosphors. Common fluorescent lamps with halophosphor coatings did not comply. EPACT also called for test procedures, standards, and labels for HID lamps where standards are technically feasible and economically justified and offer significant energy savings potential.



Indicates ballast complies with National Energy Conservation Amendments (NAECA) of 1988 to Energy Policy and Conservation Act (EPCA) of 1987

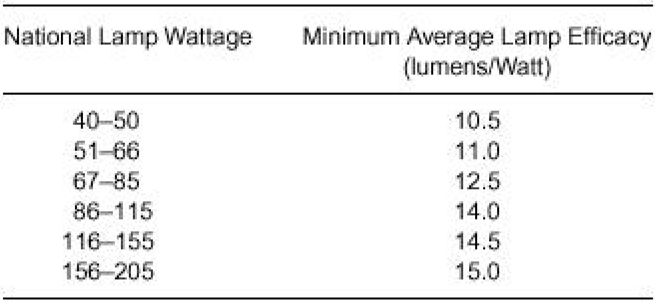
Figure 26-8. "Circle E" symbol that appears on fluorescent lamps and ballasts.



Ballast-Lamp System	Nominal Lamp Watts	Ballast Efficacy Factor
1 F40T12	40	1.805
2 F40T12	80	1.06/1.05
2 F96T12	150	0.570
2 F96T12HO	220	0.390

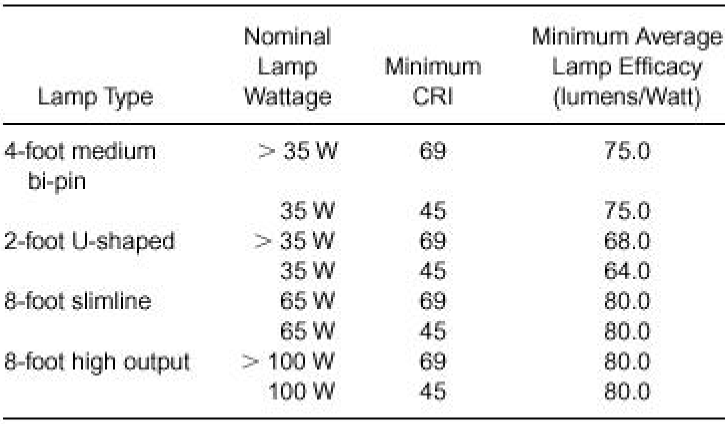
Note: BEFs apply to ballast designed for an input of 120 V or 277 V. For 2-lamp F40T12, the two BEFs listed are for 120/277 V.

Figure 26-9. U.S. Minimum Allowable Ballast Efficacy Factors



National Lamp Wattage	Minimum Average Lamp Efficacy (lumens/Watt)
40–50	10.5
51–66	11.0
67–85	12.5
86–115	14.0
116–155	14.5
156–205	15.0

Figure 26-10. U.S. EPACT Incandescent Reflector Lamp Standard Levels.



Lamp Type	Nominal Lamp Wattage	Minimum CRI	Minimum Average Lamp Efficacy (lumens/Watt)
4-foot medium bi-pin	> 35 W	69	75.0
	35 W	45	75.0
2-foot U-shaped	> 35 W	69	68.0
	35 W	45	64.0
8-foot slimline	65 W	69	80.0
	65 W	45	80.0
8-foot high output	> 100 W	69	80.0
	100 W	45	80.0

Figure 26-11. U.S. EPACT Fluorescent Lamp Standard Levels

EPACT prescribed an energy-efficiency labeling program for common general-service incandescent and fluorescent lamps, incandescent reflector lamps, and medium-base self-ballasted screw-in compact fluorescent lamps sold or imported in the United States. This program was designed by the Federal Trade Commission (FTC) and took effect in 1995. The FTC lamp labeling procedure for incandescent and compact fluorescent lamps required that lamp packages display lumen output, lamp wattage, rated lamp life, and design voltage (if other than 120 V). Full-size fluorescent lamps are not required to have package labels. Instead, the circle E symbol must be etched on the lamp itself, indicating that the lamp meets the EPACT lamp efficacy requirements described above (Figure 26-8).

EPACT called for a voluntary national testing and information program for widely used luminaires that offer potential for significant energy savings. The program was designed by the National Lighting Collaborative, composed of NEMA (National Electrical Manufacturers Association), the American Lighting Association (ALA), and other interested organizations representing lighting designers, energy-efficiency advocates, research, government, and electric utilities.

The luminaire program was based on a rating methodology, developed as NEMA Standard LE-5, called the Luminaire Efficacy Rating (LER).[13] LER is defined as the ratio of the total luminaire lumens (incorporating ballast factor and thermal effects) to the system input wattage. It includes the efficiency impact of each system component: fixture, lamp, and ballast. LER is expressed by the following formula:

$$\text{LER} = \frac{\text{total rated lamp lumens} \times \text{ballast factor} \times \text{luminaire efficiency}}{\text{luminaire input watts}}$$

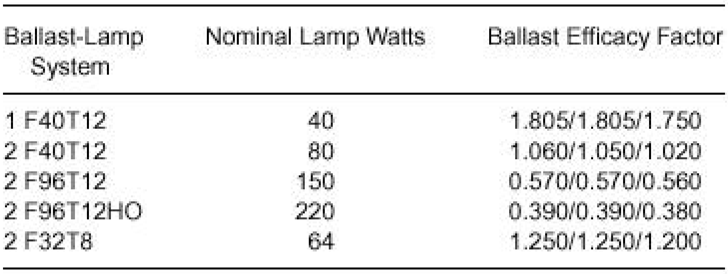
The fluorescent lamp luminaire program covers eleven categories of commonly used luminaires representing a large majority of the fluorescent lamp luminaire market. For each luminaire, the LER rating is reported along with a code for its luminaire category so that products can be compared fairly within categories (rather than between categories). The rating is designed with a placeholder for the addition of an as yet-undeveloped quality metric to indicate lighting quality. The estimated annual lighting energy cost per 1000 lumens of light output, assuming 3000 operating hours per year and $0.08 (U.S.) per kWh electricity cost, is also reported.

Canadian Standards. Natural Resources Canada has regulatory powers under the Energy Efficiency Act of 1993.[14] The first Energy Efficiency Regulations were published in 1994. NRC works with the Canadian Standards Association (CSA), which develops consensus standards for various products. National standards apply to products imported into Canada or shipped between provinces. The provinces may adopt these standards for products sold within their borders. Federal standards do not take precedence over provincial standards, in contrast with the United States, where federal standards preempt state standards on a specific product.

The first lighting product included in the Energy Efficiency Regulations was fluorescent lamp ballasts. As of 1995, ballasts must meet the minimum ballast efficacy factors specified in the CSA standard.[15] These standards are similar to those listed above for the United States, with the exceptions that F32T8 lamp ballasts are also regulated and that there are standards for ballasts with an input of 347 volts as well as 120 and 277 volts (Figure 26-12).

Canadian lamp regulations are the same as the U.S. EPACT standards for incandescent reflector and linear fluorescent lamps. These standards took effect in 1996.

There are no lamp labeling requirements in Canada similar to those in the EPACT legislation. However, regulated lighting products must carry a verification mark indicating that the energy performance of the product has been verified.



Ballast-Lamp System	Nominal Lamp Watts	Ballast Efficacy Factor
1 F40T12	40	1.805/1.805/1.750
2 F40T12	80	1.060/1.050/1.020
2 F96T12	150	0.570/0.570/0.560
2 F96T12HO	220	0.390/0.390/0.380
2 F32T8	64	1.250/1.250/1.200

Figure 26-12. Canadian Minimum Allowable Ballast Efficacy Factors

The provinces Ontario, British Columbia, Quebec, Nova Scotia, and New Brunswick have standards similar to the federal regulations for fluorescent lamp ballasts. Ontario and British Columbia have also implemented standards for incandescent reflector lamps and are looking at adopting the standards for fluorescent lamps. In addition, Ontario and British Columbia have regulated compact fluorescent lamps and cobra-head HID luminaires based on recently published CSA standards for compact fluorescent lamps and roadway lighting.

Nonregulatory Government Programs

Government agencies also promote energy efficiency and energy conservation through voluntary programs. The Green Lights Program and Energy Star Building Program are administered by the U.S. Environmental Protection Agency (EPA). These programs are voluntary initiatives designed to reduce building energy load on a national scale.

The objective of the Green Lights Program is to minimize pollution associated with the generation of energy required to operate new and existing lighting systems. Large and small companies and institutions have committed to survey lighting systems in their facilities and convert to energy-efficient lighting when economically viable. For new installations, the recommendations of ASHRAE/IESNA Standard 90.1-1999[4] are to be followed.

The Energy Star Program is a more comprehensive building initiative that encourages use of energy-efficient technologies for all major building systems, including lighting. A partnership agreement is signed between a luminaire manufacturer and EPA and the U.S. Department of Energy (DOE). EPA and DOE work with the luminaire manufacturer to promote superior products that qualify for the EPA/DOE Energy Star label. Products that carry the Energy Star label meet energy efficiency and quality criteria to assure that consumers do not sacrifice performance to save energy. The Lighting Research Center (LRC) in Troy, New York, helps EPA and DOE promote the Energy Star Program by encouraging manufacturers to participate in the program; by testing energy-efficient products and drafting performance specification for labeling programs, specifiers, and procurement groups; and by disseminating information through publications such as *Specifier Reports* and *Lighting Futures*.

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27

Lighting Controls

The lighting controls covered in this chapter are electronic controls for electric lighting. Generally light sources are equipped with these controls for one of two reasons: for aesthetic control, which matches lighting intensity to the application and therefore controls the quality of the visual environment, or for energy management control, which limits the application of light to times when there is a demand and therefore reduces unnecessary lighting energy.

Proper use of these controls can assist with compliance with ASHRAE/IESNA 90.1 and the Canadian national energy code guidelines, reduce building operating costs, and significantly benefit the environment. It is incumbent on the engineer and lighting designer to be aware of the wide variety of electronic lighting controls available and to correctly apply them to the project at hand. As in all technology-driven areas, investigation of the current state of the art must be completed periodically in order to stay current in the field.

In the past, controls were used primarily to turn lights on or off, or for special purposes such as stage, theater, and conference room lighting. More recently the use of controls has become an essential element of good lighting design and an integral part of energy management programs for lighting of commercial, residential, industrial, and exterior areas. Lighting controls for specific applications are described in the various application chapters of this Handbook.

A variety of strategies and techniques has been developed to control a building's power demand, energy consumption, lighting equipment, and working environment. Some equipment is best suited for new construction and renovation, whereas other equipment is better suited for retrofit. This section describes different types of lighting control strategies, techniques, and equipment and their effects on building systems and occupants.

Studies of buildings that have implemented control strategies have shown that it is possible to reduce overall lighting energy consumption by as much as 80% in some localities.[1,2] Cumulative savings are dependent on the building configuration, the control hardware specified, the combination of control strategies selected, and the extent to which each of the control strategies is available for use within a building.

LIGHTING CONTROL STRATEGIES

There are three major objectives for the use of lighting controls: energy management, aesthetics, and code compliance measures. Energy management controls for lighting systems provide energy and cost savings through reduced power or reduced time of use. Aesthetic controls provide the ability to change space functions and can create emotional appeal, offering control of lighting quality, mood, color, and attitude. These benefits are not necessarily in conflict. Energy management control strategies can significantly improve the quality of a space, and controls installed primarily for aesthetic purposes can produce significant energy savings. Here, however, the two benefits are discussed separately. Power density credits are often given for control systems, enabling additional lighting to be used in a space, or to reduce overall energy consumption to meet code objectives.

Energy Management Strategies[3,4]

Predictable Scheduling. Where activities in a building occur routinely during the day, luminaires throughout the space can be operated on a fixed schedule (with overrides in case there are variations in the schedule). For example, staff arrival and departure times, lunch periods, and cleaning hours are predictable for weekdays, weekends, and holidays in many manufacturing plants, offices, schools, libraries, and retail stores.

Predictable scheduling strategies are particularly effective when work schedules are well defined for the entire area. Such strategies can reduce energy by as much as 40% by eliminating energy waste caused by lights operating in unoccupied spaces. Automatic scheduling also relieves staff of the burden of operating lighting controls and can be used to signal times of particular activities, such as the opening and closing of retail stores. It is unacceptable, however, to plunge occupants into darkness when scheduling the operation of the lighting system, so some prevision for overriding the schedule should be provided.

Unpredictable Scheduling. Many events are unpredictable and unscheduled, such as workstation vacancies due to sickness, vacations, staff meetings, and business trips. Unassigned areas such as restrooms, copy centers, filing areas, conference rooms, break rooms, and retail store dressing rooms are used sporadically and are not readily scheduled. Though these areas may not be amenable to tightly scheduled lighting operation, local automatic control techniques can be more cost-effective than the usual reliance on manual operation of lights. Unpredictable scheduling strategies using occupancy/motion sensors have yielded energy savings of over 60% in some areas. To assess the benefits of automatic controls, it is important first to determine the proportion of time the space is vacant. It is also important to consider that switching lights on and off can disturb occupants of adjacent spaces, as in an open-plan office. For reasons of aesthetics, safety, and user acceptance, lights in these spaces can be dimmed rather than switched off completely. Today occupancy sensors are being used to control lighting, HVAC, and office equipment (e.g., computer monitors) in offices, warehouses, library stacks, and many other areas.

Daylighting.[5-8] In the perimeter areas of buildings, part of the desired illumination can often be supplied by daylight (see Figure 27-1 and Chapter 8, Daylighting). In these areas, reducing the power for electric lighting in response to the amount of available daylight reduces energy consumption.

Both dimming and switching strategies can be used. For successful application of daylight-based switching, high levels of daylight must be present so that sufficient illumination for the task remains after the electric lighting has been lowered (Figure 27-2).

The energy savings realized from daylighting depends on many factors, such as the climatic conditions; the building form, orientation, and design; the sensor and control design and installation; and the activities within the building. Under some conditions, daylight can reduce electric energy costs significantly when photoelectric sensor controls are used. This is particularly important during peak power demand hours when the cost of electric energy can be much higher than during off-peak hours. It is essential that control of the electric lighting be properly integrated with the daylight illumination pattern to maintain adequate quantity and quality of lighting.

With respect to photosensor controls, the size and shape of control zones are usually constrained by the rapid falloff of horizontal illuminance from the window wall. Although lighting zones can be laid out to cover a single task area, a room, or an entire building, in practice the lighting zones should be close to the daylight-admitting elements. For typical spaces illuminated by daylight from a side window, the lighting zones should be adjacent to the window wall and no more than 4 m (13 ft) deep. The row of luminaires nearest the window should be controlled on a separate circuit from those in the interior area. Occupancy sensors manufactured today can have daylight sensing as a feature. If manually operated window shading devices are used, smaller control zones may be required for daylighting to be effective.

Brightness Balance. Lighting design often dictates limits to the brightness within or among spaces. (See Chapter 3, Vision and Perception, and Chapter 10, Quality of the Visual Environment). One design goal is to balance different brightness levels so that glare and shadows are reduced. For example, lighting controls can be used to mitigate the very high brightness produced by windows in interior spaces. One control technique is to limit light entering the space with blinds or louvers. Another possibly counterintuitive approach for interior spaces is to increase the illuminance produced by the electric lights. Often controls can be used to provide a luminous transition between two spaces having very different brightness levels. Perhaps the most common example is tunnel lighting (see Chapter 22, Roadway Lighting). The illuminance produced by the electric lights in the entry zone of the tunnel depends on the level of daylight illuminance; higher illuminances are produced by the electric lights in this zone on sunny days than on cloudy days.

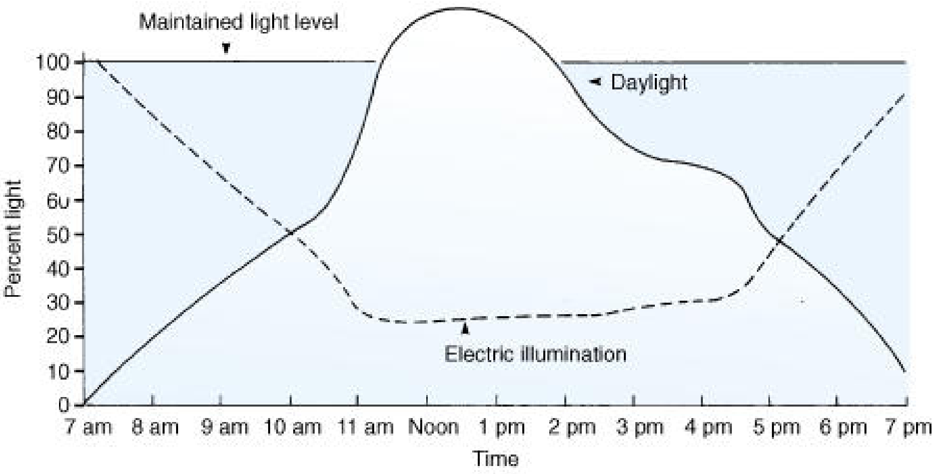


Figure 27-1. Photocell-activated dimmers maintain a constant light level by adjusting the output of electric illumination according to changing ambient illuminance.

Lumen Maintenance. Lighting systems are usually designed for a minimum maintained illuminance level. This requires the level of a new lighting system to exceed the design minimum by 20 to 35% to allow for lumen depreciation, specifically lamp lumen depreciation, luminaire dirt depreciation, and room surface dirt depreciation (see Chapter 9, Lighting Calculations and Chapter 26, Energy Management). Lumen depreciation control strategy calls for reducing the initial illumination of a new system to the designed minimum level. As lumen depreciation occurs, more power is applied to the lamps in order to maintain constant output. Thus, full power is applied only near the end of the lumen maintenance period, significantly reducing energy use over the life of the lamp (Figure 27-3).[2]

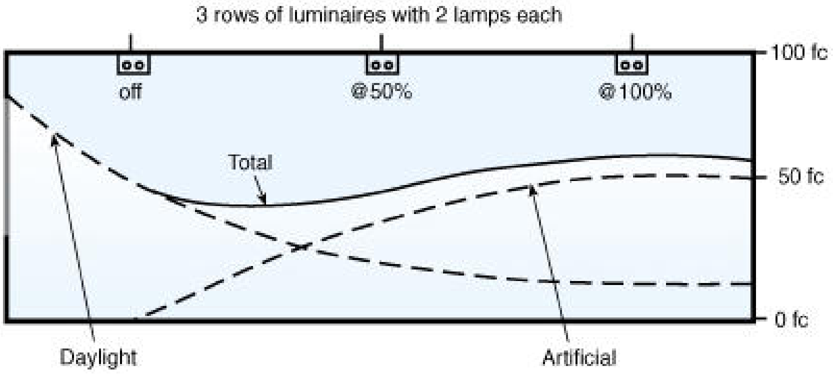


Figure 27-2. Illustration showing the rapid drop-off of illuminance from the window wall. In this space, daylight must be supplemented by electric lighting as the distance from the window wall increases.

Lumen maintenance can be accomplished through the use of a dimming system with photosensor input. The control system for lumen maintenance is most cost-effective when large blocks of luminaires are controlled together. Group relamping to maintain all of the lamps at virtually the same lumen output is required for the system to be effective in reducing both energy and maintenance costs.

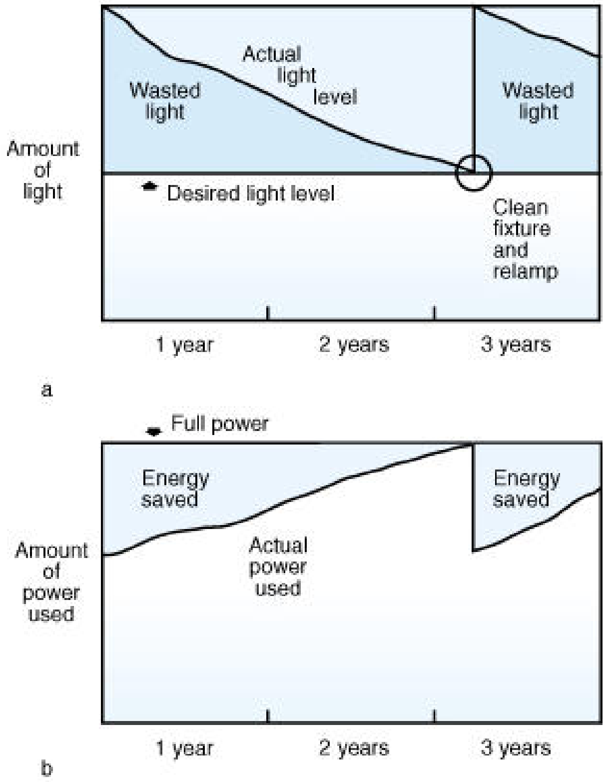


Figure 27-3. Lumen maintenance control strategy. (a) Light levels drop over time with conventional lighting systems, but power remains constant; (b) with a lumen maintenance system light levels stay constant, and energy is saved.

Task Tuning. Uniform illuminances are often provided throughout a space. With a task-tuning control strategy, however, the lighting system can be adjusted, or tuned, to provide local illumination as needed. Levels can be lowered in areas such as aisles and reception rooms and raised in areas where more difficult visual tasks occur. Considerable savings are possible through task tuning.[2] This strategy results in the efficient use of energy for lighting without sacrificing occupant visual performance.

Tuning is accomplished by varying the light output of individual or small groups of luminaires. Since it is necessary to tune the lighting only occasionally, upon a change in the space utilization or in the task being performed, the adjustment often can be done manually. Light controllers are capable of tuning a zone of luminaires.

Load Shedding and Demand Reduction. A building's lighting electrical bill can be effectively reduced by controlling lighting power demand for short periods of time. Selective reduction of illuminance in less critical areas can be particularly effective in regions where the peak electric power demand occurs in summer, because a reduction in lighting load also reduces the cooling load. Peak power demand charges are employed by many utilities to help avoid brownouts and blackouts, so the savings at peak periods can be substantial.

Aesthetic Control Strategies. Many spaces in commercial, institutional, and residential applications are used for more than one purpose. Different tasks require a variety of lighting conditions. Aesthetic controls provide the means to adjust the lighting to suit the purpose, to maintain human visual performance, and to change the mood of the space.

Aesthetic controls include switching and dimming. Dimming controls can provide dynamic effects or create strong focal points. Changes can occur rapidly to create excitement, or subtly to create a smooth transition between different room functions.

For many aesthetic applications it is necessary to control illuminance over a wide range. In a conference room, for example, a high illuminance would be required for reading tasks, whereas for a slide presentation the illuminance should be one-tenth or less of the reading level. The differences in needed illuminance are due to the differences in the task visibility and the adaptation of the eye to changes in illuminance. The square law curve for adaptation used by most controls manufacturers is shown in Figure 27-4. The curve shows, for example, that a measured illuminance of 25% of the original illuminance is perceived as a brightness of 50% of the original level. Audiovisual applications for controls generally require a measured illuminance of less than 10%, depending on the room reflectances, the screen employed, and the degree of note-taking required.

It is important to use a light source that can be appropriately dimmed. Incandescent and low-voltage incandescent sources can dim to zero output. Fluorescent sources can be dimmed to 1% output when used with certain dimming ballasts. Neon and cold cathode lamps can be dimmed to approximately 10% of maximum light output. HID sources can be dimmed to approximately 20% of maximum light output, but they have a slow response time and strong color shifts, which make them poorly suited for aesthetic applications.

The strategies used for aesthetic control include manual controls, preset control systems, and central control systems. Manual controls (switches and dimmers) are commonly used in commercial, institutional, industrial, and residential buildings. If they are to be effective, manual controls should be simple and convenient to use. The number of control channels should be minimized to avoid confusing choices. Control panels should be clearly and permanently labeled (Figure 27-5). The appearance of the controls is also important. Switches and dimmers should match each other and fit into the overall architectural style of the space.

Preset control systems allow for several lighting channels to be controlled simultaneously. All channels are programmed to provide multiple moods or scenes. Each of these scenes can be recalled with the touch of one button (Figure 27-6). Preset systems are valuable in multifunction commercial spaces such as conference rooms and ballrooms. They are also used in residential applications for areas such as living rooms, dining rooms, and media rooms.

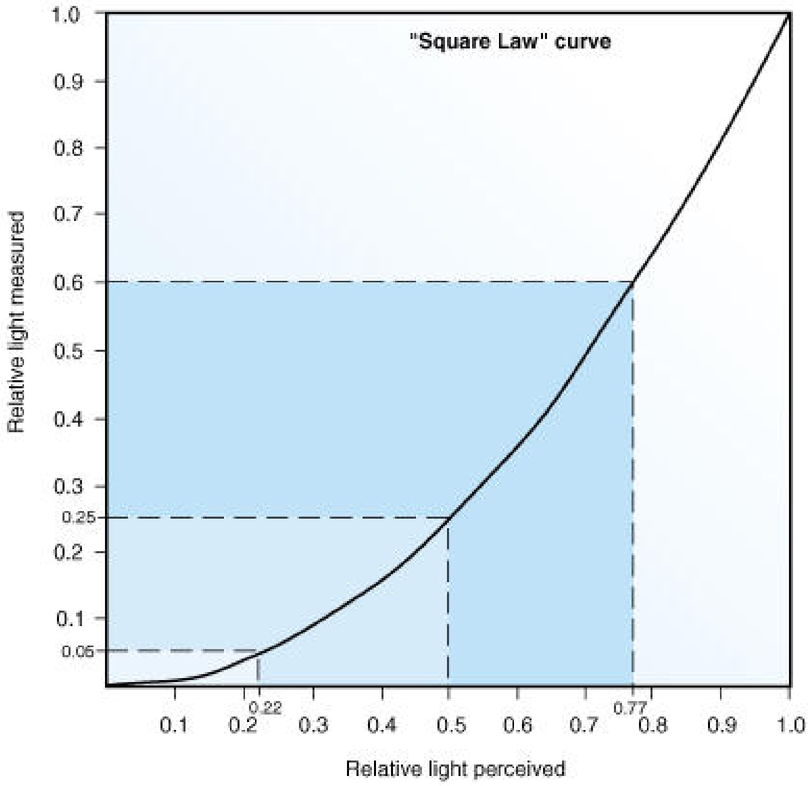


Figure 27-4. Square Law Curve--A presumed relationship between perceived illuminance and measured illuminance.

Central dimming systems are the most powerful of the group of dimming options. Like theatrical dimming systems, they have at least one central dimming panel with dimmers suitable for the type of load. The dimmers themselves are the power-handling devices. The control-function logic is typically in the control stations, which can include processors and several forms of manual or preset controls.

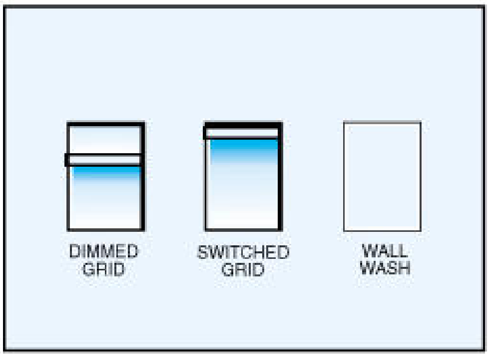


Figure 27-5. Switches and dimmers, clearly labeled for easy use.

Local, single-room systems typically consist of one control station with manual sliders or nondimming switches that can control large amounts of power. The dimmable wattage is limited only by the number of modules a dimmer panel can hold. These systems are easily expanded to multiple rooms and customized to offer many combinations of manual, preset, assigned, and time-clock control. They can incorporate energy reduction controls such as occupancy/motion sensors and photosensors and can handle emergency power functions. Some systems allow wireless remote control and can interface to audiovisual and other systems in both commercial and residential applications.

In divisible rooms, assignment control stations allow several independent lighting systems to be joined together through flexible master control. Hotel function rooms and convention center meeting rooms are the most common applications.

Whole-house systems are being used more frequently. Using local or small modular dimmers, a central computer, and master control stations, these systems can control every lighting feature. Many of these systems can also operate other electrical systems such as motorized curtains or whirlpool pumps, and they interface easily with burglar alarms, smart home systems, and other electrical control systems.

Figure 27-6. Example of multichannel preset station that provides four scenes of control for twelve

LIGHTING CONTROL TECHNIQUES[2,3]

Selection of the major control techniques is particularly important in the specification process. The following three categories establish the major choices: switching or dimming control, local or central control, and degree of control automation. After the strategies are decided, it is necessary to select the specific lighting control equipment to be employed.

Switching or Dimming

With switching control, lighting loads are switched on and off. This switching can be done manually with simple wall-box switches, remotely via relays or switchable circuit breakers, by a control system, or by occupancy sensors. It has been found that where the use of local switching controls can save energy, convenient switches might be used, but inconvenient switches are never used. Two-level switching in private offices is an inexpensive way to give the occupant the ability to modulate the environment in response to daylight or specific task needs. A different way to achieve switched light levels is through a light level switchable ballast. Rather than switching between lamps, the light level switchable ballast can reduce the light from all lamps in the luminaire.

Central switching systems can be less expensive to install per unit area than equivalent dimming systems and are most appropriate for strategies such as scheduling, where the switching action can be confined to unoccupied times. Switching techniques should be treated cautiously for other purposes, especially if the switching action can occur when the space is occupied, because sudden changes in the electric lighting can annoy building occupants, thus affecting productivity.[3]

In multiballasted lighting systems, switching can be used most effectively if the luminaires are split-wired. By split-wiring three- and four-lamp luminaires (Figures 27-7 and 27-8), multiple intensities can be provided in a single zone. With the help of a control system, full lighting can be provided for certain portions of the day while allowing a reduced lighting level (at reduced power) for times when less demanding tasks are performed. In retrofit applications, split-wiring can be expensive. Depending on the wiring system in place, relays can be installed near the circuit breaker panels to permit automatic control of blocks of lighting (Figure 27-9).

Occupancy or motion sensors can be used to control lighting in offices, conference rooms, and similar areas. In these situations, the addition of toggle switches or sensors with override switches to provide the manual off condition for certain applications (e.g., projections and maintenance) is recommended.

With dimming control, the illuminance in each zone can be varied smoothly and continuously to dynamically match visual requirements. Dimming control can be well suited to daylighting applications. However, the dynamic range of daylight is much larger than it is for electric lighting (5:1), so caution must be applied in selecting the appropriate dimming control and sensitivity setting. Similarly, dimming is effective in saving energy by compensating for the gradual light losses that occur over time with all electric lighting systems (lumen maintenance strategy).

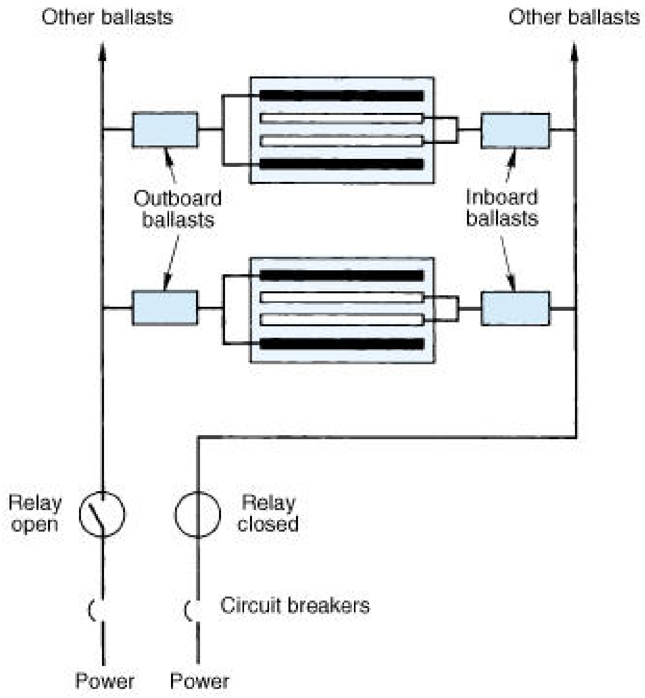


Figure 27-7. Split-level wiring scheme that permits three lighting levels (0, 50, and 100%) with four-lamp luminaires. Above luminaires are shown at 50% lighting levels.

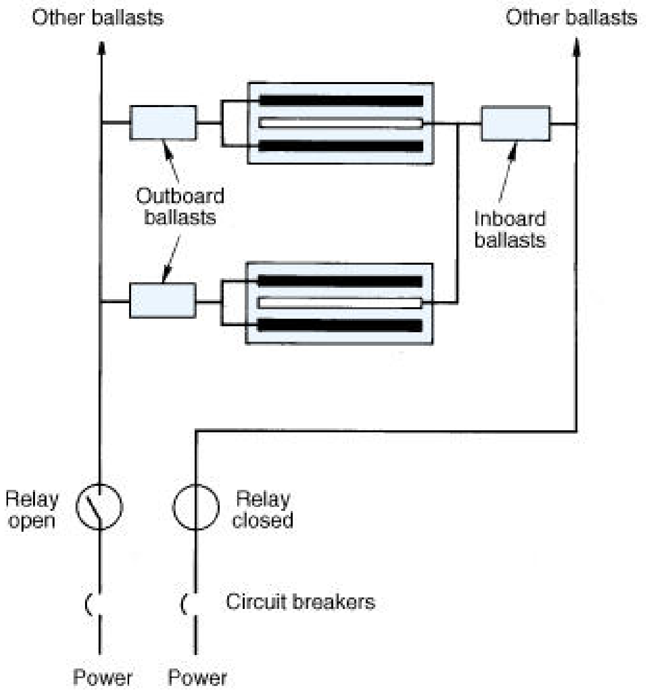


Figure 27-8. Split-level wiring scheme that permits four lighting levels (0, 33 1/3, 66 2/3, and 100%) with three-lamp luminaires. The above luminaires are shown at 33 1/3% light levels.

Local or Central

Lighting controls can be implemented in buildings using either a local approach, a central system, or some combination of the two. The two approaches are distinguished both by the size of the controlled areas and by how the control inputs are integrated into the system.

A local lighting system is divided into independently controllable zones, their size and shape typically dictated by the geometry of the building spaces (such as the locations of ceiling-high partitions, windows, or skylights) or according to functional need. Sensor inputs are wired directly to the local lighting and HVAC control rather than to a central location. Thus each module is essentially independent of other modules. The use of automatic occupancy sensors that can sense daylight availability can be especially effective in these situations.

Central systems generally combine many local zones. Some central microprocessor systems are intended to handle either the lighting and mechanical (HVAC) systems or both. Total building energy-management control and monitoring functions are easier with central systems.[4]

System Integration. One major advantage of a lighting control system is that the illuminance can be automatically adjusted to suit the activity or tasks at hand. With proper programming and sensors, some processors can control the lighting systems as well as the mechanical systems of the building. A common system permits the optimum control of energy use and also minimizes programming and training requirements. Through the use of a distributive processing configuration, the differences between mechanical and lighting inputs and control strategies are easily overcome. The local processor can be designed for the specific inputs and control outputs as well as the required interface with the central processor.

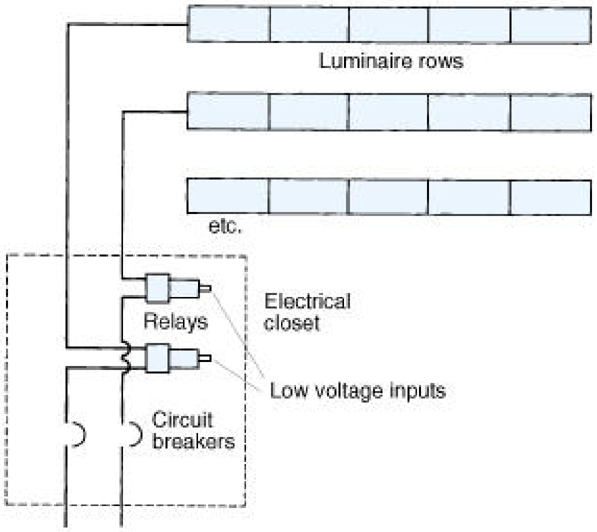


Figure 27-9. Installation of low voltage relays in an electric closet controlling different banks of luminaires.

All lighting control systems contain three major components: a power controller, a logic circuit, and a sensing device. The communication and wiring system must link these components. The controller, such as a dimmer, relay, or switch, is the "business end" of a control system that electrically changes the output of the light source. The logic circuit is the intelligence that decides when to supply electric lighting, and how much. The logic circuit receives its information from a sensing device, such as a photosensor, an occupancy/motion sensor, or a timing device. Two or more of these elements can be combined in a single system (Figure 27-10).

Control strategies can have different but overlapping sets of hardware requirements. For some combination of strategies, such as daylighting and lumen maintenance, the hardware required for either is essentially identical to that required for both. Thus, the economic benefit of employing several strategies with the same hardware can increase the cost-effectiveness of the control system investment.

Hardwiring. There are many methods available for linking the lighting control system components. The control device itself (dimmer, relay, or switch) is usually hardwired to a lighting system before the supply and the ballast (line-side controls), as shown in Figure 27-11a. Some electronic ballasts incorporate circuitry to vary the output of the lamps over a wide range, effectively combining the control device and ballast into one integrated package (Figure 27-11b).

Power Line Carrier. The power line carrier is a communication method that is finding some application in retrofit control installations. By allowing communication between the processor and the control device directly over the existing power lines, extensive rewiring is avoided. However, some wiring systems in older buildings can significantly reduce the effective range of communications between the sensor, the processor, and the controller. There are limits to the overall capacity and speed of these systems. Care must be taken to ensure that all of the control devices on the power line are compatible as a system and suitable for the application. Many other factors contribute to a successful installation, but often poor power quality and pre-existing power line carrier systems (lighting, clocks, and/or other systems) can compromise the proper operation of these systems.

Radio Links. Radio-controlled systems eliminate the need for wiring between the sensor, the processor, and the controller. These systems are relatively expensive but have found application in outdoor systems and high-bay warehouses where the controlled luminaires are difficult to access. They are also suited to retrofit situations where control wiring would be difficult or expensive to install.

Radio frequencies from many sources can interfere with proper operation of this equipment. The required frequencies and bandwidths must be found for this system to work.

Degree of Control Automation and Zoning

Controls vary greatly in degree of automation, ranging from manual (wall switches) to highly automated. In terms of energy conservation, automatic controls can reduce energy consumption because they do not rely on human initiative. In terms of cost and occupant response, automatic controls are not always the most effective. Allowing occupants to override the automatic operation when required is very important, especially when programmable controls are used for scheduling purposes. A strict lighting schedule can be employed if automatic control can be locally overridden when necessary.[2]

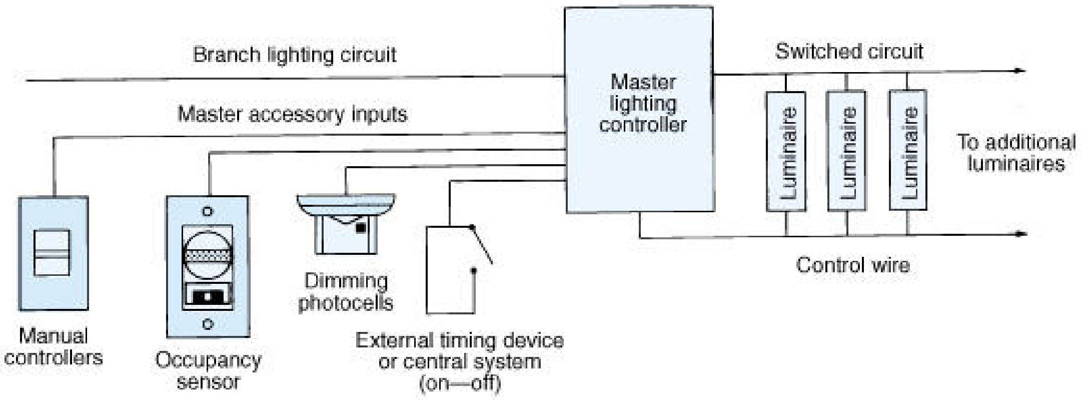


Figure 27-10. Diagram of a lighting control system.

Zoning. Compliance with energy codes, such as ASHRAE/IESNA 90.1, requires much closer coordination between the electrical engineer and the HVAC designer. Lighting and mechanical zones should match for coordinated control. In most cases this results in zones sized from 80 m^2 to 300 m^2 (800 ft^2 to 3000 ft^2). There is a tradeoff between the size of the control zone and the system cost. Smaller zones are more expensive (both in equipment and in installation costs) but offer greater flexibility and potential for reducing lighting operating costs. Some control strategies, particularly daylighting and task tuning, are best implemented with small control zones, 10 to 40 m^2 (100 to 400 ft^2), while scheduling and lumen maintenance can be used effectively even if the control zones correspond to the area illuminated by an entire branch circuit, approximately 100 to 400 m^2 (1000 to 4000 ft^2).

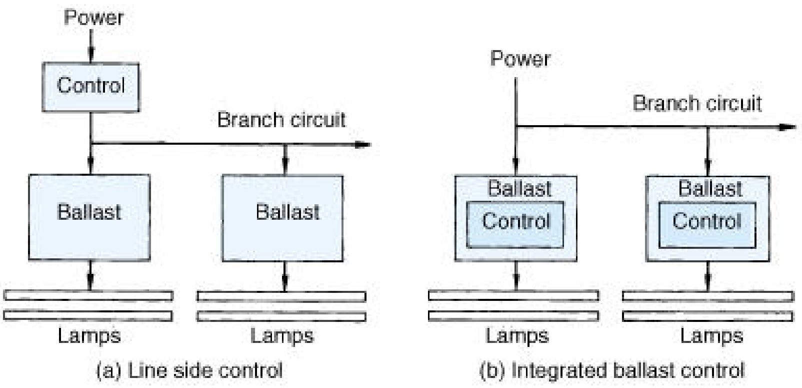


Figure 27-11. Lighting control operating lamps from (a) the line side of the luminaire; (b) integrated internally with the ballast circuitry.

LIGHTING CONTROL EQUIPMENT

Manual Switching

The energy savings achievable through switching should be the initial consideration in developing the plan for lighting circuits. The most common practice is to allow manual control of lighting. The design and the location of the manual control affects the energy consumption of the building. Since the energy savings depend on the willingness of individuals to use the switching system, the convenience and flexibility of switching greatly affect the extent of any lighting energy savings. Occupants of private offices are the most likely to use switches to modulate the illuminance in their space and to do their part in saving energy. There is evidence that light switch reminder stickers can improve occupants' switching behavior.[9]

Each lighting plan presents a unique set of switching circumstances. The following general provisions should be considered:

1. Each separate office or area should have its own control switch, and those with daylighting should have at least two-level switching.
2. In large open spaces, similar work areas should be grouped together on one circuit.
3. When single- or two-lamp luminaires are used, adjacent luminaires should be placed on alternate circuits to provide for half and full light level.
4. When three-lamp fluorescent luminaires are used, the middle lamps should be connected to a separate circuit from the outside lamps. This produces three-level lighting systems with one-third, two-thirds, and full light level.
5. When four-lamp fluorescent luminaires are used, the inside pair of lamps should be connected to a circuit separate from the outside pair to provide half and full light level.
6. Task areas with high levels of lighting should be on separate switches.
7. Luminaires along window walls should be wired on separate circuits and be controlled independently.
8. Effective labels can cause occupants to use simple wall switches.[10]

Timing and Sensing Devices

Timing Devices. The function of the timer is to control lighting in response to known or scheduled sequences of events, that is, to turn off the lighting that is not needed. Timers range in complexity from simple integral timers (spring-wound) to microprocessors that can program a sequence of events for years at a time. Coupled with microprocessors, timers can control multiple events and lighting effects. As a general rule, some form of override must be provided to accommodate deviations from the preset schedule. The override should automatically reset to the programmed functions after a suitable period. Such timers can be effective in guest bathrooms in hotels, telephone equipment rooms, and certain stack applications, where occupancy sensors cannot effectively cover the entire area, and the area is not subject to complete blackout conditions if the lighting under timer control is extinguished.

With a simple integral timer, the load is switched on and held energized for a preset period of time. Timer limits range from a few minutes to twelve hours. Some models have a hold position for continuous service. These units can handle lighting loads of up to 20 A.

An electromechanical time clock is driven by an electric motor, with contacts actuated by mechanical stops or arms affixed to the clock face. Time clocks have periods from 24 hours to 7 days and can include astronomical correction to compensate for seasonal changes. They can initiate numerous on-off operations. Some units are available with up to 16 hours of back-up power on the timing mechanism in case of power failure. Some can actuate a momentary contact switch to provide on and off pulses for actuating low-voltage relays or contactors. Wall-mounted (outlet box) units are also available to control local loads such as security lighting.

Electronic time clocks provide programmable selection of many switching operations and typically can be controlled to the nearest minute over a seven-day period. These devices offer the same switching options as the electromechanical time clock. Battery backup is available to protect the system from power outages.

Photosensors. Photosensors use electronic components that transform visible radiation (light) into an electrical signal, which is then used to control another system or lamp. Generally these sensors are either immune to or filtered from UV and IR radiation. Some sensors generate a control signal roughly proportional to the irradiance on the photosensor. The control signal can activate two modes of operation. In the first, the photosensor output activates a simple on-off switch or relay. In the second, a variable output signal is established and sent to a controller that continuously adjusts the output of the electric lighting.

When photosensors for interior applications are used in conjunction with relays for on-off control, they should utilize a "dead band," that is, the illuminance above which the lamps are switched off should be higher than the illuminance below which they are switched on. This prevents unnecessary on-off cycling near the threshold illuminance levels. It is also important to consider that switching lights on and off can disturb occupants. A photosensor can be an integral part of a luminaire, can be remote from the luminaire that it controls, or can control a circuit relay that operates several luminaires. A photosensor can also be used in conjunction with a time clock, which can switch lights off or reduce their output.

Photosensors used in outdoor applications are usually oriented to the north (in the northern hemisphere). This assures more constant illumination on the sensor as there is no direct sunlight contribution. The sensors are adjustable with respect to light levels for activation. Photosensors designed for outdoor lighting should not be used to control interior lighting because of their limited sensitivity and adjustability.

Systems that continuously vary their output disproportionally in response to the varying photosensor irradiance are most effective when employed for window or daylighting strategies. The photosensor detects an increase in illuminance and sends a compound signal to the controller to decrease the electric lighting illuminance. Systems that vary their output proportionally in response to the varying photosensor irradiance are most effective when employed for lumen maintenance. In response to the signal, the lighting system can be adjusted by stepped or continuous dimming.

The use of photosensors to control interior lighting is not trivial; proper design, placement, and calibration are critical.[10] Several techniques are currently employed. Placement of the sensor on the task surface has the advantage of direct measurement of task illuminance, but there can be difficulty in wiring the sensor to the controller and in ensuring that the sensor does not damage and is not damaged by the task materials. The second and most common method places the sensor on the ceiling, oriented toward the task. A third method measures the daylight entering through the fenestration; best results are achieved when direct sunlight cannot fall on the sensor. A fourth method measures the external illuminance directly. All methods require the sensor output to be adjusted to match the illuminance on the task as closely as possible. An accurate and easy means to calibrate the response of the sensor is essential. Lumen maintenance strategies typically use the second method, and daylighting strategies can use any of the last three methods.

A further consideration with interior lighting is the amount of area controlled by one photosensor. The most important guideline is that all of the areas controlled by a single sensor should have the same general task activity, illuminance requirements, and surround. The space controlled should have the same daylight illumination conditions (amount and direction). The entire area should be contiguous, having no high walls or partitions to divide it. This is effective only if the task area monitored is truly typical and free of brightness extremes.

Occupancy/Motion Sensors.[11] The primary function of occupancy sensors is to automatically switch off luminaires (and, in some cases, HVAC equipment) when spaces are unoccupied, so as to reduce energy use. Electrical consumption is reduced by cutting the number of hours that luminaires remain on, and electrical demand is reduced by tak-ing advantage of incomplete occupancy loads during periods of peak electrical use. Frequently, this method offers the best savings and payback of all control options. The failure of an occupancy sensor installation is almost always a result of poor sensor placement or incorrect equipment selection.

Occupancy/motion sensors provide local on-off control of luminaires in response to the presence or absence of occupants in a space. Occupancy is sensed by audio, ultrasonic, passive infrared, or optical means. These devices are designed to switch lights on as an occupant enters and keep them on while he or she remains in the space; lights are switched off after a preset time following the departure of the occupant. The normal movements of a person should sustain lighting in the occupied space. Quiet activities such as word processing, reading, or using the telephone, however, may not be detected, and lights being switched off can frustrate occupants in these situations. These nuisance actions can be minimized by suitable product selection and proper sensor location. Occupancy/motion sensors can be mounted in several ways: they can be recessed or surface mounted on the ceiling, corners, or wall; they can replace wall switches; and they can plug into receptacles. The floor area covered by individual sensors can range from 15 m^2 (150 ft^2) in individual offices or workstations to 200 m^2 (2000 ft^2) in large classroom or assembly spaces. Larger areas can be controlled by adding more sensors. Occupancy/motion sensors can be used in combination with manual switching (on or off), timers, daylighting sensors, dimmers, and central lighting controls.

When selecting a sensor and planning for its location, the designer should ensure that all important movements within the controlled area are detected, subject to the avoidance of false positive responses; that is, responses to movement by inanimate objects inside the room or by people outside the entrance. It should also be recognized that the operating life of fluorescent lamps can be reduced by increased switching. The amount of the reduction can vary greatly and is dependent on the type of lamp, ballast starting circuitry, and the frequency of switching. The actual service life of the lamps, however, can be increased by the elimination of unnecessary burning hours. Research has determined that sensible lamp life, eliminating most premature lamp failure, balanced with meaningful energy savings, can be created with time delays of 15 to 30 minutes.[12]

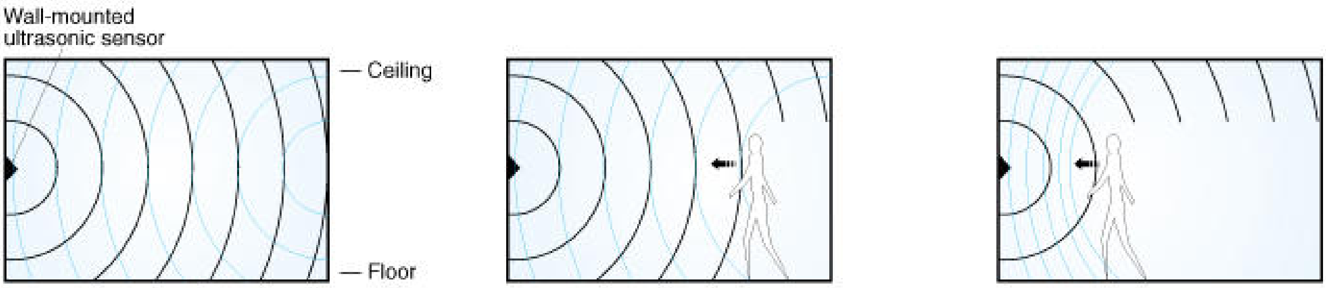
It is common for occupants to override the action of occupancy sensors when they cause inconvenience or annoyance. A defeated occupancy sensor offers no energy savings, so proper operation from the very beginning is critical to the success of the installation.

Technically occupancy/motion sensors use an electrical or mechanical mechanism to trigger a switch device. Low total harmonic distortion (THD) electronic fluorescent ballasts can create a high in-rush condition, which could cause premature failure of the occupancy sensor switching device. Some of the sensors on the market have a technical solution to managing this in-rush problem. Other technical considerations include the manner in which the sensor generates its own operating current; some devices use a neutral connection, and others use a trickle current through a connection to the ground. Finally, devices with solid-state switching devices can have a minimum load, whereas devices with dry contacts generally do not have a minimum load specification. Check the manufacturers' literature for additional details.

Large areas can require multiple sensors and multiple power devices for multiple circuits. Several combinations are available, with remote sensors, a variety of sensor technologies and coverage patterns, and voltage-specific power packs.

Ultrasonic occupancy/motion sensors transmit a low-power, high-frequency signal and receive a reflected signal, using the Doppler shift to sense movement in a space. The frequency of ultrasonic sensors is usually between 25,000 and 40,000 Hz (Figure 27-12). Ultrasonic occupancy/motion sensors are normally better at detecting small movements and detecting movements around modular walls such as would be found in restrooms and open offices. Also, most ultrasonic occupancy/motion sensors should not be mounted on ceilings above 4 to 5 m (14 to 16 ft).

There have been reports of ultrasonic occupancy/motion sensors interfering with hearing aids. Hearing aids operating above 40 kHz are not affected by ultrasonic occupancy and motion sensors. If the hearing aids are adjusted to operate within specifications, there should be no interference experienced.



This figure shows a simplified wave pattern in an empty room. Ultrasonic waves (black) are emitted by the sensor and reflect off the back wall. The reflected waves (blue) then return to the sensor.

A person, or any object in the room, reflects waves emitted by the sensor. As a person moves in the space, the frequency of the waves reflected off the person changes. The sensor detects this change in frequency, and the luminaires are turned on.

Figure 27-12. Example of motion detection with ultrasonic sensors.

Passive infrared (PIR) sensors detect the changes in infrared patterns across their segmented detection regions, tuned to the region of human body temperature (Figure 27-13).[13] PIR occupancy and motion sensors have a line-of-sight coverage pattern with very predictable pickup patterns. They can be masked for controlling unwanted coverage areas. PIR sensors are especially suitable for areas that have high ceilings or high air velocities, as well as most general applications. They are most sensitive to movements perpendicular to the direction of view.

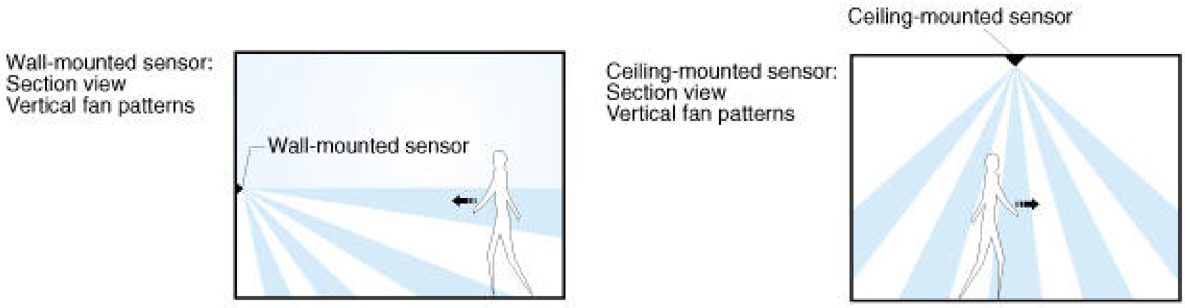


Figure 27-13. Example of motion detection with infrared sensors. The motion of a person through the pattern of receiver areas is detected as a change, and the luminaires are turned on.

Dual-technology sensors are available that can use either UV or PIR signals or both. The logic and verification that can be incorporated in one unit can assist with applications where false triggering is especially problematic. Also, packaged sensors are available for desk-top applications to control task lights and computer monitors.

Central Processors

For centralized systems, the processor is the device that assimilates the data, determines the required change, and initiates action to effect the change. More sophisticated processors can respond to a number of complex lighting conditions in the space, collect power and energy-use data, and supply summary reports for building management and tenant billing. Processors range in complexity from a microchip in a controller to a large computer. Simplicity of operation and control, coupled with automatic operation in response to the actual environment, is essential.

In general, all processors operate in the same way. Input is received from a sensor such as a photosensor or clock, data are analyzed in accordance with a predetermined set of rules, and a system change is initiated. Systems can respond to manual switches as well as to automatic functions (such as the time of day) and illuminance conditions. Outputs can include switching, dimming, and adjusting daylighting shading or reflection devices.

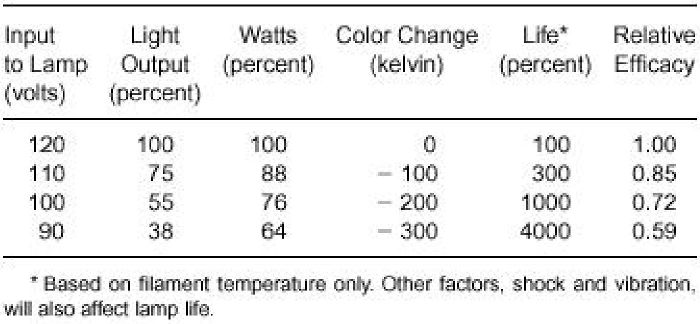
There are three types of processors: local, central, and distributed. In the local type, the processor is located in or adjacent to the device it controls. Sensor inputs go to a signal conditioner, either analog or digital, and are then fed to the processor. The central processor receives all inputs, analyzes the data, and then sends instructions to controllers located throughout a facility. This method allows coordinated control of all system elements. In distributed processing, the ongoing decision making is left to local processors, but a central processor orchestrates the entire system. It provides a time signal, operating parameters, and direction to specific points on an exception basis (one that overrides the normal routine). Most inputs are directed to the local processor. Analysis is performed locally, with only exception data being sent to the central processor. The advantage of this system is that it does not collapse from the loss of any one processor, and only the local processor has to be reprogrammed to accommodate changes.

DIMMING CONTROLS

Controllers for Incandescent Lamps

Equipment to control the light output of incandescent and tungsten-halogen lamps is readily available. Early lamp dimming controls were simply variable resistances connected in series with the lamps. The method wasted energy because some of the power saved in the lamp was dissipated in the resistor. An alternative to resistive dimmers was the autotransformer, which efficiently reduced voltage to the lamps, so transformer losses were relatively small. The autotransformer offers smooth, quiet, reliable dimming without introducing line interference, but it is bulky and heavy. Today, most dimming equipment relies on solid-state switching components that offer small size, design flexibility, and lower cost. This technology employs thyristors or transistors as the switching element to efficiently control the power to the lamps. However, the fast switching of these electronic devices can generate electromagnetic and audible noise as well as harmonic distortion that must be filtered.

Dimming incandescent and tungsten-halogen lamps affects the light output, life, and color temperature of the lamp. For example, a 12% power reduction decreases light output by 25%, and the lamp life triples. Figure 27-14 illustrates the effects of reduced voltage on light output, power, correlated color temperature, lamp life, and efficacy. Note that as the voltage is decreased, the light appears warmer. Tungsten-halogen lamps require certain minimum temperatures to operate correctly. To guarantee this, some control systems periodically operate the lamps at high levels for programmable times, to allow the halogen cycle to clean the inside of the lamp envelope. There can be an impact on overall lamp life if the lamp is operated at too low temperatures for extended periods of time. For this reason it is better to select lamps close to the desired lumen output rather than dimming high wattage lamps to lower levels.



Input to Lamp (volts)	Light Output (percent)	Watts (percent)	Color Change (kelvin)	Life* (percent)	Relative Efficacy
120	100	100	0	100	1.00
110	75	88	− 100	300	0.85
100	55	76	− 200	1000	0.72
90	38	64	− 300	4000	0.59

* Based on filament temperature only. Other factors, shock and vibration, will also affect lamp life.

Figure 27-14. Change in Characteristics of Typical Incandescent Lamps Operated Below Rated

Voltage

The dimming of low-voltage incandescent and tungsten-halogen lamps is very similar to the dimming of line-voltage incandescent lamps, with a few important exceptions. Special dimmers should be used that are specifically designed to dim these specialized loads and to protect the lighting system from the problems associated with the low-voltage transformers. Magnetic transformers require supervisory circuitry to prevent dc current from reaching the load. All dimming of low-voltage loads requires the use of approved dimmable transformers. This ensures that the transformers do not fail during the dimming process, and that they do not make objectionable noise while in operation.

Controllers for Fluorescent Lamps[14]

The fluorescent lamp is the primary light source for commercial and retail applications. Unlike the incandescent lamp, which is a pure resistive load, the fluorescent lamp is a complex negative-resistance load requiring a ballast to maintain the proper electrical input for both starting and operation. Simply reducing the input voltage, as is done to dim incandescent lamps, extinguishes the arc at some point, as well as reduces the life of the lamp. Equipment is available to dim these lamps when operated with standard magnetic ballasts, magnetic dimming ballasts, or electronic dimming ballasts. Many new products are available to control fluorescent lamps on highly efficient electronic ballasts (Figure 27-15).

Fluorescent lamps operated with special electronic dimming ballasts, typically those that dim down to 10 to 20% of maximum light output and with enhanced low level capability (and higher cost), can be dimmed to less than 1% of full light output without producing flicker. Some electronic ballasts are also designed to reduce the electrode filament voltage at full light output and to restore it when the lamps are operated in the dimmed mode at low arc current. This extends the lamp life and reduces the power requirement at full light output (Figure 27-15b). Proper luminaire grounding is essential for stable lamp operation, especially at low light levels.

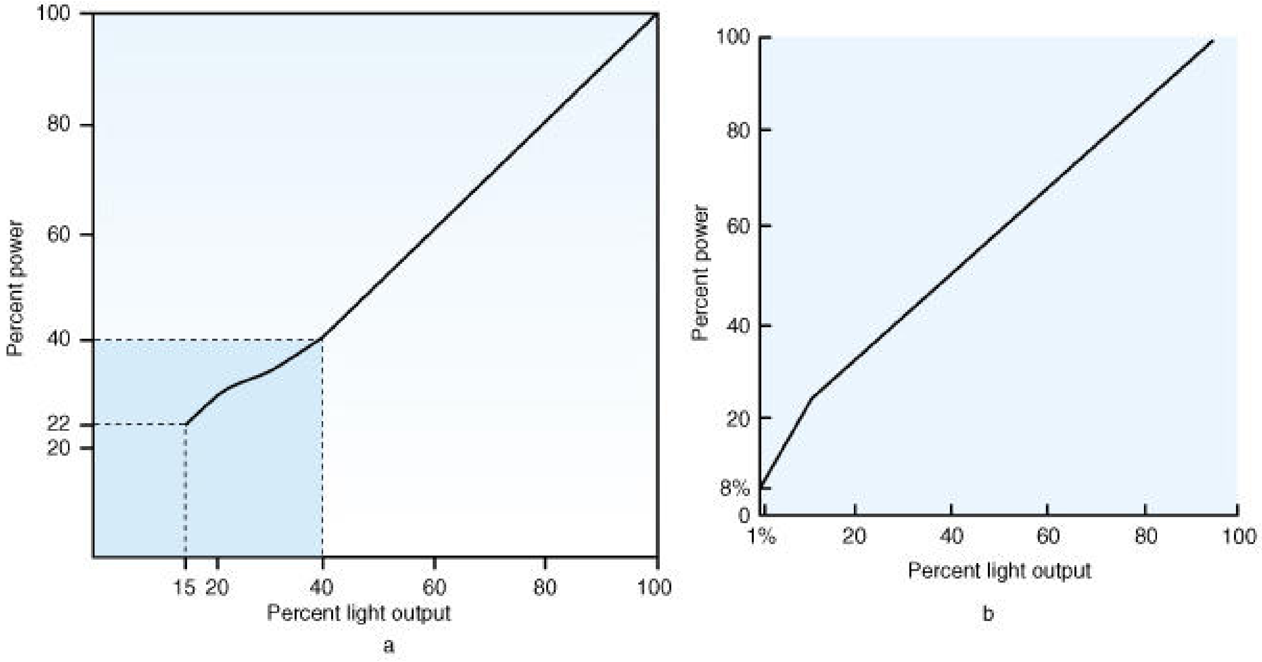


Figure 27-15. Relative light output as a function of power for (a) a two-lamp, 34-W, rapid-start fluorescent system with standard core-coil ballast. Minimum level of lighting adjustment is shown as 15% light output at 22% power; (b) three-lamp, 32-W, T-8 rapid-start fluorescent system with electronic ballast. Minimum level of lighting adjustment is shown as 1% light output at 8% power.

Control Methods. There are several types of electronic dimming ballasts on the market today. These ballasts differ in the way they are controlled by one of three methods: phase control, PWM (pulse width modulation), and low-voltage control (typically 0 to 10 V dc). The PWM control is the least used scheme, as it utilizes a high-frequency square-wave signal over separate control wires to dim lamps down to approximately 10% of maximum output. The main advantage of PWM control is its ability to control a large number of ballasts per controller.

The phase control method gives the user the most flexibility since it dims lamps to 1%. It uses a controller that controls up to 60 ballasts. This system gives very uniform dimming and lamp stability. Its main drawback is the high initial cost for equipment and installation.

The third control type is low-voltage control. A dc voltage is sent to each ballast via separate control leads. A single control device (e.g., slide dimmer, photosensor, building management system [BMS], etc.) can control 60 to 80 ballasts, with a stable dimming range of 100% to 20% or lower, depending on the low level capability of the ballast. This type of control is typical of many energy management applications.

Controlling the light output via low-voltage signals allows electronic dimming ballast systems to be more flexible than magnetic ballast systems based on conditioning the ballast input power. Large banks of electronic ballasts can be controlled as readily as a few. Thus, lighting control strategies such as task tuning, daylighting, and load shedding generally require modular control. Scheduling and lumen maintenance can be readily accomplished with electronic dimming ballast systems, since the ballast is controlled independently of the distribution system.

Multilevel Ballasts. Both magnetic and electronic multilevel ballasts are available. These provide the ability to be switched between two or more illuminances. They provide a low-cost, but limited control approach for dimming and can be used in some cases to satisfy energy codes.

Controllers for HID Lamps

High-intensity discharge (HID) lamps can be controlled using control equipment similar to that used for dimming fluorescent lamps. The long warmup, restrike delay, and color shift associated with HID lamps, however, can limit their applications. On-off control of HID lamps is most commonly used where there are long on and off periods, as for outdoor and roadway applications, where switching generally occurs twice a day. These typically use a photocell.

Multilevel ballasts are available for HID lamps, allowing the illuminance to be changed in steps. This technique is practical in warehouses, parking garages, tunnels, and daylighting applications. Recently, retrofit kits have become available to allow some existing facilities to have multilevel switching added to previously installed HID lamps. Equipment is available to dim HID lamps continuously to less than 20% of full light output. Color shift limits the range that can be used in some applications. Metal halide lamps shift color toward blue-green, and high-pressure sodium lamps shift color to yellow. The change in color becomes noticeable below 60% of rated lamp power for metal halide and 40% for high-pressure sodium lamps. See Chapter 6, Light Sources, for information on the relative change in power and light output for HID.

COST ANALYSIS

The approach used to evaluate the economics of lighting systems can be extended to include systems with controls.[15] Fundamentally, the procedure involves adding the cost of the control system to the rest of the lighting system equipment costs and determining how the use of the controls affects operating costs. Since lighting controls can affect not only the operation of the lighting system but also other building energy systems, all of the system interrelationships must be considered. In office buildings, for example, lighting controls that vary the output of the general lighting, perhaps in response to daylight, also change the amount and location of heat generated in the building. As the building's heating and cooling systems take this into account, the HVAC costs are affected. Some lighting control systems can also affect the electrical system; for example, by changing the power factor, high in-rush currents, and high harmonic currents, the performance of the lighting system itself can be altered in terms of efficacy, lamp life, and ballast life.

Energy savings depend on the size of the space, the availability of daylight, the work schedule, the kinds of activities performed, and the attitude and training of the occupants. For example, if the users are motivated to switch lights off each time they exit the area, then the installation of occupancy/motion sensors does not result in significant energy savings.

To estimate the energy that could be saved by using automatic controls, the areas to be controlled should be divided into smaller areas of similar function and occupancy, such as private offices with windows and open-plan sales offices. Users should establish a plausible use scenario for each small area, including:

- Hours of use
- Fixed or flexible work schedules
- Weekly, monthly, or yearly changes in the schedule
- Periods when areas are unoccupied, such as breaks, lunch, end of day, before cleaning
- Cleaning crew schedules
- Use of daylight to reduce electric lighting during daylight hours

The sum of the projected savings from small areas provides the total potential savings.

Cost Considerations

Some costs normally associated with the installation and operation of lighting control systems include:

- Control hardware, including sensors, control and monitoring station equipment, cabling and overcurrent protection
- Interface equipment, such as multiplexers in cases where control signals are carried by the power wiring, or data links and interconnection devices between controls and the telephone or onsite computer system
- Installation and setup labor, since several different skills (and therefore costs) can be involved in handling both signal and power level wiring, calibration, and checkout
- Maintenance labor and spare parts
- Energy costs and utility rate structures

Economic Analysis Techniques. Lighting controls are frequently cost justified on the basis of expected energy cost savings over a period of time. Methods of comparing the cost with the savings are explained in Chapter 25, Lighting Economics.[15,16]

Sources of Cost and Performance Data. Although cost information for lighting control hardware is easily obtained, performance information that affects operating and other system costs is not readily available and can be very site specific. The main operating-cost factors are the system input power and operating hours. Fairly accurate estimates for on-off control systems can be made if the operating period of the system is known, but systems with variable power inputs must be measured or carefully simulated. It can be helpful to construct a profile of system input power versus time or use computer modeling, especially if daylighting, time-of-day utility rates, or other special considerations apply.

Studies reveal that the impact of occupancy detectors is highly application dependent. The energy reduction realized from the proper use of occupancy sensors has been measured to be from 10 to 50%.[13]

IMPACT OF LIGHTING CONTROLS

Effects on the Whole Building

HVAC Effects. Lighting can be responsible for a major portion of a building's HVAC load. Thus, lighting electrical loads have a major influence on both the air-conditioning loads and fan operation. Lighting electrical loads affect the initial cost of the HVAC system as well as its annual energy consumption. If lighting controls are utilized to reduce the lighting energy consumption, it is important that the HVAC system and controls be designed to respond to changes in the operation of the lighting system. Furthermore, with the trend toward the use of daylighting to augment the electric lighting system, it is also necessary to consider the effects of the glazing system on the heating and air-conditioning system and its controls. Daylighting can increase the initial cost and the annual energy consumption if the daylighting system is not carefully designed. Indeed, payback can be longer with daylighting controls. For example, a daylighting system can increase the necessary summertime cooling load of a building by letting more heat into the building. Many modern occupancy sensors have dedicated control outputs for the simultaneous control of lighting and HVAC equipment.

By properly integrating the HVAC system and its controls with the lighting system and its controls, often both the initial cost of the HVAC system and energy consumption can be reduced. In order to achieve these benefits, the HVAC system must be properly designed with zoning and effective controls. The type of HVAC system is extremely important if full savings are to be achieved from lighting controls, especially in existing buildings where the air-distribution system is either a multizone, double-duct, or terminal reheat system; these systems supply a constant amount of air and vary the supply air temperature in order to maintain the space temperature.

In recent building designs, the use of multizone and terminal reheat systems has been eliminated by building energy codes. Most commercial systems use numerous small single-zone units or variable-air-volume (VAV) systems where the space temperature is maintained by an air supply of a constant temperature and varying volume.

Lighting controls can be integrated with the HVAC system within the building energy management and control system (EMCS). The primary application is the time scheduling of the start and stop of the various loads. The EMCS computer can also be used to consider the time of imposition of the various loads required for optimal start and stop and the thermal storage effects of the building mass.

Another consideration that affects the energy consumption of the HVAC system is the part-load efficiency of the heating and air conditioning, including the energy dissipated by fans and motors. Unless the HVAC system components and controls are designed to take into account the part-load efficiency, most of the potential HVAC energy savings from the lighting controls will not be realized.

Electrical Equipment Effects

Switching. Controls that switch lamps on and off excessively can reduce fluorescent[12] and HID lamp life. Increased cycling does not decrease ballast life or reliability. The actual service life of lamps can be extended by the elimination of unnecessary burning hours.

Interference. Radio frequency interference (RFI) or electromagnetic interference (EMI) is inherent in all control systems that rapidly switch a portion of input power. There are specific standards and limits to the radio noise permitted in the United States. The Federal Communications Commission (FCC) publishes these standards (FCC, Part 15 or 18)[17] and regulates the manufacture of devices that can emit radio noise. The Food and Drug Administration (FDA) publishes separate standards for radio noise for devices used in hospital environments. The FCC is concerned with all types of radiating devices, including various types of occupancy/motion sensors.

There are two areas of concern with regard to radio noise: conducted emission and radiated emission. Conducted emission is the noise fed directly into the power line by the device drawing power from that line. Radiated emission is the electrical noise radiated by the lamps in the luminaire, with the power line possibly acting as an antenna. Conducted emission follows the power line itself as a path of propagation. Generally, at high frequencies this noise is limited to the downstream portion of the circuit, from the branch transformer to the devices in question.

In most commercial and industrial buildings the lighting power circuits are contained within metal conduits. These conduits attenuate radiated electromagnetic energy and limit the radio noise to the circuits contained within the same conduit. Conducted emissions are of concern to the extent that they interfere with the lighting control system and any other devices on the same branch circuit feeds, such as computers or security systems. Control systems use passive and active filters to keep the conducted emissions within the allowable limits.

With shielded power lines, radiated noise is limited to the radio noise emitted directly from the controller and luminaire. It is of concern to the extent that other devices within the immediate area of the controller and luminaire can be affected. The primary antenna within the luminaire is the lamp itself. While all ballasts, lamps, and control systems emit radio noise that can interfere with some equipment, there are precautions that ballast and control manufacturers can take to reduce such noise. For conventional ballasts, noise filters are available. For solid-state high-frequency ballasts, which emit more radio noise than conventional ones, the noise is of a type and magnitude that can be more easily suppressed or designed out of the ballast. There are also luminaires with conductive lenses specifically designed to attenuate the EMI radiated by the lamps.

Power Quality

The power quality of electrical switching systems has become a concern to utilities with regard to power factor, safety, and interference. Most incandescent dimming techniques use phase control, in which the voltage to the lamp is reduced by high-speed switching. This distorts the sinusoidal line current, producing other frequencies and leading to a decrease in the power factor.

The designer should be aware of potential harmonics, as they can overload the neutral conductor in three-phase electrical distribution systems, which can damage its insulation, overheat transformers, and distort the voltage at points of coupling. In addition, if only a single leg of a three-phase system is dimmed, the system becomes unbalanced, further increasing the neutral current. In practice no problems have actually been attributed to the generation of harmonics by lighting control systems to date, but designers and engineers should become familiar with the issues when using these advanced lighting technologies.

Very low harmonic content electronic ballasts can have a high-in-rush current, associated with the front end power filtering. Consult the specific manufacturers' literature for detailed information on this.

Human Performance Effects

Lighting control systems can have a positive effect on the working environment, provided that they add to the comfort and the aesthetics of a space. Controls can have further economic benefit if the productivity of the occupants is increased. This can be true, for example, in spaces where visual display terminals (VDTs) are used because the brightness of reflected images is reduced by dimming the lighting. In general, the ceiling and task lighting can be controlled in zones over a wide range of illuminance to adjust the lighting to the specific needs of the spaces.[18]

Care should be taken when attempting to reduce peak power demand or energy use to ensure that illuminance is not reduced below that required for visual tasks in the space. Audible noise, flicker, and source color changes caused by dimmer controls can also affect performance.

Illuminance. The illuminance determines the visual adaptation level, which has been demonstrated to affect performance in visual tasks such as reading, inspecting, and assembling (see Chapter 3, Vision and Perception). Control systems must be designed so that the lighting system can provide proper illuminance for these tasks.

Audible Noise. Lighting control systems can produce audible noise in the environment, which can be a source of annoyance. The manufacturer should be consulted to minimize the noise produced by the control system. Noise control strategies include careful lamp selection, enhanced dimmer filtering, and remote dimmer locations.

Flicker. Controls that modify waveforms can cause excessive flicker. Flicker is noticeable if the variation in light amplitude is sufficiently high (see Chapter 3, Vision and Perception, and Chapter 6, Light Sources). Even imperceptible flicker can cause eyestrain and fatigue at 50 Hz.[19] While theoretically less of a problem at 60 Hz, some people are still sensitive to flicker. Proposed control systems should therefore be examined for their effect on flicker.

Flicker is typically greater with uncoated HID lamps than with fluorescent lamps. This is because the phosphors in a fluorescent lamp continue to generate light throughout the ac cycle. Most phosphor-coated HID lamps exhibit this reduced flicker. HPS lamps have high flicker because of the rapid recombination of sodium ions. Lamps should be selected that minimize flicker. Electronic fluorescent and HID ballasts should be selected because they drive the lamps without flicker. Further flicker reduction can be achieved with HID lamps by placing luminaires in a room on different supply phases.

Color Changes. During lamp dimming, there can be a small shift in lamp color with fluorescent lamps. This color shift is not usually considered significant, but it is noticeable, especially with warm CCT lamps. Other light sources, including incandescent lamps, exhibit a more significant color shift. Care must be exercised when employing such lamps. They should not be dimmed to levels that alter the aesthetics of the space, cause discomfort to the occupants, or affect tasks in which color rendition or discrimination are essential. One acceptable approach is to limit the range of dimming so that no color shift is apparent. On the other hand, the shift in incandescent lighting to a lower color temperature by dimming can actually be desirable in certain applications, such as restaurants, where a warmer atmosphere can be inviting.

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28

Lighting Maintenance

Lighting systems must be maintained to assure the lighting quantity and quality intended, whether for task performance, safety, or aesthetic reasons.[1] System components have a finite life and at some point in time must be replaced. Lamp performance changes over time before failure. Dirt accumulates on luminaire and room surfaces.

Lack of maintenance can have a negative effect on human performance, perception of an area, safety, and security. It can also waste energy. The combined effect of equipment age and dirt depreciation can reduce illuminance by 25 to 50% or more, depending on the application and equipment used. At the same time, the owner of the lighting system continues to pay the same amount for electricity as if the lamps were new and the lamps, luminaires, and room surfaces were clean.[2]

All of these factors tend to reduce illuminance or change the lighting quality. To take the above causes of light loss into account, lighting systems are generally designed with a light loss factor to provide from the onset a higher illuminance than that recommended for the task in the space.[3]

The most effective method of consistently maintaining illuminance and lighting quantity at the lowest operating and maintenance cost is through a planned program. Planned lighting maintenance entails group relamping, cleaning lamps and luminaires, and replacing defective or broken components on a scheduled basis. Painting and maintaining room surfaces are also important.[4]

CAUSES OF LIGHT LOSS

Lighting maintenance means action to recover light losses due to the following:[5]

- Lamp lumen depreciation
- Dirt accumulation on lamps and luminaires
- Lamp failure
- Luminaire surface deterioration
- Room surface dirt accumulation

Lamp Lumen Depreciation

As a lamp is operated, its lumen output gradually decreases until failure occurs. This is called lamp lumen depreciation and is characteristic of all lamps, although the rate of decrease and the overall lamp life differ for each lamp type (see Chapter 6, Light Sources).

Dirt Accumulation on Lamps and Luminaires[6]

As dirt accumulates on a lamp, it reduces the amount of light being emitted. As dirt accumulates on luminaire surfaces, it acts to reduce the amount of light reflected or transmitted by those surfaces. Dirt buildup on the luminaire's surfaces can also affect light distribution; for example, dirt on a specular aluminum reflector in a high-bay luminaire can widen the lighting distribution of that luminaire. Such a change results in lower illuminance on the workplane. The total amount of light loss due to dirt depreciation depends on the type and amount of dirt accumulated, the lamp's type and shape, and the luminaire's design and finish.

Two types of luminaires built to resist dirt accumulation are ventilated luminaires and filtered or dust-tight luminaires. Ventilated luminaires tend to collect less dirt than those with closed tops. The temperature difference between the lamp and the surrounding air causes convection currents that help carry dirt through the luminaire openings rather than allowing it to accumulate on the reflector. Filtered or dust-tight luminaires or reflector lamps minimize dirt accumulation because the lamp and reflecting surfaces are protected from dusty air.

Light losses due to dirt depend on the rate of accumulation and the characteristics of the dirt. For example, dirt buildup occurs much faster in a foundry than in a well-ventilated office. The dirt found in a suburban office is different in amount and type from dirt in an office located in an industrial area. Black steel-mill dirt is very different from the light-colored dust found in a woodworking shop. Thus, dirt accumulation affects luminaire performance differently in each of these situations.

Lamp Failure

A lamp failure decreases the local illuminance and thus affects lighting uniformity. It can also pose a hazard to other luminaire components. For example, in some fluorescent circuits, when one lamp fails, others on the same ballast glow dimly and may also fail. This can also cause rectification and high ballast current, causing the ballast either to fail immediately or to experience reduced life.

Luminaire Surface Deterioration

Luminaire construction materials differ in their ability to reflect light and resist deterioration. Porcelain enamel, for example, retains its high reflectance and is relatively easy to clean. Processed aluminum finishes tend to depreciate at a lower rate than painted finishes. Plastics (acrylics, cellulosics, polycarbonates, and vinyls), as light-controlling materials, change over time. Exposure to ultraviolet (UV) and infrared radiation (IR) causes the color and transmittance of plastics to change. The rate of change depends on the lamp type, its distance from the plastic, and the temperature to which the plastic is subjected during operation periods. Additionally, improper cleaning materials and techniques can cause added changes in transmittance because of chemical action or surface scratching.

Room Surface Dirt Accumulation

Light reaching the work plane comes directly from the luminaires in the room and from the reflected light from room surfaces. Thus, dirt accumulation on room surfaces reduces the amount of light on the workplane. Cleaning and regular repainting of walls and other surfaces will reduce the effect of dirt accumulation on these surfaces.

The effects of these light loss factors are shown in Figure 28-1. These and others are discussed in Chapter 9, Lighting Calculations.

PLANNED MAINTENANCE TECHNIQUES

During the design of a new or retrofit lighting system, an effective and properly executed maintenance plan can minimize the required number of luminaires needed for a space, thus minimizing first costs and energy costs.[4,7] The primary maintenance techniques are group relamping and cleaning. During and between relamping and cleaning, the system can be inspected for defective or broken components and other problems.

Group Relamping

Group relamping entails replacing all of the lamps in a system together after a fixed interval, called the economic group relamping interval. Group relamping can reduce the cost of operating a lighting system while keeping illuminance levels close to the design value. As discussed above, if a lighting system is analyzed during the design phase and group relamping is judged economical, then lower illuminance can be specified at system commissioning.

Group relamping saves labor costs. It typically costs less per lamp to replace all of the lamps in a system at one time than it does to replace them one by one as they fail. If the labor savings are worth more than the value of the used lamps, then from an economic standpoint it makes sense to discard used and depreciated lamps, even though they may still have some burning hours remaining. A useful rule of thumb is that group relamping should be examined if the labor cost of spot-replacing one lamp, less the cost of group-relamping one lamp, exceeds the cost of one new lamp. Large-quantity lamp purchases also lower unit costs.

Analysis techniques are available to determine the economic group relamping interval. These are based on the mortality rates of the lamp (the probability of failure as a function of time), the labor rates involved, the cost of the lamp, and its depreciation rate. Typically, the most economical time to group relamp is between 70 and 80% of rated life. This is just before the majority of lamps are expected to fail, when the greatest labor costs can be saved, and when lamp lumen depreciation makes the lamps uneconomical to continue operating from a cost-per-lumen standpoint. The calculations should take into account the cost of replacing spot failures between group relampings so that lighting quality and appearance are also maintained. Group relamping also includes a scheduled period when relamping can be economically combined with installation of new luminaire components such as specular reflectors, energy-efficient lamps, energy-efficient ballasts, and other components that improve the performance of the system.

> A three-year study known as the Luminaire Dirt Depreciation Study is nearing completion. This study has been jointly sponsored by the interNational Association of Lighting Management Companies (NALMCO) and IESNA and has been funded by the U.S. Environmental Protection Agency. The project involves taking a time series of field measurements in individual luminaires in nonindustrial interior environments.
>
> The results of this project will be used to update the Luminaire Dirt Depreciation factor characteristics that are part of the lighting system design process. The new reliable dirt depreciation data also will be used in life cycle cost analysis.
>
> It has been assumed that present interior environments are cleaner than those of the 1950s, when the existing maintenance data were developed. To the extent that this can be quantified, the initial excess illuminance allowance for dirt depreciation can be reduced. Such a reduction reduces the initial lighting system cost, the lighting system power requirements, and the heat load placed on other building components.

Periodic Planned Cleaning

Cleaning the lighting system usually entails washing or otherwise removing dirt from the luminaires (see Figure 28-2), occasionally cleaning and repainting room surfaces, and occasionally cleaning air supply vents to prevent unnecessary dirt distribution. Cleaning is another service that can economically be combined with group relamping; in environments with high concentrations of dirt or dust in the air, it should be performed often. As in the case of group relamping, periodically cleaning luminaires delivers more light per lighting dollar and ensures more consistent illuminance through the life of the lamps.

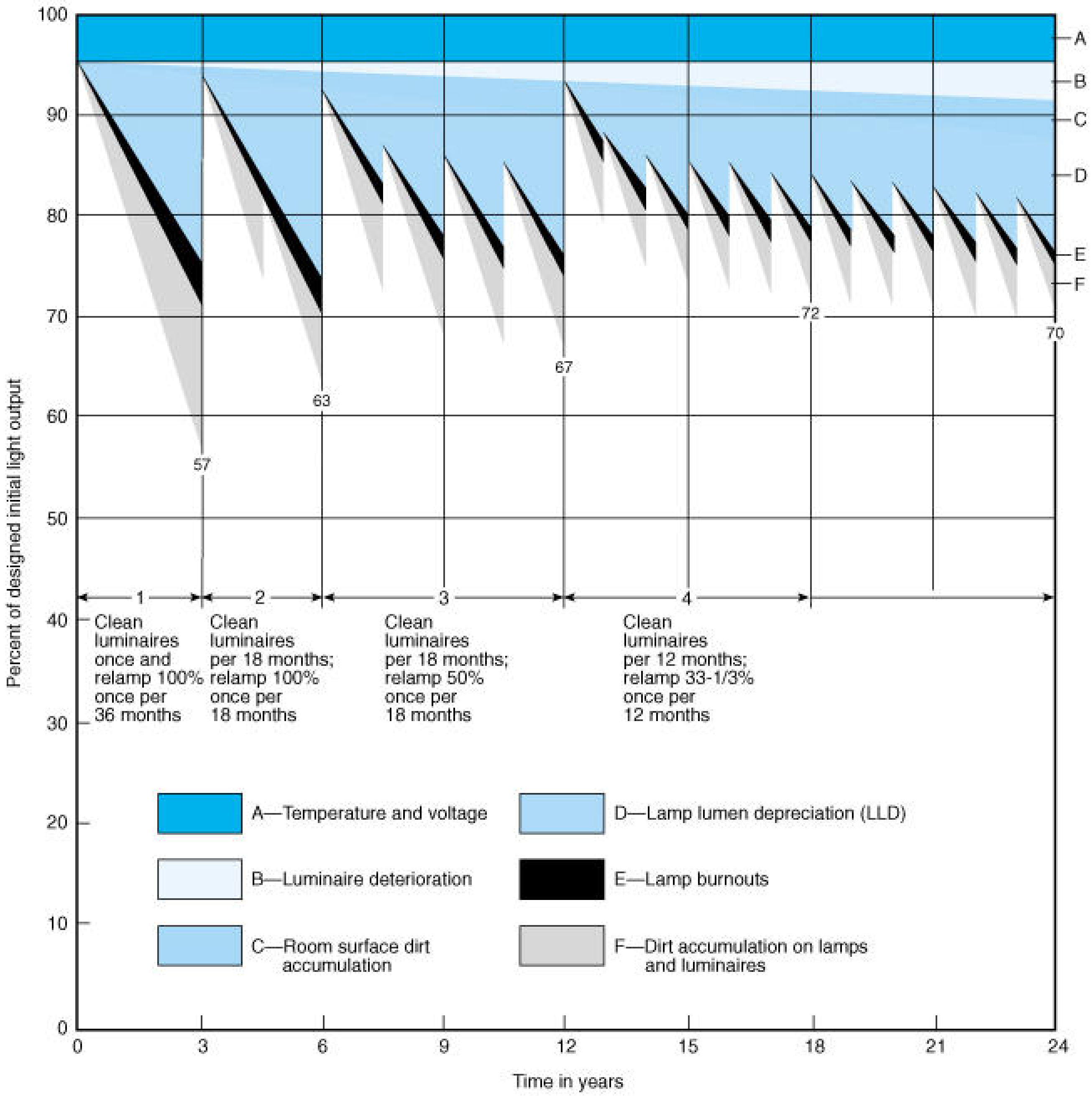

Figure 28-1. Effect of light loss factors on illuminance level. Example above used 32-W T-8 cool-white rapid-start lamps in recessed troffers, operated 10 hours per day, 5 days per week, 2600 hours per year. All four maintenance systems are shown on the same graph for convenience. For a relative comparison of the four systems, each should begin at the same time and cover the same period of time.

OPERATIONS: PROGRAMS AND METHODS

Planning

Lighting systems are becoming more complex. As a result, the requirements for resources, expertise, and competence are increasing. Often it is desirable for an organization to use a lighting management company if it does not have the proper equipment and trained staff to maintain the system properly itself.

Planning Factors

The most economical group relamping and cleaning interval must be established. Many factors are involved, so the facilities manager must:

- Establish the maintenance cycle so that there is neither excessive light loss nor wasted equipment.
- Determine the rate at which dirt accumulates in the environment.
- Evaluate the impact of dirt on luminaires and room surfaces for the specific lighting system.

Figure 28-2. A fluxometer developed to measure a luminaire's available light in order to determine the benefits of periodic cleaning.

Several options with factors applicable to the facility should be considered, and results should be compared to determine the best maintenance interval.

In addition, the application also dictates other maintenance requirements. Luminaire accessibility and rate of dirt accumulation vary in almost every circumstance. Planning must take these conditions into account. For example, in many industrial areas, not only is the rate of dirt accumulation high and the dirt dark and adhesive, but the luminaires are usually mounted high up, requiring mechanized lifts to reach them.

Plan Execution. The building's environmental characteristics greatly affect how maintenance is performed. Generally, cleaning and relamping operations require several basic steps:

1. Make the luminaires shock free. Lamp sockets present an electric shock threat to the maintenance technician. The electrical circuit must be turned off when working on luminaires.
2. Remove the shielding material and lamps. Louvers, lenses, or diffusers in frames can be unlatched for cleaning in place or removed from the luminaire and passed to the technician on the floor. Lamps are then removed and also passed down to the technician, who cleans or discards them.
3. Clean the basic unit. If present, heavy deposits of dirt should be vacuumed or brushed from the reflector or other surfaces. The entire unit is then ready to be washed with a suitable solution utilizing a brush, sponge, cloth, or spray bottle. After washing, the entire unit should then be rinsed

to remove any residue of dirt or solution. Indirect luminaires should have the dust and dirt blown out with an antistatic nozzle.

4. Clean the shielding material and lamps. While the reflective surface is being cleaned, the technician on the floor cleans shielding materials. During relamping, the old lamps should be placed in a disposal area, before new lamps are brought in for installation. Plastic lenses or louvers should be dried with a damp cloth. Dry wiping can cause electrostatic charging, which attracts dust. Drip drying can leave streaks on prismatic lenses. Parabolic louvers should be cleaned using ultrasonic machines. Antistatic fluid should be applied to the shielding material, except for glass, to retard dust accumulation.
5. Replace the lamps and shielding material. The clean shielding and new or cleaned lamps are passed up to the technician at the luminaire for installation.
6. Troubleshoot. During the above steps, the technician at the luminaire should check for damaged or defective components and be prepared to replace them with new ones. The lighting system should then be tested and checked for defective lamps, ballasts, sockets, and wiring.

Safety and Environmental Considerations

During cleaning and relamping, the cleaner and the floor technicians should observe all safety precautions. For specific professional safety requirements, consult the U.S. Occupational Safety Health Administration (OSHA) in Washington.

Equipment Disposal.[8] Replaced lamps and ballasts should be disposed of according to state and federal guidelines. Precautions should be taken when disposing of older ballasts containing PCBs. While the manufacture and distribution of older ballasts containing PCBs were banned in the United States in 1978, they can still be found in older luminaires. A ballast without PCBs is appropriately labeled, "No PCBs." If ballasts containing PCBs are encountered, a lighting management and maintenance professional, a hazardous-waste treatment professional, or any state or federal organization that offers disposal resources should be contacted. Ballasts containing PCBs must be disposed of in accordance with state and federal guidelines. The U.S. Environmental Protection Agency in Washington can be contacted for more information.

CLEANING COMPOUNDS

Different cleaning applications require different cleaning compounds. Improperly selected or used compounds can scratch or otherwise deteriorate the luminaire surface. For each application, the manufacturer's recommendations should be followed for best results. Several general tips are listed below:

Aluminum. Very mild soaps and cleaners followed by a thorough rinse with clean water prove effective with aluminum. Strong alkaline cleaners should never be used.

Porcelain Enamel. Nonabrasive cleaners can be used on porcelain. Detergents and most automobile and glass cleaners are effective.

Synthetic Enamel. Some strong cleaners may injure this finish, particularly in cases where the enamel is left to soak in the solution. Alcohol or abrasive cleaners should not be used. Detergents produce no harmful effects.

Glass. As with porcelain enamel, most nonabrasive cleaners prove effective. Most detergents work well; after cleaning, however, the lens must be rinsed. Glass reflectors may simply be wiped dry.

Plastics. Plastic should not be dry wiped after application of a rinse solution because this causes the formation of electrostatic charges. Also, plastic should not be drip dried, as this results in streaks. The most effective method of drying plastics is vacuuming. Most common detergents do not provide a high degree of permanence in their antistatic protection. Some antistatic compounds with greater permanence are available.

CLEANING EQUIPMENT

Cleaning, group relamping, and new equipment installation can be performed more efficiently with proper equipment. *Caution:* Proper safety training should be given for all maintenance equipment.

Figure 28-3. A ladder is used to change a ballast.

Ladders and Stilts. Ladders are often chosen for their low weight, low cost, and simplicity (Figure 28-3). Safety, mobility, and height restrictions limit their use, however. Aluminum or other conductive ladders must not be used. Wood or fiberglass ladders should only be used if they are OSHA approved. Stilts can also be used for maintenance in spaces with relatively low ceilings (Figure 28-4).

Scaffolding. Portable scaffolds are generally safer and more mobile than ladders. Scaffolding provides more room for equipment and firm footing for technicians. Scaffolds generally should be light, sturdy, adjustable, mobile, and easy to assemble and dismantle. The right type of scaffolding often depends on special requirements, such as mounting on uneven surfaces or clearance of obstacles such as tables or machines. In all aspects, the scaffold must conform to OSHA standards.

Telescoping Scaffolding. The telescoping scaffold (Figure 28-5) provides a quick and versatile method for reaching a variety of mounting heights. This equipment, which comes in various sizes, has platforms that can be raised and lowered either manually or electrically.

Personnel Lift. The personnel lift has proven itself as one of the quickest and most efficient maintenance devices (Figure 28-6). The platform is raised and lowered automatically. Some types of personnel lifts can be driven from the platform.

Bucket Truck. The bucket truck (Figure 28-7) is used in many outdoor applications, such as sign lighting, street lighting, and parking lot lighting.

Disconnecting Hangers. Disconnecting hangers allow the technician to lower the luminaire to a convenient work level (Figure 28-8). The luminaire's electrical circuit connection is automatically disconnected for safety. When the luminaire is raised after the work is complete, the hanger positions the luminaire and reconnects the electrical circuit automatically.

Figure 28-4. Stilts used for maintenance in spaces with low ceiling heights.

Figure 28-5. Telescoping scaffold.

Lamp Changers. Lamp changers simplify lamp replacement. They grip lamps either mechanically or with air suction. Lamp changers usually are on a pole and are used from the ground (Figure 28-9).

Catwalks, Cranes, and Cages. These types of equipment can be incorporated as an integral part of the lighting system for servicing (Figure 28-10). They enable luminaires to be maintained speedily and safely. Power to a crane must be turned off before lighting maintenance is begun.

Vacuum Cleaners. A vacuum cleaner is used to remove dust from luminaires. While some dirt can be removed this way, the luminaire should also be washed. The use of a vacuum cleaner is effective for industrial and commercial indirect luminaires.

Ultrasonic Cleaning. Ultrasonic cleaning requires that personnel be adequately trained so that they do not damage the surfaces. This method removes dirt and dust from metals, plastics, glass, and other materials by using high-frequency sound waves. A generator, a transducer, and a suitable tank constitute the ultrasonic cleaning system. The generator produces high-frequency electrical energy, which the tank-mounted transducer converts to high-frequency sound waves. These sound waves travel through the cleaning solution and cause cavitation, the formation of countless microscopic bubbles, which grow in size and then violently collapse. This phenomenon creates a scrubbing action that rapidly and forcefully removes dirt from the material immersed in the solution. Ultrasonic cleaning proves very effective with parabolic louvers. Metallic louvers, however, may be damaged by this method over time. Parts should be rinsed in deionized water after ultrasonic cleaning.

TROUBLESHOOTING AND MAINTENANCE TIPS

Planned lighting maintenance entails more than simply changing lamps and cleaning. It is also an opportunity to efficiently locate and repair defective or broken components causing system problems. See Chapter 6, Light Sources, for diagrams and explanations of the circuits described in this section.

Caution: Follow manufacturer and government environmental guidelines for proper disposal of lamps and ballasts.

Figure 28-6. Mobile platform lift.

Figure 28-7. Bucket truck.

Preheat Fluorescent Lamp Circuits

Troubleshooting

1. Replace existing lamps with lamps known to be operative.
2. Use only lamp types that are listed on the ballast label. Check to make certain lamps can be used on preheat circuits.
3. Replace existing starters with starters known to be operative and of proper rating. Refer to Chapter 6, Light Sources, for a description of the various types and the features of each.
4. Check luminaire wiring for incorrect connections, loose connections, or broken lampholders or wires. Refer to the wiring diagram printed on the ballast.
5. Check the ballast to see if the label agrees with the application with regard to temperature limitations and lamps. Replace the ballast if faulty or inappropriate.

Maintenance Hints

- Deactivated lamps should be replaced as quickly as possible. Cycling lamps cause abnormal flow current in the ballast, which causes ballast heating and reduces ballast life.
- Lamp cycling also reduces starter life.

Rapid-Start Fluorescent Lamp Circuits

Constant heater current is essential for proper starting of all rapid-start lamps. It is also essential for proper lamp operation.

Troubleshooting

1. If a lamp requires 5 to 6 seconds to start, one electrode may not be receiving the cathode heating current. This usually produces excessive darkening of that end of the lamp, which is visible after a short period of operation. With lamps removed from the sockets, check heater voltages with available testers. If a voltmeter is used, a 10-Ω, 10-W resistor should be inserted in parallel with the meter. The meter should measure at least 3 V. If proper voltage is found, check for poor contact between lamp holder and base pins or contacts on the lamp. Also check for proper spacing of lampholders. If no voltage is measured, check for open circuits caused by poor or improper connections, broken or grounded wires, or an open heater circuit on the ballast. Verify that the wiring conforms exactly to the ballast label diagram.

2. If one lamp is out and the other lamp is operating at low brightness, or if both lamps are out, only one lamp may have failed. Refer to the circuit diagram in Chapter 6, Light Sources, and note that two-lamp magnetic and some electronic circuits are of a series design.

3. Replace the ballast if the output voltage is not within its rated voltage, or if no voltage is present after determining that the input voltage to the ballast is correct.

Maintenance Hints

- Failed lamps should be replaced as quickly as possible. Rapid-start lamps require both heater current and starting voltage for proper operation. If either is missing, poor starting or short lamp life results. In a two-lamp circuit, one lamp can fail so that the second lamp operates at reduced current. This condition reduces the life of the second lamp.
- Lamps should be kept reasonably clean. All rapid-start lamps are coated with a silicone to provide reliable starting in conditions of high humidity. However, dirt can collect on the lamp surface and then absorb moisture when the humidity is high, thus nullifying the silicone coating and making the starting unreliable.

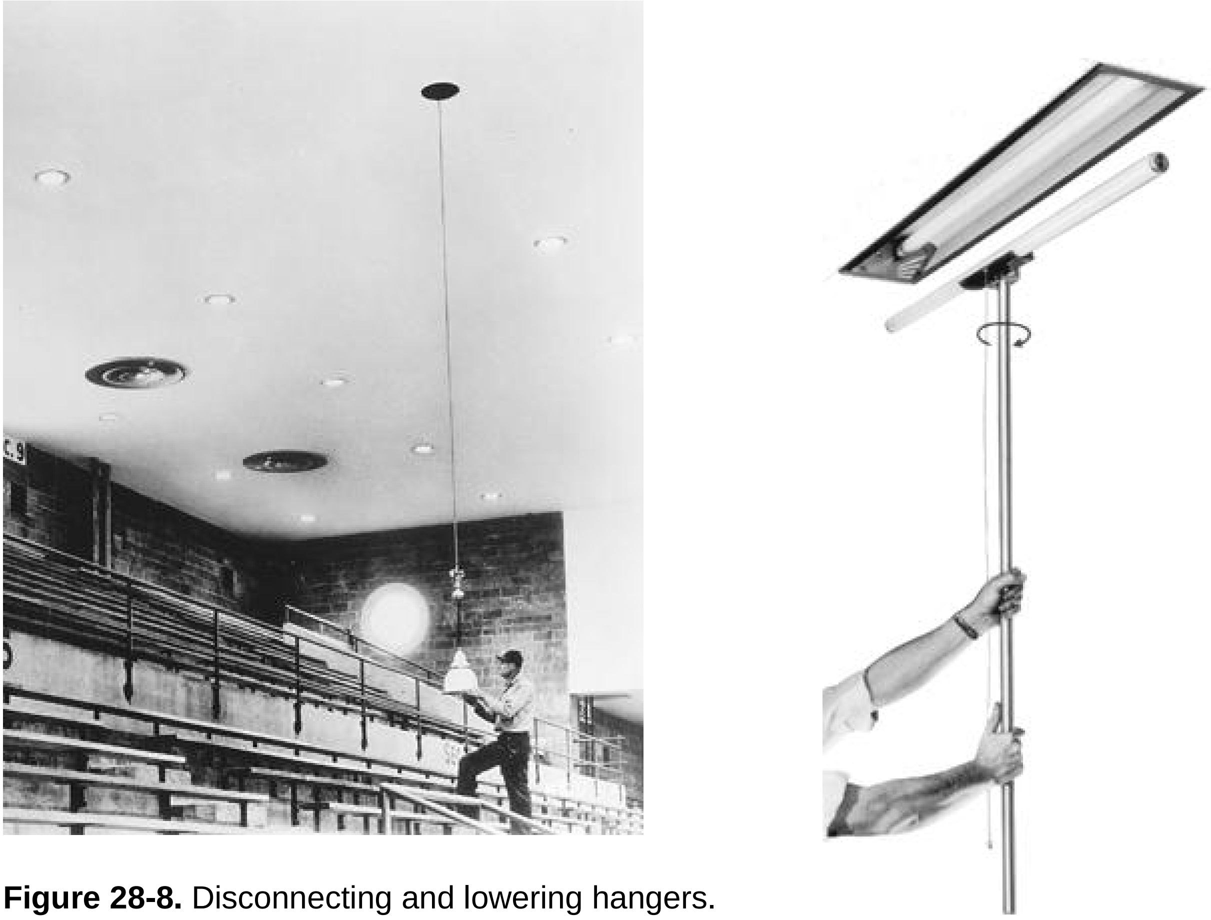

Figure 28-8. Disconnecting and lowering hangers.

Figure 28-9. Pole lamp changer.

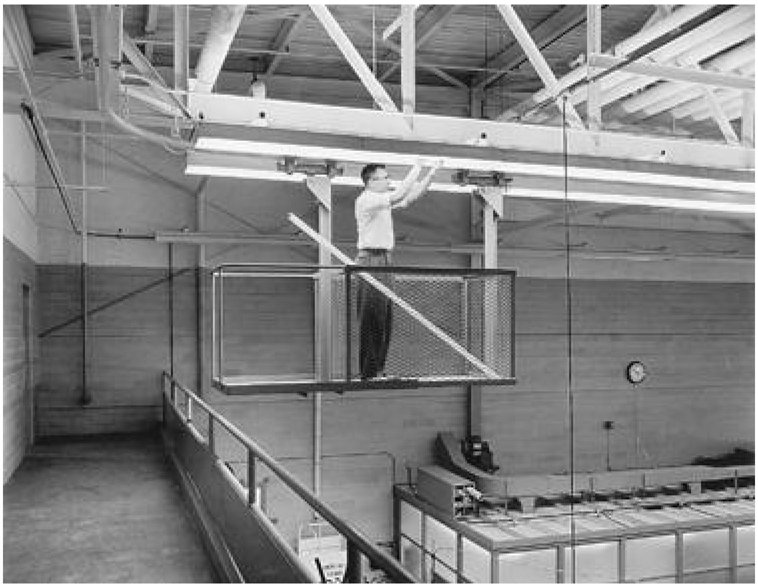

Figure 28-10. Maintenance cage.

Instant-Start Fluorescent Lamp Circuits

Two-lamp circuits can be of either lead-lag or series-sequence design. Lead-lag ballasts operate lamps in a parallel circuit, meaning that if one lamp fails, the other should continue to operate properly. Series-sequence ballasts operate lamps in series, meaning that if one lamp fails, the other fails or glows dimly. Some multilamp electronic ballasts for T-8 lamps are of instant-start design. Only the failed lamp is inoperative in this case.

Troubleshooting

1. Replace existing lamps with lamps known to be operative.
2. Check lampholders for broken or burned contacts or discolored plastic in the holders, indicating high temperature. Check circuit for improper or broken wires. Refer to the wiring diagram on the ballast.
3. If the ballast is suspected of being defective, replace it with one known to be operative. Measurement of output ballast voltages in the luminaire is difficult because the primary circuit of the ballast is automatically disconnected when a lamp is removed. Refer to the circuit diagram in Chapter 6, Light Sources.

Maintenance Hints

- Deactivated lamps should be replaced as soon as possible. In a two-lamp series magnetic circuit, one lamp can fail so that the second lamp operates at low brightness. This condition reduces the life of the second lamp and also causes an abnormal current to flow in the ballast, giving rise to ballast heating and a reduction in ballast life.
- Flickering instant-start or "slimline" lamps, which show heavy end blackening, should be replaced, even if the lamps still light. This condition is known as lamp rectification and causes reduced ballast life if it is allowed to persist.

Incandescent Lamps

Troubles with incandescent lamps are usually the result of misapplication, improper operating conditions, or poor maintenance. Apply the hints below to avoid most problems.

Maintenance Hints

- Overvoltage operation. Overvoltage operation drastically shortens lamp life. For example, a 120-V lamp operated on a 125-V circuit suffers a 40% loss in life. Refer to Chapter 6, Light Sources.
- Shock and vibration conditions. Under such conditions, the use of vibration-service or rough-service lamps is recommended. The use of general-service lamps under these conditions results in short life.
- Sockets. High-wattage lamps should not be operated in sockets designed for that wattage, or else excessive lamp and socket temperatures may result. Excessive temperatures may affect lamp performance or may shorten the life of insulated wire and sockets.
- Luminaires. Only the proper lamps for which the luminaire was designed should be used. Contact of any metal part of a luminaire with a hot lamp may result in violent failure of the lamp.
- Cleaning lamps. A wet cloth should not be used to clean a hot lamp. A violent failure may result.
- Proper burning position. Lamps should be operated in their proper burning position as specified by the lamp manufacturer. Operation of the lamps in the wrong position can cause a lamp to fail prematurely.
- Replacing lamps. Whenever possible, lamps should be replaced with the power switched off; otherwise, an arc between the lamp base and the socket can occur.
- Tungsten-halogen lamps. These lamps should always be installed with the power switched off. It is also recommended that the bulb be held with a clean cloth or tissue or gloves to avoid fingerprints that can cause bulb discoloration, reduction in light output, short life, and, possibly, violent failure. Follow lamp manufacturers' instructions on the carton.
- Dichroic reflector lamps. Certain lamps utilize a dichroic reflector designed to radiate heat back through the reflector portion of the bulb. Luminaires using these lamps should be ventilated or provided with adequate cooling of the socket and wiring adjacent to the bulb.

Metal Halide Lamps

Troubleshooting

1. Many metal halide lamps should be used only in specified operating positions, or else short life and improper light output and color will result.
2. The time to restart after a short power interruption can be much longer than it is for mercury lamps.
3. It is normal for metal halide lamps to have a short delay between the time the circuit is energized and the time the lamp starts.
4. Slight color shifts from lamp to lamp are characteristic of metal halide lamps. Also, one to two days of operation may be required to stabilize the color of a lamp and the uniformity among a group of lamps
   Caution: Follow lamp manufacturers' recommendations with respect to metal halide lamp operation in open or enclosed luminaires.
5. Replace the lamp with one known to be operative. Be sure the operative lamp is cool, because hot lamps do not restart immediately.
6. Check that the lamp is properly seated and that its base eyelet and shell make proper contact in the lampholder.
7. Check the ballast nameplate. Make sure that ballast and lamp designations match. Refer to the system of lamp and ballast designations developed by the lamp industry and American National Standards Institute (ANSI).
8. Check the ballast wiring. If a multiple-tapped primary-winding ballast is used, be sure the connected tap matches the supply voltage.
9. Check the supply circuit wiring for open circuit or incorrect connections.
10. Replace the ballast if no output voltage can be obtained and make sure that the line voltage is properly connected to the ballast input terminals.
11. If a lamp fails prematurely, especially if it does so repeatedly in the same way in the same luminaire, check for the following:

    a. Cracks or breaks in the bulb. These allow air to enter the lamp and cause arc tube seal failure.

They can be caused by rough handling, by contact with metal surfaces of a bulb changer or metal parts of the luminaire, or by water droplets falling on a hot lamp.

  b. Overly blackened or swollen arc tubes. This indicates excessive lamp current and overwattage operation (see items 7, 8, and 9 above). Also, the ballast may have failed due to a component failure, such as a shorted capacitor or core winding.

If the power is lost in an HID ballast-lamp combination for even a few cycles, the lamp extinguishes itself and then has to cool down somewhat, reignite, and warm up again before reaching maximum light output.

Caution: To prevent electric shock hazard, always turn off the power before removing or installing lamps. This is especially important when removing lamps that may have cracked or broken outer envelopes. Unless the power is turned off, the exposed metal parts of the internal lamp structure are connected to power, and touching them causes an electric shock. Always follow OSHA guidelines.

Maintenance Hints

- If a metal halide lamp is to be moved from one luminaire to another, keep it in the orientation in which it was installed while transferring it. If the lamp is rotated, color can vary.
- Operate metal halide lamps only in their allowed operating positions.
- If multiple-tapped ballasts are used, check to be sure that the tap matches the supply voltage to which the ballast tap is connected. Connecting a given line voltage to a tap marked for a higher voltage gives low light output due to underwattage operation. Connecting it to a tap marked for a lower voltage causes poor lamp lumen maintenance and short lamp and ballast life due to overwattage operation.
- The line voltage should be nearly constant. A variety of ballast types are available that provide an appropriate percentage of lamp wattage regulation with respect to the percentage of line voltage variation.
- Lamp-and-ballast combinations must be chosen so that their electrical characteristics match. This can be assured by following the system of lamp and ballast designations developed by the lamp industry and ANSI. Incorrect matching of lamp and ballast may result in short life and equipment damage.
- Lamps should be handled carefully. Rough handling can cause scratches or cracks in outer glass envelopes, resulting in short lamp life and possible injury.
  Caution: Even if the outer envelope of a lamp is broken or punctured, the arc tube may continue to burn for many hours. Turn off the power and replace the lamp immediately. Certain types of lamps are available that automatically extinguish if the outer envelope is broken or punctured.

High-Pressure Sodium Lamps

Troubleshooting

1. Follow steps 5 through 10 listed for metal halide lamps.
2. If lamps fail prematurely, especially if they do so repeatedly in the same way or in the same luminaire, check the following:
   a. Cracks or breaks in the bulb (see item 11a under "Metal Halide Lamps").

   b. Excessive discoloration of the arc tube or a metallic deposit on the inside walls of the outer envelope, which may indicate overwattage operation (see items 7, 8, and 9 under "Metal Halide Lamps"). Also, ballast components may have failed; for example, a capacitor or a core winding may be shorted.
3. A high-pressure sodium lamp must be started with an ignitor. If both the old and a known good lamp fail to start, steps must be taken to determine if the ignitor or the ballast or perhaps both are defective. First make certain that the proper line voltage is correctly connected to the ballast input. Obtain a ballast tester or voltmeter, and follow the manufacturer's instructions to determine the defect. Do not connect a voltmeter or multimeter to an open or inoperative high-pressure sodium

socket. The high- voltage pulse from the ignitor will damage the meter.

Maintenance Hints

- Follow the third through sixth bullets for metal halide lamps.
- High-pressure sodium lamps have a vacuum in the space between the ceramic arc tube and the outer envelope. Handle these lamps carefully, since vacuum lamps are known to make a loud noise if the glass should break when dropped.
- In case the outer envelope breaks during lamp operation, UV emission is not a problem.

Caution: To prevent electric shock, always turn the power off before removing or installing a lamp. This is especially important when removing lamps that may have cracked or broken outer envelopes. Unless the power is turned off, the exposed metal parts of the internal lamp structure will be live, and touching them will cause an electric shock.

Mercury Lamps

Follow the recommendations and all cautionary measures given for metal halide lamps, because these generally apply to mercury lamps.

Low-Pressure Sodium Lamps

Troubleshooting

1. Replace the lamp with a lamp known to be operative.
2. Check the lampholder for proper lamp seating and contact.
3. Check the ballast nameplate reading for compatibility.
4. Check the ballast wiring. If a multiple-tapped ballast is used, be sure the ballast tap matches the supply voltage at the ballast.
5. Check the circuit wiring for open circuit or incorrect connections.
6. Check the grounding of the luminaires.
7. Replace the ballast.
8. If lamps fail prematurely, check for the following:
    a. Lamp breakage. Check lamps for cracks or scratches in the outer bulb. These can be caused by rough handling, by contact with metal surfaces in the bulb changer or luminaire, or by moisture falling on an overheated bulb.
    b. Bulb touching the luminaire, lampholder, or any hard surface.
9. If the arc tube is cracked, blackened, or swollen early in life, or if the connecting leads inside the outer bulb are damaged, check for the following:
    a. Overwattage operation. Check the ballast rating, the voltage at the ballast, and whether the proper tap on the ballast is being used.
    b. Excessive current. Check if the ballast is shorted. Check for possible voltage surges or transients on the supply line.

Caution: Do not replace the lamp until the circuit is checked and the cause of the trouble has been corrected.

Maintenance Hints

- If multiple-tapped ballasts are used, check to be sure the tap matches the supply voltage at the ballast. Low voltage causes low light output, poor lumen maintenance, and reduced lamp life. High voltage causes short lamp life.
- The circuit should be free from voltage fluctuations. Replacement ballasts should match the particular voltage, frequency, and lamp type.

- The proper lamp type should be used for the ballast. Incorrect matching of lamp and ballast may result in short lamp life or lamps going on and off repeatedly.
- Lamps should be handled carefully to avoid breakage.

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29

Emergency, Safety, and Security Lighting

EMERGENCY LIGHTING

The designer faces no greater challenge and, possibly, no more important responsibility than making provisions for reliable emergency lighting. In many situations occupants of a building need to evacuate for such reasons as fire and power failure. These occasions can become dangerous if proper emergency lighting is not available or is inadequate. Therefore, it is the designer's responsibility to provide adequate egress route illumination and informational signage. Likewise, it is the responsibility of building engineers, owners, and property managers to ensure that these systems are properly installed and maintained.

Not every lighting failure is associated with a need for rapid evacuation, and not every evacuation is accomplished without utility power. Nevertheless, emergency lighting is required at all times. Such factors as the presence of smoke, the operation of sprinkler systems, hazards presented by manufacturing equipment or architectural features, and physical disabilities or special needs of building occupants can compromise the effectiveness of simple lighting solutions. The egress lighting system design must anticipate the full range of possible conditions.

Collaboration among the lighting designer, engineer, building owner, occupants, architect, fire officials, and utilities is highly recommended as a means of understanding and planning for the variables that might interfere with the effectiveness of building egress. These variables should be addressed early in the building design stage so that the emergency lighting system can be most effectively integrated with the design of other building systems.

The purpose of this chapter is to provide assistance in identifying these important design considerations and to make emergency lighting recommendations. Several terms are unique to emergency lighting, and definitions can be found in the Glossary.

Many of the recommendations in this chapter also apply to emergency lighting in mines; aircraft, ships, and other vehicles; and outdoor structures such as oil drilling platforms. For more information see Chapter 23, Transportation Lighting, and Chapter 19, Industrial Lighting.

EMERGENCY, SAFETY, AND SECURITY DESIGN ISSUES

Emergency
- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Modeling of Faces or Objects
- Shadows

Safety
- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Luminances of Room Surfaces
- Modeling of Faces or Objects
- Reflected Glare
- Shadows
- Source/Task/Eye Geometry

Security
- Direct Glare
- Illuminance (Horizontal)
- Illuminance (Vertical)
- Light Distribution on Surfaces
- Light Pollution/Trespass
- Modeling of Faces or Objects
- Peripheral Detection
- Shadows
- Source/Task/Eye Geometry

Codes and Standards

The designer should become familiar with the applicable codes in the project jurisdiction before designing emergency lighting systems. These codes have been developed through a number of government and private organizations, including the National Fire Protection Association (NFPA), National Research Council Institute for Research in Construction (NRC/IRC, Canada), U.S. Uniform Building Code (UBC), U.S. Southern Building Code Congress International (SBCC), Canadian Standards Association (CSA), Canadian Occupational Safety and Health Board (COSHA), Building Officials and Code Administrators International (BOCA), Commission internationale de l'Èclairage (CIE) and Underwriters Laboratories (UL), Federal Aviation Administration (FAA), and the Occupational Safety and Health Administration (OSHA). Other sources to consult are Department of Health and Human Services guidelines, local or state board of education requirements, Americans with Disabilities Act (ADA), local fire departments, and fire marshall offices as applicable to the occupancy. Some documents represent guidelines that contain no specific mandates to the designer.

Design Considerations for Emergency Egress Lighting

Illuminance. By itself, illuminance is not an adequate measure of visibility because it refers only to the quantity of light falling on a surface and not the amount reflected back to the eye. Luminance is more closely correlated with visibility (see Chapter 3, Vision and Perception); however, luminance is more difficult to predict and specify for emergency lighting applications. Nevertheless, illuminance does influence the speed of egress from furnished and cluttered spaces,[1-6] as illustrated in Figure 29-1.[4] Furthermore, an average illuminance of 0.5 lx might provide sufficient visibility to permit people to exit without colliding with furniture and other obstacles when illuminance distributions are approximately uniform (i.e., $E_{avg}/E_{min} < 2.5$).[1,3-6]

Some codes and regulations specify average rather than minimum illuminance requirements, as given above. Average illuminance is often meaningless when illuminance distributions are not uniform to the degree often found in emergency lighting installations. For emergency lighting, minimum illuminance is a more relevant criterion than average illuminance.[7]

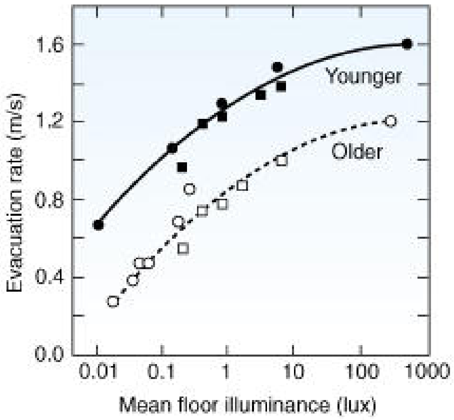


Figure 29-1. Rates of evacuation of both older and younger people in cluttered spaces.

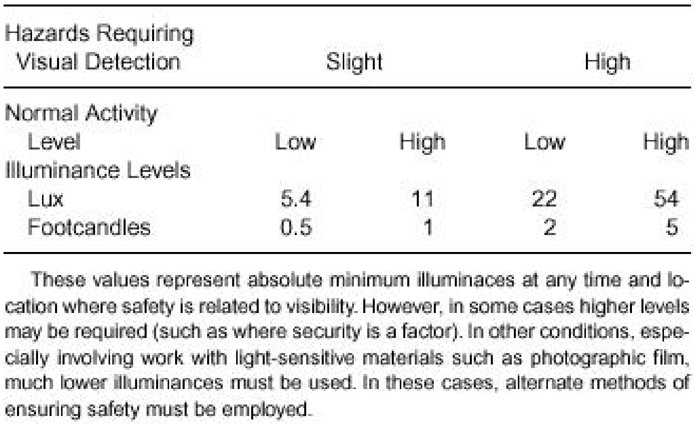
The minimum recommended illuminance at the beginning of emergency operation is 10 lx (1 fc) along the centerline of the path of egress and 1 lx (0.1 fc) along a one meter band throughout the means of egress. The maintained horizontal illuminance measured at all points along the means of egress outside the one meter band should be at least 0.5 lx (0.05 fc) whenever emergency lighting is required. In addition, such hazards as steps, curbs, slopes, and obstacles should be illuminated in accordance with Figure 29-2. These values should be increased whenever the effective reflectances of ceiling, wall, and floor are less than 0.5, 0.1, and 0.1, respectively.

Health care facilities require more illuminance in emergency situations to provide life support services to patients. The recommended illuminances for critical care areas should be maintained during emergency situations.[8]

The designer should remember that published isolux (or isofootcandle) distribution curves for directional sources (e.g., incandescent PAR lamps) are typically for a plane perpendicular to the lamp axis. The equipment is usually aimed at angles off the vertical, so the cosine of the angle must be used to calculate surface illuminance. For example, if the lamp is aimed 75° from vertical, the horizontal illuminance is reduced approximately five-fold (i.e., 1/cos[75°]).

It is also important to note that zonal cavity methods or point-by-point illuminance calculations are generally not applicable when making calculations for emergency luminaires. Layouts of emergency luminaires are often too widely spaced, and therefore too nonuniform, for these methods to be valid. See Chapter 9, Lighting Calculations, for specific information regarding lighting calculations.

Duration. Occupant evacuation times depend on the size and complexity of the space. Codes specify minimum operating periods for emergency lighting from 30 min to 8 h, with 90 min being the most common. Relevant codes such as BOCA, NFPA, and local codes should also be consulted.



Hazards Requiring Visual Detection	Slight		High	
Normal Activity Level	Low	High	Low	High
Illuminance Levels				
Lux	5.4	11	22	54
Footcandles	0.5	1	2	5

These values represent absolute minimum illuminaces at any time and location where safety is related to visibility. However, in some cases higher levels may be required (such as where security is a factor). In other conditions, especially involving work with light-sensitive materials such as photographic film, much lower illuminances must be used. In these cases, alternate methods of ensuring safety must be employed.

Figure 29-2 Illminance Levels for Safety

The designer should also give consideration to extending the operating time if unusual conditions may exist. Such circumstances might include a high occupancy rate by older persons, occupancy by the physically disabled, restaurants, and facilities requiring a long shutdown process.

The light output of battery-backed emergency lighting systems declines during the course of operation. Illuminance levels should be designed so that they do not fall below the required levels throughout the minimum operating period. In the United States, the National Electrical Code (NEC) requires that a minimum of 60% of the initial illuminance be maintained.[9]

Illuminance Uniformity. Minimum uniformity requirements help assure safe and rapid movement along the path of egress. A maximum illuminance ratio (E_{max}/E_{min}) of 10:1 provides excellent uniformity for safe movement. Ratios in excess of 40:1 can be suitable, but this ratio should be minimized wherever possible. Illuminance uniformity is more easily achieved by using a greater number of luminaires with lower light output than by employing fewer but more widely spaced luminaires with higher light output.

Hazard Visibility. Specification of floor-level illuminance is not adequate for proper illumination of all hazards. All vertical surfaces along the means of egress should be illuminated to assist in defining the escape route. Vertical surface illumination increases the occupant's confidence that obstructions and hazards are visible, and increased confidence contributes to improving evacuation speed. Any area in which a change in direction or floor level occurs along the path of egress can be considered as a hazard area (Figure 29-3).

Figure 29-3. Example of a change in direction requiring an exit sign.

Some examples of such hazard areas are:

- Intersections of corridors
- Abrupt changes of direction of the egress path
- Staircases
- Changes of floor level
- Exits and areas adjacent to exits
- Obstructions along the means of egress

Supplemental Path Delineation. Photoluminescent paints and products can be used to supplement electrical lighting evacuation systems.[10-15] They should not be used as the primary emergency lighting system. They can be applied to hazards, office furniture, baseboards, door frames, stairs, and walls to delineate the egress paths in the event of complete power failure and allow the evacuee to develop a more coherent image of the space. Illumination should be provided to these products over an extended period to keep the photoluminescent pigments activated. Some products require at least 100 lx, 24 hours per day, to remain completely activated, and they vary greatly in terms of luminance and persistence. Materials based on strontium aluminate photoluminescent pigments maintain a brighter level of discharge for a significantly longer period than those based upon zinc sulfide photopigments.[16]

Figure 29-4. This wall-mounted sealed-beam unit provides emergency lighting for fire-fighting equipment (the fire extinguisher) as well as the exit approach that should be kept clear of obstructions (e.g., the barrels shown here).

Illumination of Fire-Alarm Call Points and Fire-Fighting Equipment. Fire-alarm call points and fire-fighting equipment (Figure 29-4) along the means of egress should be illuminated at all times while the premises are occupied. During emergency lighting conditions, vertical illuminance at these locations should be greater than the immediate surroundings and at least 10 lx (1 fc).

Figure 29-5. Overhead troffers, some of which are supplied with emergency power, are aligned with the path of egress to more conspicuously delineate the path.

Location and Application of Egress Luminaires. Perhaps the best visual cues for egress come from the egress lighting system itself (independent of signage). It should be designed in such a way that it provides a clear, unambiguous, and conspicuous indication of the egress path (Figure 29-5). Illuminances on the egress path should be higher than those on immediately surrounding areas to help guide occupants to the exits. Similarly, relatively high illuminances near the exit door can make this area conspicuous and quickly identifiable.

Coverage. It is important to provide adequate illumination in all areas that constitute the means of egress. Exit access and discharge areas are frequently difficult to define with certainty, but agreement can and should be reached between the designer and the authority having jurisdiction (AHJ). It is also important to remember that the exit discharge extends outside the building and that luminaires appropriate for outdoor application are required. Many jurisdictions also require emergency lighting and exit marking at all changes of direction of travel, in windowless or underground buildings, and at elevation changes in stairwells or corridors. Locally applicable codes should always be consulted to verify that equipment is provided in all required locations.

Glare control. Inadequate glare control can substantially degrade the value of an emergency lighting system (Figure 29-6). To reduce glare, the designer should specify luminance as well as mounting and aiming angles that minimize glare. The lower the mounting height, the greater the probability of disability glare. Mounting locations and aiming angles should be chosen to position luminaires well off the line of sight to exit signage. Combining the emergency egress luminaire with the exit sign at a single location almost certainly causes disability glare, and the exit sign will be obscured if the luminaire is aimed at a high angle to the path of egress (Figure 29-6). This also helps reduce the effects of scattered ambient light that would decrease the visibility of signs in the presence of smoke.[4,17,18] Eliminating competing sources of brightness along the same line of sight also keeps exit signage conspicuous and easy to locate in clear conditions.

Figure 29-6. Directional emergency lighting equipment can create disability glare and compromise the efficiency of evacuation. In smoke, luminaires can reduce the visibility of exit signs along the same line of sight.

Shadows. Highly directional light sources and obstructions, such as partitions or merchandise racks, produce shadows. Body shadows created by evacuees on stairs lighted by a single directional light source are particularly important to avoid. Every flight of stairs should be illuminated by more than one luminaire to minimize shadows on nosings and treads.

Improperly located luminaires can become ineffective if the partitions in open-plan offices create shadows along the means of egress. This problem commonly occurs when partitions are moved to accommodate new office layouts.[19] To minimize this problem, luminaires that are easy to move or provide broad general coverage can help to minimize shadows (Figures 29-7a and b).

Smoke. The possible presence of smoke along the path of egress poses a difficult problem for the designer. The dynamics of smoke vary with the burning materials and conditions in the building. Smoke varies in temperature, color, rate of development, degree of stratification, particulate content, and optical density.[20,21]

All of these properties can hinder the effectiveness of the egress lighting system. See Figure 29-8a and b for an example of the performance of an exit sign in flame and smoke conditions.

Given the inherent variability and instability of smoke, recommendations for emergency lighting during smoke-filled conditions are currently limited. Not all equipment is tested or designed to operate in smoke or fire conditions. However, data and specification do exist on exit sign visibility in smoke.[22-24] Refer to the section "Design Consideration for Exit Markings" below.

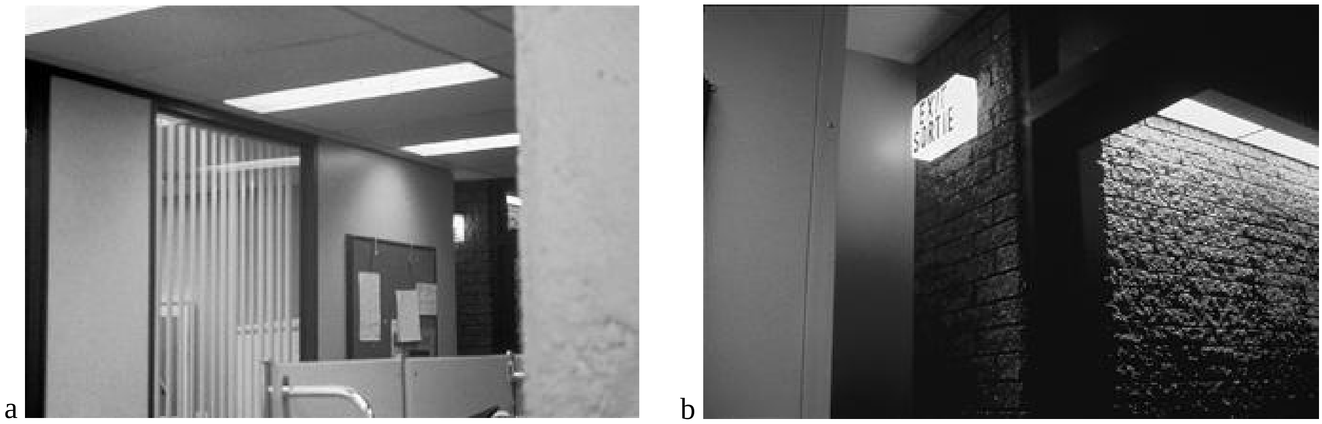


Figure 29-7. a. An exit sign, partially concealed within an alcove formed by a new wall featuring a bulletin board. These photographs (a and b) were taken in a jurisdiction that permits the placement of signs to the left of doors, as in this example. The narrow, obstructed, ill-defined exit route is a problem. Likewise, light from the fluorescent luminaire directly above the sign greatly reduces the visibility of the sign in smoke. b. A close-up view of the sign reveals that the lettering height and spacing between characters are compromised at the expense of visibility, especially when viewed from a distance by a visually impaired person or through smoke, as discussed below.

One promising design avenue in this regard is a supplemental lighting delivery system mounted near the floor (see the section "Floor Proximity Path Marking" below). Such systems can light the path while avoiding light absorption and scattering in smoke stratified at higher levels. In addition, such equipment delineates the path for the evacuee crawling beneath the smoke layer. Pathmarking systems can improve the evacuation speed in smoke-filled conditions.[25]

Areas outside the egress path. Some codes require lighting outside the egress path. A well-designed emergency lighting system should include illumination in areas that might enhance the safety and functionality of the building during loss of power. Examples of such applications include:

- Public restrooms
- Generator rooms
- Elevator equipment rooms
- Cold storage rooms
- Computer and communications equipment rooms
- Tool storage and maintenance facilities
- Classrooms
- Manufacturing areas
- Electrical equipment rooms
- Health care facilities
- Hazardous manufacturing equipment
- Underground corridors and other windowless space
- Areas of refuge, areas of rescue assistance

Figure 29-8. a. Exit sign visible in smoke-free fire. b. Exit sign nearly obscured in smoke. Visibility is greatly reduced by the glare from the overhead luminaire.

Interiors. In the United States, the Americans with Disabilities Act (ADA)[26] prohibits wall objects such as luminaires from projecting more than 10 cm (4 in.) into walks, corridors, hallways, or aisles when these objects are mounted between 67 and 200 cm (27 and 80 in.) above the finished floor. Emergency egress luminaires that are wall mounted, such as compact fluorescent sconces, should be checked for their protrusion into the egress path whenever they are to be mounted within this zone. Exit signs should also be located above the upper limit of this zone. Under the ADA and other state and local codes, the designer should be aware of special areas that might require additional emergency lighting, such as toilet facilities.

Night-light circuits, which are used to provide minimal light during unoccupied times, are commonly used when the designer selects unitary battery equipment or other normally off systems (units that are powered only during power failure) for emergency lighting. The "normally off" systems do not provide egress or ambient illumination when interior luminaires are turned off and the building is occupied by security or maintenance personnel. These night-light circuits need not be part of the emergency lighting system, but as a minimum should meet recommendations for egress lighting.

Ceiling soffits and bulkheads can completely block emergency sources. The designer should coordinate the location of these luminaires with the reflected ceiling plans and confirm with the architect. Minimum ceiling clearances in egress corridors are prescribed by NFPA, BOCA, and ADA. The designer should locate egress luminaires, especially sealed beam lamps, so that they are not obscured by soffits, bulkheads, or suspended luminaires and do not protrude below the minimum headroom set by codes. Supplementary egress luminaires might be necessary if examination of lines of sight along a corridor shows that bulkheads, building signage, or suspended luminaires obstruct the function of emergency egress luminaires and exit signs.

General-purpose luminaires that contain emergency lamps or that are entirely dedicated for emergency lighting should be marked as being part of the emergency lighting system.[7] These markings, which could be in the form of a red dot or a distinct label, should appear on the exterior of the luminaires so as to be readily apparent. The markings would help in giving the luminaires priority for maintenance and in giving them due consideration when reorganizing the space.

Exposed unit equipment and central dc systems are not always compatible with the interior design of a space. In addition, certain jurisdictions do not permit the use of concealed emergency equipment such as fluorescent inverters. Other options should be explored for spaces where exposed equipment is not desired. Some equipment, which is manufactured to be concealed behind a ceiling panel during normal operation, releases and energizes the lamps during emergency operation or power loss. Where the appearance of battery-operated equipment or the concealed ceiling panels is objectionable, a generator or inverter system can power selected luminaires that are "normally on" and integral to the lighting system. Any concealed sources should be identified after installation to help ensure that building maintenance personnel know which luminaires provide emergency egress lighting.

Failure of one emergency luminaire should never leave a space in total darkness. In stairwells, alternating a normal source with an emergency source at each landing should provide a reliable system. Emergency egress lighting circuits should not be switched, except where the controls are accessible only to an authorized person as defined by the AHJs or the local codes in effect.

In places of assembly, such as theaters and auditoriums, some jurisdictions permit egress illuminance to be reduced to 2 lx (0.2 fc) during performances or projections but require 10 lx (1 fc) or greater at all other times. Manufacturers of dimming or other control systems can provide an emergency transfer module or contactors to transfer selected luminaires to "full on" upon failure of the normal power source to the dimming control cabinet. In this way the emergency luminaires can become an integral part of the lighting system and function with the nonemergency luminaires. This requires voltage sensing of the source available to the dimming closet.

Exteriors. Most codes enforced by the local AHJ require an emergency "white light" at the exit discharge from a building. This source provides the transition from the interior egress path to the exterior. The exterior source should provide a minimum of 10 lx (1 fc) at the exit. Currently, there is no distance requirement for emergency lighting beyond the exit discharge; however, it is recommended that the transition area from the exit discharge to the exterior areas surrounding the exit discharge be illuminated in accordance with IESNA recommendations for pathways (see Chapter 21, Exterior Lighting). The exit discharge does not always lead to a sidewalk or normal building entrance, but instead leads from a discharge or stairwell directly onto grade. The emergency lighting system used at the exit discharge should be capable of reaching full output within 10 seconds after a loss of power.

Exterior sources should be located either above the door or to one side to reduce glare. Different sources are available to accomplish exit discharge lighting, and the designer should select the appropriate source for the application.

Incandescent lamps are short lived but can be a good choice when used only as an interim source during high-intensity discharge (HID) lamp restrike times or in a low-voltage dc battery-powered source during power failures. Egress lighting might be required to be on during all times of occupancy, not just during power failures, requiring the use of a battery-powered source in conjunction with a "normally on" source. This normally on source should have long life, as do HID or fluorescent sources. With any power failure, the HID arc extinguishes, so the restrike time must be covered with either a backup instant on lamp or instant restrike lamp.

Low ambient temperatures affect lamp lumen performance of some fluorescent lamps (see Chapter 6, Light Sources). The proper ballast and lamp must be specified for the expected temperature range.

Environmental conditions such as damp, wet, and hazardous locations require the additional consideration of the suitability of the equipment for use in such locations. The AHJs usually refer to the listing or labeling practices of a product testing and certification organization, acceptable to them, in determining the acceptability of the installation. The listed or labeled equipment should be marked for use in these locations.

Partially protected exterior locations under canopies, marquees, and roofed open porches, as well as interior locations subject to moderate degrees of moisture (such as some basements, some barns, and some cold storage warehouses), constitute damp locations. Exterior locations, exposed to weather and unprotected, and interior locations, subject to saturation with water or other nonflammable liquids (such as vehicle washing areas), are classified as wet locations. These locations include roofs near mechanical and elevator penthouses where exit signs are required in some jurisdictions. Locations where fire or explosion hazards might exist due to flammable gases or vapors, flammable liquids, combustible dust, or ignitible fibers in the air constitute hazardous locations.

Normally on exterior luminaires can be controlled by photocells and time clocks to conserve energy during unoccupied periods and daylighted hours. These luminaires can also be controlled by the building energy management control systems, but their circuiting must be kept separate from the building's normal power circuits.

Many interior and exterior locations require equipment that is safe from tampering and vandalism. Schools and many outdoor locations are examples of applications often requiring vandal-resistant equipment (see Chapter 12, Educational Facilities Lighting, and Chapter 21, Exterior Lighting). In addition, many schools incorporate interior courtyards that are exposed to the weather but totally enclosed by the building walls. These enclosed areas are often required to contain a path of egress back into the building. The entrances from the courtyard into the building should be marked with appropriately listed exterior location exit signs. The doors from the building into the courtyard should not be marked with exit signs unless the courtyard is specifically designated to be an area of refuge or rescue assistance. Close coordination with the AHJ, owner, and architectural team is required in these special cases.

Emergency Lighting Equipment

Unit Equipment. Unit equipment consists of a self-contained rechargeable battery, a battery charger, a battery status indicator, a transfer device, a test switch and pilot lamp, and provisions for either integral or remote lamps or both. This equipment charges a battery when normal ac power is available and transfers battery power to the emergency light source during a power failure. These luminaires operate only during normal power failures. Both halogen and incandescent sealed beam types and a variety of low-voltage lamps and reflector combinations are used as sources in these luminaires. Most unit equipment operates at 6 or 12 V dc, with the higher voltage preferred when remote lamps are used. Other voltage systems are becoming available.

Unit Inverter. The fluorescent lamp unit inverter system consists of a self-contained rechargeable battery, a dc-to-ac or high-frequency inverter, a battery charger, a transfer device, a pilot lamp, and a test switch. During a power interruption, it operates one or more fluorescent lamps from an internal battery by converting dc power to ac power at a frequency of 60 Hz or higher. When the power is returned, battery charging occurs.

Fluorescent lamp unit inverter systems operate the luminaires used for general lighting in a building. Most units fit into the luminaire ballast channel (Figure 29-9). High temperatures in this space can shorten the life of the battery. An externally mounted system should be specified if high temperatures are expected.

Figure 29-9. An example of a battery-inverter unit mounted in a suspended fluorescent luminaire adjacent to the ballast.

With fluorescent lamp unit inverters, the required test switch and pilot light should be easily visible. Some manufacturers conceal the test switch and pilot light behind a diffusing panel, making these items less apparent for performing maintenance and identification.

The combination of unit inverter and lamp should also be compatible. Inverters that accommodate different lamp types provide different lumen outputs that can be a low percentage of the initial lamp lumens.

Central dc Systems. A normally off central dc system contains a battery, a battery charger, a test switch, a transfer device, and a pilot lamp. The system powers remote incandescent lamps and dc lamps in exit signs during a power interruption. Normal emergency supply voltages are 12-, 24-, and 120-V dc. Other systems using 32, 36, and 48 V still exist.

Lamps for dc systems can be any filament lamp of equal voltage rating. However, most commonly available 24-, 32-, 36- and 48-V lamps are designed for applications other than emergency lighting and should be reviewed for life, lumen output, and future availability.

Central Inverter Systems. A central inverter system contains a battery, a battery charger, a dc-to-ac inverter, and a transfer means, plus appropriate test and monitoring equipment. The system incorporates electronic devices to convert battery dc voltage to 60-Hz line voltage. Standard transfer systems (those with transfer time over 8 ms) can operate incandescent and fluorescent lamps without significant off time. Fast-transfer and uninterruptable power supplies (UPS) can operate HID sources that need a transfer or "off" time of 4 to 8 ms or less. These supplies can also power fire-alarm systems and other crucial 60-Hz equipment. UPS that are selected for emergency power should comply with the applicable codes and standards for emergency power; those that are intended only to maintain computer operation might not be suitable for operating emergency lighting loads.

Standby Generator. The standby generator includes a starter battery, a battery charger and a transfer means, plus test and monitoring equipment. An engine generator produces 60-Hz line voltage. This kind of system powers incandescent and fluorescent lamps and other 60-Hz life safety loads. It is not suitable for HID unless supplementary incandescent or fluorescent sources are used. A standby generator system provides ac power backup as an emergency source in large buildings. Check the Life Safety Code[27] for the maximum allowable startup time.

Batteries. The emergency lighting power systems described above use batteries as a source of backup power, except for the standby generator, which uses a battery for engine cranking. Most commercial emergency lighting systems are available with a variety of battery types.

A battery consists of one or more connected cells. Batteries used for backup power are rechargeable or "secondary batteries." The three categories of rechargeable cells in emergency lighting systems contain lead-based plates with an acid electrolyte, nickel metal hydride with an alkaline electrolyte, or nickel-cadmium with an alkaline electrolyte. The major groups of commercially available cells are lead-acid, lead-calcium, lead-antimony, nickel-metal hydride, and nickel-cadmium cells.

All batteries except nickel-metal hydride can be manufactured as wet type (with liquid electrolyte), and most have a means for adding water; that is, they require maintenance. Also in production is a sealed type (starved electrolyte or gelled electrolyte) that is said to be "maintenance-free." The advantages of sealed cells are that they are easy to ship and virtually eliminate the chance of injury from electrolyte splash. However, sealed cells have shorter life than well-maintained wet cells. Wet lead-based cells offer greater plate thickness and a mid-range specific gravity, both indicators of longer life. Wet cells are normally used for large-power applications where trained maintenance personnel are responsible for their maintenance.

Automobile batteries have different recharge characteristics than those for emergency applications. Automobile batteries last only approximately six months on an emergency battery charger and therefore should not be used as replacement equipment.

Lead-calcium batteries are best suited for controlled temperature environments. They are usually tested at 25° C. Colder temperatures can improve their life but reduce their performance. At elevated temperature, both life and performance are reduced.

Nickel-cadmium batteries withstand elevated temperatures much more easily. Different types are required for various temperature ranges.

Lead-based cells and, to a lesser extent, nickel-cadmium cells emit hydrogen gas during charging and discharging. Sealed cells also provide blowout vents in case severe overcharging occurs. The worst-case hydrogen emission information on large battery installation should be checked to determine whether special ventilation (e.g., exhaust) fans are needed to avoid hydrogen buildup, which can cause explosions.

Batteries are classified as short-, medium-, and long-discharge types. A 90-min operating time corresponds to a medium discharge rate. Equal initial ampere-hour ratings do not mean equal battery capacities. Available amperes at a specific time are the only way to compare battery performance. Manufacturer information should be reviewed before a battery is chosen. Data for discharge rates and operation times provided by battery manufacturers represent ideal-temperature performance under the most favorable charging and discharging conditions. A safety factor should be added to compensate for conditions other than ideal.

The battery must be compatible with its charger, and it must operate efficiently in the application temperature range at the expected maintenance intervals. In addition, the battery must meet all load requirements. UL-924[28], from Underwriters Laboratories, and C22.2 No.141-1985,[29] from Canadian Standards Association (CSA), allow the battery to reach 87.5% of nominal voltage for maximum current capacity. In no case can the discharge time be less than 90 minutes in the United States and 30 minutes in Canada.

Because batteries are perishable, and because the time between manufacture and installation can be substantial, shelf life and no-load recharge intervals are important. For long intervals without charging after system installation, it is best to disconnect the battery to prevent deep discharge and then give boost charges at the recommended intervals. The following precautions should be carried out when installing new batteries:

- Store batteries in coolest area prior to installation.
- Check for shipping damage, leaks, dents, cracks, post damage, and post corrosion.
- Check tabs or posts for bends or separations from battery case.
- Verify that the battery is suitable for the environment in which it is installed.
- Check luminaire wiring to and from the battery for corrosion, frays, and insulation integrity.
- Determine when normal building power will be functional and not interrupted.
- Connect batteries only after normal building power is continuous.
- If wet cell, check specific gravity and electrolyte levels.
- Install in proper orientation if a sealed battery.
- Install according to manufacturer's instructions.
- Record the installation date and put the date on the product.

All batteries require maintenance, including so-called "maintenance-free" batteries, which, in this regard, differ only from other batteries in that there is no access to the electrolyte. Most batteries have rapid output decline without warning as they reach end of life. Inspections should therefore be made at least semiannually or quarterly depending on the application, ambient temperature, area humidity, and installation altitude. The following precautions should be carried out when maintaining batteries:

- Perform visual inspection; check for leaks, cracks, and corrosion.
- Check battery terminals for corrosion and clean if necessary.
- Check wet-cell battery vent caps for blockage and clean if necessary.
- Check electrical connections; tighten hardware where necessary.
- Check integrity of anticorrosive gels and add more if needed.
- Check specific gravity and electrolyte level on wet cells.
- Check wiring to and from battery for corrosion, frays, and insulation integrity.
- Check the cells closest to the positive terminal in multicell banks. The most positive cell of the battery takes the greatest electrical strain; it is the best indicator of a battery's condition.
- Check and record ampere and voltmeter readings at all charge rates.
- Use built-in electronic monitor testing if available; check self-diagnostics.
- Check electronic monitor for correct operation.
- Manually test and record battery operation; recharge should be about five times longer than operation time.
- Recognize battery type and normal life expectancy; check installation date and if product is supplied with a replacement date; replace if close to end of rated life.
- Replace only with same type and ampere hour rated battery; most chargers are factory set for specific batteries.
- Record the maintenance date, and keep the date with the maintenance log.

Chargers. Battery chargers for emergency lighting systems must conform to applicable safety standards.[28,30] This ensures that the combination of battery and charger has met the time requirements for the initial charge and recharge and that the charger has passed nationally established safety requirements.

Most wet nickel-cadmium and lead-type batteries use a two-rate charge: a high current for initial charge and a float (constant-voltage) or trickle (low-current) rate to maintain the battery at maximum capacity. The time needed to recharge depends on the charger's current-producing capacity and the battery's ability to accept that current. A fast recharge requirement can shorten battery life. If the current supplied is too great, the heat created causes a subsequent loss of electrolyte. Battery charging tolerances are critical. Even a slight increase in float voltage significantly reduces the battery life through overcharging; even a slight decrease reduces total capacity through self-discharge. Stand-alone chargers can require field adjustments for best operation. Nickel-cadmium designs use constant-current-charging techniques. These chargers are not interchangeable. For example, a 12-V nickel-cadmium battery has a different charge set point than a lead-cadmium battery.

Light Sources. Incandescent lamps used in normally off emergency lighting applications (Figure 29-10) differ in design from those used for general illumination. These usually have a lamp life of approximately 50 hours and provide significantly more lumens per watt than their longer-lived general-illumination counterparts. Typical types include sealed-beam incandescent, sealed-beam halogen, and miniature incandescent and halogen. These high-output lamps are particularly useful when operated from unit equipment and central low-voltage dc systems.

Figure 29-10. An emergency lighting unit powered by a remote source.

Emergency lamps used in normally on applications should have high reliability and long life expectancy. Maintenance of normally on emergency lamps is essential to ensure their availability during a power failure. Because of their short lives, general-illumination incandescent and halogen lamps are not good choices if an inverter or a generator is the emergency supply. Emergency lamps that are normally on should be less susceptible to filament damage from vibration, have long life, operate over a wide range of temperatures, have good socket contact, and have short (less than 10 s) restrike time. If general-illumination lamps are required for emergency lighting, the physical and electrical characteristics of candidate lamps should be checked to ensure reliability.

Compact fluorescent lamps (CFLs) have become common in emergency applications. These lamps offer long lamp life, high color rendering characteristics, and high efficacy to reduce the power requirement. It is often easier to achieve good illuminance uniformity and low glare with such lamps, because luminaires utilizing them provide wide coverage. The designer should be aware that low-temperature, high-temperature, or high-humidity exterior applications might not be suitable for these lamps, and the manufacturer should be consulted for assistance with such applications (see Chapter 6, Light Sources).

Square-wave inverters for emergency power should not be used with high-power-factor CFL ballasts. The ballast can trip the circuit breaker because its power-factor-converting capacitor can behave like a short circuit to the square wave output of the inverter.

HID lamps are generally incompatible with conventional emergency power sources such as dc systems, generators, or ac inverters. None of these systems maintains lamp operation during transfer from normal to emergency power, so the long cool-down and restrike times prevent emergency lighting from being available within the 10 s required by the Life Safety Code.[27] Fast- transfer and uninterruptible ac inverters are available to prevent this problem and are the only emergency power sources compatible with HID lamps. "Instant-restrike" HID lamps are available, as are systems that incorporate incandescent lamps during HID off periods. If HID sources are selected, the designer should be sure that the spectral characteristics of the source do not degrade the color appearance of exit markings.

Linear fluorescent lamps are also used in emergency lighting systems, particularly for illuminating paths of egress, and in normally on systems. They are used in conjunction with unit inverters, central inverters, or standby generators.

Floor Proximity Path Marking. These systems typically consist of photoluminescent materials, tritium, electroluminescent, LED, or incandescent lamps, which provide a visual delineation of the path of egress during emergency situations. These systems may be activated by fire alarm or loss of power. Available power sources are dc batteries, central inverters, and standby generators. Several path marking systems designed for use in smoke are available. These systems are covered in the Life Safety Code[27] and may be mounted in the floor or on the wall nearby. Some states, such as California, have considered requirements for such systems, and the designer should remain alert for codes adopting this emerging technology, keeping in mind that it is a supplementary rather than an alternative emergency lighting system. In the meantime, applying such systems may result in enhanced safety. For more information see the section "Supplemental Path Delineation" above.

Design Considerations for Exit Marking

Legibility and Visibility of Exit Signs. The legibility and visibility of exit signs are determined by three primary factors: sign characteristics, observer variables, and environmental conditions. Sign characteristics include sign luminance, contrast, color, uniformity, graphics, and location. Observer variables include adaptation state, visual capacity, expectations, and familiarity with the space. Environmental conditions include viewing distance, sign position, ambient illuminance, veiling luminance, veiling reflections, glare, competing graphics, colors, and contrast of the surroundings. These factors do not affect visibility equally.

Sign Characteristics

Graphics. Both NFPA 101[27] and UL-924[28] specify the following criteria for exit sign graphics with a minimum 152-mm (6-in.) legend height and an increase in proportion based on greater letter height. The word EXIT is specified in the United States, while either EXIT or SORTIE are permitted in Canada.

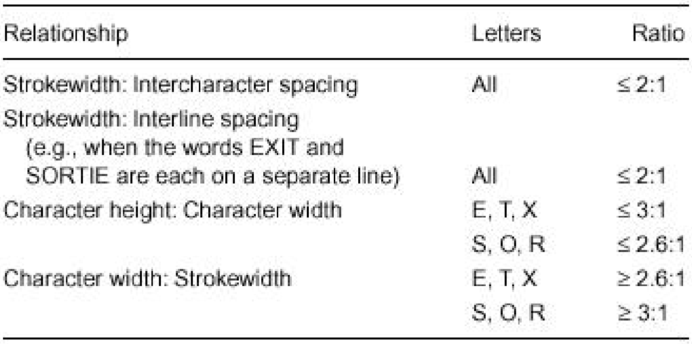
- Stroke width should be 19 mm (0.75 in.).
- Letter height should be 152 mm (6 in.).
- Letter width should be 50 mm (2 in.), except for the letter "I" in EXIT and SORTIE, which should be 19 mm (0.75 in.) wide.
- Intercharacter spacing should be 10 mm (0.37 in.).
- Optional directional indicator should be a chevron, identifiable from a minimum distance of 12 m (40 ft) and located to the left or right of the word EXIT, consistent with the correct direction of egress.

The requirements in CSA-C860[29] are similar, except that character size, stroke width, and the spacing between characters are governed by the ratios specified in Figure 29-11. Wider aspect ratios are required for characters having multiple vertical strokes, including S, O, and R.

Several codes, such as CIE,[31] ISO,[32] and NFPA,[33] have provisions for an optional pictograph for exit markings. Its graphic content contains a human figure exiting through a door.[26]

Viewing distance. The ability to locate and read an exit sign decreases as the distance between the viewer and the sign increases. The current maximum distance between signs, or between a sign and the exit, is 30 m (100 ft). This translates into a visual angle of approximately 17 min of arc for a 150-mm (6-in.) letter height, and 5.6 min of arc for a 50-mm (2-in.) letter width. Visual angles of this size should be resolvable by those with 20/100 or better vision,[34] about 95% of the population,[35] although questions remain about which features of the word EXIT constitute the critical detail necessary for recognition.

Luminance. Sign luminance is not directly specified by the Life Safety Code[27] nor by the National Building Code of Canada.[36] The Life Safety Code does state that exit signs that are externally illuminated shall have a minimum contrast of 0.50 and an illuminance of 50 lx (5 fc). Internally illuminated signs are required to be tested by an independent testing laboratory to determine compliance with the requirements in UL-924.[28]



Relationship	Letters	Ratio
Strokewidth: Intercharacter spacing	All	≤ 2:1
Strokewidth: Interline spacing (e.g., when the words EXIT and SORTIE are each on a separate line)	All	≤ 2:1
Character height: Character width	E, T, X	≤ 3:1
	S, O, R	≤ 2.6:1
Character width: Strokewidth	E, T, X	≥ 2.6:1
	S, O, R	≥ 3:1

Figure 29-11. Exit Sign Typography Requirements from CSA-C860[29]

In other codes, specifications are given for sign luminance. UL-924,[28] for example, specifies two methods for making comparison. One method is to measure the minimum luminance levels and uniformity ratios on the exit sign; the other method involves the testing of the exit sign at 30 m (100 ft), under various external illuminance conditions (on the sign and visual task area) using human observers. UL-924[28] and the NFPA Life Safety Code[27] presently allow an exception to this requirement for self-luminous and electroluminescent signs that have a minimum letter brightness of 0.2 cd/m^2 as long as they are placed at their rated and marked viewing distance as determined by an independent testing laboratory. Research, however, has shown that these signs are significantly less visible than signs meeting the 50 lx standard.[23,37] The CIE specifies a minimum luminance of 15 cd/m^2 and a maximum of 300 cd/m^2 for pictographs,[31] while a United States Aeronautics and Space code specifies 89 cd/m^2 as a minimum.[38] In Canada, the CSA-C860[29] luminance requirements depend on the luminance uniformity (L_{max}/L_{min}) within each letter of the legend and its background when illuminated (Figure 29-12). In addition, all designated points on the sign shall be no less than 8.6 cd/m^2 when illuminated.

A preponderance of research has demonstrated that increasing sign luminance can increase visibility and conspicuity in both clear and smoke conditions.[23,37,39-44] There does not appear to be an upper limit for effective sign luminance in smoke.[22,45] The existence of an upper limit for clear conditions remains uncertain. Some very low wattage exit signs such as LED, although mandated by certain energy codes, in effect can be significantly less visible than compact fluorescent or incandescent signs of higher luminance.

Contrast. The contrast between an exit sign's graphic and its background is very important in determining its visibility. The contrast can be calculated with the formula

$$|L_t - L_b|/L_b$$

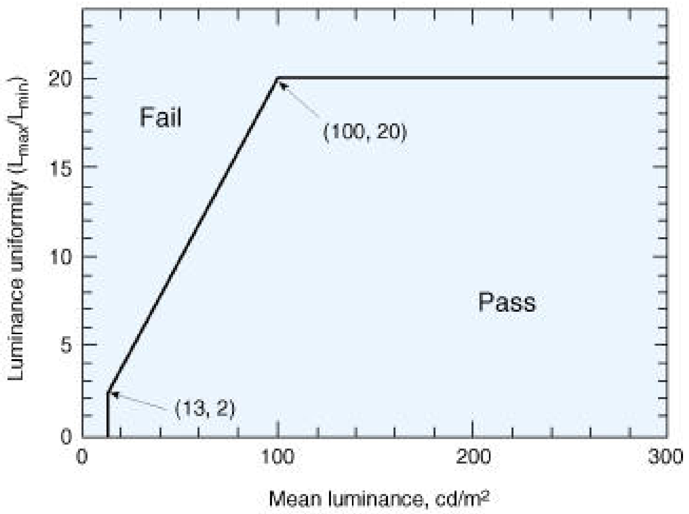


Figure 29-12. Exit sign luminance requirements from CSA-C860.

where L_t is the luminance of the character and L_b is the background luminance. NFPA-101[27] and UL-924[28] specify that an exit sign must have a minimum contrast of at least 0.5 when measured in darkness. CSA-C860[29] requirements are similar to U.S. standards for exit signs having both luminous legends and luminous backgrounds. When either field is opaque, the contrast shall be at least 0.25 with a vertical ambient illumination of 50 lx on the sign face. Ambient lighting can significantly reduce sign contrast by disproportionate reflection from the opaque and luminous fields. For edge-lighted signs, the CSA standard requires contrast of at least 0.25 with 50 lx vertical illuminance on the sign face and with a white nonspecular backdrop (ρ = 80 to 90%) behind the sign. Further, the contrast of edge-lighted signs should be at least 0.5 in darkness and with a black nonspecular backdrop behind the sign (ρ = 0 to 5%). Available research indicates that increasing contrast beyond these minimum requirements can increase sign visibility.[23,46]

Color. Neither NFPA nor UL provide specifications for exit sign color, although many local jurisdictions do. Color combinations are typically some combination of red or green letters on a contrasting background (often white), although the letter and background color can be reversed. The National Building Code of Canada calls for red letters on white, or the reverse. In other countries, codes specify green and white for exit signs.[31,32,47] Research on the visibility of exit signs of different colors has been somewhat inconclusive,[23,37] possibly because contrast or luminance often varied with color. When these factors were held constant,[45] it was found that color had a negligible effect on sign visibility when compared to the much stronger influences of luminance, contrast, and size.

Configuration and uniformity. Other sign factors that determine visibility include the configuration and uniformity of the sign. Recent research has hinted that stencil-faced signs, in which the letters are illuminated and the background is opaque, can be somewhat more visible in both smoke and clear conditions.[15,30,33] Sign uniformity has not been studied systematically enough to provide reliable luminance ratios, although some have suggested variations of no more than 3, 4, or 5:1 above the average level over the brightest area of the sign. An Australian standard specifies ratios of no more than 4 or 5:1 for internally lighted signs,[47] while the CIE suggests no more than 10:1.[31] Excessive nonuniformity can lead to obscuration of letters or critical details on the sign. CSA C860[29] permits ratios of up to 20:1, depending on sign luminance (Figure 29-12); UL-924[28] is similar except that it permits ratios of up to 20:1 for each letter or directional indicator and 50:1 for the entire sign.

Observer Characteristics. Physical disabilities in the population must be considered. For example, between 0.5 and 1% of the population can be considered legally blind,[48] even with corrective lenses. Approximately 8 to 10% of the male population suffers from color vision defects, which can result in inability to see saturated reds, or to confuse colors such as yellows and greens.[49] Other observers might suffer mobility impairments that lead to longer egress times. All observers suffer from problems due to changes in their adaptation during the first several seconds after the building lighting is extinguished. For example, normal building illuminance levels can range from 100 to 1000 lx (10-100 fc) or more for offices. The time to adjust to emergency lighting varies with the level of the emergency lighting; the lower the level, the longer the time for adaptation. For example, it takes over 2 min for foveal dark adaptation from an initial adaptation luminance of approximately 300 cd/m^2.[50] As a result, signs of very low luminance, such as self-luminous or electroluminescent signs at 0.2 cd/m^2, might be invisible during the early stages of a power failure or similar building emergency.[2] Beneficial effects have been reported from using photoluminescent markings and signs under such conditions.[13,14]

Location and Application of Exit Marking Equipment. Exit signs are required in all buildings. Exit signs should be located along the required means of egress and at all exit doors or access areas. Directional exit signs should be located at changes of direction in the egress path. Entrances to egress stairs should also be indicated with exit signs.

Exit signs are usually mounted above exit doors to allow passage beneath, and no lower than 2 m (80 in.) above the finished floor to the bottom of the sign. Signs must be visible over the heads of others located in the path of egress. Exit signs should not be more than 30 m (100 ft) apart along the egress path at each exit door,[27] at each change of direction, at entrances to stairwells, and at changes of elevation. Check local codes for other required locations. During a fire emergency, smoke can obscure signs mounted above doors (Figure 29-8). One solution has been the use of supplemental floor proximity signs, located approximately 200 mm (8 in.) above the floor (Figure 29-13). These signs are intended to be visible to a person crawling along the floor, just below the smoke.[51] Recent research suggests that such signs should have high luminance, because low-luminance signs are obscured very rapidly in smoke.[22,23,37] Some incandescent and many exit signs have low sign luminances. The designer should be aware that certification or listing by a recognized agency does not ensure proper application of an exit sign.

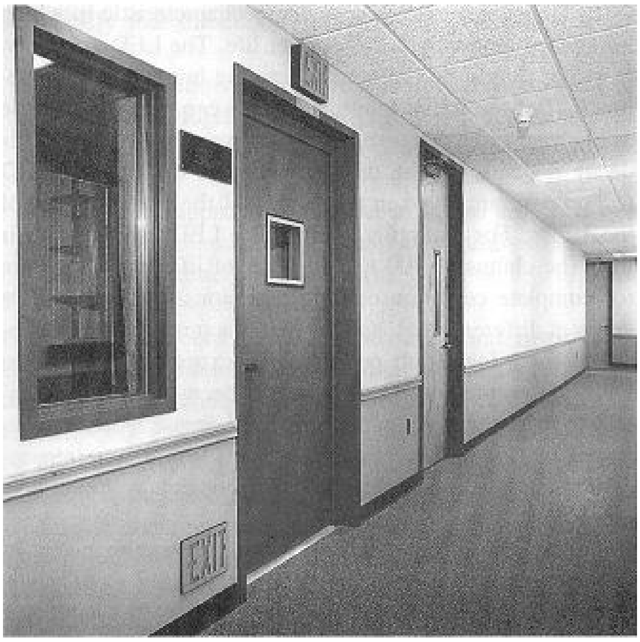


Figure 29-13. Supplemental exit signs mounted near the floor can be seen by occupants crawling along the floor in smoky conditions.

The same types of problems are encountered with positioning exit signs as with locating egress luminaires. Ceiling soffits and bulkheads can block the line of sight to exit signs (Figure 29-14). Other types of luminaires, such as surface and suspended linear, can block the view of the sign. Hindrances to proper location and mounting of exit signs are very large doors, glass above doors (Figure 29-7) , insufficient recessing or surface mounting depth to mount exit signs above doors, business signs, and emergency egress luminaires. Some exit signs with battery packs are four or more inches deeper than nonbattery types, making them extend lower into the corridor headroom or door opening space. The location of LED exit signs should be checked for viewing angles, because some of these signs can be less visible when viewed from oblique angles. All diffusing lenses used with LED matrix signs reduce luminance, some more than others. Emergency egress luminaires can produce sufficient glare to obscure the exit sign. Competing light sources and building finishes can also interfere with sign visibility by changing sign contrast, reflectance, and brightness. In exterior applications, certain light sources might not be suitable; electroluminescent signs, for example, are affected by high humidity. Also, incandescent sources can be affected by high vibration, which can damage both the source and the socket.

Figure 29-14. A ceiling soffit can block the line of sight to an exit sign.

Choice of Exit Marking Equipment. Although exit marking equipment is controlled by many regulations, many different products meet the legal criteria. Therefore, specifiers have a large selection of equipment from which to choose.

Options for exit signs include flashing, possibly combined with audible signaling. These options alert the visually-impaired via sound and the hearing-impaired via flashing. The UL-924 standard specifies the on-off duty cycle times for these accessories.[28] Some local codes require exit signs with these options to interface with a fire-alarm system as a way to provide additional information to the occupants. Again, local codes should be consulted for facilities that require these options.

Self-contained signs. Self-contained illuminated exit signs maintain sign luminance during normal power loss without the need for an external power source. Battery, battery charger, and transfer systems stay ready to sense power failure and switch to battery backup.

Remote-powered signs. Unit equipment, dc systems, inverters, and generators are all sources of emergency power for remote-powered exit signs. With unit equipment or dc systems, a separate circuit feeds directly to the exit to power emergency lamps. In these systems, the emergency lamp voltage must match the supply. Inverters or generators used as emergency power sources should continue to operate the normally on lamp without the need for additional circuits.

Because remote-powered signs do not contain a dedicated battery and charger, they are less expensive than self-contained signs. The total system cost depends on the remote power source, the distance from that source, and the voltage needed to power the sign. For example, an inverter- or generator-powered system using the same electrical distribution system as that for normal power adds no cost, but dc power needs additional wiring from the emergency source.

Exit Sign Lamps. Long-life lamps are essential for both safety and economical maintenance. A building emergency can occur without immediate power interruption. Therefore, the normally on exit source should be designed for high reliability and reasonably long life.

Many incandescent exit signs have extended-life normally on lamps and low-voltage emergency lamps that operate at the battery voltage. The burn cycle for the battery-operated incandescent lamp or lamps is short, and therefore a short-life, high-lumen-output source can be used. Incandescent lamps provide extended life and lower light output when operated below their rated voltage. Long-life incandescent lamps designed for exit applications have a rated life ten or more times that of standard lamps and still provide needed exit luminance. One advantage of filament lamps is that they can be easily circuited to flash within the specified duty cycle. High-voltage long-life lamps have thin filaments, so shock and vibration can be a problem. Vibration can also cause screwbase lamps to back out of the lampholders. Lamps with a dc bayonet base or fluorescent lamps should be considered for such applications.

Fluorescent lamps are popular choices for exit signs. Low-wattage tubular and compact types are reliable, have high luminance and good luminance uniformity, have a reasonably long life, and are more efficacious than incandescent sources. Total efficacy calculations for fluorescent sources should include ballast loss, which can be as much as 50% of the listed lamp wattage. The power factor is usually low for compact fluorescent lamps and must be considered in circuit sizing. The luminous output of fluorescent lamps depends upon temperature, so care should be taken to avoid excessively high or low temperatures. See Chapter 6, Light Sources for additional details.

Electroluminescent lamps operate between 80 and 200 V ac, require less than 1 W of power per exit face, and yield a uniform luminance pattern. Light is produced by phosphors serving as a dielectric between a conductive foil or metal-sputtered back electrode and a clear front electrode. Lamp life can be 5 years or more when operating at a low frequency and low power density. Exit signs with these sources operate the lamp at line frequency during normal times. If self-contained, they can switch to a higher frequency and higher light output during emergency operation. These are typically considered low-luminance signs and are not commonly used today.

Electroluminescent lamps decline gradually in brightness over their life. The lamp should certainly be replaced before the luminance falls below the 0.21 cd/m^2 specified by the Life Safety Code.[27] Different types of lamps decay at different rates, and the manufacturer should be consulted for information pertaining to expected lamp life and brightness decay.

Light-emitting diodes (LEDs) use 1 to 8 W per exit face. LEDs are highly resistant to vibration, temperature, and humidity because of their solid-state structure. Proper voltage and current transient protection are necessary to achieve long lamp life and good lumen maintenance. These small point sources are used in an array to spell EXIT in English-language signs, are placed behind diffusing material, or are imbedded in plastic strips within the sign. These lamps also have flashing capabilities and can be circuited to vary in intensity. Viewing angles should be checked when using signs with exposed LEDs because the luminous intensity of the LED varies with the viewing angle. This potential problem is overcome when the light-emitting diodes are placed behind diffusing material. Many LED signs have power factors as low as 0.1.[22] This is usually not a problem when connected to the building utility supply, because the low power factor of LED signs is usually leading, rather than lagging. This helps to negate the undesired influences of more common lagging nonlinear loads in buildings. Such compensatory loads might not exist when LED signs dominate an electrical circuit. In these cases, the load on the circuit can become 10 times higher than with an ideal power factor of 1. This is an important consideration when sizing backup power sources and distribution circuits. See Chapter 6, Light Sources, for further discussion on power factor.

LEDs exhibit a brightness decay characteristic in which luminance gradually declines over life. The LED assembly, or lamp, should be replaced before the luminance falls below half of the initial luminance. This can occur in as little as one year or less or take as long as five years or more. This decay depends on the driving circuitry, the type of LED technology employed in the sign, and the manufacturer of the LEDs. For example, overdriving LEDs shortens their life. The claims of 100 to 200 years of life expectancy are for complete cessation of light emissions. Different LEDs decay at different rates, and the manufacturer should be consulted for information pertaining to expected LED life to half light output and the light output decay rate. It is advisable to mark this date on the sign or otherwise record the expected LED replacement date. For units that are put into operation simultaneously, group replacement is more cost effective.

Self-luminous signs depend on the radioactive decay of tritium gas and the resultant electrons striking a phosphor-coated glass tube to produce visible radiation. The published life expectancy of these sources is 10 to 25 yr. As stated in previous sections, the luminance of such signs is very low and decays exponentially. This light source can be useful in explosion-prone areas. Areas that require expensive electrical distribution systems also benefit from this nonelectrical exit sign. These signs must be registered with the U.S. Nuclear Regulatory Commission or the Atomic Energy Control Board of Canada for use and proper disposal at end of life. The designer should make sure that the chance of breakage and exposure to the general public is minimal. In the United States, these signs are required to be placed at an interval not to exceed their marked viewing distance, which can be from 15 to 30 m (50 to 100 ft).

Maintenance Requirements

As with any luminaire, exit signs require periodic cleaning and relamping. Due to their vital need during power failures, prompt relamping and proper lamp replacement are required. Group relamping should be considered as a means of reducing maintenance cost and increasing reliability. Most problems can be prevented if installation instructions and replacement part recommendations are followed.

The following precautions should be carried out when installing exit signs:

- For a battery-operated sign, follow the steps described earlier in this chapter for initial battery installation.
- Avoid prolonged emergency lamp operation during installation. Incandescent lamps for emergency mode operation usually have high light output but short life.
- Verify that the exit circuit cannot be switched off.
- Visually inspect lamps and wiring.
- Record the installation date.
- Verify that directional indicators are oriented correctly.
- Verify that the stencil is oriented properly to spell EXIT or SORTIE.
- Make sure lamps are not in contact with the diffusers.
- Ensure the appropriate number of lamps are operational (some authorities require two lamps in both normal and emergency modes).

A permanent record of all maintenance and inspections should be kept in a log book or computer file for review by the local inspection agency, in compliance with the National Electric Code (NEC), NFPA 70;[9] National Life Safety Code, NFPA 101;[27] National Fire Code of Canada;[52] and NFPA 110, Emergency & Standby Power Systems.[53]

All self-contained emergency lighting and exit signs, including units with maintenance-free batteries, should be inspected and tested every 30 days or more often. This inspection should include, but not be limited to, depressing the test switch a minimum of 90 s and checking for lamp operation (including remotely mounted lamps) and pilot light operation. Luminaires containing wet batteries should be inspected for electrolyte level in each cell and for electrolyte leakage.[28,36]

Central systems powered by ac or dc supplies or by maintenance-free batteries should also be inspected and tested at least every 30 days. See the discussion on battery maintenance earlier in this chapter for more information. The system's output voltage, frequency, and current should also be checked against the data on the nameplate, and should be within the tolerance specified when connected to the full emergency lighting load.

Regardless of the source of power, the following steps should be carried out when maintaining exit signs:

- Visually inspect lamps and wiring. Ensure the lamps are suitable for the environment.
- Check installation date and institute a group relamping program if appropriate.
- Inspect light transmitting media for dirt or discoloration and replace with parts approved by the manufacturer, if necessary.
- Verify that the directional indicators are consistent with the egress path after maintenance.
- Record the installation date.

In addition, every 12 months, the emergency lighting and exit marking equipment should be disconnected from the normal ac supply and operated for a period of 90 min or the minimum duration for which emergency lighting is required in the given building. During this test, all emergency light sources should operate continuously. To ensure that the space always has emergency lighting when required, the test should be conducted at a time when the batteries can be recharged before the building is occupied. For large installations where reliable skilled maintenance personnel are not available, a service contract with a responsible service organization should be provided.

Where the designer anticipates little or no maintenance and inspection, self-diagnostic and so-called "smart" self-testing emergency lighting equipment should be considered. A multitude of smart equipment is currently available. It automatically monitors various vital functions of the equipment and indicates failures via visual and audible indicators. It typically runs an automatic test and diagnostic program at least once each month.

When replacing lamps, batteries, or any other parts, the maintenance personnel must select replacement parts with identical ratings and part numbers indicated on the replacement markings in order to maintain the proper visibility, illuminance, and duration of operation in accordance with code requirements. Field-installed diodes used in series with an incandescent lamp to extend lamp life and reduce power consumption should be avoided in exit signs. The diodes reduce the lumen output of the lamp, possibly affecting the visibility of the exit sign as tested by the independent testing laboratories.

In addition to the above procedures, it is also useful to periodically check the egress path to determine if architectural and furniture changes have rendered the emergency lighting system ineffective. One should check that exit signs are readily visible along the path of egress, and that emergency illuminance levels still are on the path of egress. Many building renovations take place without thought to the emergency lighting system, which results in improperly located exit signs and emergency luminaires.

Emergency lighting should be treated as life safety equipment, for without its proper function, an area can be left in total darkness, causing confusion, collisions with obstacles, panic, and even loss of life.

Exit Sign Retrofits

Retrofit kits are available to convert existing exit signs to more efficient light sources (Figure 29-15). Such efforts to conserve energy should not compromise sign visibility. Likewise, the retrofit kits should not compromise the elec-trical system. Not all kits are equal in these regards.[22] A mock-up with recognized retrofit products installed in a facility's signs can help reduce potential problems. It should be noted that in 1995, UL[28] rewrote earlier standards for retrofit kits. As a result, many previously accepted procedures have been eliminated or restricted. One should make sure that the kit's listing is indeed current and recognized by local regulatory bodies.

Figure 29-15. A variety of exit sign retrofit kits.

The following precautions should be carried out when installing exit sign retrofit kits:

- Verify the suitability of the kit for the sign, and check the original manufacturer's recommendations. Some retrofits are UL listed for single face signs only, and some for ac signs only. Not all can be used for battery backup signs.
- Check that no wire splices are made in the lamp compartment. All supply connections must be made through lampholders.
- Use the proper voltage lamp or lamp and ballast combination.
- Position the lamp for the most uniform luminance on exit face.
- Record the installation date.

LIGHTING FOR SAFETY

Lighting for safety is different from emergency lighting in that it involves ensuring proper illumination to provide safe working conditions, safe passage, and the identification of any hazards or obstructions, indoors or outdoors.

Safe conditions are essential in any areas where there are people, and the effects of lighting on safety must be considered. The environment should be designed to help compensate for the limitations of human capability. Any factor that aids visual effectiveness increases the probability that a person avoids an accident or detects the potential cause of an accident and acts to correct it.

In instances where illumination is associated with accidents, the accidents are attributed to inadequate illuminance or poor quality of illumination. However, there are many less tangible factors associated with poor illumination that can contribute to accidents. Some of these are direct glare, reflected glare, and harsh shadows, all of which hamper seeing and can cause visual confusion. Excessive visual fatigue itself can be an element leading to accidents. Accidents can also be prompted by the delayed readaptation that a person experiences when moving from bright to dark surroundings and vice versa. Some accidents that have been attributed to an individual's carelessness could have been partially due to difficulty in seeing from one or more of the above-mentioned factors. The accidents might have been avoided through the use of good lighting principles. See Chapter 3, Vision and Perception, for further discussion of factors affecting visibility, and Chapter 10, Quality of the Visual Environment, for discussion of lighting design criteria.

Lighting for safety is a concern that must be addressed in both outdoor and indoor locations. People must be made aware of such hazards such as curbs, steps, sloped walkways, and obstacles in one's path (Figure 29-16). Where the illumination is very low or designed to create a special effect, such as in hotels, restaurants, theatres, museums, art galleries, and aquariums, care must be taken to identify changes in elevation and direction without detracting from the visual effectiveness of the lighting.

The industrial environment presents many special concerns with respect to lighting for safety. Physical hazards are marked according to American National Standards Institute (ANSI) documents.[54] The color rendering properties of the light source should be considered with regard to the physical hazards present in the particular installation.[55] See Chapter 19, Industrial Lighting, for good industrial lighting practices.

Illuminances

Figure 29-2 lists illuminance levels regarded as absolute minima for safety alone. They are provided for general guidance and should not be interpreted as regulatory requirements. Consult, also, the local regulations.

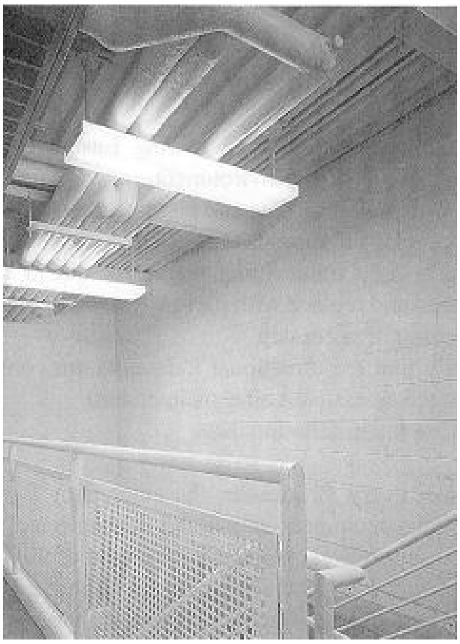


Figure 29-16. Adequate safety lighting must be used in spaces with obstructions or changes in direction or level, such as stairwells.

To ensure these values are maintained, higher initial levels must be provided as required by the maintenance conditions. In those areas that do not have fixed lighting, local illumination should be provided during occupancy by means of luminaires that are portable or mounted on material-handling equipment and vehicles.

Other Factors

A visually safe installation must be free of excessive glare and of uncontrolled, large differences in luminances. Appropriate guides to limiting glare and adaptation effects are given earlier in this section in discussions of luminance ratios and visual comfort. Maximum luminance ratios are important in avoiding temporary reductions in visibility because of changes in readaptation when alternately looking at areas of widely different brightnesses. Although the quality and quantity of illumination can be designed for safety in an area, it is necessary to know whether the design meets requirements. See Chapter 10, Quality of the Visual Environment.

SECURITY LIGHTING

Security lighting is installed to help create a perception of security and to protect people and property from criminal activities.[56] The general principles of security lighting apply to new facilities as well as to facilities being upgraded or converted to new uses. These principles are:

- Integrate light into the total security system and thereby facilitate the effectiveness of other security devices or procedures.
- Illuminate objects, people, and places to allow observation and identification and thereby physically reduce criminal concealment.
- Use illumination to deter criminal acts by creating a fear of detection, identification, and apprehension.
- Reduce the fear of crime for the innocent by enhancing a perception of security.

The reader should understand that security lighting goals may conflict with other lighting design criteria. The designer is responsible for resolving these potential conflicts. It should also be emphasized that security lighting is a segment of a total security system; the total environment must be designed with security in mind, if lighting is to be effective.

Lighting helps protect people and property from criminal activities because of its effect on vision. In public places, good security lighting is designed to help everyone see the space clearly. This can better enable a sighted person to identify and possibly avoid threats that may exist on the premises. The presence of good security lighting can also assist in protecting nonsighted persons from potential criminal activity by making would-be attackers visible to others in the area. To achieve the objectives of security lighting in both public and secure areas, attention has to be given to both vertical and horizontal illuminances, the uniformity of the illuminance distribution, the effect of obstructions, the reflectances of surfaces, background contrast, the degree of glare, the spectral power distribution of the light source, the interaction with electronic surveillance systems, and the effect on the surrounding area.

Target hardening is a useful concept for determining options and setting deterrent objectives that increase the time, resources, and planning of a perpetrator. Time is the enemy of the criminal; the longer the criminal act takes or the more security elements he has to overcome, the higher the probability he will be deterred. The target is the people or property to be protected, and the security features are the hardening elements. Hardening elements include fences, gates and locks, surveillance personnel and cameras, response personnel, and established policies and procedures for operations and maintenance.

A helpful approach to determining security needs is to study the opportunity and means of probable attackers. Security works to deny opportunity and to increase the level of risk necessary to attack the target.

The extent and type of lighting to be used as part of a security system are determined by several different factors:

- **Crime status of the area.** If the site is in a high-crime area, it is likely that many physical defenses, including lighting, are necessary to maintain overall security.
- **Nature of the site.** The type of facility or business, the hours of operation or access, and surrounding conditions affect the approach to security. Lighting should be integrated into the overall goals for the site.
- **Degree of obstruction.** Landscape design and building configurations should not retard detection and identification of unauthorized persons on premises. The means of lighting should be designed to avoid strong shadows and permit observation of the activities of those that are permitted on the site.

- Ambient brightness of the surrounding area. Security elements at one site affect the security elements on adjoining sites. If the illuminances are lower or of lower uniformity at one site compared to adjoining properties, the former may be more attractive to criminal activity.
- Impact on the surrounding area. Stray light from a security lighting installation can be considered as light trespass by neighbors. There are also possible safety effects on neighboring roads and railroads due to glare. Where signal lights are used to control traffic on roads, railroads, rivers, or at sea, care should be taken to avoid confusion caused by disability glare directly from security lighting, veiling reflections on the signals from the security lighting, or the identification of the security lighting as a signal. Local lighting ordinances should be consulted prior to any design work. Mounting height restrictions, source type, wattage limitations, shielding, and other local requirements must be followed.

It should be remembered that lighting cannot guarantee security. Crime occurs in daylight hours as well as at night. Also, as pointed out above, lighting is only one factor in security. Other elements are required for good security, including locks, doors, gates, and detection means such as cameras or personnel.

Security Lighting Applications

Broadly, there are four security lighting applications.

- Lighting for controlled sites, where there are other defenses including access control
- Lighting for public spaces (such as mall parking lots) where people may be present at any time and where there are few or no access controls
- Lighting for single-family dwellings
- Lighting for multifamily residences, where each dwelling unit is a private area with few physical defenses and where "common-areas" exist

The recommended practices of IESNA provide more detailed information and should be consulted when developing a lighting design.

Security Lighting for Controlled Sites. A question to consider is whether to light the space at all. It can be argued that lighting a secure area advertises the presence of something worth taking and hence attracts criminals, so keeping the area dark may be a better approach. However, if criminals are likely to know the area contains valuable materials, then the absence of lighting makes the target more difficult to defend. Thus, the choice of whether to light or not depends on an assessment of risk. If the risk of criminal activity is high, security lighting is essential. If the risk of criminal activity is low, and the target is relatively unknown to persons not familiar with the site, then providing security lighting may be counterproductive, especially in rural or isolated areas. It should be noted, however, that the risk of criminal attack is not the only concern for the designer. Safety lighting is also important, so egress portals and refuse storage areas need to be considered before deciding on a solution. In these cases, motion sensors can be employed.

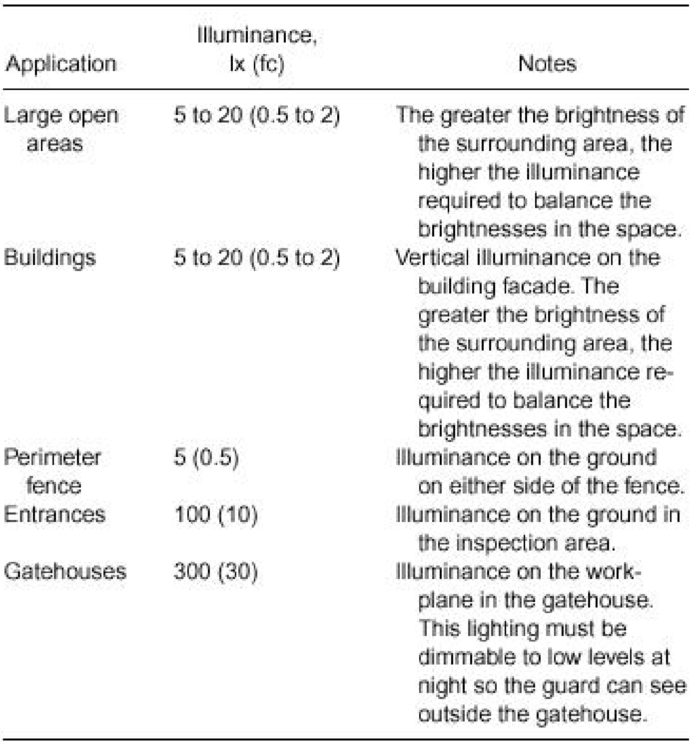
Security lighting for a controlled area should provide uniform illumination so that anyone moving in or around can be seen easily. Also, the security lighting design should provide enough illumination so that intrusion or attempted intrusion into the area can be detected, and any electronic surveillance devices such as security cameras can operate effectively.

These objectives can be achieved in many different ways depending on the site and the nature of the security system. The following provides examples of security lighting for some common sites.

Storage yards, large open areas, container terminals. Area lighting is typically accomplished with floodlighting or roadway luminaires on poles 10 m (30 ft) or more in height. The recommended average illuminance on the surface of large open areas is given in Figure 29-17. Figure 29-18 shows a typical layout. As a guide, an average-to-minimum illuminance ratio of 8:1 should be achieved. Luminaire spacing depends on the luminous intensity distribution of the luminaires.

The designer of area lighting normally determines the number of poles, the number and type of luminaires, the wattage and type of lamp, and the luminaire mounting height. If the area is unobstructed by trees, structures, or topography, the choice often is determined by simple economic considerations such as first cost, maintenance, and energy. Although simple economic considerations are important, they must be weighed against the anticipated threat and, in economic terms, potential liability from personal injury, theft, and vandalism. It is usually less expensive to provide good security lighting from the beginning.

If the area contains obstructions, as in container terminals or rail yards, a design utilizing multiple source locations reduces shadows. This is especially true if the luminaires are positioned within the site, between obstructions, and with overlapping light patterns. The reflectances of site materials can also be used to advantage. Light colors on buildings and concrete paving enhance the efficiency and uniformity of the lighting system.



Application	Illuminance, lx (fc)	Notes
Large open areas	5 to 20 (0.5 to 2)	The greater the brightness of the surrounding area, the higher the illuminance required to balance the brightnesses in the space.
Buildings	5 to 20 (0.5 to 2)	Vertical illuminance on the building facade. The greater the brightness of the surrounding area, the higher the illuminance required to balance the brightnesses in the space.
Perimeter fence	5 (0.5)	Illuminance on the ground on either side of the fence.
Entrances	100 (10)	Illuminance on the ground in the inspection area.
Gatehouses	300 (30)	Illuminance on the workplane in the gatehouse. This lighting must be dimmable to low levels at night so the guard can see outside the gatehouse.

Figure 29-17. Recommended Average Illuminances for Security Lighting

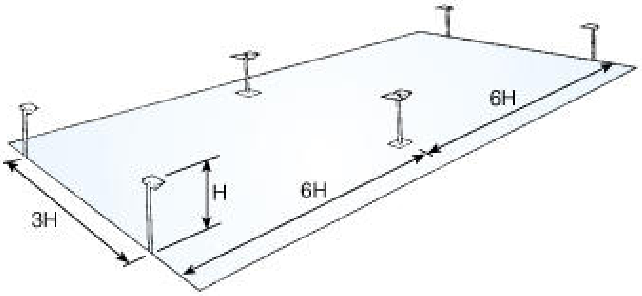


Figure 29-18. Typical layout for floodlighting open areas. *H* is the pole height fo the luminaires.

Disability glare can sometimes be used to protect a secure area by making people outside the protected area highly visible to guards inside the perimeter and making the guards more difficult to detect by people outside. In this system, high-luminance luminaires or strobes are mounted at eye level and aimed outward from the secure area. This technique has a high probability of producing light trespass and light pollution problems. To minimize the duration of these problems, motion sensors can be employed.

Building exteriors. All points of entry to the building and the areas around them should be easily seen. Depending on the construction of the building, the points of entry can consist of walls and roof as well as doors and windows. The most comprehensive approach is to light the whole building, but power density and light pollution concerns limit most security lighting to critical areas of the building and site. The illuminance to be provided on the face of the building is given in Figure 29-17. The ratio between the average and the minimum illuminance on the building facade should not be greater than 8:1. Security lighting for buildings is more effective if the building has a high-reflectance facade and the area adjacent to the building also has a high reflectance (e.g., concrete rather than asphalt).

Critical areas can be lighted by luminaires set in the ground, mounted on the building, or mounted on poles. Ground-mounted floodlights can provide uniform illuminance, but they are very accessible and hence can easily be put out of action. However, for anything other than a basic box-type building, it is difficult to adequately illuminate all of the building surfaces without using an excessive number of luminaires. Pole-mounted luminaires are usually the best option for uniformly illuminating the surfaces of the building and the surrounding area (Figure 29-19). As with any site lighting, light trespass, light pollution, and mounting height restrictions should be considered before beginning the design.

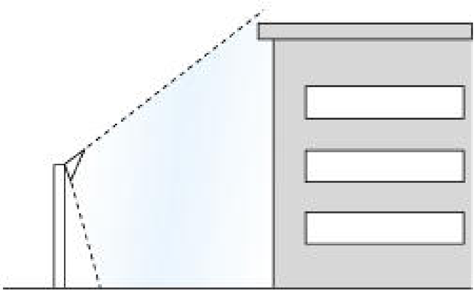


Figure 29-19. Use of pole-mounted luminaires to provide uniform illumination on the around a building.

Building interiors. Security lighting for the interiors of buildings depends on the methods of providing security. If security officers are on site or make frequent checks of the location, it is appropriate to have continuous illumination to allow for a quick visual inspection of each space as officers make patrol rounds. If the building is monitored automatically using cameras, without security officers on site, enough light should be provided to operate the cameras. If infrared motion sensors or infrared camera systems, which do not require light, are used, it is appropriate to design the building to be dark when secure and to be illuminated when trespass is detected by the monitoring equipment.

Perimeter fences and walls. The purpose of lighting perimeter walls and fences is to deter or slow trespass and to enable guards to detect intruders. Perimeter barriers come in several different forms, from masonry walls to barrier plants. The form of lighting used depends on the possibility of seeing through the barrier and whether one or both sides of the barrier is patrolled. If the wall or barrier is solid, there is no possibility of seeing through it. If both sides of the solid barrier are the subject of surveillance, lighting can be provided by positioning a luminaire over the top to reduce shadowed areas at the base of the barrier.

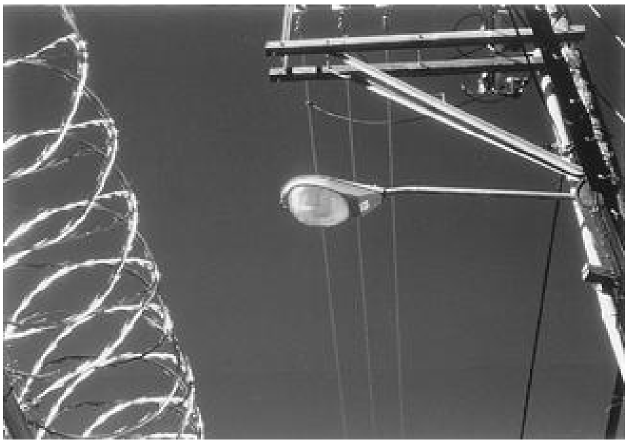


Figure 29-20. Use of a pole-mounted luminaire to light fenced perimeter areas.

If a view through the barrier is possible, and if the obstruction is patrolled from either inside or outside the secure area, it is useful to be able to see both sides. For this, lighting needs to be provided on both sides. This can be accomplished with a set of pole-mounted luminaires set back from the fence (Figure 29-20). The lighting is most effective if the luminance of the fence is lower than the luminance of the area on the side being viewed through the fence. This objective can be achieved by using a low-reflectance fence material such as black or dark green coated chain-link. If galvanized chain link is used, care should be taken with the aiming of the luminaires to reduce the illuminance directly onto the fence.[57]

Guarded entrances and gate houses. Access to a secure area is usually controlled by security personnel who stop and inspect people and vehicles entering and leaving the site (Figure 29-21). The entrance should be provided with multiple, redundant luminaires so that the loss of any one luminaire does not seriously degrade the lighting available to the guard on duty.

Luminaires should be located at entrances in order to facilitate inspection of vehicles, vehicle license plates, and vehicle contents, including the driver and the occupants. Good vertical illuminance should be provided to allow for facial identification, inspection of credentials, and receipt of packages without having to use auxiliary hand-held devices such as flashlights. In high-security areas, some luminaires should be mounted at or below pavement level to facilitate inspection of the underside of vehicles. Having a concrete road surface to increase the reflected light helps in the inspection of the underside of vehicles. Backup power supplies should be considered for use during electrical outages.

Illuminance at ground level for the inspection area should be at least 100 lx (10 fc), or twice that of the immediate surrounding areas, whichever is greater. In addition, vertical illuminance equal to 25% of the horizontal illuminance should be provided at the level of the vehicle driver. Good color rendering light sources (CRI > 50) should also be used so that the color of clothing, documents, goods, and vehicles can be easily discerned.

Figure 29-21. Secure entrances must be sufficiently illuminated to enable inspection of visitors or automobiles.

Illuminance inside the guardhouse should be limited to the minimum required for comfortable completion of assigned tasks, such as report writing and equipment use (Figure 29-17). It should be possible to dim the illuminance in the guard house to allow the guard to see clearly through the windows at night and to limit the ability of those approaching the gatehouse to see what the guard is doing. Well-shielded task luminaires are essential to avoid reflections on any surveillance monitors and the windows of the gatehouse. Fitting the gatehouse with specular-reflecting, low- transmission glass at a tilted angle, painting the inside of the gatehouse in dark colors, and ensuring that illumination can be dimmed all help limit the view into the gatehouse. Figure 29-22 shows a typical installation.

Security Lighting for Public Spaces. The lighting system should make the space look attractive and safe, and hence to encourage its use at night by allowing defensive action at a safe distance. In other words, by enhancing the visibility of people and faces, suspicious or threatening behavior can be detected early enough for evasive actions. Similarly, greater visibility provided by good lighting enables people behaving in a suspicious manner to be identified and described with greater accuracy.

Lighting designed to allow action at a distance requires that attention be paid to the illuminance levels, the illuminance uniformity, the presence of disability glare, and the spectral power distribution of the light source. Recent research has shown that for people to have a reasonable perception of security at night in parking lots and on business streets, the horizontal illuminance on the pavement should lie somewhere between 10 and 50 lx (1.0 and 5.0 fc).[58] Below 10 lx (1.0 fc), perceptions of safety deteriorate rapidly. The principle of defensive action at a safe distance requires that vertical illuminance uniformity be within a ratio of 4:1, average to minimum, and 5 to 8 lx (0.5 to 0.8 fc) at 1.5 m above the ground. To achieve this goal, luminaires should provide illumination from more than one direction.

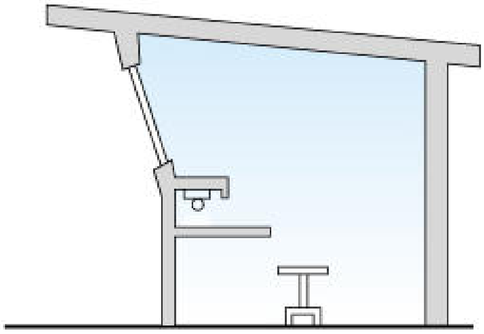


Figure 29-22. Gatehouses should be painted in dark colors and use well-shielded luminaires and tilted windows to minimize reflections and disability glare.

Disability glare is caused by light scattered in the eye. Care in the selection of luminaries and pole heights is essential if disability glare is to be avoided. Unfortunately, disability glare is common in public spaces, sometimes due to poorly aimed luminaires and often poor luminaire design. This is particularly true of some historical luminaires, which provide little shielding of the lamp and low mounting heights. In this case, low wattages should be used in the historical luminaires, and site illumination from other well-shielded sources should be used to meet security lighting design goals.

Light source spectral power distribution is important for seeing hair, eye, clothing, complexion, and vehicle colors, which are key elements in most witness statements. The ability to name colors accurately and confidently is determined by the light source spectral power distribution and the illuminance level. Research has shown that almost any nominally white light source (CRI > 50) allows accurate and confident color identification at the illuminances used in public spaces at night. High-pressure sodium lamps allow accurate but less confident color naming at high illuminances used for public spaces, but both the accuracy and confidence declines at lower illuminances. Low-pressure sodium lamps do not allow accurate color identification under any illuminance level.

Parking facilities. Techniques for lighting parking lots and parking garages are available in Chapter 22, Roadway Lighting, or IESNA RP-20-99, Lighting for Parking Facilities.[59] Walkways are discussed in IESNA DG-5-94, Lighting for Walkways and Class 1 Bikeways.[60] When security is an issue, because of crime history or changing conditions, the recommended minimum maintained security illuminance for open parking facilities should be no less than 30 lx (3.0 fc) on the pavement, with a uniformity ratio of 4:1, average to minimum. Vertical illuminance should also be 3 lx (0.3 fc) 1.5 m (5 ft) above the ground. These recommended values differ slightly from those offered in RP-20-99 for enhanced security. Functionally, however, the differences are unimportant. Sidewalks, footpaths, and grounds around open parking lots should be illuminated to a minimum of 6 lx (0.6 fc), with a uniformity ratio of 4:1, average to minimum. Vertical illuminance should also be 6 lx (0.6 fc) at 1.5 m (5 ft) above the ground.[59] These illuminances should be enough to identify a human face at 10 m (33 ft).

The threat to people and property in covered parking garages can be very high. This condition is caused by isolated floors, numerous places to hide, and a lack of effective surveillance. Recommended minimum illuminances for covered parking facilities should be no less than 60 lx (6.0 fc) on the pavement, with equal values measured vertically at 1.5 m (5 ft), and a uniformity ratio of 4:1, average to minimum. These illuminances should be maintained around the clock because daylight rarely penetrates deeply into parking garage.

Parks and public areas. Parks and public areas are areas where opportunity for violent crime is high. As with any other area where criminal activity is likely, the lighting system should enable action at a distance by illuminating potential hiding places and adjacent areas. Locations where loitering and graffiti are likely to occur should be uniformly illuminated at least to 10 lx (1 fc) at ground level with an average-to-minimum ratio of 4:1. Planners also need to consider the following issues when designing the lighting and other components of security and safety management:

- Light pollution and light trespass
- Prior history of crime in the park and surrounding areas
- Social conditions and citizen participation
- Cultural values
- Traffic patterns and access
- Patrol frequency

Trails and walkways should be illuminated to a minimum of 6 lx (0.6 fc) at ground level, with an average-to-minimum uniformity ratio of 4:1 along the length of the trail and on all sides out to a distance of 10 m (30 ft). Vertical illumination 1.5 m above the ground should be at least equal to the horizontal illuminance at ground level. Where trails are situated in woods, landscape areas, or even broken terrain, lighting designers should also attend to aesthetic issues.[62] Information on lighting for public parking lots, public walkways, and jogging trails can be found in Chapter 21, Exterior Lighting, and Chapter 22, Roadway Lighting.

Fast food restaurants. Many fast food restaurants are around-the-clock operations. The drive-through area is where criminals are most prone to attack, particularly when patrons are involved in transactions at the window. The attacker typically approaches the patron between the building and the left rear of the automobile. Building designs that allow the window service personnel to view the left sides of cars provide a deterrent to this type of mugging. Lighting that is mounted on the building, above the side window, allows good observation by the employee, although glare for the patrons in their cars should be avoided (Figure 29-23). Considering the vulnerability of drive-up customers at fast food locations and when security is an issue, lighting standards should exceed those described for parking lots discussed in RP-20-99[59] during all hours of operations. For these applications, the recommended minimum maintained illuminance for the area within 30 ft of the drive-up window(s) should be no less than 60 lx (6.0 fc) on the pavement with a uniformity ratio of 3:1, average to minimum. Sidewalks, footpaths, all areas adjacent to the structure, and the remainder of the parking lot should be illuminated to a minimum of 30 lx (3.0 fc) at grade, with an equal value measured vertically 1.5 m (5 ft) above grade and with an illuminance uniformity ratio of 4:1, average to minimum.

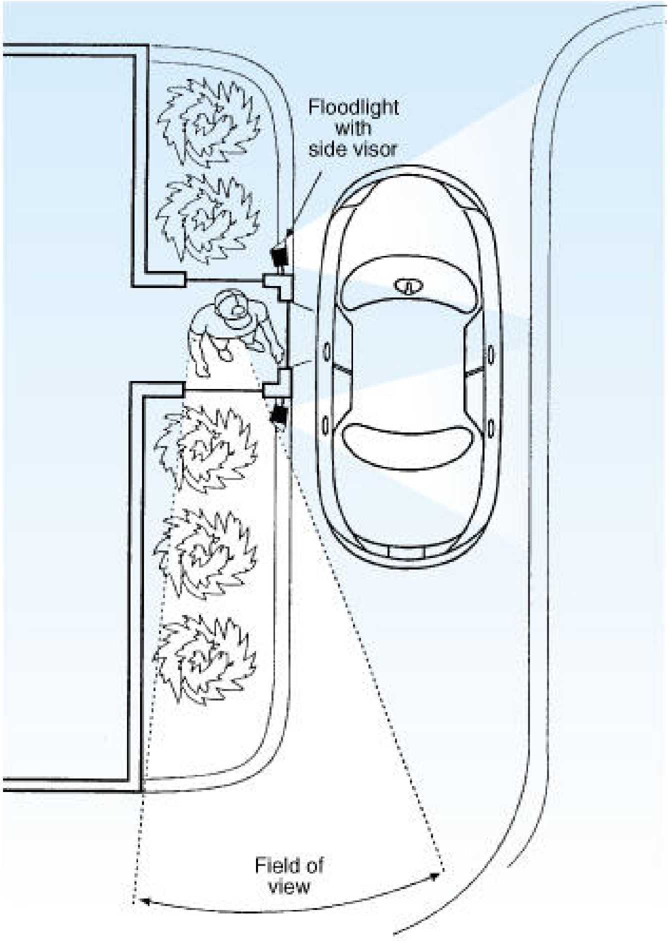


Figure 29-23. Location of luminaires for drive-up fast-food restaurant.

Convenience stores. Convenience stores often operate around the clock. When security is an issue the minimum recommended maintained horizontal illuminance should not be less than 60 lx (6.0 fc) on the parking lot pavement and customer use areas, including gasoline pumps and islands, air and water stations, and drive-up telephones. The illuminance uniformity should not exceed a ratio of 3:1, average to minimum. Surrounding, adjacent, or internal sidewalks, footpaths, refuse disposal area(s), areas adjacent to all sides of the structure, and grounds areas should be illuminated to a minimum maintained illuminance of 30 lx (3 fc) at ground level with a uniformity ratio of less than 3:1, average to minimum. It is recommended that the storefront exit and the sidewalk areas be lighted to a minimum of 50 lx (5.0 fc) at the pavement. If supplemental viewing devices such as surveillance cameras or mirrors are employed, a minimum vertical illuminance of 12 lx (1.2 fc), 1.5 m (5 ft) above ground level should be provided for lighting faces. Vertical illuminances in the parking lot improve the visibility of the outdoor parking area to people inside the store, provided the luminances of objects exceed the luminances of the reflections on the inside of the glass. Ambient lighting within the store is usually adequate for security purposes. Store management should always have a clear view of the outside sales area. After dark, more illumination is required outdoors than inside to prevent windows from acting as mirrors. Covering windows with opaque sales promotion posters should be discouraged. Reference should be made to IESNA RP-20, Lighting for Parking Facilities,[59] for additional guidance in lighting convenience store parking facilities.

Automated teller machines and night depositories.[63] Automated teller machines (ATMs) and night depositories (NDs) present opportunities for criminals to perpetrate acts of crime against the public. ATMs and NDs do not normally provide security by professional personnel, so customer security must rely on physical security features such as lighting. As with any service where the public is invited to take advantage of unattended service locations, owners, operators, and providers of such services should adhere to applicable statutes or standards of security in an attempt to minimize risk to invited users. However, it is important to recognize that there are innumerable variables in site configurations, existing lighting applications, weather, seasonal impacts, and other conditions, which require some flexibility in the implementation of recommended practices. IESNA Design Guide DG-9-97, Lighting for Automatic Teller Machines,[64] and the section "Financial Facilities" in

Chapter 11, Office Lighting, provide additional information on this subject. At the time of this printing, however, the standards for ATM/ND lighting are evolving. The reader should consult the IESNA and local codes for the latest information.

Security Lighting for Residences. The size of the residence, the distance from neighbors, the nature of the terrain, and whether the residence is in a rural, suburban, or urban area are all factors to be considered. Single-family housing and multifamily housing, such as an apartment building, have different security requirements and different security lighting needs. Deterrence is usually the number-one priority in residential security, followed by detection, recognition, and, if all else fails, a signal for help.

Deterrence. Security lighting can deter criminals by sending a message that at your residence the probability of detection and identification is high. To do this, enough light has to be provided to eliminate dark areas and to clearly reveal anyone on the property to a resident. Occupancy sensor controls are a key ingredient to deterrence in these applications.

Detection. To detect an intruder, there should be a high luminance contrast against the background. Lighting the landscape can achieve this by creating a bright background against which people can be seen. Illuminating exterior walls of a building makes it easier for neighbors to detect an intruder's silhouette against the lighted surface.

Signal for help. If deterrence has failed and an intruder has been detected outside, a call for help is desirable. Lighting can provide such a call. High-brightness strobe lights, located at eye level at points of entry and directed away from the residence, can interfere with the intruder, while providing an alarm to neighbors, passers-by, or patrols. Professional alarm or security equipment providers can furnish this equipment and integrate it into an existing electronic intrusion detection system.

Indoor lighting. Security lighting is not limited to exteriors. An intruder wanting to avoid confrontation may move to another target if the interior lights are on. Switching lights with a timer is one solution. This becomes more effective when the timer can be programmed to switch at different times during the week or month. Motion detectors that switch interior lights on when motion is detected are also effective. Illuminating critical interior entry or hallways can be effective deterrents and provide comfort to shut-ins and those who feel safer when the lights are on.

Single-family dwellings. The illumination of exterior doors is mainly for the identification of callers, for safety, and for more routine tasks such as finding keys quickly and locating lock keyways (Figure 29-24). Illumination from luminaires on both sides of the door aid in face recognition. If the luminaires are ceiling mounted, they should not be directly above or behind where the person would be standing. The minimum vertical illuminance for security lighting should be 8 lx (0.8 fc), measured 1.5 m (5 ft) above the doorway threshold.

Glare can be used effectively in residential applications if proper glare control techniques are used (Figure 29-25). Floodlights facing the street are a good deterrent, but they should produce glare only to someone standing on the property. Passers-by (whether sidewalk pedestrians or drivers in cars) and neighbors should not be subjected to glare from the security lighting.

Side-yards, or set-backs, are best illuminated from the roof eaves or soffits of the residence. Mounting heights greater than 2.4 m (8 ft) are generally more difficult to defeat by vandals or intruders. Downlighting increases light levels on the face if the correct luminaires are employed. A long-life, high-luminous-efficacy light source, such as a low-wattage HID or CFL, is preferred. Lamps can be sensor controlled or manually operated to fit the needs of the residents. Luminaire spacing along the side of the building depends on the building shape, luminaire luminous intensity distribution, and the desired illuminance uniformity.

Walls, wooden fences, perimeter barriers, and similar features should be lighted from above, if possible. Plant materials can be uplighted to eliminate shadows or hiding spaces and for aesthetics. The illuminances in Figure 29-17 are a starting point for security lighting design for residential properties in high and low crime areas.

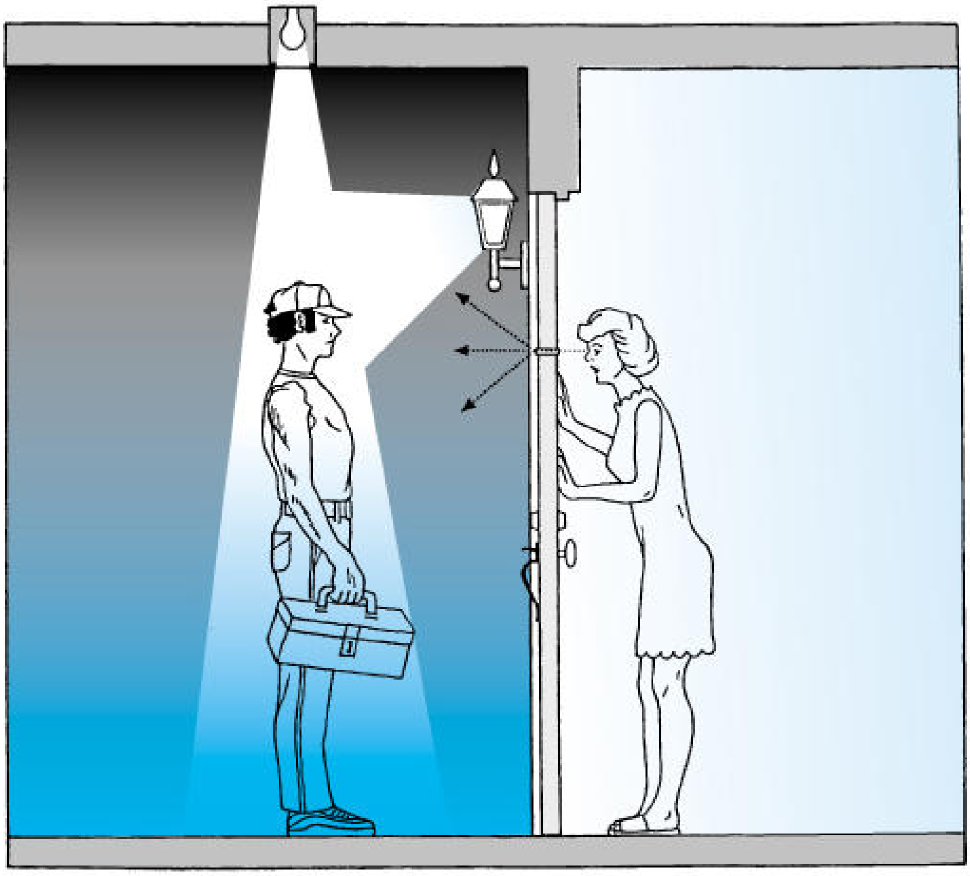


Figure 29-24. Location of luminaires for facial identification.

Multifamily residences. Multifamily residences present a security lighting challenge different from that for single family dwellings. Even when inside a structure, the occupants are not in a totally secure environment. The building is accessible to the other residents and their guests, so occupants may be at risk when moving within the building.

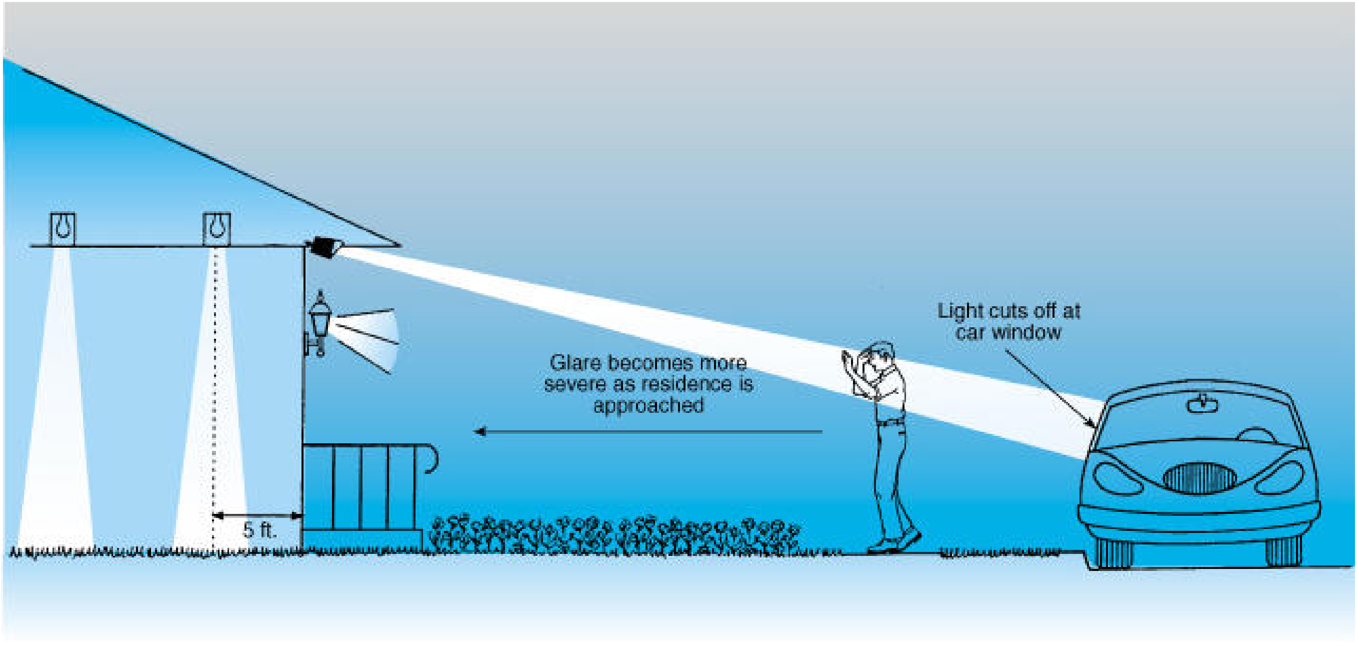


Figure 29-25. Techniques/goals for using glare as deterrent in residential applications.

Common areas (hallways, stairways, and assembly areas). Lighting that enables recognition of faces is essential to determine who belongs in the space and who does not, who is perceived as safe and who may present a danger. Corridors, hallways, and stairwells tend to be dark in many multifamily buildings. A minimum maintained horizontal illuminance of 30 lx (3.0 fc) should be provided at 1.5 m (5 ft) above floor level and should be uniform, average to minimum, at a 4:1 ratio. If the residential complex shares a common mail box area, the space, open or enclosed, should be uniformly illuminated, average to minimum, at a 4:1 ratio with a minimum of 100 lx (10 fc) 1.5 m (5 ft) above floor level.

Other areas. The illuminance requirements for mail rooms apply to other high-use gathering points such as laundry rooms, showers, locker rooms, exercise rooms, and the like, regardless of whether such facilities are closed or open in design. Care should be given to illuminate probable hiding or seclusion areas where perpetrators can prey on tenants. This includes spaces under stairways, unsecured storage lockers, roof access wells, and furnace and maintenance rooms.

Individual residence controls. Individual residences must have, as a minimum, an individual lamp by every entry door for viewing potential visitors prior to opening the door. Regardless of whether visitors are viewed through a window or security viewing device (peep hole), the resident should have sufficient illumination to clearly recognize facial features. Refer to the illuminance requirements for single-family dwellings for partially enclosed individual porches, patios, or privacy areas with entry doors to individual residences.

Parking areas. Parking structures or open parking areas should be lighted in accordance with the recommendations of Chapter 22, Roadway Lighting and IESNA RP-20-99,[59] Lighting for Parking Facilities, under normal conditions. When security is an issue, lighting should be installed consistent with the recommendations contained in the sections "Parking Facilities" and "Security Lighting for Public Spaces" above.

Maintenance considerations. Maintenance of luminaires for a multifamily residential complex is a particularly vexing problem. Stocking the number and variety of lamps, vandalism, wear and tear, and tenants who intentionally circumvent security systems are just some of the problems faced by residence managers. Nevertheless, management must maintain a formal inspection routine and record keeping process for the repair and replacement of lighting equipment. These inspections should be performed no less than weekly, with a short turnaround time for repairs of no less than 36 hours. Formal records of the inspection process and the resulting repairs should be kept and referred to often. Where police or security officers work on the property, this inspection process should be performed on every shift for which an officer makes rounds and reported on his daily activity log or other forms. Also, if battery-operated lights are used, spare batteries and lamps should be available.

Lighting Equipment

Light Sources.

Most general-purpose light sources can be used for security lighting. HID lamps are generally used for all-night security lighting. Because they provide the highest lumen package and the longest life, they are unaffected by most ambient operating temperatures and are available in a wide range of lumen ratings, spectral power distributions, and voltages. Some disadvantages: HID lamps require bulkier luminaires, control of light output is more difficult, initial cost is higher, and mounting may be more complex. These disadvantages can be offset by the benefits of needing fewer luminaires and having much longer lamp life.

The longer runup and restrike times of HID lamps make them unsuitable for use with motion sensors, or where lighting is energized only when an intruder is detected. In these situations, incandescent or fluorescent light sources are preferred. For more complete information on light sources and their individual characteristics, see Chapter 6, Light Sources, or refer to manufacturers' information for detailed lamp data.

Luminaires.

Security lighting equipment can often suffer hazards more severe than weather and usage. Manufacturers provide a wide range of tamper-resistant and destruction-resistant systems. Other than intentional abuse, the selection of the luminaire is based on the light source to be used, the desired luminous intensity distribution, aesthetics, and the degree to which the luminaire is exposed to the environment. Environmental factors to be considered include whether the location is indoor or outdoors, temperature extremes, luminaire mounting location, and the level of vulnerability of the luminaire to damage by attack. Fluorescent sources are most affected by ambient temperature extremes. Most magnetic fluorescent ballasts are rated for use down to 10°C (50°F). If colder temperatures are expected, a cold weather electronic ballast rated for cold weather starting is necessary. Even though the lamps may start at cold weather temperatures, the lumen output of the lamp may be significantly reduced. Excessively warm temperatures also have an effect on fluorescent lamps, as lumen depreciation also occurs when ambient temperatures exceed 27°C (80°F). The designer should consult Chapter 6, Light Sources, and Chapter 7, Luminaires, with regard to sources and environmental factors.

In many situations, luminaires used for security lighting are part of the general lighting system, as in parking facilities or building enhancement. Frequently, the daytime appearance of the luminaire and pole is the deciding factor in the choice of equipment. Shopping malls may use more expensive equipment in public areas and lower-cost luminaires in employee areas. However, it is important to consider that employees usually arrive and depart when few customers are present, and therefore they may be subject to greater danger.

Regardless of luminaire type, the equipment must be easily maintained; if exposed to weather, it should be listed by Underwriters Laboratories (UL) or the Canadian Standards Association (CSA) for wet locations. Luminaires may be mounted on poles, building surfaces, or on the ground. Where the luminaire may be subject to damage, vandal-resistant types should be installed.

Any luminaire mounted on a ceiling or wall and less than 3 m (10 ft) above the ground is likely to be the subject of physical abuse by vandals. A high-abuse luminaire should incorporate the following features:

- The base of the luminaire should have a step or flanged base and be solidly mounted to the building structure or mounting accessory.
- The electrical junction box should not be used as the sole luminaire support point.
- The lens or diffuser of the luminaire should be shatter proof and weather resistant.
- Exposed hardware should be tamper and weather resistant.
- The luminaire should have the ability to withstand repeated blows from an improvised club.

Lighting Poles. The higher luminaires are mounted from the ground, the fewer poles and luminaires are required to light a given area, and the lower the likelihood of vandalism. Fewer poles can cause more shadows and less uniform lighting, however. As pole heights are reduced, more poles with lower-wattage luminaires are required to avoid glare and nonuniform lighting patterns.

Controls. Security lighting should always be controlled automatically. System design should consider the possibility of power outages and lamp failure. Redundancy should be considered when assigning luminaires to control zones, so that the failure of one luminaire does not leave a large area without illumination. Further advice is given in Chapter 27, Lighting Controls.

HID systems should be designed to be energized prior to darkness at a time suitable for the runup period of the lamp. Lighting controls should be designed to energize the lighting system when the ambient natural lighting level is 1.6 times the average horizontal security illuminance design value, or 15 lx (1.5 fc), whichever is higher. This ensures that the designed illuminances are met during dusk as well as after dark.

Types of automatic controls suitable for security lighting operation include time clocks, photocontrols, dimmers, and motion detectors.

Time clocks. These are generally used to control large areas from one location, such as mall parking lots. Astronomical time clocks can be programmed to adjust on-off times with the changes of season. These types of clocks can be quite expensive and still may not be able to readjust by themselves if darkness is hastened by cloud cover. All time clocks should include a battery backup.

Photocontrols. These are used to control individual or small groups of luminaires on circuits, which are always energized. They can be designed to automatically energize luminaires during dark periods regardless of time of day. They have the added advantage of not needing to be reset after power outages or before and after daylight-saving time periods. Photocontrols should not be mounted where the light sensing area is accessible to flashlight or vehicle headlight beams.

Dimmers. These can be used to reduce illumination and power demand by approximately 50% during low traffic periods in such applications as industrial employee parking lots during working hours or mall parking lots late at night. By dimming all units, the entire area remains uniformly illuminated. This contrasts with the spotty appearance commonly caused when half the luminaires are switched off to save electricity. Dimmable fluorescent and HID units require special ballasts. Dimmed HID sources may not have the same color characteristics as when they are operated at full output. This can have implications for camera surveillance as well as the ambiance of the space.

Motion detectors. These are used to switch on specific units when motion is detected. Motion detectors employ infrared or ultrasonic technologies to detect motion.[65] Infrared detectors are the predominant choice outdoors, due to the sensitivity of ultrasonic detectors to movement caused by wind. Due to the runup time of HID light sources, motion detectors should be used only with incandescent and fluorescent light sources.

Lighting for Camera Surveillance. Cameras do not have the same spectral sensitivity as the human eye, and therefore they respond differently to light sources. Most manufacturers specify a minimum illuminance needed for their cameras to produce a clear picture. These illuminances are usually given for an incandescent lamp and, most usefully, in terms of the amount of illumination on the image sensor. Higher illuminances are required for other light sources. Further, if moving objects are to be easily seen, illuminances above the minimum are required, whatever the light source. The manufacturer should be consulted before selecting the light source to be used, if there is any doubt about the sensitivity of the camera.

Cameras also have a rather limited dynamic range. Care should be taken to mount surveillance cameras below the luminaires, so that they do not receive any light directly from the luminaires causing "white-out" of that part of the image. In addition, all surfaces that are to be seen by the camera should be evenly illuminated. The security station containing monitors for surveillance cameras should also be carefully lighted to avoid reflections from interior luminaires in the monitor screens.

Site Assessment and Maintenance. Evaluations should be conducted regularly to determine what reasonable levels of security lighting and other security features or techniques should apply to each location. These surveys or audits should be performed annually, and at a minimum, they should include crime analysis of the location and surrounding community, physical and operational changes at the site, condition of the immediate community, and lighting configuration and maintenance on the property.

No security lighting system can remain effective without regularly scheduled maintenance. A planned maintenance program should include immediate replacement of failed lamps, repair or replacement of vandalized luminaires, regular cleaning, and cutting back of any encroaching vegetation. For additional information consult Chapter 28, Lighting Maintenance.

Lamp replacement. A well-designed security lighting system should have overlapping light patterns so that no area is dependent on a single luminaire. Failed lamps should be replaced immediately, however, in case a second lamp in the same area also fails. With installations requiring special lift equipment to service the luminaires building owners or managers should consider replacing all of the lamps at the same time.

Repair or replacement. Luminaires damaged by natural causes or vandalism should be immediately repaired or replaced. Luminaire condition should be monitored on a regular and frequent schedule to assure that all are working and aimed properly to produce the desired lighting coverage.

Cleaning. Regardless of the quality of the equipment, insects and dirt collect in enclosed luminaires. Therefore, all units should be cleaned at least once each year. A more frequent schedule should be followed when inspection indicates it is required.

Pruning. Shrubbery adjacent to walkways, driveways, alleys, and park areas must be pruned regularly to prevent interference with the light pattern and eliminate shadowed areas. Landscaping around buildings must be pruned regularly to prevent growth from obscuring potential intruders.

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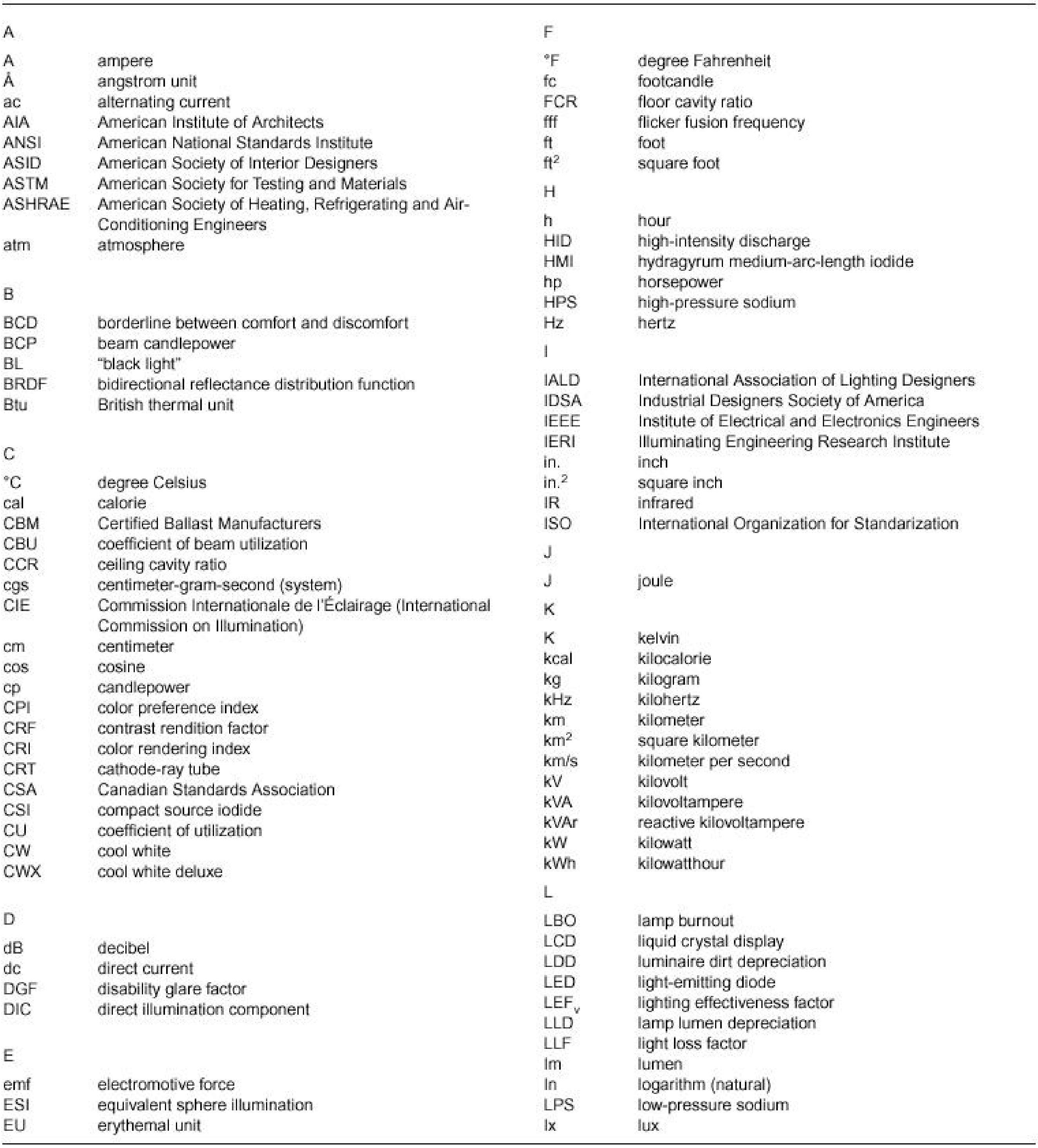
Appendix

Appendix Figure 1. Partial List of Abbreviations, Symbols, and Acronyms Used in This Handbook



A	
A	ampere
Å	angstrom unit
ac	alternating current
AIA	American Institute of Architects
ANSI	American National Standards Institute
ASID	American Society of Interior Designers
ASTM	American Society for Testing and Materials
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
atm	atmosphere
B	
BCD	borderline between comfort and discomfort
BCP	beam candlepower
BL	"black light"
BRDF	bidirectional reflectance distribution function
Btu	British thermal unit
C	
°C	degree Celsius
cal	calorie
CBM	Certified Ballast Manufacturers
CBU	coefficient of beam utilization
CCR	ceiling cavity ratio
cgs	centimeter-gram-second (system)
CIE	Commission Internationale de l'Éclairage (International Commission on Illumination)
cm	centimeter
cos	cosine
cp	candlepower
CPI	color preference index
CRF	contrast rendition factor
CRI	color rendering index
CRT	cathode-ray tube
CSA	Canadian Standards Association
CSI	compact source iodide
CU	coefficient of utilization
CW	cool white
CWX	cool white deluxe
D	
dB	decibel
dc	direct current
DGF	disability glare factor
DIC	direct illumination component
E	
emf	electromotive force
ESI	equivalent sphere illumination
EU	erythemal unit
F	
°F	degree Fahrenheit
fc	footcandle
FCR	floor cavity ratio
fff	flicker fusion frequency
ft	foot
ft^2	square foot
H	
h	hour
HID	high-intensity discharge
HMI	hydragyrum medium-arc-length iodide
hp	horsepower
HPS	high-pressure sodium
Hz	hertz
I	
IALD	International Association of Lighting Designers
IDSA	Industrial Designers Society of America
IEEE	Institute of Electrical and Electronics Engineers
IERI	Illuminating Engineering Research Institute
in.	inch
$in.^2$	square inch
IR	infrared
ISO	International Organization for Standarization
J	
J	joule
K	
K	kelvin
kcal	kilocalorie
kg	kilogram
kHz	kilohertz
km	kilometer
km^2	square kilometer
km/s	kilometer per second
kV	kilovolt
kVA	kilovoltampere
kVAr	reactive kilovoltampere
kW	kilowatt
kWh	kilowatthour
L	
LBO	lamp burnout
LCD	liquid crystal display
LDD	luminaire dirt depreciation
LED	light-emitting diode
LEF_v	lighting effectiveness factor
LLD	lamp lumen depreciation
LLF	light loss factor
lm	lumen
ln	logarithm (natural)
LPS	low-pressure sodium
lx	lux

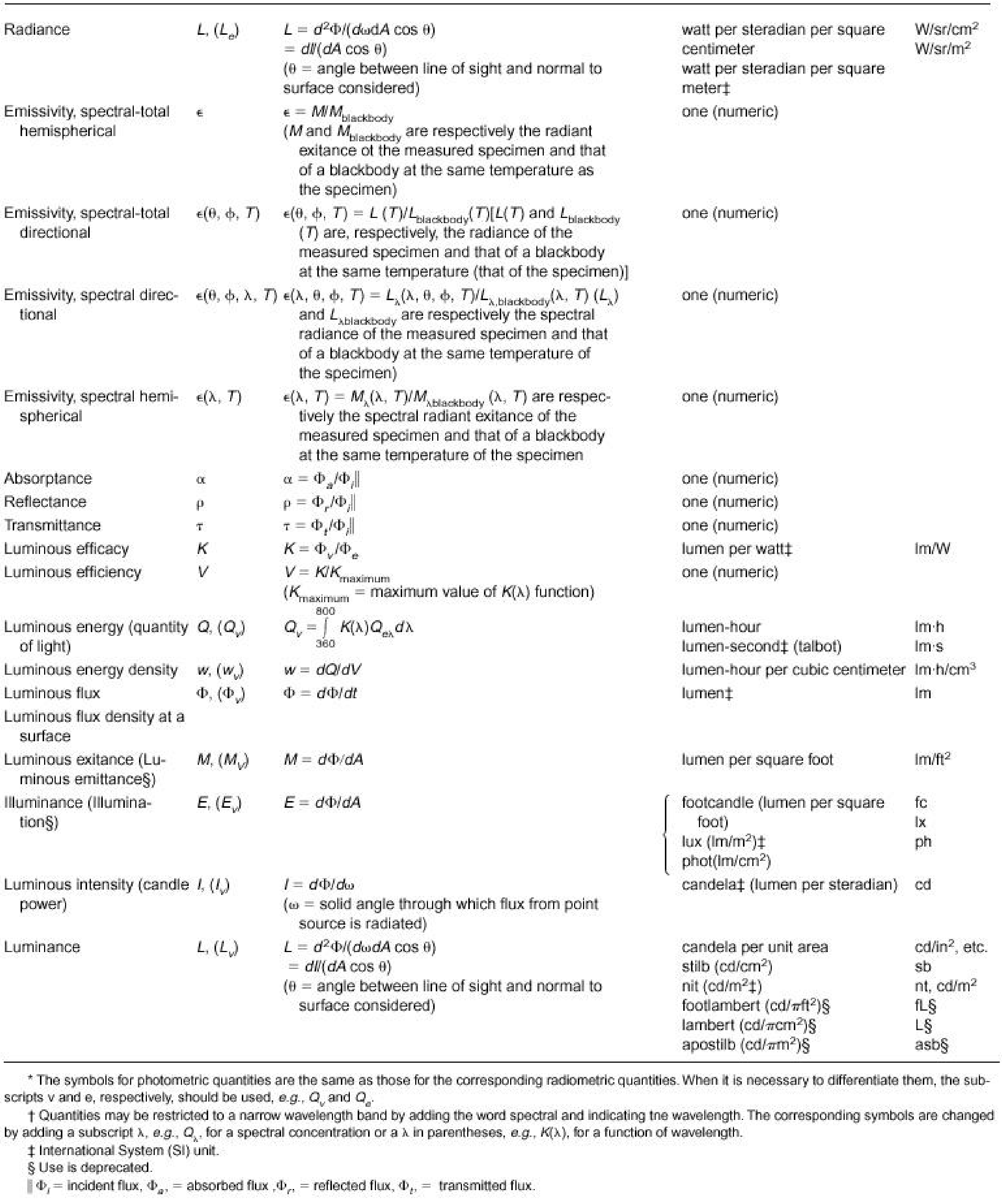
Appendix Figure 1. *Continued*

M	
m	meter
m^2	square meter
mA	milliampere
max	maximum
MF	maintenance factor
MH	mounting height
MHz	megahertz
min	minimum
min	minute (time)
mm	millimeter
mm^2	square millimeter
mol wt	molecular weight
MPE	minimal perceptable erythema
mph	miles per hour
N	
NBS	National Bureau of Standards
NEC	National Electrical Code
NEMA	National Electrical Manufacturers Association
nm	nanometer
O	
OSA	Optical Society of America
P	
PAR	pressed-reflector lamp
pf	power factor
R	
R	reflectance lamp
rad	radian
RCR	room cavity ratio
RCS	relative contrast sensitivity
rms	root mean square
RSDD	room surface dirt depreciation
RTP	relative task performance
RVP	relative visual performance
RVR	runway visual range
S	
s	second
sin	sine
SPD	spectral power distribution
sq	square
sr	steradian
T	
TAF	transient adaptation factor
tan	tangent
temp	temperature
U	
UV	ultraviolet
UL	Underwriters Laboratories
V	
V	volt
VA	voltampere
VAr	reactive voltampere
VASIS	visual approach slope indicator system
VCP	visual comfort probability
VDU	visual display unit
VHO	very high output (lamp)
VI	visibility index
VL	visibility level
VTE	visual task evaluator
VTP	visual task photometer
W	
W	watt
WW	warm white
WWX	warm white deluxe
μA	microampere
μV	microvolt
μW	microwatt
ρ_{CC}	effective ceiling cavity reflectance
ρ_{FC}	effective floor cavity reflectance
′	minute (angular measure)
″	second (angular measure)
°	degree

Appendix Figure 2. Units, Symbols, and Defining Equations for Fundamental Photometric and Radiometric Quantities*

Quantity†	Symbol†	Defining Equation	Unit	Symbol
Radiant energy	Q, (Q_e)		erg joule‡ calorie kilowatt-hour	erg J cal kWh
Radiant energy density	w, (w_e)	$w = dQ/dV$	joule per cubic meter‡ erg per cubic centimeter	J/m^3 erg/cm^3
Radiant flux	Φ, (Φ_e)	$\Phi = dQ/dt$	erg per second watt‡	erg/s W
Radiant flux density at a surface				
Radiant exitance (Radiant emittance§)	M, (M_e)	$M = d\Phi/dA$	watt per square centimeter, watt per square meter,‡ etc.	W/cm^2 W/m^2
Irradiance	E, (E_e)	$E = d\Phi/dA$		
Radiant intensity	I, (I_e)	$I = d\Phi/d\omega$ (ω = solid angle through which flux from point source is radiated)	watt per steradian‡	W/sr

Appendix Figure 2. *Continued*



Radiance	L, (L_e)	$L = d^2\Phi/(d\omega dA \cos\theta)$ $= dI/(dA \cos\theta)$ (θ = angle between line of sight and normal to surface considered)	watt per steradian per square centimeter watt per steradian per square meter‡	W/sr/cm^2 W/sr/m^2
Emissivity, spectral-total hemispherical	ϵ	$\epsilon = M/M_{\text{blackbody}}$ (M and $M_{\text{blackbody}}$ are respectively the radiant exitance ot the measured specimen and that of a blackbody at the same temperature as the specimen)	one (numeric)	
Emissivity, spectral-total directional	$\epsilon(\theta, \phi, T)$	$\epsilon(\theta, \phi, T) = L(T)/L_{\text{blackbody}}(T)$[$L(T)$ and $L_{\text{blackbody}}$ (T) are, respectively, the radiance of the measured specimen and that of a blackbody at the same temperature (that of the specimen)]	one (numeric)	
Emissivity, spectral directional	$\epsilon(\theta, \phi, \lambda, T)$	$\epsilon(\lambda, \theta, \phi, T) = L_\lambda(\lambda, \theta, \phi, T)/L_{\lambda,\text{blackbody}}(\lambda, T)$ (L_λ) and $L_{\lambda\text{blackbody}}$ are respectively the spectral radiance of the measured specimen and that of a blackbody at the same temperature of the specimen)	one (numeric)	
Emissivity, spectral hemispherical	$\epsilon(\lambda, T)$	$\epsilon(\lambda, T) = M_\lambda(\lambda, T)/M_{\lambda\text{blackbody}}$ (λ, T) are respectively the spectral radiant exitance of the measured specimen and that of a blackbody at the same temperature of the specimen	one (numeric)	
Absorptance	α	$\alpha = \Phi_a/\Phi_i$‖	one (numeric)	
Reflectance	ρ	$\rho = \Phi_r/\Phi_i$‖	one (numeric)	
Transmittance	τ	$\tau = \Phi_t/\Phi_i$‖	one (numeric)	
Luminous efficacy	K	$K = \Phi_v/\Phi_e$	lumen per watt‡	lm/W
Luminous efficiency	V	$V = K/K_{\text{maximum}}$ (K_{maximum} = maximum value of $K(\lambda)$ function)	one (numeric)	
Luminous energy (quantity of light)	Q, (Q_v)	$Q_v = \int_{360}^{800} K(\lambda) Q_{e\lambda} d\lambda$	lumen-hour lumen-second‡ (talbot)	lm·h lm·s
Luminous energy density	w, (w_v)	$w = dQ/dV$	lumen-hour per cubic centimeter	lm·h/cm^3
Luminous flux	Φ, (Φ_v)	$\Phi = d\Phi/dt$	lumen‡	lm
Luminous flux density at a surface				
Luminous exitance (Luminous emittance§)	M, (M_v)	$M = d\Phi/dA$	lumen per square foot	lm/ft^2
Illuminance (Illumination§)	E, (E_v)	$E = d\Phi/dA$	footcandle (lumen per square foot) lux (lm/m^2)‡ phot(lm/cm^2)	fc lx ph
Luminous intensity (candle power)	I, (I_v)	$I = d\Phi/d\omega$ (ω = solid angle through which flux from point source is radiated)	candela‡ (lumen per steradian)	cd
Luminance	L, (L_v)	$L = d^2\Phi/(d\omega dA \cos\theta)$ $= dI/(dA \cos\theta)$ (θ = angle between line of sight and normal to surface considered)	candela per unit area stilb (cd/cm^2) nit (cd/m^2‡) footlambert (cd/πft^2)§ lambert (cd/πcm^2)§ apostilb (cd/πm^2)§	cd/in^2, etc. sb nt, cd/m^2 fL§ L§ asb§

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* The symbols for photometric quantities are the same as those for the corresponding radiometric quantities. When it is necessary to differentiate them, the subscripts v and e, respectively, should be used, *e.g.*, Q_v and Q_e.

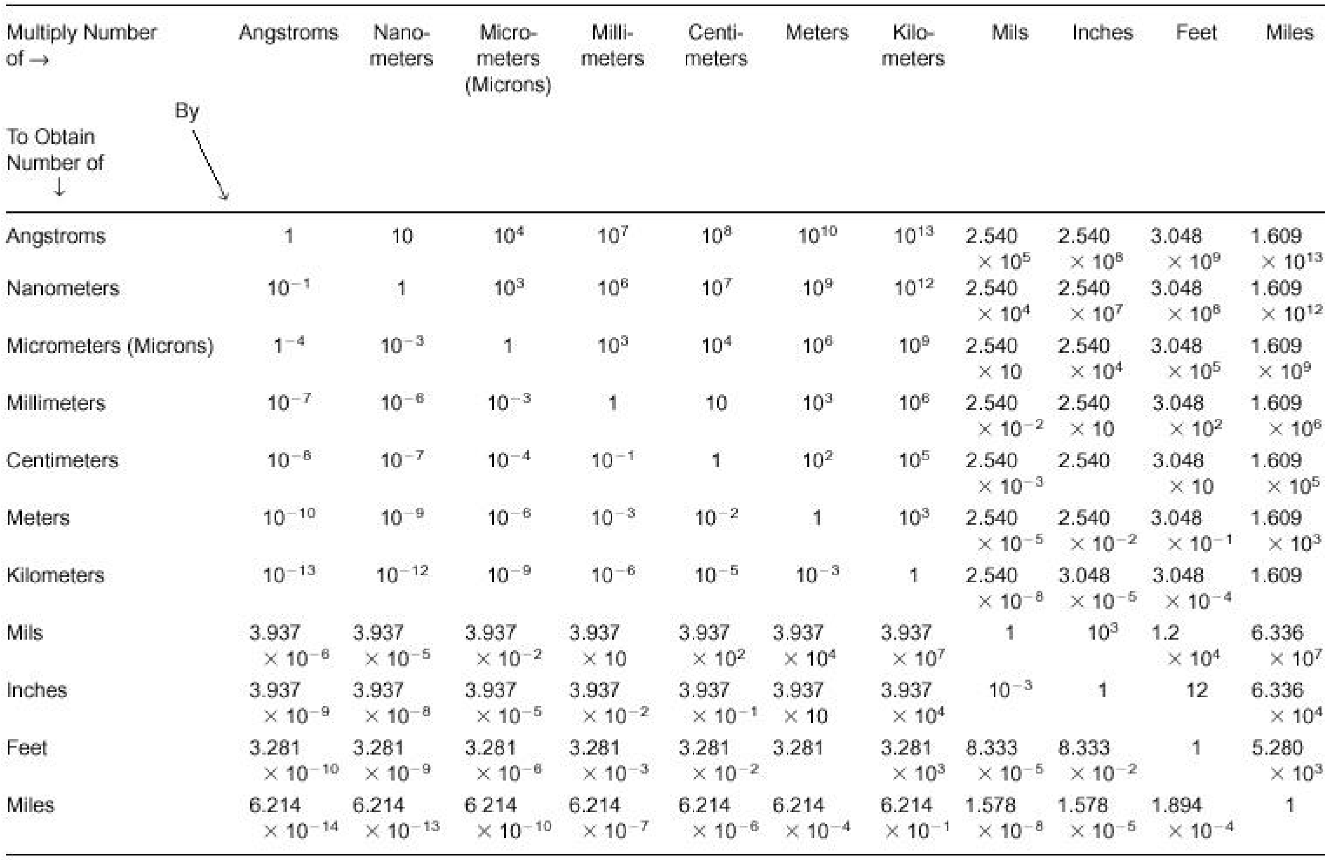
† Quantities may be restricted to a narrow wavelength band by adding the word spectral and indicating tne wavelength. The corresponding symbols are changed by adding a subscript λ, *e.g.*, Q_λ, for a spectral concentration or a λ in parentheses, *e.g.*, $K(\lambda)$, for a function of wavelength.

‡ International System (SI) unit.

§ Use is deprecated.

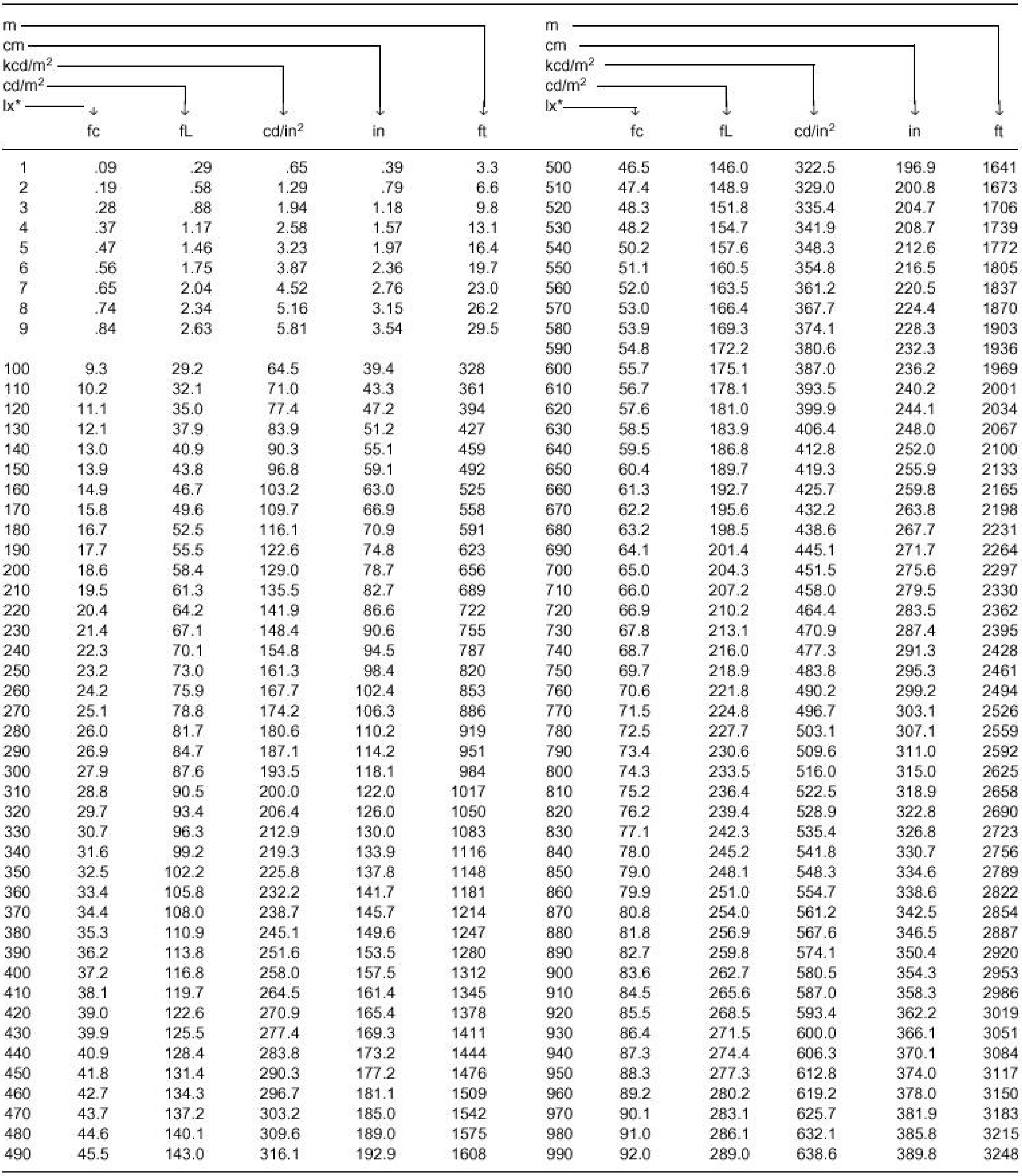
‖ Φ_i = incident flux, Φ_a, = absorbed flux ,Φ_r, = reflected flux, Φ_t, = transmitted flux.

Appendix Figure 3. Conversion Factors for Units of Length



Multiply Number of → By To Obtain Number of ↓	Angstroms	Nano-meters	Micro-meters (Microns)	Milli-meters	Centi-meters	Meters	Kilo-meters	Mils	Inches	Feet	Miles
Angstroms	1	10	10^4	10^7	10^8	10^{10}	10^{13}	2.540×10^5	2.540×10^8	3.048×10^9	1.609×10^{13}
Nanometers	10^{-1}	1	10^3	10^6	10^7	10^9	10^{12}	2.540×10^4	2.540×10^7	3.048×10^8	1.609×10^{12}
Micrometers (Microns)	1^{-4}	10^{-3}	1	10^3	10^4	10^6	10^9	2.540×10	2.540×10^4	3.048×10^5	1.609×10^9
Millimeters	10^{-7}	10^{-6}	10^{-3}	1	10	10^3	10^6	2.540×10^{-2}	2.540×10	3.048×10^2	1.609×10^6
Centimeters	10^{-8}	10^{-7}	10^{-4}	10^{-1}	1	10^2	10^5	2.540×10^{-3}	2.540	3.048×10	1.609×10^5
Meters	10^{-10}	10^{-9}	10^{-6}	10^{-3}	10^{-2}	1	10^3	2.540×10^{-5}	2.540×10^{-2}	3.048×10^{-1}	1.609×10^3
Kilometers	10^{-13}	10^{-12}	10^{-9}	10^{-6}	10^{-5}	10^{-3}	1	2.540×10^{-8}	3.048×10^{-5}	3.048×10^{-4}	1.609
Mils	3.937×10^{-6}	3.937×10^{-5}	3.937×10^{-2}	3.937×10	3.937×10^2	3.937×10^4	3.937×10^7	1	10^3	1.2×10^4	6.336×10^7
Inches	3.937×10^{-9}	3.937×10^{-8}	3.937×10^{-5}	3.937×10^{-2}	3.937×10^{-1}	3.937×10	3.937×10^4	10^{-3}	1	12	6.336×10^4
Feet	3.281×10^{-10}	3.281×10^{-9}	3.281×10^{-6}	3.281×10^{-3}	3.281×10^{-2}	3.281	3.281×10^3	8.333×10^{-5}	8.333×10^{-2}	1	5.280×10^3
Miles	6.214×10^{-14}	6.214×10^{-13}	$6\,214 \times 10^{-10}$	6.214×10^{-7}	6.214×10^{-6}	6.214×10^{-4}	6.214×10^{-1}	1.578×10^{-8}	1.578×10^{-5}	1.894×10^{-4}	1

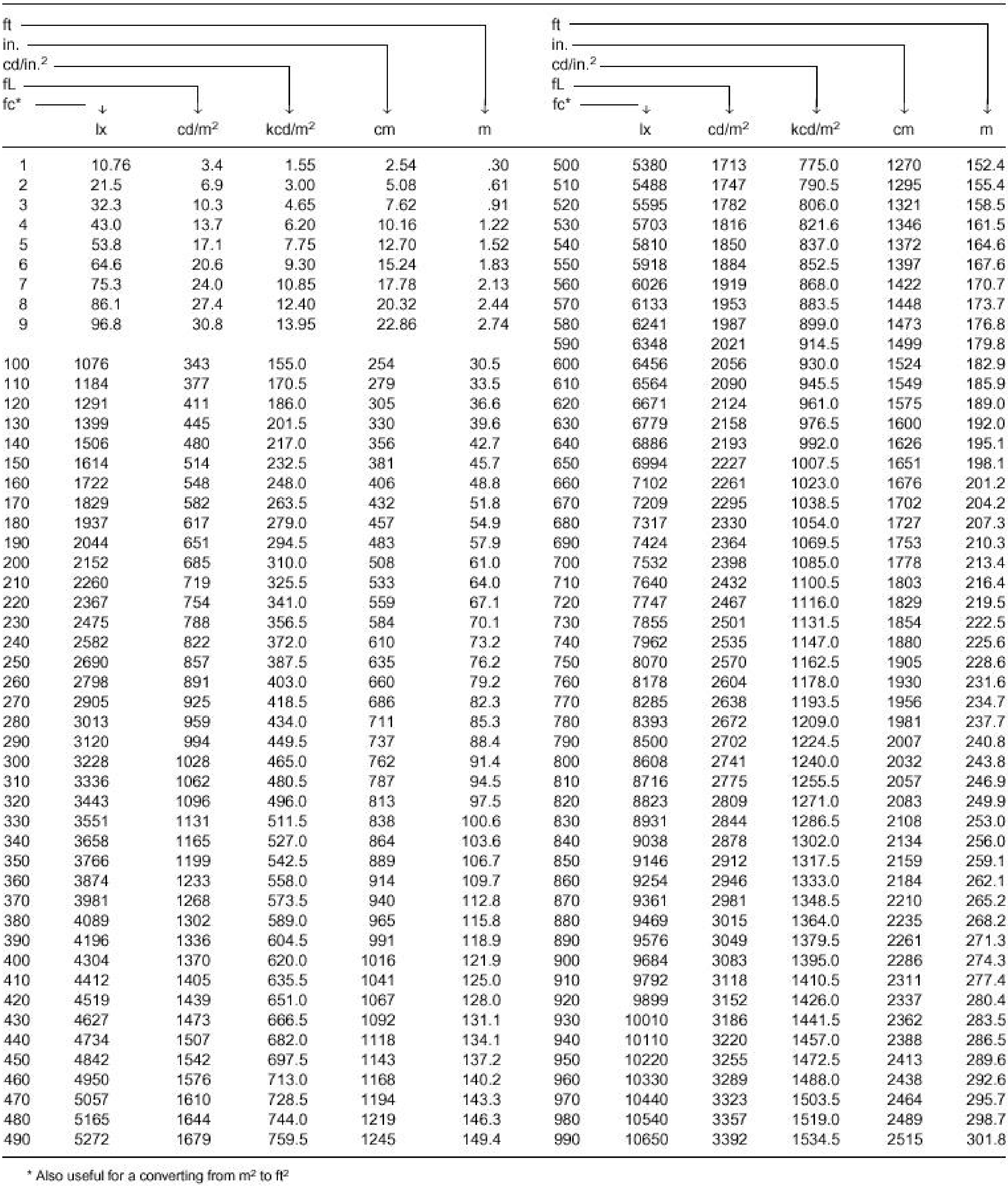
Appendix Figure 4. Conversion from Values in SI Units



m cm kcd/m^2 cd/m^2 lx*	fc	fL	cd/in^2	in	ft	m cm kcd/m^2 cd/m^2 lx*	fc	fL	cd/in^2	in	ft
1	.09	.29	.65	.39	3.3	500	46.5	146.0	322.5	196.9	1641
2	.19	.58	1.29	.79	6.6	510	47.4	148.9	329.0	200.8	1673
3	.28	.88	1.94	1.18	9.8	520	48.3	151.8	335.4	204.7	1706
4	.37	1.17	2.58	1.57	13.1	530	48.2	154.7	341.9	208.7	1739
5	.47	1.46	3.23	1.97	16.4	540	50.2	157.6	348.3	212.6	1772
6	.56	1.75	3.87	2.36	19.7	550	51.1	160.5	354.8	216.5	1805
7	.65	2.04	4.52	2.76	23.0	560	52.0	163.5	361.2	220.5	1837
8	.74	2.34	5.16	3.15	26.2	570	53.0	166.4	367.7	224.4	1870
9	.84	2.63	5.81	3.54	29.5	580	53.9	169.3	374.1	228.3	1903
						590	54.8	172.2	380.6	232.3	1936
100	9.3	29.2	64.5	39.4	328	600	55.7	175.1	387.0	236.2	1969
110	10.2	32.1	71.0	43.3	361	610	56.7	178.1	393.5	240.2	2001
120	11.1	35.0	77.4	47.2	394	620	57.6	181.0	399.9	244.1	2034
130	12.1	37.9	83.9	51.2	427	630	58.5	183.9	406.4	248.0	2067
140	13.0	40.9	90.3	55.1	459	640	59.5	186.8	412.8	252.0	2100
150	13.9	43.8	96.8	59.1	492	650	60.4	189.7	419.3	255.9	2133
160	14.9	46.7	103.2	63.0	525	660	61.3	192.7	425.7	259.8	2165
170	15.8	49.6	109.7	66.9	558	670	62.2	195.6	432.2	263.8	2198
180	16.7	52.5	116.1	70.9	591	680	63.2	198.5	438.6	267.7	2231
190	17.7	55.5	122.6	74.8	623	690	64.1	201.4	445.1	271.7	2264
200	18.6	58.4	129.0	78.7	656	700	65.0	204.3	451.5	275.6	2297
210	19.5	61.3	135.5	82.7	689	710	66.0	207.2	458.0	279.5	2330
220	20.4	64.2	141.9	86.6	722	720	66.9	210.2	464.4	283.5	2362
230	21.4	67.1	148.4	90.6	755	730	67.8	213.1	470.9	287.4	2395
240	22.3	70.1	154.8	94.5	787	740	68.7	216.0	477.3	291.3	2428
250	23.2	73.0	161.3	98.4	820	750	69.7	218.9	483.8	295.3	2461
260	24.2	75.9	167.7	102.4	853	760	70.6	221.8	490.2	299.2	2494
270	25.1	78.8	174.2	106.3	886	770	71.5	224.8	496.7	303.1	2526
280	26.0	81.7	180.6	110.2	919	780	72.5	227.7	503.1	307.1	2559
290	26.9	84.7	187.1	114.2	951	790	73.4	230.6	509.6	311.0	2592
300	27.9	87.6	193.5	118.1	984	800	74.3	233.5	516.0	315.0	2625
310	28.8	90.5	200.0	122.0	1017	810	75.2	236.4	522.5	318.9	2658
320	29.7	93.4	206.4	126.0	1050	820	76.2	239.4	528.9	322.8	2690
330	30.7	96.3	212.9	130.0	1083	830	77.1	242.3	535.4	326.8	2723
340	31.6	99.2	219.3	133.9	1116	840	78.0	245.2	541.8	330.7	2756
350	32.5	102.2	225.8	137.8	1148	850	79.0	248.1	548.3	334.6	2789
360	33.4	105.8	232.2	141.7	1181	860	79.9	251.0	554.7	338.6	2822
370	34.4	108.0	238.7	145.7	1214	870	80.8	254.0	561.2	342.5	2854
380	35.3	110.9	245.1	149.6	1247	880	81.8	256.9	567.6	346.5	2887
390	36.2	113.8	251.6	153.5	1280	890	82.7	259.8	574.1	350.4	2920
400	37.2	116.8	258.0	157.5	1312	900	83.6	262.7	580.5	354.3	2953
410	38.1	119.7	264.5	161.4	1345	910	84.5	265.6	587.0	358.3	2986
420	39.0	122.6	270.9	165.4	1378	920	85.5	268.5	593.4	362.2	3019
430	39.9	125.5	277.4	169.3	1411	930	86.4	271.5	600.0	366.1	3051
440	40.9	128.4	283.8	173.2	1444	940	87.3	274.4	606.3	370.1	3084
450	41.8	131.4	290.3	177.2	1476	950	88.3	277.3	612.8	374.0	3117
460	42.7	134.3	296.7	181.1	1509	960	89.2	280.2	619.2	378.0	3150
470	43.7	137.2	303.2	185.0	1542	970	90.1	283.1	625.7	381.9	3183
480	44.6	140.1	309.6	189.0	1575	980	91.0	286.1	632.1	385.8	3215
490	45.5	143.0	316.1	192.9	1608	990	92.0	289.0	638.6	389.8	3248

* Also useful for converting from ft^2 to m^2.

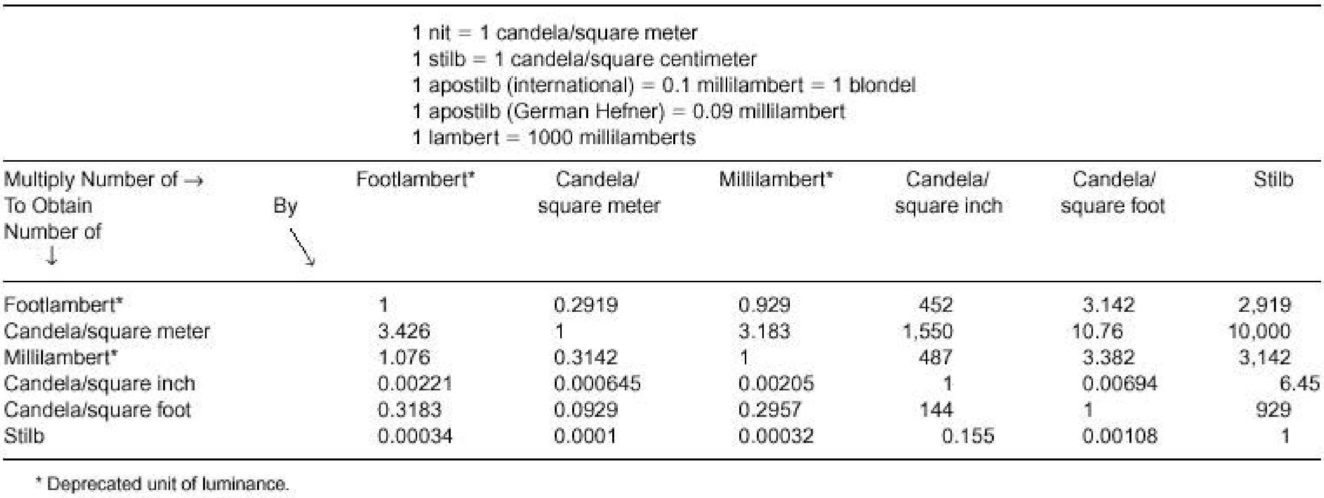
Appndix Figure 5. Conversion to Values in SI Units



ft in. cd/in.^{2} fL fc*	lx	cd/m^2	kcd/m^2	cm	m	ft in. cd/in.^{2} fL fc*	lx	cd/m^2	kcd/m^2	cm	m
1	10.76	3.4	1.55	2.54	.30	500	5380	1713	775.0	1270	152.4
2	21.5	6.9	3.00	5.08	.61	510	5488	1747	790.5	1295	155.4
3	32.3	10.3	4.65	7.62	.91	520	5595	1782	806.0	1321	158.5
4	43.0	13.7	6.20	10.16	1.22	530	5703	1816	821.6	1346	161.5
5	53.8	17.1	7.75	12.70	1.52	540	5810	1850	837.0	1372	164.6
6	64.6	20.6	9.30	15.24	1.83	550	5918	1884	852.5	1397	167.6
7	75.3	24.0	10.85	17.78	2.13	560	6026	1919	868.0	1422	170.7
8	86.1	27.4	12.40	20.32	2.44	570	6133	1953	883.5	1448	173.7
9	96.8	30.8	13.95	22.86	2.74	580	6241	1987	899.0	1473	176.8
						590	6348	2021	914.5	1499	179.8
100	1076	343	155.0	254	30.5	600	6456	2056	930.0	1524	182.9
110	1184	377	170.5	279	33.5	610	6564	2090	945.5	1549	185.9
120	1291	411	186.0	305	36.6	620	6671	2124	961.0	1575	189.0
130	1399	445	201.5	330	39.6	630	6779	2158	976.5	1600	192.0
140	1506	480	217.0	356	42.7	640	6886	2193	992.0	1626	195.1
150	1614	514	232.5	381	45.7	650	6994	2227	1007.5	1651	198.1
160	1722	548	248.0	406	48.8	660	7102	2261	1023.0	1676	201.2
170	1829	582	263.5	432	51.8	670	7209	2295	1038.5	1702	204.2
180	1937	617	279.0	457	54.9	680	7317	2330	1054.0	1727	207.3
190	2044	651	294.5	483	57.9	690	7424	2364	1069.5	1753	210.3
200	2152	685	310.0	508	61.0	700	7532	2398	1085.0	1778	213.4
210	2260	719	325.5	533	64.0	710	7640	2432	1100.5	1803	216.4
220	2367	754	341.0	559	67.1	720	7747	2467	1116.0	1829	219.5
230	2475	788	356.5	584	70.1	730	7855	2501	1131.5	1854	222.5
240	2582	822	372.0	610	73.2	740	7962	2535	1147.0	1880	225.6
250	2690	857	387.5	635	76.2	750	8070	2570	1162.5	1905	228.6
260	2798	891	403.0	660	79.2	760	8178	2604	1178.0	1930	231.6
270	2905	925	418.5	686	82.3	770	8285	2638	1193.5	1956	234.7
280	3013	959	434.0	711	85.3	780	8393	2672	1209.0	1981	237.7
290	3120	994	449.5	737	88.4	790	8500	2702	1224.5	2007	240.8
300	3228	1028	465.0	762	91.4	800	8608	2741	1240.0	2032	243.8
310	3336	1062	480.5	787	94.5	810	8716	2775	1255.5	2057	246.9
320	3443	1096	496.0	813	97.5	820	8823	2809	1271.0	2083	249.9
330	3551	1131	511.5	838	100.6	830	8931	2844	1286.5	2108	253.0
340	3658	1165	527.0	864	103.6	840	9038	2878	1302.0	2134	256.0
350	3766	1199	542.5	889	106.7	850	9146	2912	1317.5	2159	259.1
360	3874	1233	558.0	914	109.7	860	9254	2946	1333.0	2184	262.1
370	3981	1268	573.5	940	112.8	870	9361	2981	1348.5	2210	265.2
380	4089	1302	589.0	965	115.8	880	9469	3015	1364.0	2235	268.2
390	4196	1336	604.5	991	118.9	890	9576	3049	1379.5	2261	271.3
400	4304	1370	620.0	1016	121.9	900	9684	3083	1395.0	2286	274.3
410	4412	1405	635.5	1041	125.0	910	9792	3118	1410.5	2311	277.4
420	4519	1439	651.0	1067	128.0	920	9899	3152	1426.0	2337	280.4
430	4627	1473	666.5	1092	131.1	930	10010	3186	1441.5	2362	283.5
440	4734	1507	682.0	1118	134.1	940	10110	3220	1457.0	2388	286.5
450	4842	1542	697.5	1143	137.2	950	10220	3255	1472.5	2413	289.6
460	4950	1576	713.0	1168	140.2	960	10330	3289	1488.0	2438	292.6
470	5057	1610	728.5	1194	143.3	970	10440	3323	1503.5	2464	295.7
480	5165	1644	744.0	1219	146.3	980	10540	3357	1519.0	2489	298.7
490	5272	1679	759.5	1245	149.4	990	10650	3392	1534.5	2515	301.8

* Also useful for a converting from m^2 to ft^2

Appendix Figure 6. Luminance Conversion Factors

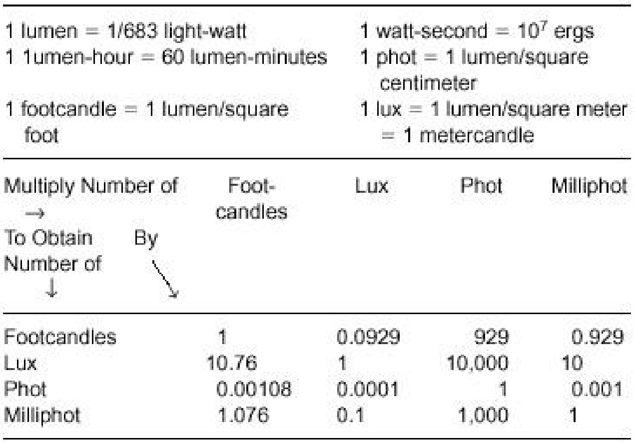


1 nit = 1 candela/square meter
1 stilb = 1 candela/square centimeter
1 apostilb (international) = 0.1 millilambert = 1 blondel
1 apostilb (German Hefner) = 0.09 millilambert
1 lambert = 1000 millilamberts

Multiply Number of → To Obtain Number of ↓ By ↘	Footlambert*	Candela/ square meter	Millilambert*	Candela/ square inch	Candela/ square foot	Stilb
Footlambert*	1	0.2919	0.929	452	3.142	2,919
Candela/square meter	3.426	1	3.183	1,550	10.76	10,000
Millilambert*	1.076	0.3142	1	487	3.382	3,142
Candela/square inch	0.00221	0.000645	0.00205	1	0.00694	6.45
Candela/square foot	0.3183	0.0929	0.2957	144	1	929
Stilb	0.00034	0.0001	0.00032	0.155	0.00108	1

* Deprecated unit of luminance.

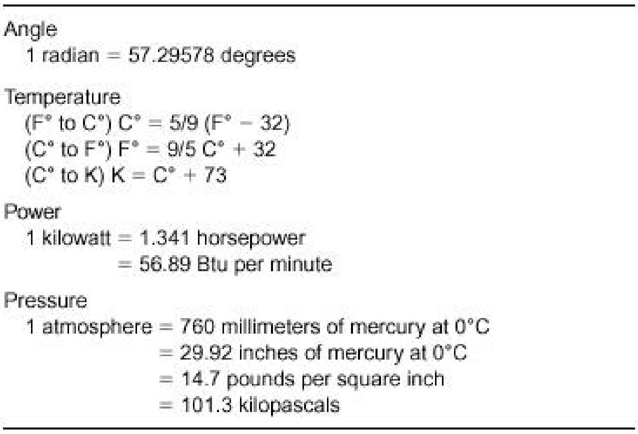
Appendix Figure 7. Illuminance Conversion Factors



1 lumen = 1/683 light-watt
1 1umen-hour = 60 lumen-minutes
1 footcandle = 1 lumen/square foot
1 watt-second = 10^7 ergs
1 phot = 1 lumen/square centimeter
1 lux = 1 lumen/square meter = 1 metercandle

Multiply Number of → To Obtain Number of ↓ By ↘	Foot-candles	Lux	Phot	Milliphot
Footcandles	1	0.0929	929	0.929
Lux	10.76	1	10,000	10
Phot	0.00108	0.0001	1	0.001
Milliphot	1.076	0.1	1,000	1

Appendix Figure 8. Angular Measure, Temperature, Power, and Pressure Conversion Equations



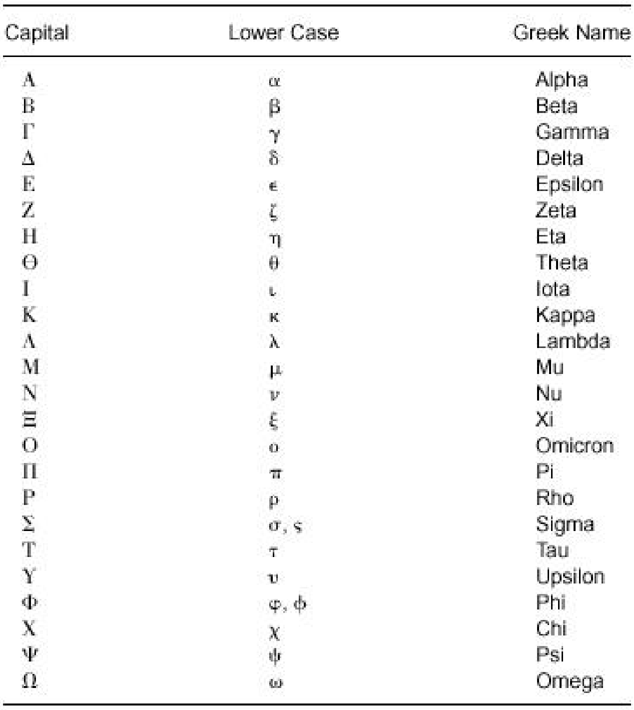
Angle
1 radian = 57.29578 degrees

Temperature
(F° to C°) C° = 5/9 (F° − 32)
(C° to F°) F° = 9/5 C° + 32
(C° to K) K = C° + 73

Power
1 kilowatt = 1.341 horsepower
= 56.89 Btu per minute

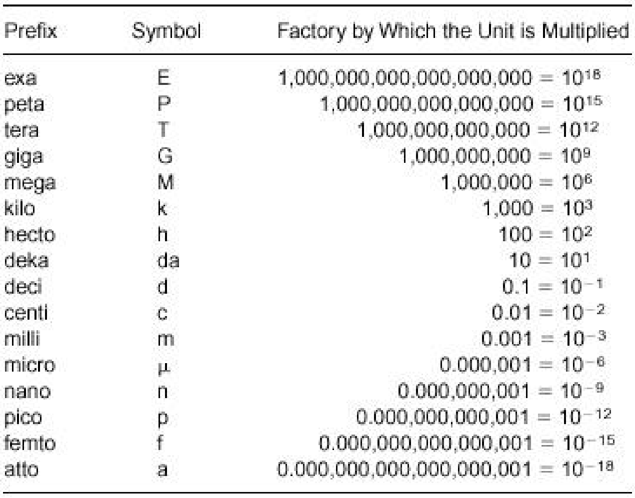
Pressure
1 atmosphere = 760 millimeters of mercury at 0°C
= 29.92 inches of mercury at 0°C
= 14.7 pounds per square inch
= 101.3 kilopascals

Appendix Figure 9. Greek Alphabet
(Capital and Lowercase)

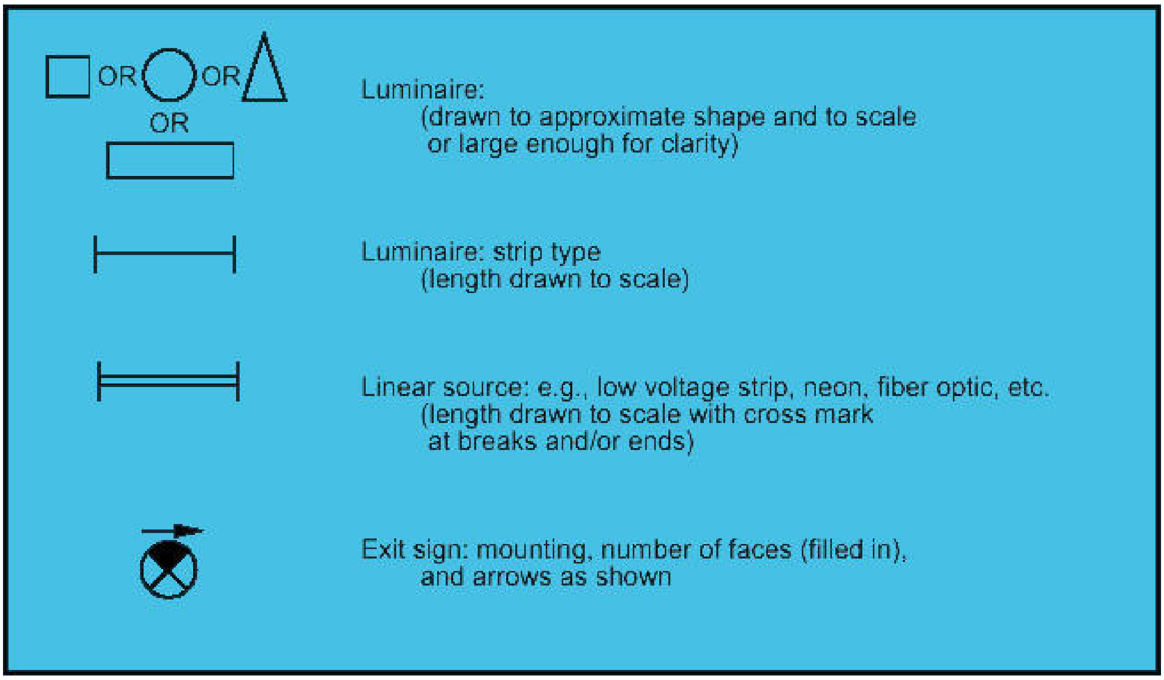


Capital	Lower Case	Greek Name
Α	α	Alpha
Β	β	Beta
Γ	γ	Gamma
Δ	δ	Delta
Ε	ϵ	Epsilon
Ζ	ζ	Zeta
Η	η	Eta
Θ	θ	Theta
Ι	ι	Iota
Κ	κ	Kappa
Λ	λ	Lambda
Μ	μ	Mu
Ν	ν	Nu
Ξ	ξ	Xi
Ο	ο	Omicron
Π	π	Pi
Ρ	ρ	Rho
Σ	σ, ς	Sigma
Τ	τ	Tau
Υ	υ	Upsilon
Φ	φ, ϕ	Phi
Χ	χ	Chi
Ψ	ψ	Psi
Ω	ω	Omega

Appendix Figure 10. Unit Prefixes



Prefix	Symbol	Factory by Which the Unit is Multiplied
exa	E	$1{,}000{,}000{,}000{,}000{,}000{,}000 = 10^{18}$
peta	P	$1{,}000{,}000{,}000{,}000{,}000 = 10^{15}$
tera	T	$1{,}000{,}000{,}000{,}000 = 10^{12}$
giga	G	$1{,}000{,}000{,}000 = 10^{9}$
mega	M	$1{,}000{,}000 = 10^{6}$
kilo	k	$1{,}000 = 10^{3}$
hecto	h	$100 = 10^{2}$
deka	da	$10 = 10^{1}$
deci	d	$0.1 = 10^{-1}$
centi	c	$0.01 = 10^{-2}$
milli	m	$0.001 = 10^{-3}$
micro	μ	$0.000{,}001 = 10^{-6}$
nano	n	$0.000{,}000{,}001 = 10^{-9}$
pico	p	$0.000{,}000{,}000{,}001 = 10^{-12}$
femto	f	$0.000{,}000{,}000{,}000{,}001 = 10^{-15}$
atto	a	$0.000{,}000{,}000{,}000{,}000{,}001 = 10^{-18}$



Luminaire:
(drawn to approximate shape and to scale
or large enough for clarity)

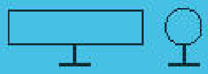
Luminaire: strip type
(length drawn to scale)

Linear source: e.g., low voltage strip, neon, fiber optic, etc.
(length drawn to scale with cross mark
at breaks and/or ends)

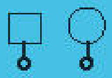
Exit sign: mounting, number of faces (filled in),
and arrows as shown

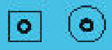
MOUNTING


Recessed

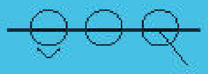

Wall-mounted


Suspended: pendant, chain, stem, or cable hung


Pole-mounted with arm


Pole-mounted on top


Ground- or floor-mounted
(box around symbol)


Track-mounted: length, luminaire types, and
quantities as shown
(track length drawn to scale)

OPTIC ORIENTATION


Horizontal zero line
(indicates horizontal zero; drawn from photometric
center with length as needed for clarity)

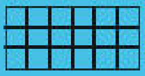
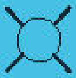
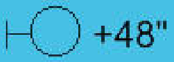
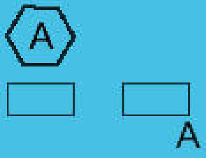
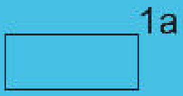
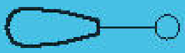
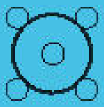

Directional arrowhead
(indicates primary lumen orientation)


Directional aiming line
(drawn from photometric center to a small, filled
circle at the actual aiming point)

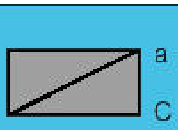
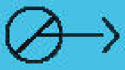
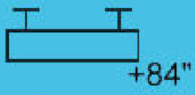
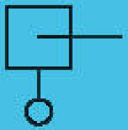
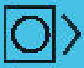
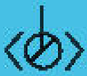
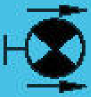
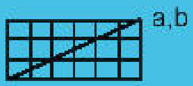
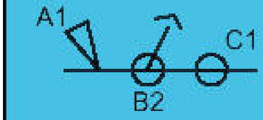
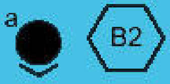
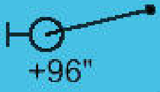
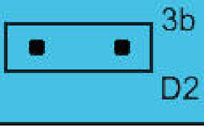
EMERGENCY


Luminaire providing emergency illumination
(filled in, solid, or screened)

NOTE: Modifiers are shown with typical base symbols. Each modifier can be used with any base symbol. For clarity, base symbols here are shown shaded, and modifiers are shown bold.

	Louvers
	Luminaire: bollard type
	Mounting height
	Luminaire identifier: see luminaire schedule for type (use hexagon or subscript to refer to luminaire schedule)
	Subscripts adjacent to luminaire are used for additional identification, such as 1,2,3, etc. – circuit or aiming schedule number a,b,c, etc. – switch identification
	Night light
	Roadway luminaire: Cobra head (note: alternate to pole mounted with arm)
	Pole-mounted lowering device

NOTE: Modifiers are shown with typical base symbols. Each modifier can be used with any base symbol. For clarity, base symbols here are shown shaded, and modifiers are shown bold.

	Recessed, 2' x 4', emergency, switch a, type C (optional screening used to indicate emergency)
	Recessed with optic orientation shown: horizontal zero and primary lumen orientation coincide
	Chain-hung striplight, emergency
	Wall-mounted at 84" A.F.F. to center
	Pole-mounted with horizontal zero to side
	Ground-mounted wall wash
	Recessed with optic orientation shown; horizontal zero and multiple maximum lumen zones
	Wall-mounted, double face exit w/arrows
	2' x 4' recessed luminaire with louver controlled by switches a and b
	Track with three different luminaire types
	Directional surface-mounted luminaire, type B2, emergency, switch a
	Pendant-mounted, emergency, at 72", switch b
	Wall-mounted at 96" with aiming line to point
	Pendant-hung, 1' x 4', type D2 on circuit 3 controlled by switch b

Glossary of Lighting Terminology

As the title implies, this last chapter contains terminology directly related to light and lighting practice. All terms are presented in alphabetical order and are followed by their standard symbols or abbreviations and their defining equations where applicable, by their definitions, and by other related terms of interest. No attempt has been made to provide information on pronunciations or etymologies. Definitions of electrical terms common to lighting and to other fields are available in the *American National Standard Dictionary of Electrical and Electronics Terms* (ANSI/IEEE 100-1984).

Any of the radiometric and photometric quantities that follow may be restricted to a narrow wavelength interval $\Delta\lambda$ by the addition of the word "spectral" and the specification of the wavelength λ. The corresponding symbols are changed by adding a subscript λ, as in Q_λ for a spectral concentration, or a λ in parentheses, as in $K(\lambda)$ for a function of wavelength. The appendix is a tabulated summary of standard units, symbols, and radiometric quantities. Other symbols, abbreviations, and conversion factors are also given in the appendix.

Most of the definitions in this glossary have been adapted from ANSI/IES RP-16-1996, *Nomenclature and Definitions for Illuminating Engineering*. Those marked with a dagger (†) do not appear in the ANSI standard.

A

absolute luminance threshold luminance threshold for a bright object like a disk on a totally dark background.

absorptance, $\alpha = \Phi_a/\Phi_I$ the ratio of the absorbed flux to the incident flux. See *absorption*.

Note The sum of the hemispherical reflectance, the hemispherical transmittance, and the absorptance is one.

absorption a general term for the process by which incident flux is converted to another form of energy, usually and ultimately to heat.

Note All of the incident flux is accounted for by the processes of reflection, transmission, and absorption.

accent lighting directional lighting to emphasize a particular object or surface feature or to draw attention to a part of the field of view. See *directional lighting*.

acceptance half-angle† the acceptance half-angle is set by the refractive indices of the core and cladding of fiber optics, and it is expressed in terms of the numerical aperture (NA). The numerical aperture is given as NA = $n_0 \sin p$.†

accommodation the process by which the eye changes focus from one distance to another.

actinic a term meaning photochemically active.

action spectrum the quantitative actinic response of a chemical or biological substance or living organism as a function of an appropriate spectral parameter such as wavelength or photon energy.

adaptation the process by which the retina becomes accustomed to more or less light than it was exposed to during an immediately preceding period. It results in a change in the sensitivity to light. See *scotopic vision, photopic vision,* and *chromatic adaptation.*

Note Adaptation is also used to refer to the final state of the process, such as reaching a condition of adaptation to a specific luminance level.

adaptive color shift the change in the perceived object color caused solely by change of the state of chromatic adaptation.

adverse weather lamp† See *fog lamp*.

aerodrome beacon an aeronautical beacon used to indicate the location of an aerodrome.

Note An aerodrome is any defined area on land or water--including any buildings, installations, and equipment--intended to be used either wholly or in part for the arrival, departure, and movement of aircraft.

aeronautical beacon an aeronautical ground light visible at all azimuths, either continuously or intermittently, to designate a particular location on the surface of the earth. See *aerodrome beacon, airway beacon, hazard or obstruction beacon,* and *landmark beacon*.

aeronautical ground light any light specially provided as an aid to air navigation, other than a light displayed on an aircraft. See *aeronautical beacon, angle-of-approach lights, approach lights, approach-light beacon, bar (of lights), boundary lights, circling guidance lights, course light, channel lights, obstruction lights, perimeter lights, runway alignment indicator, runway end identification light, runway lights, taxi-channel lights,* and *taxiway lights*.

aeronautical light any luminous sign or signal that is specially provided as an aid to air navigation.

after image a visual response that occurs after the stimulus causing it has ceased.

aircraft aeronautical light any aeronautical light specially provided on an aircraft. See *anticollision light, ice detection light, fuselage lights, landing light, navigation light system, position lights,* and *taxi light.*

airway beacon an aeronautical beacon used to indicate a point on the airway.

alphanumeric display (digital display) an electrically operated display of letters and/or digits. Tungsten filaments, gas discharges, light-emitting diodes, liquid crystals, projected numerals, illuminated numbers, fluorescent screens, and other principles of operation can be used.

altitude (in daylighting) the angular distance of a heavenly body measured on the great circle that passes, perpendicular to the plane of the horizon, through the body and through the zenith. It is measured positively from the horizon to the zenith, from 0° to 90°.

ambient lighting lighting throughout an area that produces general illumination.

anchor light (aircraft) an aircraft light designed for use on a seaplane or amphibian to indicate its position when at anchor or moored.

ampere† the intensity of electrical current flow. The symbol often used in equations is I, although A is also acceptable.

angle-of-approach lights aeronautical ground lights arranged so as to indicate a desired angle of descent during an approach to an aerodrome runway. (Also called *optical glide path lights*.)

angle of collimation the angle subtended by a light source at a point on an irradiated surface.

angstrom,Å† a unit of wavelength equal to 10^{-10} m (one ten-billionth of a meter).

anticollision light a flashing aircraft aeronautical light or system of lights designed to provide a red signal throughout 360° of azimuth for the purpose of giving long-range indication of an aircraft's location to pilots of other aircraft.

aperture color† the perceived color of the sky or of a patch seen through an aperture and not identifiable as belonging to a specific object.

apostilb (asb) a lambertian unit of luminance equal to $1/\pi = 0.3183$ cd/m^2. This term is obsolete, and its use is deprecated.

approach-light beacon an aeronautical ground light placed on the extended centerline of the runway at a fixed distance from the runway threshold to provide an early indication of position during an approach to a runway.

Note The runway threshold is the beginning of the runway usable for landing.

approach lights a configuration of aeronautical ground lights located in extension of a runway or channel before the threshold to provide visual approach and landing guidance to pilots. See *angle-of-approach lights, approach-light beacon,* and *VASIS*.

arc discharge an electric discharge characterized by high cathode current densities and a low voltage drop at the cathode.

Note The cathode voltage drop is small compared with that in a glow discharge, and secondary emission plays only a small part in electron emission from the cathode.

arc lamp a discharge lamp in which the light is emitted by an arc discharge or by its electrodes.

Note The electrodes can be either of carbon (operating in air) or of metal.

artificial pupil a device or arrangement for confining the light passing through the pupil of the eye to an area smaller than the natural pupil.

atmospheric transmissivity the ratio of the directly transmitted flux incident on a surface after passing through unit thickness of the atmosphere to the flux that would be incident on the same surface if the flux had passed through a vacuum.

average luminance luminance is a property of a geometric ray. Luminance as measured by conventional meters is averaged with respect to two independent variables, area and solid angle; both must be defined for a complete description of a luminance measurement.

azimuth the angular distance between the vertical plane containing a given line or celestial body and the plane of the meridian.

B

back light illumination from behind (and usually above) a subject to produce a highlight along its edge and consequent separation between the subject and its background. See *side-back light*.

backing lighting the illumination provided for scenery in off-stage areas visible to the audience.

back-up lamp a lighting device mounted on the rear of a vehicle for illuminating the region near the back of the vehicle while moving in reverse. It normally can be used only while backing up.

bactericidal (germicidal) **effectiveness** the capacity of various portions of the ultraviolet (UV) spectrum to destroy bacteria, fungi, and viruses.

bactericidal (germicidal) **efficiency of radiant flux** the ratio of the bactericidal effectiveness of that wavelength to that of wavelength 265.0 nm, which is rated as unity.

Note Tentative bactericidal efficiency of various wavelengths of radiant flux are given in Chapter 5, Nonvisual Effects of Radiant Energy.

bactericidal (germicidal) **exposure** the product of bactericidal flux density on a surface and time. It usually is measured in bactericidal $\mu W \times min/cm^2$ or bactericidal $W \times min./ft^2$.

bactericidal (germicidal) **flux** radiant flux evaluated according to its capacity to produce bactericidal effects. It usually is measured in microwatts of UV radiation weighted in accordance with its bactericidal efficiency. Such quantities of bactericidal flux would be in bactericidal microwatts.

Note Ultraviolet radiation of wavelength 253.7 nm usually is referred to as "ultraviolet microwatts" or "UV watts."

bactericidal (germicidal) **flux** density the bactericidal flux per unit area of the surface being irradiated. It is equal to the quotient of the incident bactericidal flux divided by the area of the surface when the flux is uniformly distributed. It usually is measured in $\mu W/cm^2$ or W/ft^2 of bactericidally weighted UV radiation (bactericidal $\mu W/cm^2$ or bactericidal W/ft^2).

bactericidal lamp a UV lamp that emits a significant portion of its radiative power in the UV-C band (100 to 280 nm).

baffle a single opaque or translucent element to shield a source from direct view at certain angles, to absorb or block unwanted light, or to reflect and redirect light.

balcony lights luminaires mounted on the front edge of an auditorium balcony.

ballast a device used with an electric-discharge lamp to obtain the necessary circuit conditions (voltage, current, and waveform) for starting and operating. See *reference ballast*.

ballast factor the fractional flux of a fluorescent lamp operated on a ballast compared to the flux when operated on the standard (reference) ballast specified for rating lamp lumens.

Note The lamp is at specified ambient temperature conditions for photometric testing.

ballast-lamp photometric factor ratio of fluorescent luminaire lumen output using given ballast and lamp types (under photometric test conditions) to the lumen output using the lamp and ballast types used to generate a photometric test.

Note This factor is applicable when "energy-conserving" lamps and ballasts are used in a luminaire photometered with standard lamps and conventional ballasts; it is also applied in the converse situation.

bar (of lights) a group of three or more aeronautical ground lights placed in a line transverse to the axis, or extended axis, of the runway. See *barrette*.

bare (exposed) lamp a light source with no shielding.

barn doors a set of adjustable flaps--usually two, four, or eight--which can be attached to the front of a luminaire (usually a Fresnel spotlight) in order to partially control the shape and spread of the light beam.

barrette (in aviation) a short bar in which the lights are closely spaced so that from a distance they appear to be a linear light.

Note Barrettes are usually no longer than 4.6 m (15 ft) in length.

base light uniform, diffuse, near-shadowless illumination sufficiently intense for a television or film picture of acceptable quality at a desired lens opening. Acceptable base level of unaccented stage illumination.

beacon a light (or mark) used to indicate a geographic location. See *aerodrome beacon, aeronautical beacon, airway beacon, approach-light beacon, hazard or obstruction beacon, identification beacon,* and *landmark beacon*.

beam angle the angle between the two directions for which the intensity is 50% of the maximum intensity as measured in a plane through the nominal beam centerline. For beams that do not possess rotational symmetry, the beam angle is generally given for two planes at 90°, typically the maximum and minimum angles.

Note In certain fields of application, the beam angle was formerly measured to 10% of maximum intensity.

beam axis of a projector a line midway between two lines that intersect the intensity distribution curve at points equal to a stated percentage of its maximum (usually 50%).

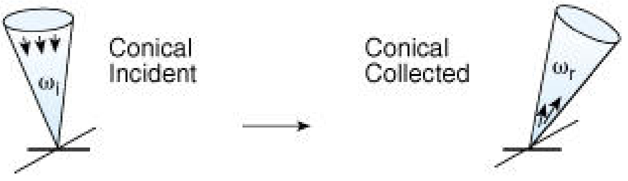
beam lumens the total flux in that region of space where the intensity exceeds 50% of the maximum intensity.

beam projector a luminaire with the light source at or near the focus of a paraboloidal reflector, producing near-parallel rays of light in a beam of small divergence. Some are equipped with spill rings to reduce spill and glare. In most types, the lamp can be moved toward or away from the reflector to vary the beam spread.

beam spread (in any plane) the angle between the two directions in the plane in which the intensity is equal to a stated percentage of the maximum beam intensity.

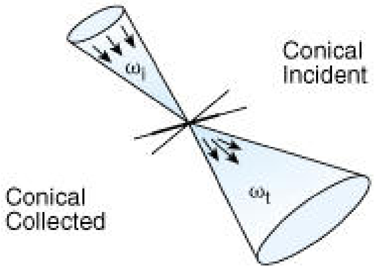
biconical reflectance, $\rho(\omega_i;\omega_r)$ ratio of the reflected flux collected through a conical solid angle to the incident flux limited to a conical solid angle.

Note The directions and extent of each cone must be specified; the solid angle need not be a right circular cone.



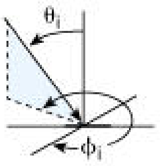
biconical transmittance, $\tau(\omega_i;\omega_t)$ ratio of transmitted flux collected through a conical solid angle to the incident flux limited to a conical solid angle.

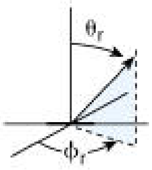
Note The directions and extent of each cone must be specified.



bidirectional reflectance, $\rho(\theta_i,\varphi_i;\theta_r,\varphi_r)$ ratio of reflected flux collected over an element of solid angle surrounding the given direction to essentially collimated incident flux.

Note The directions of incidence and collection and the size of the solid angle "element" of collection must be specified. In each case of conical incidence or collection, the solid angle is not restricted to a right circular cone, but can be of any cross section, including a rectangle, a ring, or a combination of two or more solid angles.





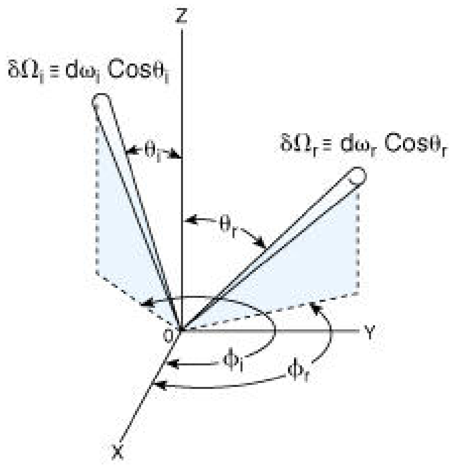
bidirectional reflectance distribution function (BRDF), f_r the ratio of the differential luminance of a ray $dL_r(\theta_r,\varphi_r)$ reflected in a given direction (θ_r,φ_r) to the differential luminous flux density $dE_i(\theta_i,\varphi_i)$ incident from a given direction of incidence, (θ_i,φ_i), that produces it.

$$f_r(\theta_i,\phi_i;\,\theta_r,\phi_r) \equiv \frac{dL_r(\theta_r,\phi_r)}{dE_i(\theta_i,\phi_i)}\,(sr^{-1})$$

$$= \frac{dL_r(\theta_r,\phi_r)}{L_i(\theta_i,\phi_i)\,d\Omega_i}$$

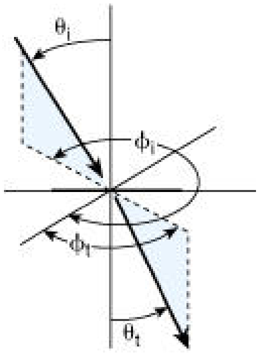
where $d\Omega \equiv d\omega \cos\theta$

Notes (i) This distribution function is the basic parameter for describing (geometrically) the reflecting properties of an opaque surface element (negligible internal scattering). (ii) It can have any positive value and approaches infinity in the specular direction for ideally specular reflectors. (iii) The spectral and polarization aspects must be defined for complete specification, since the BRDF as given above defines only the geometric aspects.



bidirectional transmittance, $\tau(\theta_i,\varphi_i;\theta_t,\varphi_t)$ ratio of incident flux collected over an element of solid angle surrounding the given direction to essentially collimated incident flux.

Note The direction of incidence and collection and the size of the solid angle element must be specified.



bidirectional transmittance distribution function (BTDF), $\mathbf{f_t}$ the ratio of the differential luminance $dL_t(\theta_t,\varphi_t)$ for a ray transmitted in a given direction (θ_t,φ_t) to the differential luminous flux density $dE_i(\theta_i,\varphi_i)$ incident from a given direction of incidence (θ_i,φ_i) that produces it:

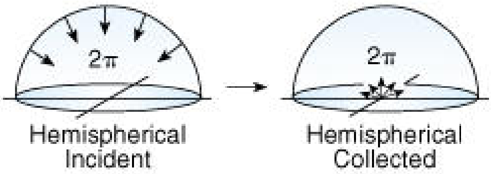
$$f_t(\theta_i,\phi_i;\,\theta_t,\phi_t) \equiv \frac{dL_t(\theta_t,\phi_t)}{dE_i(\theta_i,\phi_i)}\,(\mathrm{sr}^{-1})$$

$$= \frac{dL_t(\theta_t,\phi_t)}{L_i(\theta_i,\phi_i)\,d\Omega_i}$$

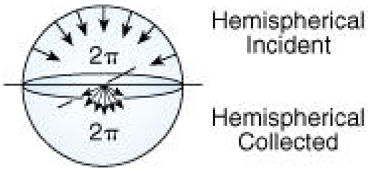
where $d\Omega \equiv d\omega \cos\theta$

Notes (i) This distribution is the basic parameter for describing (geometrically) the transmitting properties of a thin scattering film (with negligible internal scattering) so that the transmitted radiation emerges from a point that is not significantly separated from the point of incidence of the incident ray(s). The governing considerations are similar to those for application of the *bidirectional reflectance distribution function (BRDF)*, rather than the *bidirectional scattering-surface reflectance distribution function (BSSRDF)*. (ii) It can have any positive value and approaches infinity in the direction for regular transmission (possibly with refraction but without scattering). (iii) The spectral and polarization aspects must be defined for complete specification, since the BTDF as given above defines only the geometrical aspects.

bihemispherical reflectance, $\rho(2\pi; 2\pi)$ ratio of reflected flux collected over the entire hemisphere to the flux incident from the entire hemisphere.



bihemispherical transmittance, $\tau(2\pi; 2\pi)$ ratio of transmitted flux collected over the entire hemisphere to the incident flux from the entire hemisphere.



binocular portion of the visual field that portion of space where the fields of the two eyes overlap.

biological rhythm a characteristic periodic change in a living organism or life-related process. Some biological rhythms are induced and/or synchronized by light.

blackbody a temperature radiator of uniform temperature whose radiant exitance in all parts of the spectrum is the maximum obtainable from any temperature radiator at the same temperature. Such a radiator is called a blackbody because it absorbs all the radiant energy that falls upon it. All other temperature radiators can be classed as nonblackbodies. Nonblackbodies radiate less in some or all wavelength intervals than a blackbody of the same size and the same temperature.

Note The blackbody is practically realized over limited solid angles in the form of a cavity with opaque walls at a uniform temperature and with a small opening for observation. It is variously called a standard radiator, an ideal radiator, or a complete radiator.

blackbody (planckian) **locus** the locus of points on a chromaticity diagram representing the chromaticities of blackbodies having various (color) temperatures.

black light the popular term for UV energy near the visible spectrum.

Note For engineering purposes the wavelength range 320 to 400 nm has been found useful for rating lamps and their effectiveness upon fluorescent materials (excluding phosphors used in fluorescent lamps). By confining black light applications to this region, germicidal and erythemal effects are, for practical purposes, eliminated.

black-light flux radiant flux within the wavelength range 320 to 400 nm. It is usually measured in milliwatts. See *fluoren*.

Note The floren is used as a unit of black-light flux and is equal to one milliwatt of radiant flux in the wavelength range 320 to 400 nm. Because of the variability of the spectral sensitivity of materials irradiated by black light in practice, no attempt is made to evaluate black-light flux according to its capacity to produce effects.

black-light flux density black-light flux per unit area of the surface being irradiated. It is equal to the incident black-light flux divided by the area of the surface when the flux is uniformly distributed. It usually is measured in milliwatts per unit area of black-light flux.

black-light lamp an ultraviolet lamp that emits a significant portion of its radiative power in the UV-A band (315 to 400 nm).

blending lighting general illumination used to provide smooth transitions between the specific light areas on a stage.

blinding glare glare that is so intense that for an appreciable length of time after it has been removed, no object can be seen.

Blondel-Rey law the ratio of the thresholds of a square-form flashing light (E_a) and of a steady light (E_o), in point vision conditions at night. The ratio depends on the duration in seconds of the flash (t):

$$\frac{E_o}{E_a} = \frac{t}{0.21 + t}$$

bollard† luminaires having the appearance of a short, thick post, used for walkway and grounds lighting. The optical components are usually top-mounted.

borderlight a long continuous striplight hung horizontally above a stage and aimed down to provide general diffuse illumination or to light the cyclorama or a drop; usually wired in three or four color circuits. Also available in portable versions.

borderline between comfort and discomfort (BCD) the average luminance of a source in a field of view that produces a sensation between comfort and discomfort.

boundary lights aeronautical ground lights delimiting the boundary of a land aerodrome without runways. See *range lights*.

bowl an open-top diffusing glass or plastic enclosure used to shield a light source from direct view and to redirect or scatter the light.

bracket (mast arm) an attachment to a lamp post or pole from which a luminaire is suspended.

brightness (of a perceived aperture color) the attribute by which an area of color of finite size is perceived to emit, transmit, or reflect a greater or lesser amount of light. No judgment is made as to whether the light comes from a reflecting, transmitting or self-luminous object. See also *brightness of a perceived light source color*, *luminance*, *subjective brightness*, and *veiling brightness*.

brightness contrast threshold when two patches of color are separated by a brightness contrast border as in the case of a bipartite photometric field or of a disk-shaped object surrounded by its background, the border between the two patches is a brightness contrast border. The contrast that is just detectable is known as the brightness contrast threshold.

brightness of a perceived light source color† the attribute in accordance with which the source seems to emit more or less luminous flux per unit area.

bulb† See *lamp*.

C

candela, cd the SI unit of luminous intensity, equal to one lumen per steradian (lm/sr). Formerly *candle*. See Chapter 2, Measurement of Light and Other Radiant Energy.

Note The fundamental luminous intensity definition in the SI is the candela. The candela is the luminous intensity in a given direction of a source that emits monochromatic radiation of frequency 540×10^{12} Hz that has a radiant intensity in that direction of 1/683 watt per steradian. The candela so defined is the base unit applicable to photopic quantities, scotopic quantities, and quantities to be defined in the mesopic domain. From 1909 until January 1, 1948, the unit of luminous intensity in the United States, as well as in France and Great Britain, was the international candle, which was maintained by a group of carbon-filament vacuum lamps. For the present unit as defined above, the internationally accepted term is *candela*. The difference between the candela and the old international candle is so small that only measurements of high precision are affected. From 1948 to 1979, the unit of luminous intensity was defined in terms of a complete (blackbody) radiator. From this relation, K_m and K'_m, and consequently the lumen, were determined. One candela was defined as the luminous intensity of 1/600,000 m^2 of projected area of a blackbody radiator operating at the temperature of solidification of platinum, at a pressure of 101,325 newtons per square meter ($N/m^2 = Pa$).

candlepower (cp), $I = d\varphi/d\omega$ luminous intensity expressed in candelas.

carbon-arc lamp an electric-discharge lamp employing an arc discharge between carbon electrodes. One or more of these electrodes can have cores of special chemicals that contribute importantly to the radiation.

cavity ratio (CR) a number indicating cavity proportions. See *ceiling cavity ratio*, *floor cavity ratio*, and *room cavity ratio*.

$$\mathrm{CR} = \frac{5 \times (\mathrm{Height}_{\mathrm{cavity}}) \times (\mathrm{Length}_{\mathrm{cavity}} + \mathrm{Width}_{\mathrm{cavity}})}{(\mathrm{Length}_{\mathrm{cavity}}) \times (\mathrm{Width}_{\mathrm{cavity}})}$$

For cavities of irregular shape:

$$\mathrm{CR} = \frac{2.5 \times (\mathrm{Height}_{\mathrm{cavity}}) \times (\mathrm{Perimeter}_{\mathrm{cavity}})}{(\mathrm{Area\ of\ Cavity\ Base})}$$

Note The relationship between cavity ratio and room coefficient should be noted. If the entire room is considered as a cavity, the room height becomes $\mathrm{Height}_{\mathrm{cavity}}$ and $\mathrm{CR} = 10 \times K_r$

ceiling area lighting a general lighting system in which the entire ceiling is, in effect, one large luminaire.

Note Ceiling area lighting includes luminous ceilings and louvered ceilings.

ceiling cavity the cavity formed by the ceiling, the plane of the luminaires, and the wall surfaces between these two planes.

ceiling cavity ratio (CCR) a number computed by using the distance from the plane of the luminaire to the ceiling (h_c) as $\text{Height}_{\text{cavity}}$ in the equations given for *cavity ratio.*

ceiling projector a device designed to produce a well-defined illuminated spot on the lower portion of a cloud for the purpose of providing a reference mark for the determination of the height of that part of the cloud.

ceiling ratio the ratio of the luminous flux reaching the ceiling directly to the upward component from the luminaire.

central (foveal) **vision** the seeing of objects in the central or foveal part of the visual field, approximately 2° in diameter. It permits seeing much finer detail than does peripheral vision.

central visual field that region of the visual field that corresponds to the foveal portion of the retina.

channel an enclosure containing the ballast, starter, lamp holders, and wiring for a fluorescent lamp. Can also be a similar enclosure on which filament lamps (usually tubular) are mounted.

channel lights aeronautical ground lights arranged along the sides of a channel of a water aerodrome. See *taxi-channel lights*.

characteristic curve a curve that expresses the relationship between two variable properties of a light source, such as candlepower and voltage or flux and voltage.

chromatic adaptation the process by which the chromatic properties of the visual system are modified by the observation of stimuli of various chromaticities and luminances. See *state of chromatic adaptation*.

chromatic color perceived color possessing a hue. In everyday speech, the word *color* is often used in this sense in contradistinction to white, gray, or black.

chromatic contrast threshold (color contrast threshold) a threshold of chromaticity difference between two patches of color juxtaposed and separated only by a color contrast border, below which they cannot be perceived as different in chromaticness or separated by a contrast border. A contrast border can involve differences both in luminance and in chromaticity between the sides.

chromaticity coordinates of a color, **x, y, z** the ratios of each of the tristimulus values of the color to the sum of the three tristimulus values.

chromaticity diagram a plane diagram formed by plotting one of the three chromaticity coordinates against another.

chromaticity difference threshold the smallest difference in chromaticity between two colors of the same luminance that makes them perceptibly different. The difference can be a difference in hue or saturation, or a combination of the two.

chromaticity of a color the dominant or complementary wavelength and purity aspects of the color taken together, or of the aspects specified by the chromaticity coordinates of the color taken together.

chromaticness† the attribute of a visual sensation according to which the (perceived) color of an area appears to be more or less chromatic.

CIE *(L*, a*, b*)* uniform color space, CIELAB a transformation of CIE tristimulus values X, Y, Z into three coordinates (L^*, a^*, and b^*) that define a space in which equal distances are more nearly representative of equal magnitudes of perceived color difference. This space is specially useful in cases of colorant mixtures (for example, dye-stuffs, paints).

CIE (*L*, u*, v) uniform color space, CIELUV** a transformation of CIE tristimulus values *X, Y, Z* into three rectangular coordinates (*L*, u**, and *v**) that define a space in which equal distances are more nearly representative of equal magnitudes of perceived color difference. This space is specially useful in cases where colored lights are mixed additively, for example, color television.

CIE standard chromaticity diagram one in which the x and y chromaticity coordinates are plotted in rectangular coordinates.

circling guidance lights aeronautical ground lights provided to supply additional guidance during a circling approach when the circling guidance furnished by the approach and runway lights is not adequate.

clear sky a sky that has less than 30% cloud cover.

clearance lamp lighting devices for the purpose of indicating the width and height of a vehicle.

clerestory that part of a building that rises clear of the roofs or other parts and whose walls contain windows for lighting the interior.

cloudy sky a sky that has more than 70% cloud cover.

coefficient of attenuation (at a point in a given direction), μ the decrement in flux per unit distance in a given direction within a medium. It is defined by the relation $\varphi_x = \varphi_0 e^{-\mu x}$ where φ_x is the flux at any distance x from a reference point having flux φ_0. More generally, where the coefficient varies from point to point; $\mu = \mu(x)$ along the path.

$$\phi_x = \phi_0 e^{-\int_0^x \mu(x)dx}$$

coefficient of beam utilization (CBU) the ratio of the luminous flux (lumens) reaching a specified area directly from a floodlight or projector to the total beam luminous flux (lumens).

coefficient of utilization (CU) the ratio of luminous flux (lumens) calculated as received on the work plane to the total luminous flux (lumens) emitted by the lamps alone. It is equal to the product of room utilization factor and luminaire efficiency. See Chapter 9, Lighting Calculations.

coffer a recessed panel or dome in the ceiling.

cold-cathode lamp an electric-discharge lamp whose mode of operation is that of a glow discharge and that has electrodes so spaced that most of the light comes from the positive column between them.

color† the characteristic of light by which a human observer can distinguish between two structure-free patches of light of the same size and shape. See *light source color* and object color.

color difference thresholds the difference in chromaticity and/or luminance between two colors that makes them just perceptibly different. The difference can be a difference in hue, saturation, brightness (lightness for surface colors), or a combination of the three.

color comparison or color grading the judgment of equality, or of the amount and character of difference, of the color of two objects viewed under identical illumination.

color contrast threshold† See *chromaticity difference threshold*.

color correction (of a photograph or printed picture) the adjustment of a color reproduction process to improve the perceived-color conformity of the reproduction to the original.

color discrimination the perception of differences between two or more colors.

color matching the action of making a color appear the same as a given color.

color-matching functions (spectral tristimulus values), $\bar{x}(\lambda) = X_\lambda/\varphi_{e\lambda}$, $\bar{y}(\lambda) = Y_\lambda/\varphi_{e\lambda}$, $\bar{z}(\lambda) = Z_\lambda/\varphi_{e\lambda}$ the tristimulus values per unit wavelength interval and unit spectral radiant flux.

Note Color-matching functions have been adopted by the Commission Internationale de l'Eclairage (CIE). They are tabulated as functions of wavelength throughout the spectrum and are the basis for the evaluation of radiant energy as light and color. The standard values adopted by the CIE in 1931 are given in Chapter 4, Color. The $\bar{y}$ values are identical with the values of the spectral luminous efficiency for photopic vision. The $\bar{x}$, $\bar{y}$, and $\bar{z}$ values for the 1931 Standard Observer are based on a 2° bipartite field and are recommended for predicting matches for stimuli subtending between 1 and 4°. Supplementary data based on a 10° field were adopted in 1964 for use for angular subtends greater than 4°.

color preference index (of a light source), R_p Measure appraising a light source for enhancing the appearance of an object or objects by making their colors tend toward people's preferences. Judd's "Flattery Index" is an example. See *flattery index.*

color rendering† a general expression for the effect of a light source on the color appearance of objects in conscious or subconscious comparison with their color appearance under a reference light source.

color rendering improvement (of a light source)† the adjustment of spectral composition to improve color rendering.

color rendering index (of a light source) (CRI) a measure of the degree of color shift objects undergo when illuminated by the light source as compared with those same objects when illuminated by a reference source of comparable color temperature.

color temperature of a light source the absolute temperature of a blackbody radiator having a chromaticity equal to that of the light source. See also *correlated color temperature* and *distribution temperature.*

colorfulness† See *chromaticness*.

colorfulness of a perceived color the attribute according to which it appears to exhibit more or less chromatic color. For a stimulus of a given chromaticity, colorfulness normally increases as the absolute luminance is increased.

colorimetric purity (of a light), p_c the ratio L_1/L_2, where L_1 is the luminance of the single-frequency component that must be mixed with a reference standard to match the color of the light, and L_2 is the luminance of the light. See *excitation purity*.

colorimetric shift the change of chromaticity and luminance factor of an object color due to change of the light source. See *adaptive color shift* and *resultant color shift.*

colorimetry the measurement of color.

compact-arc lamp† See *short-arc lamp.*

compact source iodide lamp (CSI) an arc source utilizing a mercury vapor arc with metal halide additives to produce illumination typically in the 5000 to 6000 K range. Requires a ballast and ignitor-system for operation.

comparison lamp a light source having a constant, but not necessarily known, luminous intensity with which standard and test lamps are successively compared.

complementary wavelength (of a light), λ_c the wavelength of radiant energy of a single frequency that, when combined in suitable proportion with the light, matches the color of a reference standard. See *dominant wavelength.*

complete diffusion that in which the diffusing medium completely redirects the incident flux by scattering so that no incident flux can remain in an image-forming state.

cones retinal receptors that dominate the retinal response when the luminance level is high and provide the basis for the perception of color.

configuration factor, $C_{1\rightarrow 2}$ the ratio of the illuminance on a surface at point 1 (due to the flux directly received from lambertian surface 2) to the exitance of surface 2. It is used in flux transfer theory.

$$C_{1\rightarrow 2} = E_1/M_2$$

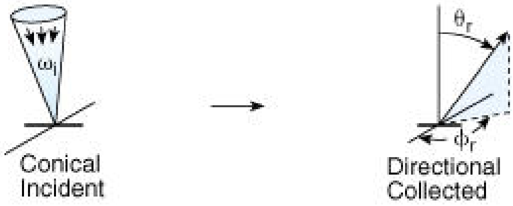
Also, the ratio of the differential flux directly received by surface 2 (and due to element 1) to the total differential flux emitted by differential lambertian surface element 1:

$$C_{1\rightarrow 2} = d\phi_{1\rightarrow 2}/(d\phi_1)$$

Note In the literature this ratio is also called the angle factor, illumination factor, point configuration factor, and sky factor.

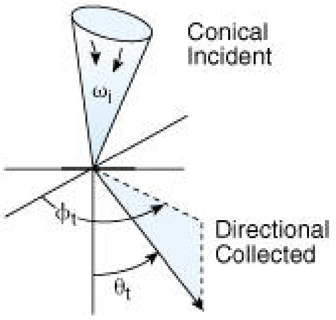
conical-directional reflectance, $\rho(\omega_i; \theta_r, \varphi_r)$ ratio of reflected flux collected over an element of solid angle surrounding the given direction to the incident flux limited to a conical solid angle.

Note The direction and the extent of the cone must be specified, and the direction of collection and size of the solid angle "element" must be specified.



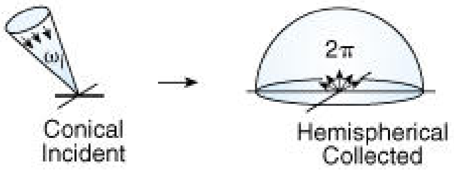
conical-directional transmittance, $\tau(\omega_i; \theta_t, \varphi_t)$ ratio of transmitted flux, collected over an element of solid angle surrounding the direction to the incident flux limited to a conical solid angle.

Note The direction and extent of the cone must be specified, and the direction of collection and size of the solid angle "element" must be specified.



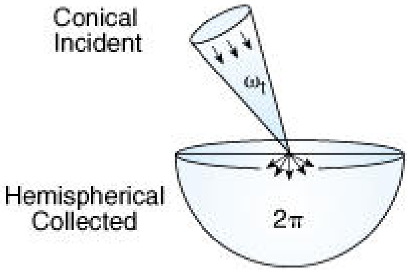
conical-hemispherical reflectance, $\rho(\omega_i; 2\pi)$ ratio of reflected flux collected over the entire hemisphere to the incident flux limited to a conical solid angle.

Note The direction and extent of the cone must be specified.



conical-hemispherical transmittance, $\tau(\omega_t; 2\pi)$ ratio of transmitted flux collected over the entire hemisphere to the incident flux limited to a conical solid angle.

Note The direction and extent of the cone must be specified.



conspicuity the capacity of a signal to stand out in relation to its background so as to be readily discovered by the eye.

contrast† See *luminance contrast.*

contrast rendition factor (CRF) the ratio of the visual task contrast with a given lighting environment to the contrast with sphere illumination. Also known as the contrast rendering factor.

contrast sensitivity the ability to detect the presence of luminance differences. Quantitatively, it is equal to the reciprocal of the brightness contrast threshold.

cornice lighting lighting comprising sources shielded by a panel parallel to the wall and attached to the ceiling and distributing light over the wall.

correlated color temperature (of a light source) (CCT) the absolute temperature of a blackbody whose chromaticity most nearly resembles that of the light source.

cosine law a law stating that the illuminance on any surface varies as the cosine of the angle of incidence. The angle of incidence is the angle between the normal to the surface and the direction of the incident light. The inverse square law and the cosine law can be combined as $E = (I \cos \theta)/d^2$. See *cosine-cubed law* and *inverse square law.*

cosine corrected light meter† a light meter that properly accepts and measures light from the hemisphere above the detector proportional to the cosine of the incident angle.

cosine-cubed law an extension of the cosine law in which the distance d between the source and surface is replaced by h/cos θ, where h is the perpendicular distance of the source from the plane in which the point is located. It is expressed by $E = (I \cos^3 \theta)/h^2$.

counter-key light illumination on a subject from a direction that is opposite to that of the key light.

country beam† See *upper (driving) beams.*

course light† an aeronautical ground light, supplementing an airway beacon, for indicating the direction of the airway and to identify by a coded signal the location of the airway beacon with which it is associated.

cove lighting lighting comprising sources shielded by a ledge or horizontal recess, and distributing light over the ceiling and upper wall.

criteria rating a technique that determined the probability that a specific criterion will be met anywhere in a defined area. The name of the criteria rating includes the name of the criterion being rated. It is expressed in shorthand notation by listing the rating in percent followed by the criterion itself and separated by "@". For example, a lighting system producing a luminance of 100 cd/m^2 over 60% of the specified area could have its luminance rating expressed as 60%@100 cd/m^2.

critical flicker frequency (CFF)† See *flicker fusion frequency.*

critical fusion frequency (CFF)† See *flicker fusion frequency.*

cross lighting illumination from two sources on opposite sides of the subject. Often different color media are used in the luminaires for the same area to give the illusion of shadow while providing sufficient illumination for good visibility.

cucoloris an opaque cutout panel mounted between a light source (sun or arc) and a target surface in order to project a shadow pattern (clouds or leaves are typical) upon scenery, cyclorama, or acting area.

cutoff angle (of a luminaire) the angle, measured up from nadir, between the vertical axis and the first line of sight at which the bare source is not visible.

D

dark adaptation the process by which the retina becomes adapted to a luminance less than about 0.034 cd/m^2 = 2.2 × 10^{-5} cd/in.^{2} = 0.01 fL.

daylight availability the luminous flux from sun plus sky at a specific location, time, date, and sky condition.

daylight factor a measure of daylight illuminance at a point on a given plane, expressed as the ratio of the illuminance on the given plane at that point to the simultaneous exterior illuminance on a horizontal plane from the whole of an unobstructed sky of assumed or known luminance distribution. Direct sunlight is excluded from both interior and exterior values of illuminance.

daylight lamp a lamp producing a spectral distribution approximating that of a specified daylight.

densitometer a photometer for measuring the optical density (common logarithm of the reciprocal of the transmittance or reflectance) of materials.

dichroic filter† a filter that transmits certain wavelengths and reflects those not transmitted; the absorption is small.

diffuse reflectance the ratio of the flux leaving a surface or medium by diffuse reflection to the incident flux.

Note Provision for the exclusion of regularly reflected flux, which is nearly always present, must be clearly described.

diffuse reflection that process by which incident flux is redirected over a range of angles.

diffuse transmission that process by which the incident flux passing through a surface or medium is scattered.

diffuse transmittance the ratio of the diffusely transmitted flux leaving a surface or medium to the incident flux.

Note Provision for the exclusion of regularly transmitted flux must be clearly described.

diffused lighting lighting provided on the work plane or on an object that is not incident predominantly from any particular direction.

diffuser a device to redirect or scatter light from a source, primarily by the process of diffuse transmission.

diffusing panel a translucent material covering the lamps in a luminaire in order to reduce the brightness by distributing the flux over an extended area.

diffusing surfaces and media those surfaces and media that redistribute at least some of the incident flux by scattering. See *complete diffusion, incomplete diffusion, narrow-angle diffusion, perfect diffusion, and wide-angle diffusion.*

digital display† See *alphanumeric display.*

dimmer a device used to control the intensity of light emitted by a luminaire by controlling the voltage or current available to it.

direct component that portion of the light from a luminaire that arrives at the work plane without being reflected by room surfaces. See *indirect component.*

direct glare glare resulting from high luminances or insufficiently shielded light sources in the field of view. It is usually associated with bright areas, such as luminaires, ceilings, and windows, that are outside the visual task or region being viewed. A direct glare source can also affect performance by distracting attention.

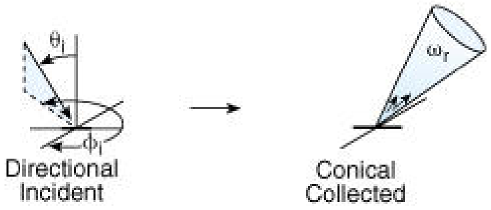
direct-indirect lighting a variant of general diffuse lighting in which the luminaires emit little or no light at angles near the horizontal.

direct lighting lighting involving luminaires that distribute 90 to 100% of the emitted light in the general direction of the surface to be illuminated. The term usually refers to light emitted in a downward direction.

direct ratio the ratio of the luminous flux that reaches the floor of a room cavity directly to the downward component from the luminaire.

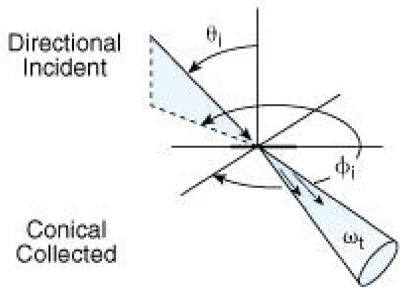
directional-conical reflectance, $\rho(\theta_i, \varphi_i; \omega_r)$ ratio of reflected flux collected through a conical solid angle to essentially collimated incident flux.

Note The direction of incidence must be specified, and the direction and extent of the cone must be specified.



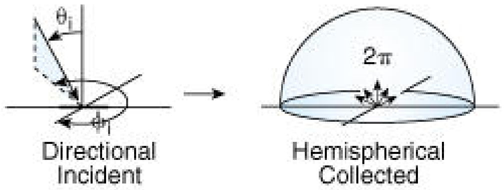
directional-conical transmittance, $\tau(\theta_i, \varphi_i; \omega_t)$ ratio of transmitted flux collected through a conical solid angle to essentially collimated incident flux.

Note The direction of incidence must be specified, and the direction and extent of the cone must be specified.



directional-hemispherical reflectance, $\rho(\theta_i, \varphi_i; 2\pi)$ ratio of reflected flux collected over the entire hemisphere to essentially collimated incident flux.

Note The direction of incidence must be specified.



directional-hemispherical transmittance, $\tau(\theta_i, \varphi_i; 2\pi)$ ratio of transmitted flux collected over the entire hemisphere to essentially collimated incident flux.
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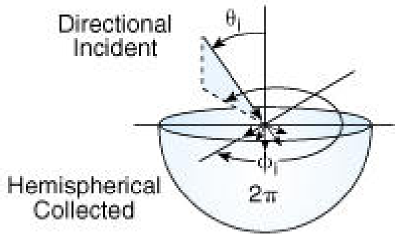


directional lighting lighting provided on the workplane
or on an object. Light that is predominantly from a preferred direction. See *accent lighting, key light, and cross light.*

disability glare the effect of stray light in the eye whereby visibility and visual performance are reduced. A direct glare source that produces discomfort can also produce disability glare by introducing a measurable amount of stray light in the eye.

disability glare factor (DGF) a measure of the visibility of a task in a given lighting installation in comparison with its visibility under reference lighting conditions, expressed in terms of the ratio of luminance contrasts having an equivalent effect upon task visibility. The value of the DGF takes account of the equivalent veiling luminance produced in the eye by the pattern of luminances in the task surround.

discomfort glare† glare that produces discomfort. It does not necessarily interfere with visual performance or visibility.

discomfort glare factor the numerical assessment of the capacity of a single source of brightness, such as a luminaire, in a given visual environment for producing discomfort (this term is obsolete and is retained only for reference and literature searches). See *glare* and *discomfort glare.*

discomfort glare rating (DGR) a numerical assessment of the capacity of a number of sources of luminance, such as a luminaire, in a given visual environment for producing discomfort. See *discomfort glare factor*. See also Chapter 9, Lighting Calculations.

distal stimuli in the physical space in front of the eye one can identify points, lines and surfaces, and three-dimensional arrays of scattering particles that constitute the distal physical stimuli that form optical images on the retina. Each element of a surface or volume to which an eye is exposed subtends a solid angle at the entrance pupil. Such elements of solid angle make up the field of view, and each has a specifiable luminance and chromaticity. Points and lines are specific cases that have to be dealt with in terms of total intensity and intensity per unit length. Distal stimuli are sometimes referred to simply as lights or colors.

distribution temperature (of a light source) the absolute temperature of a blackbody whose relative spectral distribution is most nearly the same in the visible region of the spectrum as that of the light source.

dominant wavelength (of a light), λ_d the wavelength of radiant energy of a single frequency that, when combined in suitable proportion with the radiant energy of a reference standard, matches the color of the light. See *complementary wavelength.*

downlight a small direct lighting unit that directs the light downward and can be recessed, surface-mounted, or suspended.

downward component that portion of the luminous flux from a luminaire that is emitted at angles below the horizontal. See *upward component.*

driving beam† See *upper (driving) beams.*

dual headlighting system two double headlighting units, one mounted on each side of the front end of a vehicle. Each unit consists of two sealed-beam lamps mounted in a single housing. The upper or outer lamps have two filaments that supply the low beam and part of the high beam, respectively. The lower or inner lamps have one filament that provides the primary source of light for the high beam.

dust-proof luminaire a luminaire so constructed or protected that dust does not interfere with its successful operation.

dust-tight luminaire a luminaire so constructed that dust does not enter the enclosing case.

E

effective ceiling cavity reflectance, ρ_{CC} a number giving the combined reflectance effect of the wall and ceiling reflectance of the ceiling cavity. See *ceiling cavity ratio.*

effective floor cavity reflectance, ρ_{FC} a number giving the combined reflectance effect of the wall and floor reflectance of the floor cavity. See *floor cavity ratio.*

effective intensity, I_e The effective intensity (I_e) of a flashing light is, conventionally,

$$I_e = \frac{I_0 \times t}{t + 0.2}$$

where the source has constant magnitude I_0 over a time duration t. For a time-varying source $I(t)$:

$$I_e = \frac{\int_{t_1}^{t_2} I(t) \times dt}{(t_2 - t_1) + 0.2}$$

expressed in candelas. The times t_1 and t_2 are so chosen as to maximize the calculated effective intensity.

It is then found that the actual intensity I_t at time t_1 or t_2 is equal to the calculated equivalent intensity I_e.

efficacy† See *luminous efficacy of a source of light* and *spectral luminous efficacy of radiant flux.*

efficiency† See *luminaire efficiency, luminous efficacy of a source of light,* and *spectral luminous efficiency of radiant flux.*

egress† See *means of egress.*

egress lighting† emergency lighting for egress.

electric discharge† See *arc discharge, gaseous discharge,* and *glow discharge.*

electric-discharge lamp a lamp in which light (or radiant energy near the visible spectrum) is produced by the passage of an electric current through a vapor or gas. See *carbon arc lamp, cold-cathode lamp, fluorescent lamp, glow lamp, high intensity discharge (HID) lamp,* and *hot cathode lamp.*

Note Electric-discharge lamps can be named after the filling gas or vapor that is responsible for the major portion of the radiation, for example, mercury lamps, sodium lamps, neon lamps, and argon lamps. A second method of designating the electric-discharge lamps is by physical dimensions of operating parameters, for example, short-arc lamps, high-pressure lamps, and low-pressure lamps. A third method of designating electric discharge lamps is by their application. In addition to lamps for illumination there are photochemical lamps, bactericidal lamps, blacklight lamps, sun lamps, and others.

electroluminescence the emission of light from a phosphor excited by an electromagnetic field.

electromagnetic spectrum† a continuum of electric and magnetic radiation encompassing all wavelengths. See *regions of the electromagnetic spectrum.*

elevation the angle between the axis of a searchlight drum and the horizontal. Elevation is positive for angles above the horizontal, and negative below the horizontal.

ellipsoidal reflector spotlight a spotlight in which a lamp and an ellipsoidal reflector are mounted in a fixed relationship directing a beam of light into an aperture, where it can be shaped by a pattern, iris, shutter system, or other insertion. The beam then passes through a single or compound lens system that focuses it as required, producing a sharply defined beam with variable edge definition.

emergency† any condition, external or internal to the premises, that compromises the effectiveness of the lighting in an occupied area for safe movement within and out of that area and safe operation of equipment within the space. An emergency can include any or all of the following:

- Utility power failure
- Utility power voltage reduction (brownout) below the minimum required to support the arc in fluorescent or HID lamps
- Power interruption within the premises including total power loss or individual phase or branch circuit failure
- Fire or smoke.

emergency exit† a way out of the premises that is intended to be used only during an emergency.

emergency lighting lighting designed to supply illumination essential to the safety of life and property in the event of failure of the normal supply.

emissivity, ε the ratio of the radiance (for directional emissivity) or radiant exitance (for hemispherical emissivity) of an element of surface of a temperature radiator to that of a blackbody at the same temperature.

emittance, ε The ratio of radiance in a given direction (for directional emittance) or radiant exitance (for hemispherical emittance) of a sample of a thermal radiator to that of a blackbody radiator at the same temperature.

enclosed and gasketed† See *vapor-tight luminaire.*

equal interval (isophase) **light** a rhythmic light in which the light and dark periods are equal.

equipment operating factor the ratio of the lumens of a high-intensity discharge (HID) lamp-ballast-luminaire combination in a given operating position to the lumens of the lamp-ballast-luminaire combination (a) operated in the position for rating lamp lumens, and (b) using the standard (reference) ballasting specified for rating lamp lumens.
Note If the given lamp operating position is not the same as the lamp rating position, the lumens ratio for the operating ballast to standard rating ballast is determined in the given operating position. This ratio is multiplied by the lamp position factor to obtain the equipment operating factor.

equivalent contrast, $\tilde{C}$ a numerical description of the relative visibility of a task. It is the contrast of the standard visibility reference task giving the same visibility as that of a task whose contrast has been reduced to threshold when the background luminances are the same. See *visual task evaluator*.

equivalent contrast, $\tilde{C}_e$ the actual equivalent contrast in a real luminous environment with nondiffuse illumination. This actual equivalent contrast $\tilde{C}_e$ is less than the equivalent contrast due to veiling reflection. $\tilde{C}_e = \tilde{C} \times \text{CRF}$. See *contrast rendition factor.*

equivalent luminous intensity of an extended source at a specified distance the intensity of a point source that would produce the same illuminance at that distance. Formerly, apparent luminous intensity of an extended source.

equivalent sphere illumination (ESI) the level of sphere illumination that would produce task visibility equivalent to that produced by a specific lighting environment.

equivalent veiling luminance the luminance of the reflected image of a bright surface that is superimposed on a test object to measure the veiling effect equivalent to that produced by stray light in the eye produced by a disability glare source. The disability glare source is turned off when the reflected image is turned on.

erythema a temporary reddening of the skin such as produced by exposure to actinic UV radiation. UV-induced erythema is due to actinic action and is a delayed effect occurring several hours after exposure. This differs from IR-induced erythema, a thermal effect occurring only for the duration of time that the skin temperature is elevated.
Note The degree of erythema is used as a guide to dosages applied in UV therapy.

erythemal effectiveness the capacity of various portions of the ultraviolet spectrum to produce erythema.

erythemal efficiency of radiant flux (for a particular wavelength) the ratio of the erythemal effectiveness of a particular wavelength to that of wavelength 296.7 nm, which is rated as unity.
Note This quantity formerly was called relative erythemal factor.

erythemal exposure the product of erythemal flux density on a surface and time. It usually is measured in $\mu\text{W} \times \text{min/cm}^2$.
Note For average untanned skin a minimum perceptible erythema requires about 300 $\mu\text{W} \times \text{min/cm}^2$ of

radiation at 296.7 nm.

erythemal flux radiant flux evaluated according to its capacity to produce erythema of the untanned human skin. It usually is measured in microwatts of UV radiation weighted in accordance with its erythemal efficiency. Such quantities of erythemal flux are said to be in erythemal microwatts. See *erythemal efficiency of radiant flux and erythemal unit.*
Note A commonly used practical unit of erythemal flux is the erythemal unit (EU) or E-viton (erytheme), which is equal to the amount of radiant flux that produces the same erythemal effect as 10 µW of radiant flux at wavelength 296.7 nm.

erythemal flux density the erythemal flux per unit area of the surface being irradiated. It is equal to the quotient of the incident erythemal flux divided by the area of the surface when the flux is uniformly distributed. It usually is measured in $\mu W/cm^2$ of erythemally weighted UV radiation (erythemal $\mu W/cm^2$). See *finsen.*
Note A suggested practical unit of erythemal flux density is the finsen, which is equal to one E-viton per square centimeter.

erythemal threshold† See *minimal perceptible erythema.*

erythemal unit (EU)† a unit of erythemal flux that is equal to the amount of radiant flux that produces the same erythemal effect as 10 µW of radiant flux at wavelength 296.7 nm. Also called *E-viton.*

E-viton (erytheme)† See *erythemal unit.*

exit† the portion of a means of egress that segregates all other spaces in the building or structure by fire-resistant construction in order to provide a protected way of travel to the exit discharge. Exits include exterior exit doors, exit passageways, horizontal exits, and separated exit stairs or ramps.

exit access† the portion of a means of egress that leads to an exit.

exit discharge† the portion of a means of egress between the conclusion of an exit and a public way.

exit sign† a graphic device including words or symbols that indicates or identifies an escape route or the location of, or direction to, an exit or emergency exit.

exitance† See *luminous exitance* and *radiant exitance.*

exitance coefficient, *EC* the ratio of the average (time zero) wall or ceiling cavity exitance to the quotient of the total lamp flux divided by the floor area.
Note (i) Exitance is measured in lumens per unit area, where the units of area agree with those of the floor area. (ii) Average wall or ceiling cavity luminances can be determined by noting the underlying assumption of lambertian room surfaces where $L = M/\pi$; L is in candela per unit area, where the units of area agree with those of M. (iii) Exitance coefficients and former luminance coefficients are numerically identical.

excitation purity of a light, p_e the ratio of the distance on the CIE chromaticity diagram between the reference-point and the light-point to the distance in the same direction between the reference-point and the spectrum locus or the purple boundary. See *colorimetric purity.*

explosion-proof luminaire a luminaire that is completely enclosed and capable of withstanding an explosion of a specific gas or vapor that can occur within it, and preventing the ignition of a specific gas or vapor surrounding the enclosure by sparks, flashes, or explosion of the gas or vapor within. It must operate at such an external temperature that a surrounding flammable atmosphere is not ignited thereby.

externally illuminated exit sign† an exit sign with an externally mounted light source. The exit legend and background are typically opaque and rely on reflected light for visibility.

eye light illumination on a person to produce a specular reflection from items such as eyes, teeth, and jewelry without significantly increasing the total illumination of the subject.

F

far (long-wavelength) **infrared†** the region of the electromagnetic spectrum extending from 5000 to 1,000,000 nm.

far ultraviolet† the region of the electromagnetic spectrum extending from 100 to 200 nm.

fay light a luminaire that uses incandescent parabolic reflector lamps with a dichroic coating to provide "daylight" illumination.

fenestra method a procedure for predicting the interior illuminance received from daylight through windows.

fenestration any opening or arrangement of openings (normally filled with media for control) for the admission of daylight.

field angle the angle between the two directions for which the intensity is 10% of the maximum intensity as measured in a plane through the nominal beam centerline. For beams that do not possess rotational symmetry, the beam angle is generally given for two planes at 90°, typically the maximum and minimum angles. Note that in certain fields of applications the angle of the 10% of maximum directions was formerly called *beam angle.*

fill light illumination added to reduce shadows or contrast range.

film (or aperture) **color†** the perceived color of the sky or a patch of color seen through an aperture.

filter a device for changing, by transmission or reflection, the magnitude or spectral composition of the flux incident upon it. Filters are called selective (or colored) or neutral, according to whether or not they alter the spectral distribution of the incident flux. Alternatively, a component of an electronic dimmer used to control electromagnetic or radio-frequency interference.

filter factor the transmittance of black light by a filter.
Note The relationship between glow factor and filter factor is illustrated by the following formula for determining the luminance (L) of fluorescent materials exposed to black light:

$$L = \frac{E}{\pi} \times f_g \times f_f \times [\mathrm{cd} \times \mathrm{m}^{-2}]$$

where

E = [fluorens × m^{-2}]

f_g = glow factor

f_f = filter factor.

When integral-filter black-light lamps are used, the filter factor is dropped from the formula because it already has been applied in assigning fluoren ratings to these lamps.

finsen† a suggested practical unit of erythemal flux density equal to one E-viton per square centimeter.

fixed light a light having a constant luminous intensity when observed from a fixed point.

fixture† See *luminaire.*

flashing light a rhythmic light in which the periods of light are of equal duration and are clearly shorter than the periods of darkness. See *group flashing light, interrupted quick-flashing light,* and *quick-flashing light.*

flashtube a tube of glass or fused quartz with electrodes at the ends and filled with a gas, usually xenon. It is designed to produce high-intensity light flashes of extremely short duration.

flattery index (of a light source), R_f† a measure appraising a light source for appreciative viewing of colored objects, for promoting an optimistic viewpoint by flattery (making the view more pleasant), or for enhancing the perception of objects in terms of color. Also sometimes called color preference index (CPI).

flicker fusion frequency (FFF) the frequency of intermittent stimulation of the eye at which flicker disappears. It also is called the *critical fusion frequency* (CFF) or *critical flicker frequency (CFF).*

flicker index a measure of the cyclic variation in output of a light source, taking into account the waveform of the light output. It is the ratio of the area under the light output curve that is above the average light output level to the total area under the light output curve for a single cycle. See Chapter 6, Light Sources.

flicker photometer† See *visual photometer.*

floodlight a projector designed for lighting a scene or object to a luminance considerably greater than its surroundings. It usually is capable of being pointed in any direction and is of weatherproof construction. **Note** The beam spread of floodlights can range from narrow field angles (10°) to wide ones (more than 100°). See *beam angle, field angle, heavy-duty floodlight, general-purpose (GP) floodlight, ground-area open floodlight,* and *ground-area open floodlight with reflector insert.*

floodlighting a system designed for lighting a scene or object to a luminance greater than its surroundings. It can be for utility, advertising, or decorative purposes.

floor cavity the cavity formed by the workplane, the floor, and the wall surfaces between those two planes.

floor cavity ratio (FCR) a number computed by using the distance from the floor to the workplane (h_f) as $\text{Height}_{\text{cavity}}$ in the equations given in cavity ratio. See Chapter 9, Lighting Calculations.

floor lamp a portable luminaire on a high stand suitable for standing on the floor. See *torchère.*

fluoren† a unit of black-light flux equal to one milliwatt of radiant flux in the wavelength range 320 to 400 nm.

fluorescence the emission of light as the result of, and only during, the absorption of radiation of shorter wavelengths (time scale less than approximately 10^{-8} s).

fluorescent lamp a low-pressure mercury electric-discharge lamp in which a fluorescing coating (phosphor) transforms some of the UV energy generated by the discharge into light. See *instant-start* *fluorescent lamp, preheat (switch-start) fluorescent lamp,* and *rapid-start fluorescent lamp.*

flush-mounted or recessed luminaire a luminaire that is mounted above the ceiling (or behind a wall or other surface) with the opening of the luminaire level with the surface.

flux transfer theory a method of calculating the illuminance in a room by taking into account the interreflection of the light flux from the room surfaces based on the average flux transfer between surfaces.

fog (adverse-weather) **lamps** units that can be used in lieu of headlamps or in connection with the lower-beam headlights to provide road illumination under conditions of rain, snow, dust, or fog.

follow spot (light) any instrument operated so as to follow the movement of an actor. Follow spots are usually high-intensity, controlled-beam luminaires.

footcandle, fc a unit of illuminance equal to 1 lm/ft^2 or 10.76 lx.

footcandle meter† See *illuminance (lux or footcandle) meter.*

footlambert, fL a lambertian unit of luminance equal to $1/\pi$ candela per square foot. This term is obsolete, and its use is deprecated.

footlights a set of striplights at the front edge of the stage platform used to soften face shadows cast by overhead luminaires and to add general toning lighting from below.

form factor, $f_{1\rightarrow 2}$ the ratio of the flux directly received by surface 2 (and due to lambertian surface 1) to the total flux emitted by surface 1. It is used in flux transfer theory.

$$f_{1\rightarrow 2} = \frac{\Phi_{1\rightarrow 2}}{\Phi_1}$$

Also, the ratio of the average illuminance on surface 1 to the causative exitance of lambertian surface 2:

$$f_{1\rightarrow 2} = \frac{E_1}{M_2}$$

Note In the literature, this quantity is also called the *angle factor*, *configuration factor, geometrical factor, I-factor, illumination factor,* and *shape modulus.*

formation light a navigation light especially provided to facilitate formation flying.

fovea a small region at the center of the retina, subtending about 2°, that contains cones but no rods and that forms the site of most distinct vision.

foveal vision† See *central (foveal) vision.*

Fresnel spotlight a luminaire containing a lamp and a Fresnel lens (stepped flat lens with a textured back) that has variable field and beam angles obtained by changing the spacing between lamp and lens (flooding and spotting). Produces a smooth, soft-edged, defined beam of light.

fuselage lights aircraft aeronautical lights, mounted on the top and bottom of the fuselage, used to supplement the navigation lights.

G

gas-filled lamp an incandescent lamp in which the filament operates in a bulb filled with one or more inert gases.

gaseous discharge the emission of light from gas atoms excited by an electric current.

general color rendering index, R_a Measure of the average shift of eight standardized colors chosen to be of intermediate saturation and spread throughout the range of hues. If the color rendering index is not qualified as to the color samples used, R_a is assumed.

general diffuse lighting lighting involving luminaires that distribute 40 to 60% of the emitted light downward and the balance upward, sometimes with a strong component at 90° (horizontal). See *direct-indirect lighting.*

general lighting lighting designed to provide a substantially uniform level of illuminance throughout an area, exclusive of any provision for special local requirements. See *ceiling area lighting, direct lighting, direct-indirect lighting, general diffuse lighting, indirect lighting, localized general lighting, semidirect lighting,* and *semi-indirect lighting.*

general-purpose floodlight (GP) a weatherproof unit so constructed that the housing forms the reflecting surface. The assembly is enclosed by a cover glass.

germicidal effectiveness† See *bactericidal (germicidal) effectiveness.*

germicidal efficiency of radiant flux† See *bactericidal (germicidal) efficiency of radiant flux.*

germicidal exposure† See *bactericidal (germicidal) exposure.*

germicidal flux and flux density† See *bactericidal (germicidal) flux* and *bactericidal (germicidal) flux density.*

germicidal lamp a low-pressure mercury lamp in which the envelope has high transmittance for 254-nm radiation. See *bactericidal lamp.*

glare the sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted, which causes annoyance, discomfort, or loss in visual performance and visibility. See *blinding glare, direct glare, disability glare,* and *discomfort glare.*

Note The magnitude of the sensation of glare depends on such factors as the size, position, and luminance of a source; the number of sources; and the luminance to which the eyes are adapted.

globe a transparent or diffusing enclosure intended to protect a lamp, to diffuse and redirect its light, or to change the color of the light.

glossometer an instrument for measuring gloss as a function of the directionally selective reflecting properties of a material in angles near to and including the direction giving specular reflection.

glow discharge an electric discharge characterized by a low, approximately constant current density at the cathode (on the order of 10 $\mu A/mm^2$) at low cathode temperature and a high voltage drop (typically 50 V or more). Secondary emission from the cathode is much greater than the thermionic emission.

Note A distinction is made between the normal cathode drop (potential difference due to space charge near the cathode) that occurs when the glow does not cover the cathode completely (with constant current density) and that is independent of the discharge current, and the abnormal cathode drop that occurs when the glow covers the cathode completely (with increased current density) and that depends on the discharge current.

glow factor a measure of the visible light response of a fluorescent material to black light. It is equal to π times the luminance in cd/m^2 produced on the material divided by the incident black-light flux density in mW/m^2. It can be measured in lm/mW.

glow lamp an electric-discharge lamp whose mode of operation is that of a glow discharge and in which light is generated in the space close to the electrodes.

goniophotometer a photometer for measuring the directional light distribution characteristics of sources, luminaires, media, and surfaces.

graybody a temperature radiator whose spectral emissivity is less than unity and the same at all wavelengths.

ground-area open floodlight (O) a unit providing a weatherproof enclosure for the lamp socket and housing. No cover glass is required.

ground-area open floodlight with reflector insert (OI) a weatherproof unit so constructed that the housing forms only part of the reflecting surface. An auxiliary reflector is used to modify the distribution of light. No cover glass is required.

ground light visible radiation from the sun and sky reflected by surfaces below the plane of the horizon.

group flashing light a flashing light in which the flashes are combined in groups, each including the same number of flashes, and in which the groups are repeated at regular intervals. The duration of each flash is clearly less than the duration of the dark periods between flashes, and the duration of the dark periods between flashes is clearly less than the duration of the dark periods between groups.

H

hard light light that causes an object to cast a sharply defined shadow.

hazard or obstruction beacon an aeronautical beacon used to designate a danger to air navigation.

hazardous location an area where ignitable vapors or dust can cause a fire or explosion created by energy emitted from lighting or other electrical equipment or by electrostatic generation.

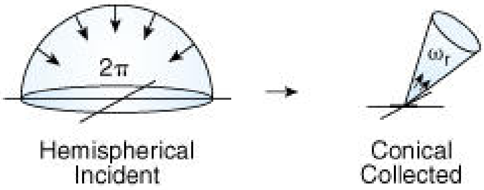
headlamp a major lighting device mounted on a vehicle and used to provide illumination ahead of it. Also called a *headlight*. See *multiple-beam headlamp* and *sealed-beam headlamp.*

headlight† an alternative term for headlamp.

heat extraction thermal factor the fractional lumen loss or gain due to passage of room air being returned to the plenum through the lamp compartment of the luminaire.

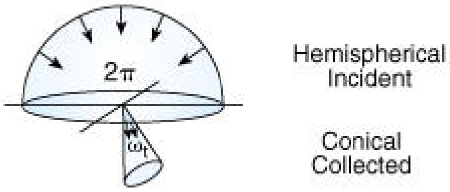
heavy-duty floodlight (HD) a weatherproof unit having a substantially constructed metal housing into which is placed a separate and removable reflector. A weatherproof hinged door with cover glass encloses the assembly but provides an unobstructed light opening at least equal to the effective diameter of the reflector.

hemispherical-conical reflectance, $\rho(2\pi; \omega_r)$ the ratio of reflected flux collected over a conical solid angle to the incident flux from the entire hemisphere.

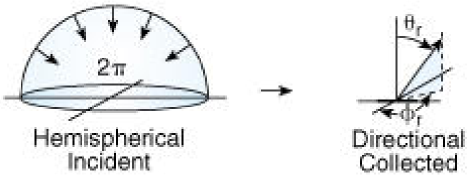


Note The direction and extent of the cone must be specified.

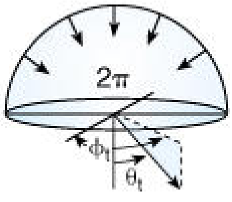
hemispherical-conical transmittance, $\tau(2\pi;\ \omega_t)$ the ratio of transmitted flux collected over a conical solid angle to the incident flux from the entire hemisphere.
Note The direction and extent of the cone must be specified.



hemispherical-directional reflectance, $\rho(2\pi;\ \theta_r,\ \varphi_r)$ the ratio of reflected flux collected over an element of solid angle surrounding the given direction to the incident flux from the entire hemisphere.
Note The direction of collection and the size of the solid angle element must be specified.



hemispherical-directional transmittance, $\tau(2\pi;\ \theta_t,\ \varphi_t)$ the ratio of transmitted flux collected over an element of solid angle surrounding the given direction to the incident flux from the entire hemisphere.
Note The direction of collection and size of the solid angle element must be specified.



hemispherical reflectance the ratio of all of the flux leaving a surface or medium by reflection to the incident flux. The use of this term is deprecated. See *hemispherical transmittance.*

hemispherical transmittance the ratio of the transmitted flux leaving a surface or medium to the incident flux. The use of this term is deprecated.

high-bay lighting interior lighting where the roof trusses or ceiling height is greater than approximately 7.6 m (25 ft) above the floor.

high-intensity discharge (HID) **lamp** an electric-discharge lamp in which the light-producing arc is stabilized by bulb wall temperature, and the arc tube has a bulb wall loading in excess of 3 W/cm^2. HID lamps include groups of lamps known as mercury, metal halide, and high-pressure sodium.

high-key lighting a type of lighting that, applied to a scene, results in a picture having gradations from middle gray to white with comparatively limited areas of dark gray and black. Also, intense, overall illumination. In motion pictures, high-level accent lighting with strong contrast (dark deep shadows with little or no middle gray). See *low-key lighting.*

high-mast lighting illumination of a large area by means of a group of luminaires that are designed to be mounted in fixed orientation at the top of a high mast, generally 20 m (65 ft) or higher.

high-pressure sodium (HPS) **lamp** a high-intensity discharge (HID) lamp in which light is produced by radiation from sodium vapor operating at a partial pressure of about 1.33×10^4 Pa (100 Torr). Includes clear and diffuse-coated lamps.

horizontal exit† an escape route from one building to an area of refuge in another building on approximately the same level. It also is an escape route through or around a fire barrier to an area of refuge on approximately the same level in the same building.

horizontal plane of a searchlight the plane that is perpendicular to the vertical plane through the axis of the searchlight drum and in which the train lies.

hot-cathode lamp an electric-discharge lamp whose mode of operation is that of an arc discharge. The cathodes can be heated by the discharge or by external means.

house lights the general lighting system installed in the audience area (house) of a theatre, film or television studio, or arena.

hue of a perceived color the attribute that determines whether it is red, yellow, green, blue, or the like.

hue of a perceived light-source color† the attribute that determines whether the color is red, yellow, green, blue, or the like. See *hue of a perceived color.*

hydrargyrum medium-arc-length iodide (HMI) **lamp** an arc light source utilizing mercury vapor and metal halide additives to produce illumination in the 5000 to 6000 K range. Requires a ballast and ignitor system for operation.

I

ice detection light an inspection light designed to illuminate the leading edge of the aircraft wing to check for ice formation.

ideal radiator† See *blackbody.*

identification beacon an aeronautical beacon emitting a coded signal by means of which a particular point of reference can be identified.

ignitor a device, either by itself or in association with other components, that generates voltage pulses to start discharge lamps without preheating of electrodes.

illuminance, ***E*** = ***d*Φ/*dA*** the areal density of the luminous flux incident at a point on a surface

illuminance (footcandle or lux) **meter** an instrument for measuring illuminance on a plane. Instruments that accurately respond to more than one spectral distribution are color-corrected, that is, the spectral response is balanced to $V(\lambda)$ or $V'(\lambda)$. Instruments that accurately respond to more than one spatial distribution of incident flux are cosine-corrected, that is, the response to a source of unit luminous intensity, illuminating the detector from a fixed distance and from different directions, decreases as the cosine of the angle between the incident direction and the normal to the detector surface. The instrument is comprised of some form of photodetector with or without a filter driving a digital or analog readout through appropriate circuitry.

illumination an alternative but deprecated term for illuminance. It is frequently used because "illuminance" is subject to confusion with "luminance" and "illuminants," especially when not clearly pronounced.
Note The term illumination also is commonly used in a qualitative or general sense to designate the act of illuminating or the state of being illuminated. Usually, the context indicates which meaning is intended, but occasionally it is desirable to use the expression "level of illumination" to indicate that the quantitative meaning is intended.

incandescence the self-emission of radiant energy in the visible spectrum due to the thermal excitation of atoms or molecules.

incandescent filament lamp a lamp in which light is produced by a filament heated to incandescence by an electric current.
Note Normally, the filament is of coiled or coiled-coil (doubly coiled) tungsten wire. However, it can be uncoiled wire, a flat strip, or of material other than tungsten.

incomplete diffusion (partial diffusion) that in which the diffusing medium partially redirects the incident flux by scattering while the remaining fraction of incident flux is redirected without scattering; that is, a fraction of the incident flux can remain in an image-forming state.

index of sensation (***M***) **(of a source)** a number that expresses the effects of source luminance (L_s), solid angle factor (Q), position index (P), and the field luminance (F) on discomfort glare rating. See Chapter 9, Lighting Calculations. See *discomfort glare rating (DGR),* where L_s and F are expressed in cd/m^2.

$$M = \frac{0.5 L_s Q}{P F^{0.44}}$$

For an equation defining Q see *solid angle factor*.
Note A restatement of this formula lends itself more directly to computer applications.

indirect component the portion of the luminous flux from a luminaire that arrives at the workplane after being reflected by room surfaces. See *direct component.*

indirect lighting lighting involving luminaires that distribute 90 to 100% of the emitted light upward.

infrared lamp a lamp that radiates predominately in the infrared; the visible radiation is not of principal interest.

infrared (IR) **radiation** for practical purposes any radiant energy within the wavelength range of 770 to 10^6 nm is considered infrared energy.

inhibition (visual) reduction in magnitude of the sensation aroused by the stimulus (or a reduction in visual sensitivity) caused by some other stimulation that is adjacent spatially or temporally.

initial luminous exitance This term can be used in two different ways. In flux transfer it is the density of luminous flux leaving a surface within an enclosure before interreflections occur. In lighting calculations it is the total exitance at time zero before depreciation (light losses) occur.
Note For light sources this is the luminous exitance as defined in *luminous exitance*. For nonself-luminous surfaces it is the reflected luminous exitance of the flux received directly from sources within the enclosure or from daylight.

instant-start fluorescent lamp a fluorescent lamp designed for starting by a high voltage without preheating of the electrodes.
Note In the UK, a cold-start lamp.

integrating photometer a photometer that enables geometrically total luminous flux to be determined by a single measurement. The usual type is the Ulbricht sphere with associated photometric equipment for measuring the indirect illuminance of the inner surface of the sphere. (The measuring device is shielded from the source under measurement.)

intensity† a shortening of the terms *luminous intensity* and *radiant intensity*. Often misused for level of illumination or illuminance.

intensity (candlepower) **distribution curve** a curve, often polar, that represents the variation of luminous intensity of a lamp or luminaire in a plane through the light center.
Note A vertical intensity distribution curve is obtained by taking measurements at various angles of elevation about a source in a vertical plane through the light center; unless the plane is specified, the vertical curve is assumed to represent an average such as would be obtained by rotating the lamp or luminaire about its vertical axis. A horizontal intensity distribution curve represents measurements made at various angles of azimuth in a horizontal plane through the light center.

internally illuminated exit sign† a transilluminated exit sign containing its own light source.

interreflected component That portion of the luminous flux from a luminaire that arrives at the workplane after being reflected one or more times from room surfaces, as determined by the flux transfer theory. Also called interflectance. See *flux transfer theory*.

interreflection The multiple reflection of light by the various room surfaces before it reaches the work plane or other specified surface of a room. Also called interflectance.

interrupted quick-flashing light a quick-flashing light in which the rapid alternations are interrupted by periods of darkness at regular intervals.

inverse square law A law stating that the illuminance E at a point on a surface varies directly with the intensity I of a point source and inversely as the square of the distance d between the source and the point. If the surface at the point is normal to the direction of the incident light, the law is expressed by $E = I/d^2$.
Note For sources of finite size having uniform luminance, this gives results that are accurate within 1% when d is at least 5 times the maximum dimension of the source as viewed from the point on the surface. Even though practical interior luminaires do not have uniform luminance, this distance d is frequently used as the minimum for photometry of such luminaires when the magnitude of the measurement error is not critical.

iris an assembly of flat metal leaves arranged to provide an easily adjustable near-circular opening, placed near the focal point of the beam (as in an ellipsoidal reflector spotlight) or in front of the lens to act as a mechanical dimmer as in older types of carbon arc follow spotlights.

irradiance, E † the density of radiant flux (power) incident on a surface.

isocandela line a line plotted on any appropriate set of coordinates to show directions in space, about a source of light, in which the intensity is the same. A series of such curves, often for equal increments of intensity, is called an isocandela diagram.

isolux (isofootcandle) **line** a line plotted on any appropriate set of coordinates to show all the points on a surface where the illuminance is the same. A series of such lines for various illuminance values is called an isolux (isofootcandle) diagram.

K

Kelvin† the unit of temperature used to designate the color temperature of a light source. A temperature scale where each degree is the same size as a centigrade degree, but the Kelvin scale has its zero at 273°C.

key light the apparent principal source of directional illumination falling upon a subject or area.

kicker a luminaire used to provide an additional highlight or accent on a subject.

klieg light a high-intensity carbon arc spotlight, typically used in motion picture lighting.

L

laboratory reference standard† the highest-ranking order of standards at each laboratory.

Lambert a lambertian unit of luminance equal to $1/\pi$ candela per square centimeter. This term is obsolete, and its use is deprecated.

lambertian surface a surface that emits or reflects light in accordance with Lambert's cosine law. A lambertian surface has the same luminance regardless of viewing angle.

Lambert's cosine law, $I_\theta = I_0 \cos \theta$ the law stating that the luminous intensity in any direction from an element of a perfectly diffusing surface varies as the cosine of the angle between that direction and the perpendicular to the surface element.

lamp a generic term for a source created to produce optical radiation. By extension, the term is also used to denote sources that radiate in regions of the spectrum adjacent to the visible.
Note Through popular usage, a portable luminaire consisting of a lamp with shade, reflector, enclosing globe, housing, or other accessories is also sometimes called a lamp. In such cases, in order to distinguish between the assembled unit and the light source within it, the latter is often called a bulb or tube, if it is electrically powered. See also *luminaire.*

lamp burnout factor the fractional loss of task illuminance due to burned-out lamps left in place for long periods.

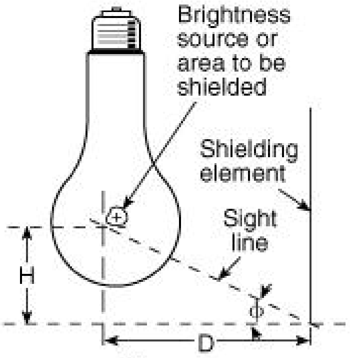
lamp lumen depreciation (LLD) **factor** the fractional loss of lamp lumens at rated operating conditions that progressively occurs during lamp operation.

lamp position factor The ratio of the luminous flux of a lamp at a given operating position to the luminous flux when the lamp is operated in the position at which the lamp lumens are rated.

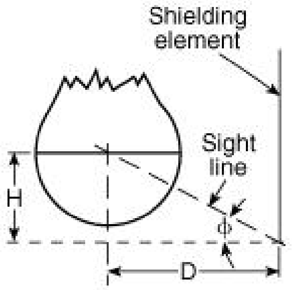
lamp post a standard support provided with the necessary internal attachments for wiring and the external attachments for the bracket and luminaire.

lamp shielding angle, φ the angle between the plane of the baffles or louver grid and the plane most

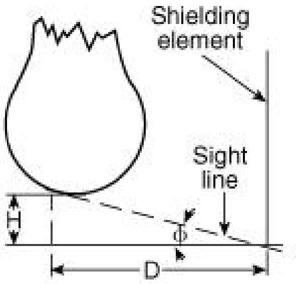
nearly horizontal that is tangent to both the lamps and the louver blades.
Notes (i) The lamp shielding angle is formed by a sight line tangent to the lowest part of the brightness area to be shielded. *H* is the vertical distance from the brightness source to the bottom of the shielding element. *D* is the horizontal distance from the brightness source to the shielding element. Lamp shielding angle φ = arctan (*H*/*D*). (ii) The lamp shielding angle frequently is larger than the louver shielding angle, but never smaller. See *louver shielding angle.*



Clear source



Silvered bowl [opaque bottom] source



Frosted or diffusing source

landing direction indicator a device to indicate visually the direction currently designated for landing and takeoff.

landing light an aircraft aeronautical light designed to illuminate a ground area from the aircraft.

landmark beacon an aeronautical beacon used to indicate the location of a landmark used by pilots as an aid to en route navigation.

laser an acronym for light amplification by stimulated emission of radiation. The laser produces a highly monochromatic and coherent (spatially and temporally) beam of radiation. A steady oscillation of nearly a single electromagnetic mode is maintained in a volume of an active material bounded by highly reflecting surfaces, called a resonator. The frequency of oscillation varies according to the material used and the methods of initially exciting or pumping the material.

lateral width of a light distribution in roadway lighting, the lateral angle between the reference line and the width line, measured in the cone of maximum candlepower. This angular width includes the line of maximum candlepower. See *reference line* and *width line.*

lens† a glass or plastic element used in luminaires to change the direction and control the distribution of light rays; also, the part of the eye that allows objects at different distances to be focused onto the retina.

level of illumination† See *illuminance.*

life performance curve a curve that presents the variation of a particular characteristic of a light source (such as luminous flux, intensity, etc.) throughout the life of the source.
Note Life performance curves sometimes are called maintenance curves, for example, lumen maintenance

curves.

life test of lamps a test in which lamps are operated under specified conditions for a specified length of time for the purpose of obtaining information on lamp life. Measurements of photometric and electrical characteristics can be made at specified intervals of time during this test.

light radiant energy that is capable of exciting the retina and producing a visual sensation. The visible portion of the electromagnetic spectrum extends from about 380 to 770 nm.
Note The subjective impression produced by stimulating the retina is sometimes designated as light. Visual sensations are sometimes arbitrarily defined as sensations of light, and in line with this concept, it is sometimes said that light cannot exist until an eye has been stimulated. Electrical stimulation of the retina or the visual cortex is described as producing flashes of light. In illuminating engineering, however, light is a physical entity--radiant energy weighted by the luminous efficiency function. It is a physical stimulus that can be applied to the retina. See *spectral luminous efficacy of radiant flux* and *values of spectral luminous efficiency for photopic vision.*

light adaptation the process by which the retina becomes adapted to a luminance greater than about 3.4 cd/m^2. See also *dark adaptation.*

light center (of a lamp) the center of the smallest sphere that would completely contain the light-emitting element of the lamp.

light center length the distance from the light center to a specified reference point on the lamp.

light-emitting diode (LED) a p-n junction solid-state diode whose radiated output is a function of its physical construction, material used, and exciting current. The output can be in the IR or in the visible region.

light loss factor (LLF) Formerly called *maintenance factor*. The ratio of illuminance (or exitance or luminance) for a given area to the value that would occur if lamps operated at their (initial) rated lumens and if no system variation or depreciation had occurred. Components of this factor can be either initial or maintained.
Note The light loss factor is used in lighting calculations as an allowance for lamp(s) or luminaire(s) operating at other than rated conditions (initial) and for the depreciation of lamps, light control elements, and room surfaces to values below the initial or design conditions, so that a minimum desired level of illuminance can be maintained in service. The light loss factor had formerly been widely interpreted as the ratio of average illuminance in service to initial illuminance.

light meter A common name for an illuminance meter. See *illuminance (lux or footcandle) meter.*

light source color the color of the light emitted by a source.
Note The color of a point source can be defined by its luminous intensity and chromaticity coordinates; the color of an extended source can be defined by its luminance and chromaticity coordinates. See *color temperature, correlated color temperature,* and *perceived light source color.*

lighting effectiveness factor (LEF) the ratio of equivalent sphere illumination to measured or calculated task illuminance.

lightness (of a perceived patch of surface color) the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

linear light a luminous signal having a perceptible physical length.

linear polarization the process by which the transverse vibrations of light waves are oriented in or parallel to a specific plane. Polarization can be obtained by using either transmitting or reflecting media.

Linnebach projector a lensless scenic projector using a concentrated source in a black box and a slide or cutout between the source and the projection surface.

liquid crystal display (LCD) a display made of material whose reflectance or transmittance changes when an electric field is applied.

local lighting lighting providing illuminance over a relatively small area or confined space without providing any significant general surrounding lighting.

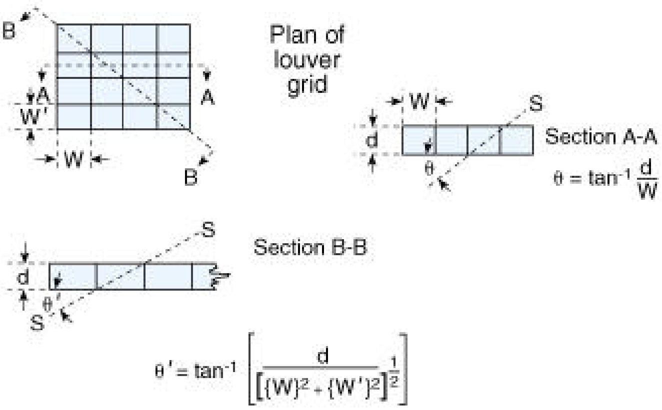
localized general lighting lighting utilizing luminaires above the visual task and contributing also to the illuminance of the surround.

long-arc lamp an arc lamp in which the distance between the electrodes is large.
Note This type of lamp (such as xenon) generally has an arc tube containing gas at high pressure. The arc fills the discharge tube and is therefore wall stabilized.

longitudinal roadway line (LRL) any line along a roadway that is parallel to the curb line.

louver (or louver grid) a series of baffles used to shield a source from view at certain angles, to absorb or block unwanted light, or to reflect or redirect light. The baffles are usually arranged in a geometric pattern.

louver shielding angle, θ the angle between the horizontal plane of the baffles or louver grid and the plane at which the louver conceals all objects above. See *lamp shielding angle.*
Note The planes usually are so chosen that their intersection is parallel with the louvered blade.



louvered ceiling a ceiling-area lighting system composed of a wall-to-wall installation of multicell louvers shielding the light sources mounted above it. See *luminous ceiling.*

low-bay lighting interior lighting where the roof trusses or ceiling height is approximately 7.6 m (25 ft) or less above the floor.

low-key lighting a type of lighting that, applied to a scene, results in a picture having gradations from middle gray to black with comparatively limited areas of light grays and whites. See *high-key lighting.*

low-pressure mercury lamp a discharge lamp (with or without a phosphor coating) in which the partial pressure of the mercury vapor does not exceed 100 Pa during operation.

low-pressure sodium (LPS) **lamp** a discharge lamp in which light is produced by radiation from sodium vapor operating at a partial pressure of 0.1 to 1.5 Pa (approximately 10^{-3} to 10^{-2} Torr).

lower (passing) beams one or more beams directed low enough on the left to avoid glare in the eyes of oncoming drivers and intended for use in congested areas and on highways when meeting other vehicles within a distance of 300 m (1000 ft). Formerly *traffic beam.*

lumen, lm SI unit of luminous flux. Radiometrically, it is determined from the radiant power as in *luminous flux*. Photometrically, it is the luminous flux emitted within a unit solid angle (1 sr) by a point source having a uniform luminous intensity of 1 cd.

lumen depreciation† the decrease in lumen output that occurs as a lamp is operated, until failure.

lumen (or flux) **method** a lighting design procedure used for predetermining the relation between the number and types of lamps or luminaires, the room characteristics, and the average illuminance on the workplane. It takes into account both direct and reflected flux.

lumen-second (lm × **s)** a unit of quantity of light, the SI unit of luminous energy (also called a *talbot*). It is the quantity of light delivered in one second by a luminous flux of 1 lumen.

luminaire (light fixture) a complete lighting unit consisting of a lamp or lamps and ballast(s) (when applicable) together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply.

luminaire ambient temperature factor the fractional lumen change of a fluorescent luminaire due to internal luminaire temperatures differing from the temperatures at which photometry was performed. This factor takes into consideration a variation in ambient temperature surrounding the luminaire, the means and conditions of mounting the luminaire, and the use of any insulation in conjunction with the application of the luminaire.

luminaire dirt depreciation (LDD) the fractional loss of task illuminance due to luminaire dirt accumulation.

luminaire efficiency the ratio of luminous flux (lumens) emitted by a luminaire to that emitted by the lamp or lamps used therein.

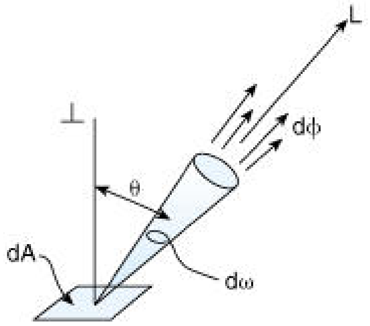
luminaire spacing criterion (SC)† a classification parameter for indoor luminaires relating to the distribution of the direct illuminance component produced on the work plane. The SC of a luminaire is an estimated maximum ratio of spacing to mounting height above the work plane for a regular array of that luminaire such that the work plane illuminance will be acceptably uniform.
Note The SC is not a recommendation for the spacing-to-mounting-height ratio for an installation. It is a characteristic that assists in identifying appropriate luminaires when illuminance uniformity is a design goal. The SC evolved but is distinctly different from an obsolete luminaire parameter called the *spacing-to-mounting-height ratio.* See Chapter 9, Lighting Calculations, for the SC algorithm.

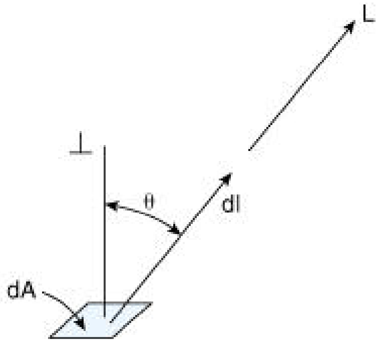
luminaire surface depreciation factor the fractional loss of task illuminance due to permanent deterioration of luminaire surfaces.

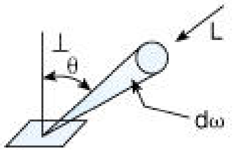
luminance, $L = d^2\varphi/(d\omega\, dA \cos\theta)$ (in a direction and at a point of a real or imaginary surface) the quotient of the luminous flux at an element of the surface surrounding the point, and propagated in directions defined by an elementary cone containing the given direction, by the product of the solid angle of the cone and the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction. The luminous flux can be leaving, passing through, and/or arriving at the surface. Formerly, *photometric brightness*.
By introducing the concept of *luminous intensity*, luminance can be expressed as $L = dI/(dA \cos\theta)$. Here, luminance at a point on a surface in a direction is interpreted as the quotient of luminous intensity in the given direction, produced by an element of the surface surrounding the point, by the area of the orthogonal projection of the element of surface on a plane, perpendicular to the given direction. Luminance can be measured at a receiving surface by using

$$L = dE/(dA \cos\theta).$$

This value can be less than the luminance of the emitting surface due to the attenuation of the transmitting media.







Note In common usage the term *brightness* usually refers to the strength of sensation that results from viewing surfaces or spaces from which light comes to the eye. This sensation is determined in part by the definitely measurable luminance defined above and in part by conditions of observation such as the state of adaptation of the eye. In much of the literature, brightness, when used alone, refers to both luminance and sensation. The context usually indicates which meaning is intended. Previous usage not withstanding, neither the term brightness nor the term photometric brightness should be used to denote the concept of luminance.

luminance coefficient (LC) The ratio of average wall or ceiling cavity luminance to the total lamp flux (lumens) divided by the floor area. This requires the luminance in the nonstandard units of footlamberts, where floor area is in square feet. See *exitance coefficient for current terminology.*

luminance contrast the relationship between the luminances of an object and its immediate background. It is equal to $(L_1 - L_2)/L_1$ or $(L_2 - L_1)/L_1 = |\Delta L/L_1|$, where L_1 and L_2 are the luminances of the background and object, respectively. The form of the equation must be specified. The ratio $\Delta L/L_1$ is known as Weber's fraction.
Note See note under *luminance*. Because of the relationship among luminance, illuminance, and reflectance, contrast often is expressed in terms of reflectance when only reflecting surfaces are involved. Thus, contrast is equal to $(\rho_1 - \rho_2)/\rho_1$, or $(\rho_2 - \rho_1)/\rho_1$, where ρ_1 and ρ_2 are the reflectances of the background and object, respectively. This method of computing contrast holds only for perfectly diffusing surfaces; for other surfaces it is only an approximation unless the angles of incidence and view are taken into consideration. See *reflectance.*

luminance difference the difference in luminance between two areas, such as the detail of a visual task and its immediate background, in which case it is quantitatively equal to the numerator in the formula for luminance contrast. See note under *luminance.*

luminance factor, β the ratio of the luminance of a surface or medium under specified conditions of incidence, observation, and light source, to the luminance of a completely reflecting or transmitting, perfectly diffusing surface or medium under the same conditions.
Note The reflectance or transmittance cannot exceed 1, but luminance factor can have any value from 0 to values approaching infinity.

luminance ratio the ratio between the luminances of any two areas in the visual field.

luminance threshold the minimum perceptible difference in luminance for a given state of adaptation of the eye.

luminescence any emission of light not ascribable directly to incandescence. See *electroluminescence, fluorescence,* and *phosphorescence.*

luminous ceiling a ceiling area lighting system comprising a continuous surface of transmitting material of a diffusing or light-controlling character with light sources mounted above it. See *louvered ceiling.*

luminous density, $w = dQ/dV$ quantity of light (luminous energy) per unit volume.

luminous efficacy of radiant flux the quotient of the total luminous flux by the total radiant flux. It is expressed in lumens per watt.

luminous efficacy of a source of light the quotient of the total luminous flux emitted the total lamp power input. It is expressed in lumens per watt.
Note The term luminous efficiency has in the past been extensively used for this concept.

luminous efficiency† See *spectral luminous efficiency of radiant flux.*

luminous energy† See *quantity of light.*

luminous exitance, $M = d\varphi/dA$ the areal density of luminous flux leaving a surface at a point. Formerly luminous emittance (deprecated).
Note This is the total luminous flux emitted, reflected, and transmitted from the surface and is independent of direction.

luminous flux, Φ radiant flux (radiant power); the time rate of flow of radiant energy, evaluated in terms of a standardized visual response:

$$\Phi_v = K_m \int \Phi_{e,\lambda} V(\lambda)\, d\lambda$$

where

Φ_v = lumens
Φe, λ = watts per nanometer
λ = nanometers

$V(\lambda)$ = the spectral luminous efficiency

K_m = the maximum spectral luminous efficacy in lumens per watt

Unless otherwise indicated, the luminous flux is defined for photopic vision. For scotopic vision, the corresponding spectral luminous efficiency $V(\lambda)$ and the corresponding maximum spectral luminous efficacy K_m are substituted in the above equation. K_m and K'_m are derived from the basic SI definition of luminous intensity and have the values 683 lm/W and 1754 lm/W, respectively.

luminous flux density at a surface, **$d\Phi/dA$** the luminous flux per unit area at a point on a surface.
Note This need not be a physical surface; it can also be a mathematical plane. See also *illuminance* and *luminous exitance.*

luminous intensity, $I = d\Phi/d\omega$ **(of a point source of light in a given direction)** the luminous flux per unit solid angle in the direction in question. Hence, it is the luminous flux on a small surface centered on and normal to that direction divided by the solid angle (in steradians) that the surface subtends at the source. Luminous intensity can be expressed in candelas or in lumens per steradian (lm/sr).
Note Mathematically a solid angle must have a point as its apex; the definition of luminous intensity, therefore, applies strictly only to a point source. In practice, however, light emanating from a source whose dimensions are negligible in comparison with the distance from which it is observed can be considered as coming from a point. Specifically, this implies that with change of distance (1) the variation in solid angle subtended by the source at the receiving point approaches 1/distance^2, and that (2) the average luminance of the projected source area as seen from the receiving point does not vary appreciably. For extended sources see equivalent luminous intensity of an extended source at a specified distance. The word *intensity* as defined above is used to designate luminous intensity (or *candlepower*). It is also widely used in other ways, either formally or informally, in other disciplines. Stimulus intensity can be used to designate the retinal illuminance of a proximal stimulus (see *proximal stimuli*) or the luminance of a distal stimulus (see *distal stimuli*). Intensity is used in the same sense with respect to other modulates such as audition. Intensity has been used to designate the level of illuminance on a surface or the flux density in the cross section of a beam of light. In physical optics, "intensity" usually refers to the square of the wave amplitude.

luminous intensity distribution curve† See *intensity distribution curve.*

luminous reflectance any of the geometric aspects of reflectance in which both the incident and the reflected flux are weighted by the spectral luminous efficiency of radiant flux, $V(\lambda)$.
Note Unless otherwise qualified, the term *reflectance* means luminous reflectance.

luminous transmittance any of the geometric aspects of transmittance in which the incident and transmitted flux are weighted by the luminous efficiency of radiant flux, $V(\lambda)$.
Note Unless otherwise qualified, the term transmittance means luminous transmittance.

lux, lx the SI unit of illuminance. One lux is one lumen per square meter (lm/m^2). See the Appendix for conversion values.

lux meter† See *illuminance (lux or footcandle) meter.*

M

maintenance factor (MF)† a factor formerly used to denote the ratio of the illuminance on a given area after a period of time to the initial illuminance on the same area. This term is obsolete and is no longer valid. See *light loss factor.*

matte surface a surface from which the reflection is predominantly diffuse, with or without a negligible specular component. See *diffuse reflection.*

mean horizontal intensity (candlepower) the average intensity (in candelas) of a lamp in a plane perpendicular to the axis of the lamp that passes through the luminous center of the lamp.

mean spherical luminous intensity the average value of the luminous intensity in all directions for a source. Also, the quotient of the total emitted luminous flux of the source by 4π.

$$I_{\text{ms}} = \frac{1}{4\pi} \int_{0}^{4\pi} I \, d\omega = \frac{\Phi_{\text{total}}}{4\pi}$$

mean zonal candlepower the average intensity (candelas) of a symmetrical luminaire or lamp at an angle to the luminaire or lamp axis that is in the middle of the zone under consideration.

means of egress† An unobstructed and continuous way of exit from any point in a building or structure to a public way. It consists of three distinct parts: the exit access, the exit, and the exit discharge. A means of egress consists of the vertical and horizontal travel ways including intervening room spaces, doorways, hallways, corridors, passageways, ramps, stairs, lobbies, horizontal exits, escalators, enclosures, courts, balconies, and yards.

mercury lamp a high-intensity discharge (HID) lamp in which the major portion of the light is produced by radiation from mercury operating at a partial pressure in excess of 10^5 Pa (approximately 1 atm). Includes clear, phosphor-coated (mercury-fluorescent), and self-ballasted lamps.

mercury-fluorescent lamp (phosphor mercury lamp) an electric-discharge lamp having a high-pressure mercury arc in an arc tube and an outer envelope coated with a fluorescing substance (phosphor) that transforms some of the ultraviolet energy generated by the arc into light.

mesopic vision vision with fully adapted eyes at luminance conditions between those of photopic and scotopic vision, that is, between about 3.4 and 0.034 cd/m^2.

metal halide lamp a high-intensity discharge (HID) lamp in which the major portion of the light is produced by radiation of metal halides and their products of dissociation--possibly in combination with metallic vapors such as mercury. Includes clear and phosphor-coated lamps.

metamers lights of the same color but of different spectral power distribution.
Note The term "metamers" is also used to denote objects that, when illuminated by a given source and viewed by a given observer, produce metameric lights.

middle ultraviolet† a portion of the electromagnetic spectrum in the range of 200 to 300 nm.

minimal perceptible erythema, MPE the erythemal threshold.

mired† See *reciprocal color temperature.*

modeling light illumination that reveals the depth, shape, and texture of a subject; key light, cross lighting, counter-key light, side light, back light, and eye light are types of modeling light.

modulation threshold in the case of sinisoidal wave gratings, manipulation of luminance differences can be specified in terms of modulation and the threshold can be called the modulation threshold. Periodic patterns that are not sinusoidal can be similarly specified in terms of the modulation of the fundamental sine wave component. The number of periods or cycles per degree of visual angle represents the spatial frequency.

$$\text{modulation} = \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} + L_{\text{min}}}$$

monocular visual field the field for a single eye. See *binocular portion of the visual field.*

mounting height (roadway)† the vertical distance between the roadway surface and the center of the apparent light source of a luminaire.

mounting height above the floor (MH_f)† the distance from the floor to the light center of the luminaire, or to the plane of the ceiling for recessed equipment.

mounting height above the workplane (MH_{wp})† the distance from the work plane to the light center of the luminaire, or to the plane of the ceiling for recessed equipment.

multiple-beam headlamp a headlamp so designed as to permit the driver of a vehicle to use any one of two or more distributions of light on the road.

Munsell chroma, C an index of perceived chroma of the object color defined in terms of the luminance factor (Y) and chromaticity coordinates (x, y) for CIE Standard Illuminant C and the CIE 1931 Standard Observer.

Munsell color system a system of surface-color specification based on perceptually uniform color scales for the three variables: Munsell hue, Munsell value, and Munsell chroma. For an observer of normal color vision, adapted to daylight and viewing a specimen when illuminated by daylight and surrounded with a middle-gray to white background, the Munsell hue, value, and chroma of the color correlate well with the hue, lightness, and perceived chroma.

Munsell hue, H the index of the hue of the perceived object color defined in terms of the luminance factor (Y) and coordinates (x, y) for CIE Standard Illuminant C and the CIE 1931 Standard Observer.

Munsell value, V the index of the lightness of the perceived object color defined in terms of the luminance factor Y for CIE Standard Illuminant C and the CIE 1931 Standard Observer.
Note The exact definition gives Y as a fifth-power function of V, so that tabular or iterative methods are needed to find V as a function of Y. However, V can be estimated within ± 0.1 by $V = 11.6(Y/100)^{1/3} - 1.6$ or within ± 0.6 by $V = Y^{1/2}$, where Y is the luminance factor expressed in percent.

N

nanometer, nm† a unit of wavelength equal to 10^{-9} m. See the Appendix for conversion values.

narrow-angle diffusion that in which flux is scattered at angles near the direction that the flux would take by regular reflection or transmission. See *wide-angle diffusion.*

narrow-angle luminaire a luminaire that concentrates the light within a cone of a comparatively small solid angle. See *wide-angle luminaire.*

national standard of light† a primary standard of light that has been adopted as a national standard. See *primary standards of light.*

navigation lights† an alternative term for *position lights*.

navigation light system a set of aircraft aeronautical lights provided to indicate the position and direction of motion of an aircraft to pilots of other aircraft or to ground observers.

near infrared† the region of the electromagnetic spectrum from 770 to 1400 nm.

near ultraviolet† the region of the electromagnetic spectrum from 300 to 380 nm.

night the hours between the end of evening civil twilight and the beginning of morning civil twilight.
Note Civil twilight ends in the evening when the center of the sun's disk is 6° below the horizon, and begins in the morning when the center of the sun's disk is 6° below the horizon.

nit, nt† a unit of luminance equal to 1 cd/m^2.
Note the candela per square meter (cd/m^2) is the SI unit of luminance.

nonrecoverable light loss factors (initial or maintained) factors that give the fractional light loss that cannot be recovered by cleaning or lamp replacement. Comprised of those components that account for the lamps operating at other than their rated luminous value. This factor is applied to lighting calculations irrespective of the age of the lighting system.

normal ac power† power supplied to a facility during non-emergency situations. It is usually supplied by a local electric utility.

normal lighting† permanently installed task and corridor electric lighting normally for use when the premises are occupied.

numerical display (digital display)† an electrically operated display of digits. Tungsten filaments, gas discharges, light-emitting diodes, liquid crystals, projected numerals, illuminated numbers, and other principles of operation can be used.

O

object color† the color of the light reflected or transmitted by an object when illuminated by a standard light source, such as CIE source A, B, C, or D_{65}. See *standard source* and *perceived object color.*

obstruction beacon† See *hazard or obstruction beacon*.

obstruction lights aeronautical ground lights provided to indicate obstructions.

occulting light a rhythmic light in which the periods of light are clearly longer than the periods of darkness.

opaque† impenetrable to light; not able to transmit, or not transmitting light.

orientation the relation of a building with respect to compass directions.

Ostwald color system a system of describing colors in terms of color content, white content, and black content. It is usually exemplified by color charts in triangular form with full color, white, and black mixtures at the apices providing a gray scale of white and black mixtures, and parallel scales of constant white content as these grays are mixed with varying proportions of the full color. Each chart represents a constant dominant wavelength (called hue), and the colors lying on a line parallel to the gray scale represent constant purity (called shadow series).

overcast sky one that has 100% cloud cover; the sun is not visible.

overhang the distance between a vertical line passing through a specified point (often the photometric center) of a luminaire and the curb or edge of a roadway.

ozone-producing radiation UV energy of wavelength shorter than 220 nm that decomposes oxygen, O_2, thereby producing ozone, O_3. Some UV sources generate energy at 184.9 nm, which is particularly effective in producing ozone.

P

panel (open) **face exit sign**† a transilluminated sign where both the exit legend and background are translucent.

PAR lamp See *pressed reflector lamp*.

parking lamp a lighting device placed on a vehicle to indicate its presence when parked.

partial diffusion† See *incomplete diffusion*.

partly cloudy sky a sky that has 30 to 70% cloud cover.

passing beams† See *lower (passing) beams*.

pendant luminaire† See *suspended (pendant) luminaire*.

perceived light source color the color perceived to belong to a light source.

perceived object color† the color perceived to belong to an object resulting from characteristics of the object, of the incident light, and of the surround, the viewing direction, and observer adaptation. See *object color*.

percent flicker a relative measure of the cyclic variation in output of a light source (percent modulation). It is given by the expression where A is the maximum and B is the minimum output during a single cycle. See Chapter 6, Light Sources.

$$100\,\frac{A - B}{A + B}$$

perfect diffusion that in which flux is uniformly scattered in accord with Lambert's cosine law.

perimeter lights aeronautical ground lights provided to indicate the perimeter of a landing pad for helicopters.

period life the time interval until lamps are replaced or luminaires are cleaned.

peripheral vision the seeing of objects displaced from the primary line of sight and outside the central visual field.

peripheral visual field that portion of the visual field that falls outside the region corresponding to the foveal portion of the retina.

phosphor mercury lamp† see *mercury-fluorescent lamp*.

phosphorescence the emission of light as the result of the absorption of radiation, and continuing for a noticeable length of time after excitation (longer than approximately 10^{-8} s).

phot, ph a unit of illuminance equal to one lumen per square centimeter. The use of this unit is deprecated.

photobiology a branch of biology that deals with the effects of optical radiation on living systems.

photochemical radiation energy in the ultraviolet, visible, and infrared regions capable of producing chemical changes in materials.
Note Examples of photochemical processes are accelerated fading tests, photography, photoreproduction, and chemical manufacturing. In many such applications a specific spectral region is of importance.

photoelectric receiver† a device that reacts electrically in a measurable manner in response to incident radiant energy.

photoflash lamp a lamp in which combustible metal or other solid material is burned in an oxidizing atmosphere to produce light of high intensity and short duration for photographic purposes.

photoflood lamp an incandescent filament lamp of high color temperature for lighting objects for photography or videography.

photometer an instrument for measuring photometric quantities such as luminance, luminous intensity, luminous flux, or illuminance. See *densitomer, goniophotometer, illuminance (lux or footcandle) meter, integrating photometer, reflectometer, spectrophotometer, and transmissometer.*

photometry the measurement of quantities associated with light.
Note Photometry can be either visual, in which the eye is used to make a comparison, or physical, in which measurements are made by means of physical receptors.

photometric brightness† a term formerly used for luminance.

photoperiod the environmental light/dark cycle to which living organisms may be exposed; for example, the natural cycle at the earth's equator of light (L) for 12 hours and darkness (D) for 12 hours. This is expressed as LD 12:12.

photopic vision vision mediated essentially or exclusively by the cones. It is generally associated with adaptation to a luminance of at least 3.4 cd/m^2. See *scotopic vision*.

photosynthetic irradiance irradiance within the wavelength band 400 to 700 nm. Unit: watts per square meter.

photosynthetic photon flux density (PPFD) the number of photons per unit time and per unit area in the wavelength band 400 to 700 nm. Unit: micromoles per second and per square meter.
Note (1) There are 6.0222 × 10^{23} photons in one mole; (2) this unit was formerly known as microeinsteins per second and per square meter.

photosynthetically active radiation (PAR) photon flux in the wavelength band 400 to 700 nm.

phototherapy the treatment of disease involving the use of optical radiation.

physical photometer an instrument containing a physical receptor and associated filters that is calibrated so as to read photometric quantities directly. See *visual photometer*.

pilot house control a mechanical means for controlling the elevation and train of a searchlight from a position on the other side of the bulkhead or deck on which it is mounted.

Planck radiation law an expression representing the spectral radiance of a blackbody as a function of the wavelength and temperature. This law commonly is expressed by the formula

$$L_\lambda = \frac{dI_\lambda}{dA'} = c_{1L}\lambda^{-5}(e^{c_2/\lambda T} - 1)^{-1}$$

where

L_λ = the spectral radiance

dI_λ = the spectral radiant intensity

dA' = the projected area (dA cos θ) of the aperture of the blackbody

e = the base of natural logarithms (2.71828)

T = absolute temperature

c_{1L} and c_2 = constants designated as the first and second radiation constants.

Note The symbol c_{1L} is used to indicate that the equation in the form given here refers to the radiance L, or to the intensity I per unit projected area A′, of the source. Numeric values are commonly given not for c_{1L} but for c_1, which applies to the total flux radiated from a blackbody aperture, that is, in a hemisphere (2π sr), so that, with the Lambert cosine law taken into account, $c_1 = \pi\ c_{1L}$. The currently recommended value of c_1 is 3.741832×10^{-16} W × m^2, or 3.741832×10^{-12} W × cm^2. Then c_{1L} is 1.191062×10^{-16} W × $m^2 \times sr^{-1}$, or 1.191062×10^{-12} W × $cm^2 \times sr^{-1}$. If, as is more convenient, wavelengths are expressed in micrometers and area in square centimeters, then $c_{1L} = 1.191062 \times 10^4$ W × $\mu m^4 \times cm^{-2} \times sr^{-1}$, L_λ being given in W × $cm^{-2} \times sr^{-1} \times \mu m^{-1}$. The currently recommended value of c_2 is 1.438786×10^{-2} m × K.

The Planck law in the following form gives the energy radiated from the blackbody in a given wavelength interval ($\lambda_1\lambda_2$):

$$Q = \int_{\lambda_1}^{\lambda_2} Q_\lambda \, d\lambda = Atc_1 \int_{\lambda_1}^{\lambda_2} \lambda^{-5}(e^{c_2/\lambda T} - 1)^{-1} \, d\lambda$$

If A is the area of the radiation aperture or surface in square centimeters, t is the time in seconds, λ is the wavelength in micrometers, and $c_1 = 3.741832 \times 10^4$ W × $\mu m^4 \times cm^{-2}$, then Q is the total energy in watt-seconds (joules), emitted from this area (that is, in the solid angle 2π) in time t within the wavelength interval ($\lambda_1\lambda_2$).

planckian locus† See *blackbody (planckian) locus.*

plano-convex spotlight a spotlight embodying a plano-convex lens and a lamp movable within the housing in relation to the lens in order to vary beam and field angles.

point of fixation a point or object in the visual field at which the eyes look and upon which they are focused.

point of observation for most purposes it can be assumed that the distribution of luminance in the field of view can be described as if there were a single point of observation located at the midpoint of the baseline connecting the centers of the entrance pupils of the two eyes. For many problems it is necessary, however, to regard the centers of the entrance pupils as separate points of observation for the two eyes.

point-by-point method† a method of lighting calculation, now called the *point method*.

point method a lighting design procedure for predetermining the illuminance at various locations in lighting installations by use of luminaire photometric data. The direct component of illuminance due to the luminaires and the interreflected component of illuminance due to the room surfaces are calculated separately. The sum is the total illuminance at a point.

point source a source of radiation whose dimensions are sufficiently small, compared with the distance between the source and the irradiated surface, that these dimensions can be neglected in calculations and measurements.

point vision the mode of vision of a small source of light such that the sensation is determined by its intensity rather than by its size. Point vision occurs with sources so small that their form or shape is not perceived and that they appear as points of light; this generally means less than 1-minute angular subtense.

polarization† the process by which unpolarized radiation is polarized. It can be accomplished by either a reflection process or a transmission process.

polarized radiation† radiation whose electromagnetic field, which is transverse, is oriented in defined directions. The polarization can be rectilinear, elliptic, or circular.

pole (roadway lighting) a standard support generally used where overhead lighting distribution circuits are employed.

portable lighting lighting involving equipment designed for manual portability.

portable luminaire a lighting unit that is not permanently fixed in place. See *table lamp* and *floor lamp*.

portable traffic control light a signaling light designed for manual portability that produces a controllable distinctive signal for purposes of directing aircraft operations in the vicinity of an aerodrome.

position index, P a factor that represents the relative average luminance for a sensation at the borderline between comfort and discomfort (BCD) for a source located anywhere within the visual field.

position lights aircraft aeronautical lights forming the basic, internationally recognized navigation light sys tem.
Note The system is composed of a red light showing from dead ahead to 110° to the left, a green light showing from dead ahead to 110° to the right, and a white light showing to the rear through 140°. Position lights are also called *navigation lights*.

prefocus lamp a lamp in which, during manufacture, the luminous element is accurately adjusted to a specified position with respect to the physical location element (usually the base).

preheat (switch start) **fluorescent lamp** a fluorescent lamp designed for operation in a circuit requiring a manual or automatic starting switch to preheat the electrodes in order to start the arc.

pressed reflector lamp an incandescent filament or electric-discharge lamp in which the outer bulb is formed of two pressed parts that are fused or sealed together; namely, a reflectorized bowl and a cover, which can be clear or patterned for optical control.
Note Often called a projector or PAR lamp.

primary (light) any one of three lights in terms of which a color is specified by giving the amount of each required to match it by additive combination.

primary line of sight the line connecting the point of observation and the point of fixation. For a single eye, it is the line containing the point of fixation and the center of the entrance pupil.

primary standards of light a light source by which the unit of light is established and from which the values of other standards are derived. This order of standard also is designated as the national standard.

See *national standard of light*.
Note A satisfactory primary (national) standard must be reproducible from specifications (see *candela*). Primary (national) standards usually are found in national physical laboratories such as the National Institute of Standards and Technology (NIST) in the United States.

projection lamp a lamp with physical and luminous characteristics suited for projection systems (e.g., motion picture projectors, slide projectors, and microfilm viewers).

projector a lighting unit that, by means of mirrors and lenses, concentrates the light to a limited solid angle so as to obtain a high value of luminous intensity. See *floodlight, searchlight,* and *signaling light*.

protective lighting a system intended to facilitate the nighttime policing of industrial and other properties.

proximal stimuli the distribution of illuminance on the retina constitutes the proximal stimulus.

public way† any road, alley, or other similar parcel of land essentially open to the outside air, permanently appropriated for public use, and having a clear height and width of not less than 3 m (10 ft).

pupil (pupillary aperture) the opening of the iris that admits light into the eye. See *artificial pupil*.

Purkinje phenomenon the reduction in subjective brightness of a red light relative to that of a blue light when the luminances are reduced in the same proportion without changing the respective spectral distributions. In passing from photopic to scotopic vision, the curve of spectral luminous efficiency changes, the wavelength of maximum efficiency being displaced toward the shorter wavelengths.

purple boundary the straight line drawn between the ends of the spectrum locus on a chromaticity diagram.

Q

quality of lighting pertains to the distribution of luminance in a visual environment. The term is used in a positive sense and implies that all luminances contribute favorably to visual performance, visual comfort, ease of seeing, safety, and aesthetics for the specific visual tasks involved.

quantity of light (luminous energy), $Q = \int \Phi \mathbf{dt}$ the product of the luminous flux by the time it is maintained. It is the time integral of luminous flux.

quartz-iodine lamp† an obsolete term for the tungsten halogen lamp.

quick-flashing light a single flashing light at a frequency equal to or greater than 1 Hz. There is no agreed verbal differentiation between lights that flash at 1 Hz and those that flash more rapidly (a quick-flashing light can be a sequence of single flashes or a sequence of multiflick flashes, at 1-s intervals; there is no restriction on the ratio of the durations of the light to the dark periods).

R

radiance, $L = d^2\Phi/[d\omega\,(dA\cos\theta)]^V = dI(dA\cos\theta)$ **(in a direction, at a point on the surface of a source, of a receiver, or of any other real or virtual surface)** the quotient of the radiant flux leaving, passing through, or arriving at an element of the surface surrounding the point, and propagated in directions defined by an elementary cone containing the given direction, by the product of the solid angle of the cone, and the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction.

Note In the defining equation, θ is the angle between the normal to the element of the source and the given direction.

radiant energy, Q energy traveling in the form of electromagnetic waves. It is measured in units of energy such as joules or kilowatt hours. See *spectral radiant energy*.

radiant energy density, $w = dQ/dV$ radiant energy per unit volume, for example, joules per cubic meter.

radiant exitance, M† the density of radiant flux leaving a surface. It is expressed in watts per unit area of the surface.

radiant flux (radiant power), $\Phi = dQ/dt$ the time rate of flow of radiant energy. It is expressed preferably in watts. See *spectral radiant flux.*

radiant flux density at a surface† the quotient of radiant flux of an element of surface to the area of that element, in units such as W/m^2. When referring to radiant flux emitted from a surface, this has been called radiant emittance (deprecated); the preferred term is *radiant exitance*: The radiant exitance per unit wavelength interval is called *spectral radiant exitance*. The radiant flux density incident on a surface is called *irradiance* (E).

radiant intensity, $I = d\Phi/d\omega$ **(in a given direction)** the radiant flux proceeding from a source per unit solid angle in a given direction, for example, W/sr. See *spectral radiant intensity.*
Note Mathematically, a solid angle must have a point at its apex; the definition of radiant intensity therefore applies strictly only to a point source. In practice, however, radiant energy emanating from a source whose dimensions are negligible in comparison with the distance from which it is observed can be considered as coming from a point. Specifically, this implies that with change of distance (1) the variation in solid angle subtended by the source at the receiving point approaches $1/\text{distance}^2$, and that (2) the average radiance of the projected source area as seen from the receiving point does not vary appreciably.

radiator an emitter of radiant energy.

radiometry the measurement of quantities associated with radiant energy and power.

range lights groups of color-coded boundary lights provided to indicate the direction and limits of a preferred landing path (normally) on an aerodrome without runways, but exceptionally on an aerodrome with runways.

rapid-start fluorescent lamp a fluorescent lamp designed for operation with a ballast that provides a low-voltage winding for preheating the electrodes and initiating the arc without a starting switch or the application of high voltage.

rated lamp life the life value assigned to a particular type lamp. This is commonly a statistically determined estimate of average or of median operational life. For certain lamp types other criteria than failure to light can be used; for example, the life can be based on the average time until the lamp type produces a given fraction of initial luminous flux.

reaction time the interval between the beginning of a stimulus and the beginning of the response of an observer.

recessed luminaire† See *flush-mounted or recessed luminaire.*

reciprocal color temperature color temperature (T_c) expressed on a reciprocal scale ($1/T_c$). An important use stems from the fact that a given small increment in reciprocal color temperature is approximately equally perceptible regardless of color temperature. Also, color temperature conversion

filters for sources approximating graybody sources change the reciprocal color temperature by nearly the same amount anywhere on the color temperature scale.
Note The unit is the reciprocal megakelvin (MK^{-1}). The reciprocal color temperature expressed in this unit has the numerical value of $10^6/T_c$ when T_c is expressed in kelvins. The acronym mirek (for micro-reciprocal-kelvin) occasionally has been used in the literature. The acronym *mired* (for micro-reciprocal-degree) is now considered obsolete as the name for this unit.

recoverable light loss factors factors that give the fractional light loss that can be recovered by cleaning or lamp replacement. Comprised of those components that account for depreciation of luminous quantities in a lighting system. This factor is a function of lighting system age and maintenance processes and is applied to lighting calculations for systems after time zero.

redirecting surfaces and media those that change the direction of the flux without scattering the redirected flux.

reference ballast a ballast that is specially constructed, having certain prescribed characteristics and that is used for testing electric-discharge lamps and other ballasts.

reference line (roadway lighting) either of two radial lines where the surface of the cone of maximum intensity is intersected by a vertical plane parallel to the curb line and passing through the light center of the luminaire.

reference standard† an alternative term for secondary standard.

reflectance of a surface or medium, $\rho = \Phi_r/\Phi_i$ the ratio of the reflected flux to the incident flux. Reflectance is a function of:

1. Geometry
    - a. of the incident flux
    - b. of collection for the reflected flux

2. Spectral distribution
    - a. characteristic of the incident flux
    - b. weighting function for the collected flux

3. Polarization
    - a. of the incident flux
    - b. component defined for the collected flux.

Note Unless the state of polarization for the incident flux and the polarized component of the reflected flux are stated, it should be considered that the incident flux is unpolarized and that the total reflected flux (including all polarization) is evaluated. Spectral reflectance depends on only the beam geometry and the character of the reflecting surface (and on polarization). Luminous reflectance also is a function of the spectral distribution of the incident flux. If no qualifying geometric adjective is used, the reflectance for hemispherical collection is meant. Certain of the reflectance terms are theoretically imperfect and are recognized only as practical concepts to be used when applicable. Physical measurements of the incident and reflected flux are always biconical in nature. Directional reflectances cannot exist, since one component would be finite while the other was infinitesimal; here the reflectance distribution function is required. However, the concepts of directional and hemispherical reflectance have practical application in instrumentation, measurements, and calculations when including the effect of the nearly zero or nearly 2π conical angle would increase complexity without appreciably affecting the immediate results. In each case of conical incidence or collection, the solid angle need not be a right cone but can be of any cross section, including a rectangle, a ring, or a combination of two or more solid angles. For many geometrically specified reflectance properties it is assumed that the radiance (luminance) is isotropic over the specified solid angle of incidence. Otherwise, the property is a function of the directional distribution of the radiance (luminance) as well as the beam geometry and the character of the reflecting surface.

reflectance factor, R the ratio of the flux actually reflected by a sample surface to that which would be reflected into the same reflected-beam geometry by an ideal (glossless), perfectly diffuse (lambertian), completely reflecting standard surface irradiated in exactly the same way as the sample. Note the analogies to reflectance in the fact that nine canonical forms are possible that "spectral" can be applied as a modifier, that it can be luminous or radiant reflectance factor, and so on. Note that reflectance cannot exceed unity, but reflectance factor can have any value from zero to values approaching infinity.

reflected glare glare resulting from reflections of high luminances in polished or glossy surfaces in the field of view. It usually is associated with reflections from within a visual task or areas in close proximity to the region being viewed. See *veiling reflection*.

reflection a general term for the process by which the incident flux leaves a (stationary) surface or medium from the incident side without change in frequency.
Note Reflection is usually a combination of regular and diffuse reflection. See *regular (specular) reflection, diffuse reflection,* and *veiling reflection.*

reflectivity† reflectance of a layer of a material of such a thickness that there is no change of reflectance with increase in thickness.

reflectometer a photometer for measuring reflectance.
Note Reflectometers can be visual or physical instruments.

reflector a device used to redirect the flux from a source by the process of reflection. See *retro-reflector*.

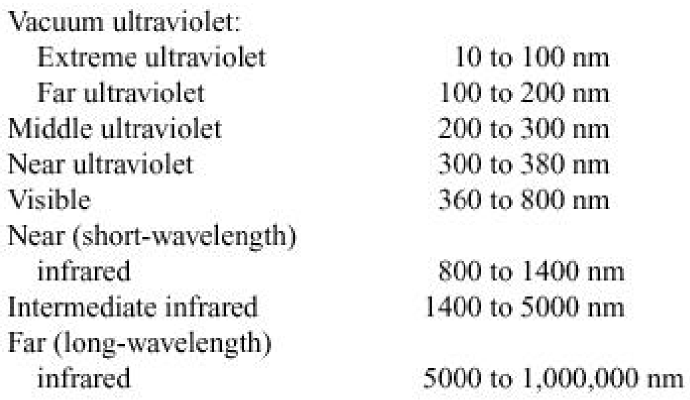
reflector lamp an incandescent filament or electric-discharge lamp in which the outer blown glass bulb is coated with a reflecting material so as to direct the light (such as R- or ER-type lamps). The light-transmitting region can be clear, frosted, patterned, or phosphor coated.

reflex reflector† See *retro-reflector*.

refraction† the process by which the direction of a ray of light changes as it passes obliquely from one medium to another in which its speed is different.

refractor a device used to redirect the flux from a source, primarily by the process of refraction.

regions of the electromagnetic spectrum for convenience of reference, the electromagnetic spectrum is arbitrarily divided as follows:
Note The spectral limits indicated above have been chosen as a matter of practical convenience. There is a gradual transition from region to region without sharp delineation. Also, the division of the spectrum is not unique. In various fields of science the classifications can differ due to the phenomena of interest.



Vacuum ultraviolet:	
Extreme ultraviolet	10 to 100 nm
Far ultraviolet	100 to 200 nm
Middle ultraviolet	200 to 300 nm
Near ultraviolet	300 to 380 nm
Visible	360 to 800 nm
Near (short-wavelength) infrared	800 to 1400 nm
Intermediate infrared	1400 to 5000 nm
Far (long-wavelength) infrared	5000 to 1,000,000 nm

Another division of the UV spectrum often used by photobiologists is given by the Commission Internationale de l'Eclairage (CIE):

UV-A	315 to 400 nm
UV-B	280 to 315 nm
UV-C	100 to 280 nm

regressed luminaire a luminaire mounted above the ceiling with its opening above the ceiling line. See *flush-mounted, surface-mounted, suspended,* and *troffer luminaires*.

regular (specular) **reflectance** the ratio of the flux leaving a surface or medium by regular (specular) reflection to the incident flux. See *regular (specular) reflection.*

regular (specular) **reflection** that process by which incident flux is redirected at the specular angle. See *bihemispherical reflectance and specular angle.*

regular transmission that process by which incident flux passes through a surface or medium without scattering. See *regular transmittance*.

regular transmittance the ratio of the regularly transmitted (straight through) flux leaving a surface or medium to the incident flux.

relative contrast sensitivity (RCS) the relation between the reciprocal of the luminous contrast of a task at visibility threshold and the background luminance expressed as a percentage of the value obtained under a very high level of diffuse task illumination.

relative erythemal factor† See *erythemal efficiency of radiant flux.*

relative luminosity† an obsolete term for the spectral luminous efficiency of radiant flux.

relative luminosity factor† an obsolete term for the spectral luminous efficiency of radiant flux.

resolving power the ability of the eye to perceive the individual elements of a grating or any other periodic pattern with parallel elements measured by the number of cycles per degree that can be resolved. The resolution threshold is the period of the pattern that can be just resolved. The visual acuity, in such a case, is the reciprocal of one-half the period expressed in minutes. The resolution threshold for a pair of points or lines is the distance between their centers when they can be distinguished as two, not one, expressed in minutes of arc.

resultant color shift the difference between the perceived color of an object illuminated by a test source and of the same object illuminated by the reference source, taking account of the state of chromatic adaptation (see *state of chromatic adaptation*) in each case; that is, the resultant of colorimetric shift and adaptive color shift.

retina a membrane lining the posterior part of the inside of the eye. It comprises photoreceptors (cones and rods) that are sensitive to light and nerve cells that transmit to the optic nerve the responses of the receptor elements.

retro-reflector (reflex reflector) a device designed to reflect light in a direction close to that at which it is incident, whatever the angle of incidence.

rhythmic light a light that when observed from a fixed point has a luminous intensity that changes periodically. See *equal interval (isophase) light, flashing light, group flashing light, interrupted quick-flashing light,* and *occulting light*.

ribbon filament lamp an incandescent lamp in which the luminous element is a tungsten ribbon.
Note This type of lamp is often used as a standard in pyrometry and radiometry.

rods retinal receptors that respond at low levels of luminance even below the threshold for cones. At these levels there is no basis for perceiving differences in hue and saturation. No rods are found near the center of the fovea.

room cavity the cavity formed by the plane of the luminaires, the work plane, and the wall surfaces between these two planes.

room cavity ratio (RCR) a number indicating room cavity proportions, calculated from the length, width, and height. See *zonal-cavity interreflectance method.*

room utilization factor (utilance) the ratio of the luminous flux (lumens) received on the workplane to that emitted by the luminaire.
Note This ratio sometimes is called *interflectance*. Room utilization factor is based on the flux emitted by a complete luminaire, whereas *coefficient of utilization* is based on the total flux generated by the lamps in a luminaire.

room surface dirt depreciation (RSDD) the fractional loss of task illuminance due to dirt on the room surfaces.

runway alignment indicator a group of aeronautical ground lights arranged and located to provide early direction and roll guidance on the approach to a runway.

runway centerline lights runway lights installed in the surface of the runway along the centerline indicating the location and direction of the runway centerline; of particular value in conditions of very poor visibility.

runway edge lights lights installed along the edges of a runway marking its lateral limits and indicating its direction.

runway end identification lights a pair of flashing aeronautical ground lights symmetrically disposed on each side of the runway at the threshold to provide additional threshold conspicuity.

runway exit lights lights placed on the surface of a runway to indicate a path of the taxiway centerline.

runway lights aeronautical ground lights arranged along or on a runway. See *runway centerline lights, runway edge lights, runway end identification light,* and *runway exit lights.*

runway threshold† the beginning of the part of the runway usable for landing.

runway visibility the meteorological visibility along an identified runway. Where a transmissometer is used for measurement, the instrument is calibrated in terms of a human observer; for example, the sighting of dark objects against the horizon sky during daylight and the sighting of moderately intense unfocused lights of the order of 25 candelas at night. See *visibility (meteorological).*

runway visual range (RVR) in the United States, an instrumentally derived value based on standard calibrations that represents the horizontal distance a pilot sees down the runway from the approach end; it is based either on the sighting of high-intensity runway lights or on the visual contrast of other targets, whichever yields the greater visual range.

S

saturation of a perceived color the attribute according to which it appears to exhibit more or less chromatic color judged in proportion to its brightness. In a given set of viewing conditions, and at luminance levels that result in photopic vision, a stimulus of a given chromaticity exhibits approximately constant saturation for all luminances.

scoop a floodlight consisting of a lamp in an ellipsoidal or paraboloidal matte reflector, usually in a fixed relationship, though some types permit adjustment of the beam shape.

scotopic vision vision mediated essentially or exclusively by the rods. It is generally associated with adaptation to a luminance below about 0.034 cd/m^2. See *photopic vision.*

sealed-beam headlamp an integral optical assembly designed for headlighting purposes, identified by the name "Sealed Beam" branded on the lens.

sealed-beam lamp A pressed-glass reflector lamp (PAR) that provides a closely controlled beam of light.
Note This term is generally applied in transportation lighting (for instance, automotive headlamps and aircraft landing lights) to distinguish sealed-beam lamps from similar devices in which the light source is replaceable within the reflector-lens unit.

searchlight a projector designed to produce an approximately parallel beam of light.
Note The optical system of a searchlight has an aperture of greater than 20 cm (8 in).

secondary standard source† a constant and reproducible light source calibrated directly or indirectly by comparison with a primary standard. This order of standard is also called a *reference standard*.
Note National secondary (reference) standards are maintained at national physical laboratories; laboratory secondary (reference) standards are maintained at other photometric laboratories. A self-calibrated detector can be used as a secondary standard.

self-ballasted lamps any arc discharge lamp of which the current-limiting device is an integral part.

self-luminous exit sign† an exit sign consisting of phosphor-coated glass tubes filled with a radioactive tritium gas. When the radioactive gas bombards the phosphor, the tube emits light (luminescence) and illuminates the exit legend, typically between 0.2 and 0.7 cd/m^2.

semi-direct lighting lighting involving luminaires that distribute 60 to 90% of the emitted light downward and the balance upward.

semi-indirect lighting lighting involving luminaires that distribute 60 to 90% of the emitted light upward and the balance downward.

service period the number of hours per day for which daylighting provides a specified illuminance level. It often is stated as a monthly average.

set light in theatrical lighting, the separate illumination of background or scenic elements.

shade a screen made of opaque or diffusing material that is designed to prevent a light source from being directly visible at normal angles of view.

shielding angle (of a luminaire) the angle between a horizontal line through the light center and the line of sight at which the bare source first becomes visible. See *cutoff angle (of a luminaire).*

short-arc lamp an arc lamp in which the distance between the electrodes is small (on the order of 1 to 10 mm).
Note This type of lamp (e.g., xenon or mercury) generally has an arc tube containing gas at very high pressure.

side-back light illumination from behind the subject in a direction not parallel to a vertical plane through the optical axis of the cameras. See *back light*.

side light lighting from the side to enhance subject modeling and place the subject in depth, apparently separated from the background.

side marker lamps lamps indicating the presence of a vehicle when seen from the front and sometimes serving to indicate its width. When seen from the side they can also indicate its length.

signaling light a projector used for directing light signals toward a designated target zone.

signal shutter a device that modulates a beam of light by mechanical means for the purpose of transmitting intelligence.

size threshold the minimum perceptible size of an object. It also is defined as the size that can be detected some specific fraction of the time it is presented to an observer, usually 50%. It usually is measured in minutes of arc. See *visual acuity*.

sky factor the ratio of the illuminance on a horizontal plane at a given point inside a building due to the light received directly from the sky, to the illuminance due to an unobstructed hemisphere of sky of uniform luminance equal to that of the visible sky.

sky light† visible radiation from the sun redirected by the atmosphere.

sky luminance distribution function for a specified sky condition, the luminance of each direction of the sky relative to the zenith luminance.

soft light (1) diffuse illumination that produces soft-edged, poorly defined shadows on the background when an object is placed in its path; (2) a luminaire designed to produce such illumination.

solar efficacy the ratio of the solar illuminance constant to the solar irradiance constant. The current accepted value is 94.2 lm/W.

solar illuminance constant the solar illuminance at normal incidence on a surface in free space at the earth's mean distance from the sun. The currently accepted value is 127.5 klx (11,850 fc).

solar (irradiance) constant† the irradiance, averaging 1353 W/m^2 (125.7 W/ft^2), from the sun at its mean distance from the earth, 1.5×10^{11} m (92.9×10^6 mi), before modification by the earth's atmosphere.

solar radiation simulator a device designed to produce a beam of collimated radiation having a spectrum, flux density, and geometric characteristic similar to those of the sun outside the earth's atmosphere.

solid angle, ω a measure of that portion of space about a point bounded by a conic surface whose vertex is at the point. It is defined as the ratio of intercepted surface area of a sphere centered on that point to the square of the sphere's radius. It is expressed in steradians.

solid angle factor, Q a function of the solid angle ω, given in steradians, subtended by a source and is given by $Q = 20.4\omega + 1.52\omega^{0.2} - 0.75$. See *index of sensation.*

spacing† for roadway lighting, the distance between successive lighting units, measured along the centerline of the street. For interior applications see Chapter 9, Lighting Calculations.

spacing-to-mounting-height ratio, S/MH_{wp}† the ratio of the actual distance between luminaire centers to the mounting height above the workplane. Also, an obsolete term that described a characteristic of interior luminaires. See *luminaire spacing criterion*.

special color rendering index, R_i measure of color shift of various standardized special colors, including saturated colors, typical foliage, and Caucasian skin. It also can be defined for other color samples when the spectral reflectance distributions are known.

spectral-directional emissivity, ε **(λ,θ,φ,*T*) (of an element of surface of a temperature radiator at a given wavelength and in a given direction)** the ratio of its spectral radiance at that wavelength and in the given direction to that of a blackbody at the same temperature and wavelength:

$$\epsilon(\lambda,\theta,\phi,T) = L_{\lambda}(\lambda,\theta,\phi,T)L_{\lambda\ \text{blackbody}}(\lambda,T)$$

spectral hemispherical emissivity, ε**(λ, T) (of an element of surface of an opaque temperature radiator that has an optical smooth surface)** the ratio of its spectral radiant exitance to that of a blackbody at the same temperature.

$$\begin{aligned}\epsilon(\lambda, T) &= \frac{1}{\pi}\int_{2\pi} \epsilon(\lambda,\theta,\phi,T)\cos\theta\, d\omega \\ &\equiv \frac{M_{\lambda}(\lambda,T)}{M_{\lambda\ \text{blackbody}}(\lambda, T)}\end{aligned}$$

Note Hemispherical emissivity is frequently called "total" emissivity. However, "total" is ambiguous and should be avoided, since it can also refer to the spectral total (all wavelengths) as well as directional total (all directions). See *spectral-total hemispherical emissivity.*

spectral (spectroscopic) **lamp** a discharge lamp that emits a significant portion of its radiative power in a line spectrum and that, in combination with filters, can be used to obtain monochromatic radiation.

spectral luminous efficacy of radiant flux, $K(\lambda) = \Phi_{v\lambda}/\Phi_{e\lambda}$ the quotient of the luminous flux at a given wavelength by the radiant flux at that wavelength. It is expressed in lm/W. See also *radiant flux* and *spectral radiant flux*.
Note This quantity formerly was called the luminosity factor. The reciprocal of the maximum luminous efficacy of radiant flux, that is, the ratio between radiant and luminous flux at the wavelength of maximum luminous efficacy, is sometimes called the mechanical equivalent of light; that is, the ratio between radiant and luminous flux at the wavelength of maximum luminous efficacy. The most probable value is 0.00146 W/lm, corresponding to 683 lm/W as the maximum possible luminous efficacy. For scotopic vision values the maximum luminous efficacy is 1754 scotopic lm/W.

spectral luminous efficiency for photopic vision, V(λ)† See *values of spectral luminous efficiency for photopic vision.*

spectral luminous efficiency for scotopic vision, $V(\lambda)$**†** See *values of spectral luminous efficiency for scotopic vision.*

spectral luminous efficiency of radiant flux† the ratio of the luminous efficacy for a given wavelength to the value for the wavelength of maximum luminous efficacy. It is dimensionless.
Note This term replaces the previously used terms *relative luminosity* and *relative luminosity factor*.

spectral radiant energy, $Q_\lambda = dQ/d\lambda$ radiant energy per unit wavelength interval, for example, joules per nanometer. $Q_\lambda(\lambda) = dQ/d\lambda$ at wavelength λ.

spectral radiant exitance, M_λ, and irradiance, E_λ spectral concentration of radiant exitance, $M_\lambda = dM/d\lambda$, and spectral concentration of irradiance, $E_\lambda = dE/d\lambda$. See *radiant flux density at a surface*.

spectral radiant flux, $\Phi_\lambda = d\Phi/d\lambda$ radiant flux per unit wavelength interval at wavelength λ, for example, W/nm.

spectral radiant intensity, $I_\lambda = dI/d\lambda$ radiant intensity per unit wavelength interval, for example, W/sr × nm.

spectral reflectance of a surface or medium, $\omega(\lambda) = \Phi_{r\lambda}/\Phi_{i\lambda}$ **†** the ratio of the reflected flux to the incident flux at a particular wavelength, λ, or within a small band of wavelengths, Δλ, about λ.
Note The various geometrical aspects of reflectance can each be considered restricted to a specific region of the spectrum and can be so designated by the use of the adjective "spectral."

spectral-total directional emissivity, $\varepsilon(\theta,\varphi,T)$ **(at a point on the surface of a thermal radiator and in a given direction)** the ratio of the radiance of the thermal radiator at temperature T at the point and in the given direction, to that of a blackbody at the same temperature, T.

$$\epsilon(x,y,\theta,\phi,T) = \frac{L(x,y,\theta,\phi,T)}{L_{\text{blackbody}}(T)}$$

where

x, y are the coordinates of the point,

θ, φ define the direction.

spectral-total hemispherical emissivity, $\varepsilon(x,y,2\pi,T)$ **(at a point on the surface of a thermal radiator)†** the ratio of the radiant exitance of the thermal radiator at temperature T, at the given point on the surface, to that of a blackbody at the same temperature T:

$$\epsilon(x, y, 2\pi, T) = \frac{1}{\pi}\int_{2\pi} \epsilon(x,y,\theta,\phi,T) \times \cos\theta \times d\omega$$

$$= \frac{1}{\pi}\int_0^\infty\int_{2\pi} \epsilon(\lambda,x,y,\theta,\phi,T) \times \cos\theta \times d\omega \times d\lambda$$

$$= \frac{M(x,y,T)}{M_{\text{blackbody}}(T)}$$

spectral transmittance of a medium, $\tau(\lambda) = \Phi_{t\lambda}/\Phi_{i\lambda}$ the ratio of the transmitted flux to the incident flux at a particular wavelength, λ, or within a small band of wavelengths, $\Delta\lambda$, about λ.
Note The various geometrical aspects of transmittance can each be considered restricted to a specific region of the spectrum and can be so designated by the addition of the adjective "spectral."

spectral tristimulus values† See *color-matching functions*.

spectrophotometer an instrument for measuring the transmittance and reflectance of surfaces and media as a function of wavelength.

spectroradiometer an instrument for measuring radiant flux as a function of wavelength.

spectrum locus the locus of points representing the colors of the visible spectrum in a chromaticity diagram.

specular angle that angle between the perpendicular to the surface and the reflected ray that is numerically equal to the angle of incidence, and that lies in the same plane as the incident ray and the perpendicular, but on the opposite side.

specular reflectance† See *regular (specular) reflectance.*

specular reflection† See *regular (specular) reflection*.

specular surface one from which the reflection is predominantly regular. See *regular (specular) reflection*.

speed of light† the speed of all radiant energy, including light, is 2.9979258×10^8 m/s in vacuum (approximately 186,000 mi/s). In all material media the speed is less and varies with the material's index of refraction, which itself varies with wavelength.

speed of vision the reciprocal of the duration of the exposure time required for something to be seen.

sphere illumination illumination on a task from a source providing equal luminance in all directions about that task, such as an illuminated sphere with the task located at the center.

spherical reduction factor the ratio of the mean spherical luminous intensity to the mean horizontal intensity. Retained for reference or literature search.

spotlight any of several different types of luminaires with narrow beam angle designed to illuminate a well-defined area. In motion pictures, generic for Fresnel lens luminaires. Also, a form of floodlight, usually equipped with lenses and reflectors to give a fixed or adjustable narrow beam.

standard illuminant A a blackbody at a temperature of 2856 K. It is defined by its relative spectral power distribution over the range from 300 to 830 nm.

standard illuminant B a representation of noon sunlight with a correlated color temperature of approximately 4900 K. It is defined by its relative spectral power distribution over the range from 320 to 770 nm.
Note It is anticipated that at some future date, that is yet to be decided, illuminant B will be dropped from the list of recommended standard illuminants.

standard illuminant C a representation of daylight having a correlated color temperature of approximately 6800 K. It is defined by its relative spectral power distribution over the range from 320 to 770 nm.
Note It is anticipated that at some future date, that is yet to be decided, illuminant C will be dropped from

the list of recommended standard illuminants.

standard illuminant D_{65} a representation of daylight at a correlated color temperature of approximately 6500 K. It is defined by its relative spectral power distribution over the range from 300 to 830 nm.
Note At present, no artificial source for matching this illuminant has been recommended.

standard source an electric light source having the same spectral power distribution as a specified standard illuminant.

standard source A a tungsten filament lamp operated at a color temperature of 2856 K (International Practical Temperature Scale, 1968) and approximating the relative spectral power distribution of standard illuminant A.

standard source B an approximation of standard illuminant B obtained by a combination of source A and a special filter.

standard source C an approximation of standard illuminant C obtained by a combination of source A and a special filter.

starter a device used in conjunction with a ballast for the purpose of starting an electric-discharge lamp.

state of chromatic adaptation the condition of the chromatic properties of the visual system at a specified moment as a result of exposure to the totality of colors of the visual field currently and in the past.

Stefan-Boltzmann law the statement that the radiant exitance or radiance of a blackbody radiator is proportional to the fourth power of its absolute temperature; that is,
Note The currently recommended value of σ is 5.67032×10^{-8} ($W \times m^{-2} \times K^{-4}$) and that of σ_L is 1.80492×10^{-8} ($W \times m^{-2} \times sr^{-1} \times K^{-4}$)

$$M = \sigma T^4 \qquad \text{or} \qquad L = \sigma_L T^4$$

stencil face exit sign† a transilluminated sign where either the exit legend or the background are opaque. Usually the exit legend is translucent and the background is die cut from an opaque medium such as plastic or metal.

steradian, sr (unit of solid angle)† the solid angle subtended at the center of a sphere by an area on the surface of the sphere equal to the square of the sphere radius.

stilb a cgs (cm-gram-second) unit of luminance. One stilb equals 1 cd/cm^2. The use of this term is deprecated.

Stiles-Crawford effect the reduced luminous efficiency of rays entering the peripheral portion of the pupil of the eye. This effect applies only to cones and not to rods. Hence, there is no Stiles-Crawford effect in scotopic vision.

stop lamp a device giving a steady warning light to the rear of a vehicle or train of vehicles, to indicate the intention of the operator to diminish speed or to stop.

stray light (in the eye) light from a source that is scattered onto parts of the retina lying outside the retinal image of the source.

street lighting luminaire a complete lighting device consisting of a light source and ballast, where

appropriate, together with its direct appurtenances such as globe, reflector, refractor, housing, and such support as is integral with the housing. The pole, post, or bracket is not considered part of the luminaire.
Note Modern street lighting luminaires contain the ballasts for high-intensity discharge lamps where such lamps are used; a photocontrol can be mounted on the luminaire.

street lighting unit the assembly of a pole or lamp post with a bracket and a luminaire.

striplight (theatrical) once an open trough reflector containing a series of lamps; now usually a compartmentalized luminaire with each compartment containing a lamp, reflector, and color frame holder, wired in rotation in three or four circuits and used as borderlights, footlights, or cyclorama lighting from above or below. Often in short 0.9- to 2.4-m [3- to 8-ft] portable sections.

stroboscopic lamp (strobe light) a flash tube designed for repetitive flashing.

subjective brightness the subjective attribute of any light sensation giving rise to the perception of luminous magnitude, including the whole scale of qualities of being bright, light, brilliant, dim, or dark. See *saturation of a perceived color*.
Note The term brightness often is used when referring to the measurable luminance. While the context usually makes it clear as to which meaning is intended, the term *luminance* should be used for the photometric quantity, thus reserving brightness for the subjective sensation.

sun bearing the angle measured in the plane of the horizon between a vertical plane at a right angle to the window wall and the position of this plane after it has been rotated to contain the sun.

sunburn inflammation with reddening (erythema) of the skin, of variable degree, caused by exposure to direct or diffuse solar radiation or artificial optical radiation.

sun lamp an ultraviolet lamp that radiates a significant portion of its radiative power in the UV-B band (280 to 315 nm).

sunlight direct visible radiation from the sun.

suntan a darkening of the skin due to an increase of melanin pigmentation above constitutive level and induced by UV radiation.

supplementary lighting lighting used to provide an additional quantity and quality of illumination that cannot readily be obtained by a general lighting system and that supplements the general lighting level, usually for specific work requirements.

supplementary standard illuminant D_{55} a representation of a phase of daylight at a correlated color temperature of approximately 5500 K.

supplementary standard illuminant D_{75} a representation of a phase of daylight at a correlated color temperature of approximately 7500 K.

surface-mounted luminaire a luminaire that is mounted directly on a ceiling.

suspended (pendant) luminaire a luminaire that is hung from a ceiling by supports.

switch start fluorescent lamp† See preheat *(switch start) fluorescent lamp*.

Systeme Internationale (SI)† a measurement system used throughout the world, commonly referred to as the metric system. Public Law 100-418 designated the metric system as the preferred system of weights and measures for the United States.

T

table lamp a portable luminaire with a short stand, suitable for standing on furniture.

tail lamp a lighting device used to designate the rear of a vehicle by a warning light.

talbot, T† a unit of light equal to one lumen-second.

tanning lamp an ultraviolet lamp that emits a significant portion of its radiative power in the UV-A band (315 to 400 nm) or UV-B band (280 to 315 nm).

task ambient lighting a combination of task lighting and ambient lighting within an area such that the general level of ambient lighting is lower than and complementary to the task lighting.

task lighting lighting directed to a specific surface or area that provides illumination for visual tasks.

taxi-channel lights aeronautical ground lights arranged along a taxi channel of a water airdrome to indicate the route to be followed by taxiing aircraft.

taxi light an aircraft aeronautical light designed to provide necessary illumination for taxiing.

taxiway centerline lights taxiway lights placed along the centerline of a taxiway except on curves or corners having fillets. These lights are placed a distance equal to half the normal width of the taxiway from the outside edge of the curve or corner.

taxiway edge lights taxiway lights placed along or near the edges of a taxiway.

taxiway holding-post light a light or group of lights installed at the edge of a taxiway near an entrance to a runway, or to another taxiway, to indicate the position at which the aircraft should stop and obtain clearance to proceed.

taxiway lights aeronautical ground lights provided to indicate the route to be followed by taxiing aircraft. See *taxiway centerline lights*, *taxiway edge lights*, and *taxiway holding-post light*.

temperature radiator an ideal radiator whose radiant flux density (radiant exitance) is determined by its temperature and the material and character of its surface and is independent of its previous history. See *blackbody* and *graybody*.

thermopile† a thermal radiation detector consisting of a number of thermocouples interconnected in order to increase the sensitivity to incident radiant flux.

threshold the value of a variable of a physical stimulus (such as size, luminance, contrast, or time) that permits the stimulus to be seen a specific percentage of the time or at a specific accuracy level. In many psychophysical experiments, thresholds are presented in terms of 50% accuracy, or accurately 50% of the time. However, the threshold also is expressed as the value of the physical variable that permits the object to be just barely seen. The threshold can be determined by merely detecting the presence of an object, or it can be determined by discriminating certain details of the object. See *absolute luminance threshold, brightness contrast threshold, luminance threshold*, and *modulation threshold.*

threshold lights runway lights so placed as to indicate the longitudinal limits of that portion of a runway, channel, or landing path usable for landing.

top light illumination of a subject directly from above, employed to outline the upper margin or edge of the subject.

torchère an indirect floor lamp that sends all or nearly all of its light upward.

tormentor lighting luminaires mounted directly behind the sides of the stage arch.

total emissivity† See *spectral-total directional emissivity* and *spectral-total hemispherical emissivity*.

total internal reflectance (TIR)† total reflection of a light ray at a surface of a transmitting medium occurs when the angle of incidence exceeds a certain value whose sine equals n_2/n_1, the ratio of indices of refraction, or when sin $r = 1$, where r equals the angle of reflection.

touchdown zone lights barrettes of runway lights installed in the surface of the runway between the runway edge lights and the runway centerline lights to provide additional guidance during the touchdown phase of a landing in conditions of very poor visibility.

traffic beam† See *lower (passing) beams*.

train the angle between the vertical plane through the axis of a searchlight drum and the corresponding plane in which this plane lies when the searchlight is in a position designated as having zero train.

transient adaptation factor (TAF) a factor that reduces the equivalent contrast due to readaptation from one luminous background to another.

transition lighting in roadway lighting, lighting gauged to compensate for visual adaptation between regions of high and low light level, as when entering tunnels.

translucent† transmitting light diffusely or imperfectly.

transmission a general term for the process by which incident flux leaves a surface or medium on a side other than the incident side, without change in frequency.
Note Transmission through a medium is often a combination of regular and diffuse transmission. See *diffuse transmission, regular transmission,* and *transmittance*.

transmissometer a photometer for measuring transmittance.
Note Transmissometers can be visual or physical instruments.

transmittance, $\tau = \Phi_t/\Phi_i$ the ratio of the transmitted flux to the incident flux. It should be noted that transmittance refers to the ratio of flux emerging to flux incident; therefore, reflections at the surface as well as absorption within the material operate to reduce the transmittance. Transmittance is a function of

1. Geometry
   - a. of the incident flux
   - b. of collection for the transmitted flux
2. Spectral distribution
   - a. characteristic of the incident flux
   - b. weighting function for the collected flux
3. Polarization
   - a. of the incident flux
   - b. component defined for the collected flux.

Notes (i) Unless the state of polarization for the incident flux and the polarized component of the transmitted flux are stated, it should be considered that the incident flux is unpolarized and that the total transmitted flux (including all polarization) is evaluated. (ii) Spectral transmittance depends on the beam geometry and the character of the transmitting surfaces and media (and polarization). In addition, luminous transmittance is a function of the spectral distribution of the incident beam. (iii) If no qualifying geometric adjective is used, transmittance for hemispherical collection is meant. (iv) In each case of conical incidence or collection, the solid angle is not restricted to a right circular cone but can be of any cross section, including a rectangle, a ring, or a combination of two or more solid angles. (v) These concepts must be applied with care if the area of the transmitting element is not large compared to its thickness, due to internal transmission across the boundary of the area. (vi) For all of the following geometrical quantitites--biconical transmittance, bidirectional transmittance, bihemispherical transmittance, conical-directional transmittance, conical-hemispherical transmittance, directional-conical transmittance, directional-hemispherical transmittance, hemispherical-conical transmittance, and hemispherical-directional transmittance--it is assumed that the radiance (luminance) is isotropic over the specified solid angle of incidence. Otherwise, the property is a function of the directional distribution of incident radiance (luminance) as well as the beam geometry and the character of the transmitting surfaces and/or media. The following breakdown of transmittance quantities is applicable only to the transmittance of thin films with negligible internal scattering, so that the transmitted radiation emerges from a point that is not significantly separated from the point of incidence of the incident ray that produces the transmitted ray(s). The governing considerations are similar to those for application of the *bidirectional reflectance distribution function* (BRDF), rather than the bidirectional scattering-surface reflectance distribution function (BSSRDF).

transparent† having the property of transmitting rays of light through its substance so that bodies situated beyond or behind can be distinctly seen (opposed to opaque and usually distinguished from translucent).

transverse roadway line (TRL) any line across a roadway that is perpendicular to the curb line.

tristimulus values of a light, X, Y, Z the amounts of each of three specific primaries required to match the color of the light.

troffer a long recessed lighting unit usually installed with the opening flush with the ceiling. The term is derived from "trough" and "coffer"

troland a unit of retinal illuminance that is defined as the product of object luminance (candela per square meter) and pupillary aperture area (square millimeters), that is, one troland is the retinal illuminance produced when the luminance of the distal stimulus is 1 cd/m^2 and the area of the pupil is 1 mm^2. The troland can be photopic or scotopic.
Note The troland makes no allowance for interocular attenuation or for the *Stiles-Crawford effect.*

tube† See *lamp*.

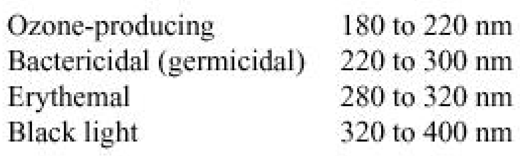
tungsten-halogen lamp a gas-filled tungsten filament incandescent lamp containing a certain proportion of halogens in an inert gas whose pressure exceeds 3 atm.
Note The tungsten-iodine lamp (U.K.) and quartz iodine lamp (U.S.) belong to this category. Obsolete U.S. term.

Turn-signal operating unit that part of a signal system by which the operator of a vehicle indicates the direction a turn will be made, usually by a flashing light.

U

ultraviolet lamp a lamp that emits a significant portion of its radiative power in the ultraviolet (UV) part of the spectrum; the visible radiation is not of principal interest.

ultraviolet radiation for practical purposes, any radiant energy within the wavelength range 100 to 400 nm is considered ultraviolet radiation. See *regions of the electromagnetic spectrum*.
Note On the basis of practical applications and the effect obtained, the ultraviolet region often is divided into the following bands:



Ozone-producing	180 to 220 nm
Bactericidal (germicidal)	220 to 300 nm
Erythemal	280 to 320 nm
Black light	320 to 400 nm

There are no sharp demarcations between these bands, the indicated effects usually being produced to a lesser extent by longer and shorter wavelengths. For engineering purposes, the black light region extends slightly into the visible portion of the spectrum.

units of luminance† the luminance of a surface in a specified direction can be expressed as luminous intensity per unit of projected area of surface or as luminous flux per unit of solid angle and per unit of projected surface area.
Note Typical units are cd/m^2 [$lm/(sr \times m^2)$] and cd/ft^2 [$lm/(sr \times ft^2)$]. The luminance of a surface in a specified direction is also expressed (incorrectly) in lambertian units as the number of lumens per unit area that would leave the surface if the luminance in all directions within the hemisphere on the side of the surface being considered were the same as the luminance in the specified direction. A typical unit in this system is the footlambert (fL), equal to 1 lm/ft^2. This method of specifying luminance is equivalent to stating the number of lumens that would leave the surface if the surface were replaced by a perfectly diffusing surface with a luminance in all directions within the hemisphere equal to the luminance of the actual surface in the direction specified. In practice no surface follows exactly the cosine formula of emission or reflection; hence the luminance is not uniform but varies with the angle from which it is viewed. For this reason, this practice is denigrated.

unrecoverable light loss factors† See *nonrecoverable light loss factors*.

upper (driving) beams† one or more beams intended for distant illumination and for use on the open highway when not meeting other vehicles. Often referred to as high beams. Formerly country beams. See lower (passing) beams.

upward component that portion of the luminous flux from a luminaire emitted at angles above the horizontal. See *downward component*.

utilance† See *room utilization factor*.

V

vacuum lamp an incandescent lamp in which the filament operates in an evacuated bulb.

valance a longitudinal shielding member mounted across the top of a window or along a wall (and is usually parallel to the wall) to conceal light sources, giving both upward and downward distributions.

valance lighting lighting comprising light sources shielded by a panel parallel to the wall at the top of a window.

values of spectral luminous efficiency for photopic vision, $V(\lambda)$ values at 5-nm intervals (see Chapter 1, Light and Optics) were provisionally adopted by the CIE in 1924 and were adopted in 1933 by the International Committee for Weights and Measures as a basis for the establishment of photometric standards of types of sources differing from the primary standard in spectral distribution of radiant flux.
Note These standard values of spectral luminous efficiency were determined by observations with a 2°

photometric field having a moderately high luminance. Photometric evaluations based upon them consequently do not apply exactly to other conditions of observation. Watts weighted in accord with these standard values are often referred to as light watts.

values of spectral luminous efficiency for scotopic vision, **$V'(\lambda)$** values at 10-nm intervals (see Chapter 1, Light and Optics) were provisionally adopted by the CIE in 1951.
Note These values of spectral luminous efficiency were determined by observation by young dark-adapted observers using extra-foveal vision at near-threshold luminance.

vapor-tight luminaire a luminaire designed and approved for installation in damp or wet locations. It also is described as enclosed and gasketed.

VASIS (Visual Approach Slope Indicator System) the system of angle-of-approach lights accepted as a standard by the International Civil Aviation Organization, comprising two bars of lights located at each side of the runway near the threshold and showing red or white or a combination of both (pink) to the approaching pilot, depending on his or her position with respect to the glide path.

veiling brightness a brightness superimposed on the retinal image that reduces its contrast. It is this veiling effect produced by bright sources or areas in the visual field that results in decreased visual performance and visibility.

veiling reflection regular reflections that are superimposed upon diffuse reflections from an object that partially or totally obscure the details to be seen by reducing the contrast. This sometimes is called *reflected glare*. Another kind of veiling reflection occurs when one looks through a plate of glass. A reflected image of a bright element or surface can be seen superimposed on what is viewed through the glass plate.

vertical plane of a searchlight the plane through the axis of the searchlight drum that contains the elevation angle. See *horizontal plane of a searchlight.*

visibility the quality or state of being perceivable by the eye. In many outdoor applications, visibility is defined in terms of the distance at which an object can be just perceived by the eye. In indoor applications it usually is defined in terms of the contrast or size of a standard test object, observed under standardized viewing conditions, having the same threshold as the given object. See *visibility (meteorological).*

visibility (meteorological) a term than denotes the greatest distance that selected objects (visibility markers) or lights of moderate intensity on the order of 25 candles (25 cd) can be observed and identified under specified conditions of observation. The distance can be expressed in kilometers or miles in the United States until the metric system becomes more widely used.

visibility level (VL) a contrast multiplier to be applied to the visibility reference function to provide the luminance contrast required at different levels of task background luminance to achieve visibility for specified conditions relating to the task and observer.

visibility performance criteria function (VL8) a function representing the luminance contrast required to achieve 99% visual certainty for the same task used for the visibility reference function, including the effects of dynamic presentation and uncertainty in task location.

visibility reference function (VL1) a function representing the luminance contrast required at different levels of task background luminance to achieve visibility threshold for the visibility reference task consisting of a disk that subtends 4 minutes of arc exposed for 0.2 s.

vision† See *central (foveal) vision, mesopic vision, peripheral vision, photopic vision,* and *scotopic vision*.

visual acuity a measure of the ability to distinguish fine details, measured with a set of optotypes (test types for determining visual acuity) of different sizes. Quantitatively, it is the reciprocal of the minimum angular size in minutes of the critical detail of an object that can just be seen.

visual angle the angle that an object or detail subtends at the point of observation. It usually is measured in minutes of arc.

visual approach slope indicator system† See *VASIS.*

visual comfort probability (VCP) the rating of a lighting system expressed as a percent of people who, when viewing from a specified location and in a specified direction, will be expected to find it acceptable in terms of discomfort glare. Visual comfort probability is related to the *discomfort glare rating (DGR).*

visual field the locus of objects or points in space that can be perceived when the head and eyes are kept fixed. Separate monocular fields for the two eyes can be specified or the combination of the two. See *binocular portion of the visual field, central visual field, monocular visual field*, and *peripheral visual field.*

visual perception the interpretation of impressions transmitted from the retina to the brain in terms of information about a physical world displayed before the eye.
Note Visual perception involves any one or more of the following recognizing the presence of something (object, aperture, or medium); identifying it; locating it in space; noting its relation to other things; and identifying its movement, color, brightness, or form.

visual performance the quantitative assessment of the performance of a visual task, taking into consideration speed and accuracy.

visual photometer one in which the equality of brightness of two surfaces is established visually. See *physical photometer.*
Note The two surfaces usually are viewed simultaneously side by side. This is satisfactory when the color difference between the test source and comparison source is small. However, when there is a color difference, a flicker photometer provides more precise measurements. In this type of photometer the two surfaces are viewed alternately at such a rate that the color sensations either nearly or completely blend, and the flicker due to brightness difference is balanced by adjusting the comparison source.

visual range (of a light or object) the maximum distance at which that particular light (or object) can be seen and identified.

visual surround includes all portions of the visual field except the visual display used in performing a task.

visual task conventionally designates those details and objects that must be seen for the performance of a given activity, and includes the immediate background of the details or objects.
Note The term *visual task* as used is a misnomer because it refers to the visual display itself and not the task of extracting information from it. The task of extracting information also has to be differentiated from the overall task performed by the observer.

visual task evaluator (VTE) a form of visibility meter that measures the level of contrast of a given visual display above the threshold of visibility. The ratio of the contrast of a display to its threshold contrast represents its level of visibility. Used to evaluate the visibility level (VL).

vitrine† a transparent enclosure of glass or acrylic around an artifact, usually the top of a display case.

volt† the difference in electrical potential between two points in a circuit. It is also called the electromotive force. The symbol often used in equations is "E" (from the latter term), although "V" is also acceptable.

voltage-to-luminaire factor the fractional loss of illuminance due to improper voltage at the luminaire.

W

watt† the unit of power (rate of doing work). In electrical calculations, one watt is the power produced by a current of one ampere across a potential difference of one volt. The symbol often used in equations is "P," although "W" is also acceptable.

wavelength† the distance between two successive points of a periodic wave, in the direction of propagation, at which the oscillation has the same phase. The three commonly used units are listed in the following table:

The use of the terms micron and angstrom is deprecated.

Name	Symbol	Size
micrometer (micron)	µm	10^{-6} m
nanometer	nm	10^{-9} m
angstrom	Å	10^{-10} m

Weber's fraction† See *luminance contrast.*

wide-angle diffusion that in which flux is scattered at angles far from the direction that it would take by regular reflection or transmission. See *narrow-angle diffusion*.

wide-angle luminaire a luminaire that concentrates the light within the cone of a comparatively large solid angle. See *narrow-angle luminaire.*

width line (roadway lighting) the radial line (the one that makes the larger angle with the reference line) that passes through the point of one-half maximum intensity on the lateral intensity distribution curve plotted on the surface of the cone of maximum intensity.

Wien displacement law an expression representing, in a functional form, the spectral radiance of a blackbody as a function of the wavelength and the temperature:

$$L_\lambda = \frac{dI_\lambda}{dA'} = c_{1L}\lambda^{-5} f(\lambda T)$$

The two principal corollaries of this law are

$$\lambda_\mathrm{m} T = b \qquad \frac{L_\mathrm{m}}{T^5} = b'$$

which show how the maximum spectral radiance L_m and the wavelength λ_m at which it occurs are related to the absolute temperature *T*. See *Wien radiation law.*

Note The currently recommended value of b is 2.8978×10^{-3} m × K or 2.8978×10^{-1} cm × K. From the Planck radiation law, b′ is found to be 4.0956×10^{-14} ($\mathrm{W} \times \mathrm{cm}^{-2} \times \mathrm{sr}^{-1} \times \mu\mathrm{m}^{-1} \times \mathrm{K}^{-5}$).

Wien radiation law an expression representing approximately the spectral radiance of a blackbody as a function of its wavelength and temperature. It commonly is expressed by the formula

This formula is accurate to 1% or better for values of λT less than 3000 µm × K.

$$L_\lambda = \frac{dI_\lambda}{dA'} = c_{1L}\lambda^{-5}e^{-c_2/\lambda T}$$

wing clearance lights a pair of aircraft lights provided at the wing tips to indicate the extent of the wing span when the navigation lights are located an appreciable distance inboard of the wing tips.

working standard a standardized light source for regular use in photometry.

workplane the plane on which a visual task is usually done, and on which the illuminance is specified and measured. Unless otherwise indicated, this is assumed to be a horizontal plane 0.76 m (30 in.) above the floor.

Z

zonal-cavity interreflectance method a procedure for calculating coefficients of utilization, wall exitance coefficients, and ceiling cavity exitance coefficients, taking into consideration the luminaire intensity distribution, room size and shape (cavity ratio concepts), and room reflectances. It is based on flux transfer theory.

zonal constant a factor by which the mean intensity emitted by a source of light in a given angular zone is multiplied to obtain the lumens in the zone. See Chapter 2, Measurement of Light and Other Radiant Energy.

zonal factor interreflection method a procedure used for calculating coefficients of utilization, based on integral equations, that takes into consideration the ultimate disposition of luminous flux from every 10° zone from luminaires.

zonal factor method a procedure for predetermining, from typical luminaire photometric data in discrete angular zones, the proportion of luminaire output that would be incident initially (without interreflections) on the workplane, ceiling, walls, and floor of a room.

zonal multipliers multipliers for the flux in each 10-degree conical zone from 0° (nadir) to 90° (horizontal) from a luminaire, expressing the fraction of that zonal flux that is directly incident on the floor of a room cavity. These multipliers are a function of the room cavity ratio and are used to determine the direct ratio.