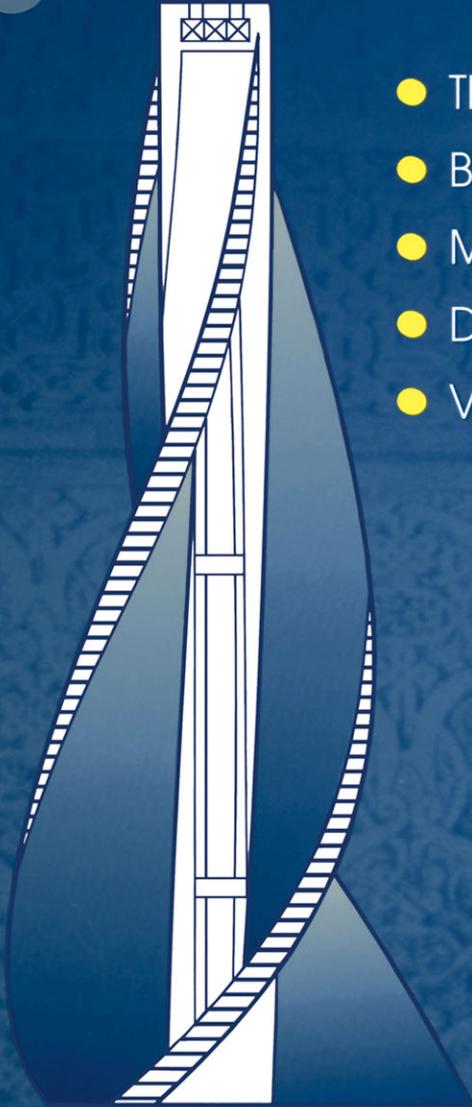


ARCHITECTURE



COMFORT AND ENERGY



- Thermal Comfort
- Bioclimatic Design
- Microclimatic Elements
- Daylighting
- Ventilation

Edited by
C. Gallo M. Sala A.M.M. Sayigh



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ARCHITECTURE: COMFORT AND ENERGY

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ARCHITECTURE: COMFORT AND ENERGY

Editors

C. Gallo, M. Sala, A.A.M. Sayigh



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**RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS**

Introduction

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Energy and architecture form a natural marriage if indoor comfort and respect for environment are secured. The role of energy within buildings varies from country to country, climate to climate; from 30% in OECD countries, 50% in non-OECD Europe to 70% in developing countries. Population growth and demand for housing have forced politicians to embark on massive housing schemes without consideration of comfort, energy demand and environmental issues. In this book we are seeking to understand how previous generations lived in harsh climates and without abundant sources of energy, yet managed to design and build appropriate dwellings providing both comfort and harmony with the environment. We have only to look at the Vernacular architecture which existed in the areas of extreme climate such as India, Africa and Scandinavia where indigenous materials were utilised to construct attractive and comfortable homes.

Modern technology has provided us with excellent new materials such as “switchable” material; light but strong structural materials and a variety of insulations. It is now commonly accepted by architects and builders that due consideration must be given to energy conservation; the use of natural lighting and use of solar energy for both heating and cooling; as well as enhanced natural ventilation and minimal impact on the environment.

In this book we seek to approach the architecture-energy combination and its relationship to the environment. There are chapters on thermal comfort, low energy architecture dealing with various criterion for comfort in different parts of the World. For example in the State of Qatar 50% of the energy used in that country can be saved by using low energy buildings with several measures such as shading, evaporative cooling, the use of appropriate thermal mass and natural ventilation coupled with radiative cooling. Contemporary architecture, in some cases, ignores most of these elements and concentrates on using excessive energy to cool or heat buildings. In the Gulf Region, 70% of the electricity generated is used for cooling the buildings.

Other chapters state the principles of thermal comfort, how the thermal exchange takes place between man and the various parts of the building elements. Some authors developed their own models to evaluate such exchange. The bioclimatic concept in Vernacular Architecture was addressed thoroughly in one chapter starting a good comparison between Vernacular and contemporary architecture, then addressing the impact of climate on the building forms. The climate which plays a major role at

different locations and how this dictates the shape and form of the buildings and save some energy. The igloo of the Inuit and the open courtyard houses of the Mediterranean are good examples of typologies depending on the climate.

Another chapter is devoted to the importance of micro-climate and its various elements and usage to obtain comfort such as the air movement, the Sun effect, the thermal mass, the vegetation, shading devices and the use of water and moisture in improving living conditions in a dry climate.

One of the most important energy saving elements in buildings is the use of daylighting to conserve and reduce heat gain into buildings. It explains the various conditions of the sky, the basic physical principle of lighting, the physiology of vision, and goes to the use of daylighting in architecture to improve the building design and accesses this use effectively.

Ventilation and its importance in buildings was presented in another chapter where the indoor pollutants, ventilation strategies, the air flow principles, air leakage in buildings, natural and solar induced ventilation and mechanical ventilation were explained and their usage was demonstrated.

The last chapter outlines in depth the technology for modern architecture. The elements and concepts such as ventilated roofs, active curtain walls, the use of greenhouses, movable shading devices, light ducts, integrated ventilation, cooling elements and the use of outdoor spaces are all researched and their uses have been illustrated in this chapter.

We hope the book will be of use to architectural students; building technologists; energy experts and urban and town planners. It will be equally interesting to all those who are concerned about the environment and advocate the use of appropriate technologies to reduce energy consumption.



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**RENEWABLE
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Chapter 1—Thermal comfort and the development of bioclimatic concept in building design

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1. Introduction

In the past few decades, there have been several attempts to develop a systematic methodology for adapting the design of a building to human requirements and climatic conditions. Such attempts include the development of the building bioclimatic charts and Mahony tables. These attempts were aimed at defining the appropriate building design strategies, for a certain region. This chapter details an attempt to adopt the building bioclimatic chart concept as well as Mahony tables to Qatar, which is used as an example, in order to determine the most appropriate building design strategies.

2. Thermal comfort

According to ASHRAE 55-74 standard [1], thermal comfort is defined as “That condition of mind which expresses satisfaction with the thermal environment”. However, the comfort zone is defined as the range of climatic conditions within which the majority of people would not feel thermal discomfort, either of heat or cold. Thermal comfort studies either based on field surveys or on controlled climatic chambers. The Fanger comfort equation and Humphrey’s Thermal Neutrality correlation are among the most commonly adopted concepts.

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2.1. Fanger thermal equation

Macpherson [2] identified six factors that affect thermal sensation. These factors are air temperature, humidity, air speed, mean radiant temperature (MRT), metabolic rate and clothing levels. He also identified nineteen indices for the assessment of the thermal environment. Each of these indices incorporate one or more of the six factors.

The Fanger comfort equation is the most commonly adopted. It is based on experiments with American college-age persons exposed to a uniform environment under steady state conditions. The comfort equation establishes the relationship among the environment variables, clothing type and activity levels. It represents the heat balance of the human body in terms of the net heat exchange arising from the effects of the six factors identified by Macpherson. The satisfaction of eqn (1) is a necessary condition for optimal comfort.

$$\begin{aligned} & (M/A_{Du})(1-\eta) - 0.35[1.92t_s - 25.3 - P_a] - (E_{sw}/A_{Du}) - 0.0023(M/A_{Du})(44 - P_a) \\ & - 0.0014(M/A_{Du})(34 - t_a) = 3.4 \times 10^{-8} f_{cl}[t_{cl} + 273]^4 - (t_{mrt} + 273)^4 \\ & + f_{cl}h_c(t_{cl} - t_a) \end{aligned} \quad (1)$$

Equation (1) contains three physiological variables; the heat loss by evaporation of sweat, skin temperature and metabolic rate. Based on his experimental data and others, Fanger proposed the following equations for these variables as functions of the internal heat production per surface area, (H/A_{Du})

$$t_s = 35.7 - 0.032(H/A_{Du}) \quad (2)$$

$$E_{sw} = 0.42 A_{Du}[(H/A_{Du}) - 50] \quad (3)$$

Substituting eqns (2) and (3) into eqn (1) Fanger derived the general comfort equation

$$\begin{aligned} & (M/A_{Du})(1-\eta) - 0.35[43 - 0.061(M/A_{Du})(1-\eta) - P_a] \\ & - 0.42[(M/A_{Du})(1-\eta) - 50] - 0.0023(M/A_{Du})(44 - P_a) - 0.0014(M/A_{Du})(34 - t_a) \\ & = 3.4 \times 10^{-8} f_{cl}[t_{cl} + 273]^4 - (t_{mrt} + 273)^4 + f_{cl}h_c(t_{cl} - t_a) \end{aligned} \quad (4)$$

It is clear from eqn (4) that the human thermal comfort is a function of:

- (i) The type of clothing t_{cl} , f_{cl}
- (ii) The type of activity, η , V and M/a_{Du}
- (iii) Environmental variables V , t_a , t_{mrt} and P_a

2.2. Predicted mean vote (PMV)

The thermal comfort equation is only applicable to a person in thermal equilibrium with the environment. However, the equation only gives information on how to reach optimal thermal comfort by combining the variables involved. Therefore, it is not

directly suitable to ascertain the thermal sensation of a person in an arbitrary climate where these variables may not satisfy the equation. Fanger used the heat balance equation to predict a value for the degree of sensation using his own experimental data and other published data for any combination of activity level, clothing value and the four thermal environmental parameters. As a measure for the thermal sensation index the commonly used seven point psycho-physical ASHRAE scale was employed. Table 1 summarises the commonly used scales. The term Predicted Mean Vote (PMV) is the mean vote expected to arise from averaging the thermal sensation vote of a large group of people in a given environment. The PMV is a complex mathematical expression involving activity, clothing and the four environmental parameters. It is expressed by eqn (5)

$$\begin{aligned}
 PMV = & (0.352e^{-0.042(M/A_{Du})} + 0.032)[M/A_{Du}](1-\eta) \\
 & - 0.35[43 - 0.061(M/A_{Du})(1-\eta) - P_a] \\
 & - 0.42[M/A_{Du}](1-\eta) - 50] - 0.0023(M/A_{Du})(44 - P_a) \\
 & - 0.0014(M/A_{Du})(34 - t_a) - 3.4 \times 10^{-8} f_{cl}[t_{cl} + 273]^4 \\
 & - (t_{mrt} + 273)^4] + f_{cl} h_c (t_{cl} - t_a)
 \end{aligned} \tag{5}$$

here h_c is calculated as follows:

$$\begin{aligned}
 h_c &= 2.05(t_{cl} - t_a)^{0.25} \text{ for } 2.05(t_{cl} - t_a)^{0.25} > 10.4\sqrt{V} \\
 h_c &= \sqrt{V} \text{ for } 2.05(t_{cl} - t_a)^{0.25} < 10.4\sqrt{V}
 \end{aligned}$$

The thermal sensation scales assumes equal intervals between the expressions of thermal sensation. Hence, the degree of deviation from the neutral or optimal conditions of thermal comfort are transferred into numbers rather than expressions. Such transformation of the facts from expressions to numbers enabled the workers to further investigate the percentages of responses of individuals to certain conditions. The conditions vary according to environmental, human activity level and body insolation factors. Accordingly, such conditions can be plotted in thermal comfort charts. From these charts the level of thermal comfort can be measured at certain conditions of the previously mentioned factors. Fanger [3] suggested such charts

Table 1
Thermal sensation scales

Expression	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
ASHRAE	1	2	3	4	5	6	7
Fanger	-3	-2	-1	0	1	2	3

which were updated and modified afterwards. Based on more recent research Markus and Morris [4] worked out 55 thermal comfort charts. The scale used is similar to Fanger's PMV, with neutrality at zero, with negative values in the cold and positive ones on the warm. The charts have two distinct advantages. First, they have been validated over a wide range of conditions and not merely the normal 'room' conditions. Second, they express judgements in degrees of discomfort (DISC) and thus equivalences can be found between cold and warm conditions in terms of a common human response. Between DISC -0.5 and $+0.5$, 80% of the population will be satisfied, and between -1.0 and $+1.0$, it drops to 70%. The charts were based on a range of human activities, environmental conditions and body insolation factors:

- (i) Clothing: 0.0 (nude), 0.6, 0.9, 2.4 and 4.0 clo.
- (ii) Activity: 1, 3 and 5 Met.
- (iii) Air velocity: 0.1, 0.5, 2.0, 5.0 and 10 ms^{-1} .

Knowing the activities of the people inside a specific space, their type of clothing and air velocity inside the space, one can obtain from the thermal comfort charts the following design parameters:

- (i) The standard effective temperature, SET.
- (ii) The degree of discomfort, DISC;
- (iii) The skin wettedness, w (which is defined as the equivalent percentage of the human body which is covered with moisture).

The thermal comfort chart presented, as an example, in Fig. 1 for the conditions of 0.6 clo. of clothing, 0.1 ms^{-1} air velocity (still air) and 1.0 Met of activity (sedentary).

2.3. Thermal neutrality

Humphrey [5] Auliciemes investigated the thermal neutrality of the human body. It was defined as the temperature at which the person feels thermally neutral (comfortable). Their studies were based on laboratory and field works in which people were thermally investigated under different conditions. The results of their experiments were statistically analysed by using regression analysis. Figure 2 shows that thermal neutrality as a function of the prevailing climatic conditions. Humphreys showed that 95% of the neutral temperature is associated with the variation of outdoor mean temperature. For free running buildings, the regression equation is approximated by

$$T_n = 11.9 + 0.534T_m \quad (6)$$

A different empirical correlation function was carried out by Auliciemes is

$$T_n = 17.6 + 0.314T_m \quad (7)$$

Based on the above equations, the predicted neutral temperature for Qatar for the different months of the year are as indicated in Table 2. Table 2 indicates that Auliciemes overvalues the thermal neutrality temperatures for the winter months,

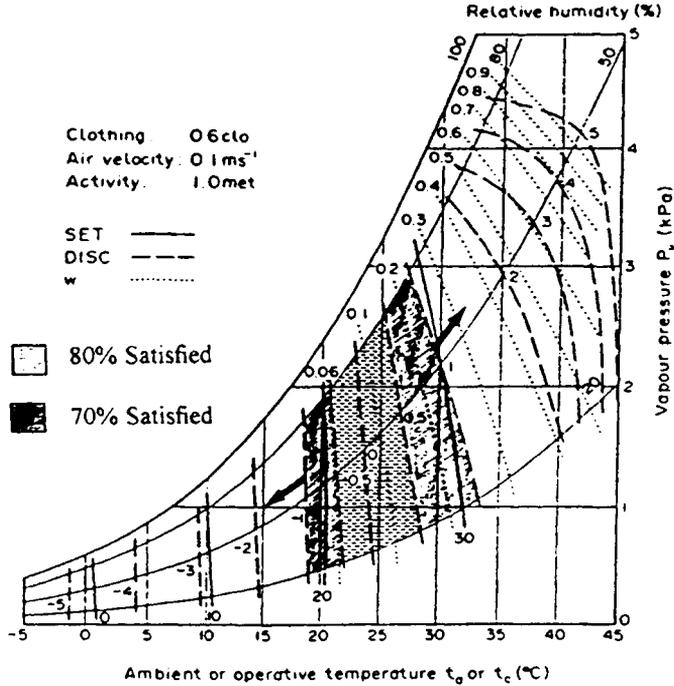


Fig. 1. The thermal comfort chart, for the conditions: 0.6 clo, 0.1 ms⁻¹ and 1.0 Met [4].

while Humphrey does the same for the summer months. The summer neutrality temperature for Qatar is about 28.5°C whereas in winter it drops to about 23°C.

3. Degree day method for estimating heating and cooling requirements for Qatar

The degree day method is a pure climatic concept to estimate the cooling and heating requirements at any location. It can be visualized as the annual cumulative time weighted temperature deficit (heating degree-days) or surplus (cooling degree-days). A reference temperature is set and every days mean outdoor temperature is compared with the reference temperature. The differences are added for every day to give the annual number of degree days. Table 3 lists the annual cooling and heating degree days for Qatar. Two reference temperatures were considered, according to ASHRAE standard and Humphreys neutral temperature as indicated in Table 3. The reference temperatures for Qatar, in accordance with ASHRAE standard, are generally lower than that estimated by Humphrey's equation. This resulted in higher cooling degree days and lower heating degree days with ASHRAE standard compared to those obtained with Humphreys correlation. It is also clear from Table 3 that the

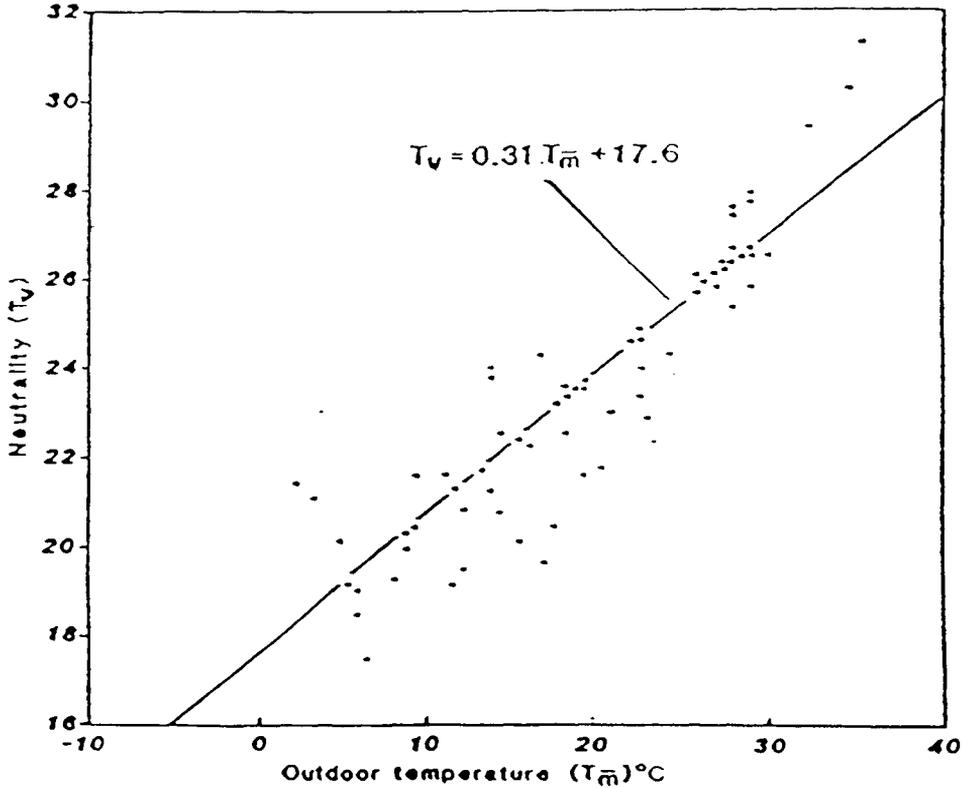


Fig. 2. Correlation of outdoor mean temperature and thermal neutrality [5].

Table 2
Thermal neutrality temperatures for Qatar

Month	Humphreys $T_n(^{\circ}$ C)	Auliciemes $T_n(^{\circ}$ C)
J	20.9	22.7
F	22.0	23.2
M	23.5	24.2
A	26.0	25.7
M	29.2	27.5
J	30.1	28.0
J	31.0	28.5
A	30.9	28.5
S	29.8	27.8
O	27.7	26.6
N	25.5	25.4
D	20.8	22.7

Table 3

Degree day method applied to Qatar based on ASHRAE standard and neutrality temperature concept

Month	Cooling Degree-Days $T_{\text{ref}} = 26^{\circ}\text{C}$		Heating Degree-Days $T_{\text{ref}} = 18.3^{\circ}\text{C}$	
	ASHRAE $T_{\text{ref}} = 26^{\circ}\text{C}$	Humphrey's $T_n = 28.5$	ASHRAE $T_{\text{ref}} = 18.3^{\circ}\text{C}$	Humphrey's $T_n = 23^{\circ}\text{C}$
J	0	0	59	202
F	0	0	73	195
M	0	0	2	49
A	31	7	0	0
M	180	102	0	0
J	227	152	0	0
J	286	208	0	0
A	280	203	0	0
S	209	134	0	0
O	90	25	0	0
N	6	0	0	0
D	0	0	68	133
Total	1309	831	202	578

cooling requirements are high, and generally, extending from May to October. The months of March, April and November can be considered as being comfortable.

4. Building bioclimatic charts

Bioclimatic charts facilitate the analysis of the climate characteristics of a given location from the viewpoint of human comfort, as they present, on a psychrometric chart, the concurrent combination of temperature and humidity at any given time. They can also specify building design guidelines to maximize indoor comfort conditions when the building's interior is not mechanically conditioned. All such charts are structured around, and refer to, the 'comfort zone'. The comfort zone is defined as the range of climatic conditions within which the majority of persons would feel thermally comfortable.

4.1. Olgays bioclimatic chart

Olgays bioclimatic chart [6], Fig. 3, was one of the first attempts at an environmentally conscious building design. It was developed in the 1950s to incorporate the outdoor climate into building design. The chart indicates the zones of human comfort in relation to ambient temperature and humidity, mean radiant temperature (MRT), wind speed, solar radiation and evaporative cooling. On the chart, dry bulb tem-

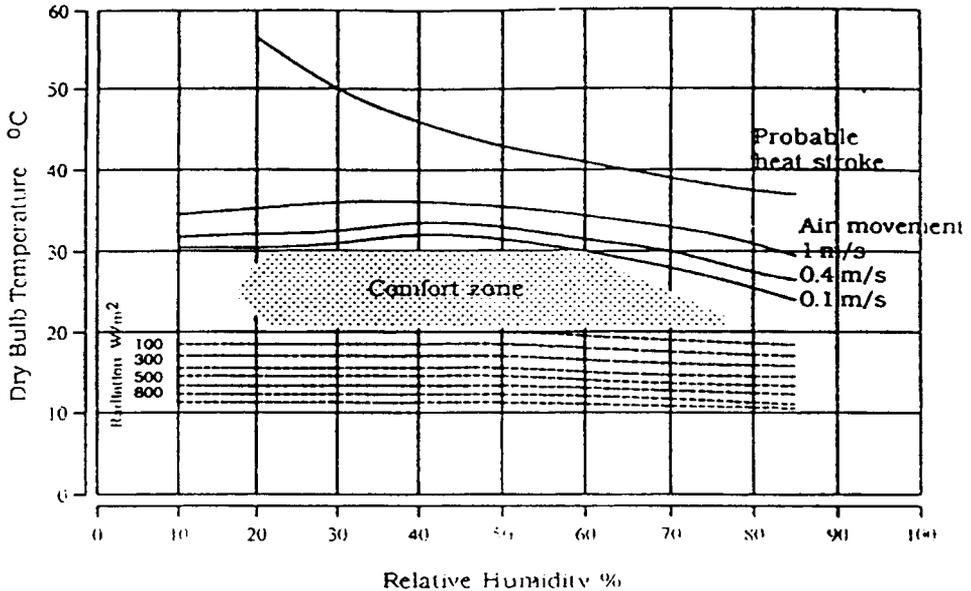


Fig. 3. Olgays building bioclimatic chart [6].

perature is the ordinate and relative humidity is the abscissa. The comfort zone is in the centre, with winter and summer ranges indicated separately (taking seasonal adaptation into account). The lower boundary of the zone is also the limit above which shading is necessary. At temperatures above the comfort limit the wind speed required to restore comfort is shown in relation to humidity. Where the ambient conditions are hot and dry, the evaporative cooling (EC) necessary for comfort is indicated. Variation in the position of the comfort zone with mean radiant temperature (MRT) is also indicated.

4.1.1. Limitations and problems impairing the use of Olgays bioclimatic chart

The concept of the chart was based on the outdoor climatic conditions. This resulted in some limitations in analysing the physiological requirements of the indoor environment of the building. Therefore the chart is applicable to a hot humid climate since there is no high range fluctuations between indoor and outdoor conditions.

4.1.2. Applicability of Olgays bioclimatic chart to Qatar

The bioclimatic chart of Qatar is shown in Fig. 4. The twelve lines represent the different months of the year. They represent the average daily maxima and average daily minima data of both relative humidity and dry bulb temperature. The chart indicates that for the months of April–June, October and November shading ventilation can be effective tools in restoring comfort. On the other hand, for the months of July, August and September the temperature and relative humidity is so high that only conventional dehumidification and air conditioning can restore comfort. For the

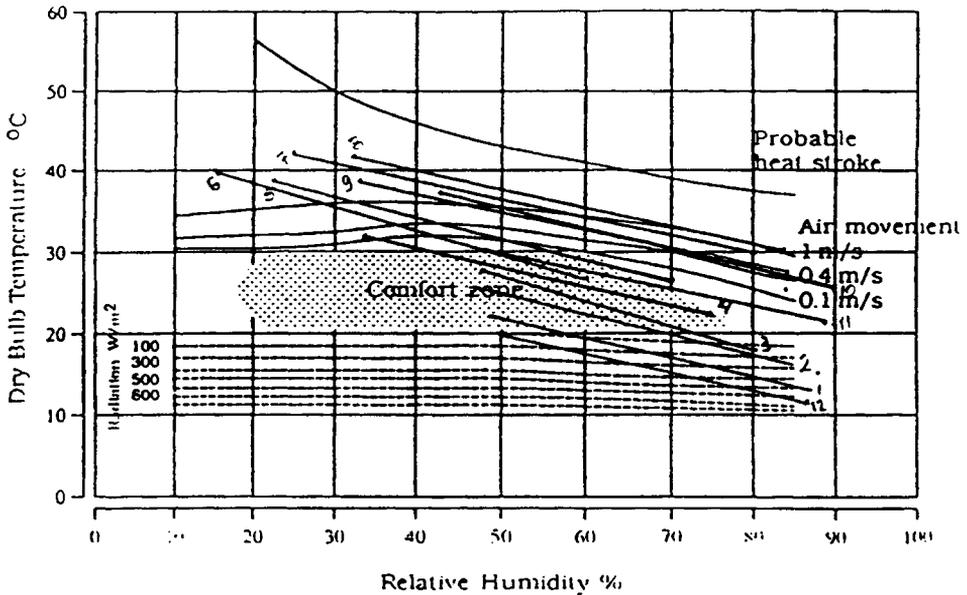


Fig. 4. Olgays chart applied to Qatar.

winter months (December–March) the chart indicates that solar radiation should be encouraged. For example, in January, the radiation needed to bring the outdoor condition to the lower limit of the comfort zone is about 600 Wm^{-2} .

4.2. Givoni's bioclimatic chart

Givoni's bioclimatic chart [7], Fig. 5, aimed at predicting the indoor conditions of the building according to the outdoor prevailing conditions. He based his study on the linear relationship between the temperature amplitude and vapour pressure of the outdoor air in various regions. In his chart and according to the relationship between the average monthly vapour pressure and temperature amplitude of the outdoor air, the proper passive cooling strategies are defined according to the climatic conditions prevailing outside the building envelope. The chart combines different temperature amplitude and vapour pressure of the ambient air plotted on the psychrometric chart and correlated with specific boundaries of the passive cooling techniques overlaid on the chart. These techniques include evaporative cooling, thermal mass, natural ventilation cooling, passive heating.

4.2.1. Limitations of Givoni's bioclimatic chart

In 1981 Watson [8] identified the limitations of Givoni's bioclimatic chart analysis as:

- (i) It can be applied mainly to residential scale structures which are free of any internal heat gains .

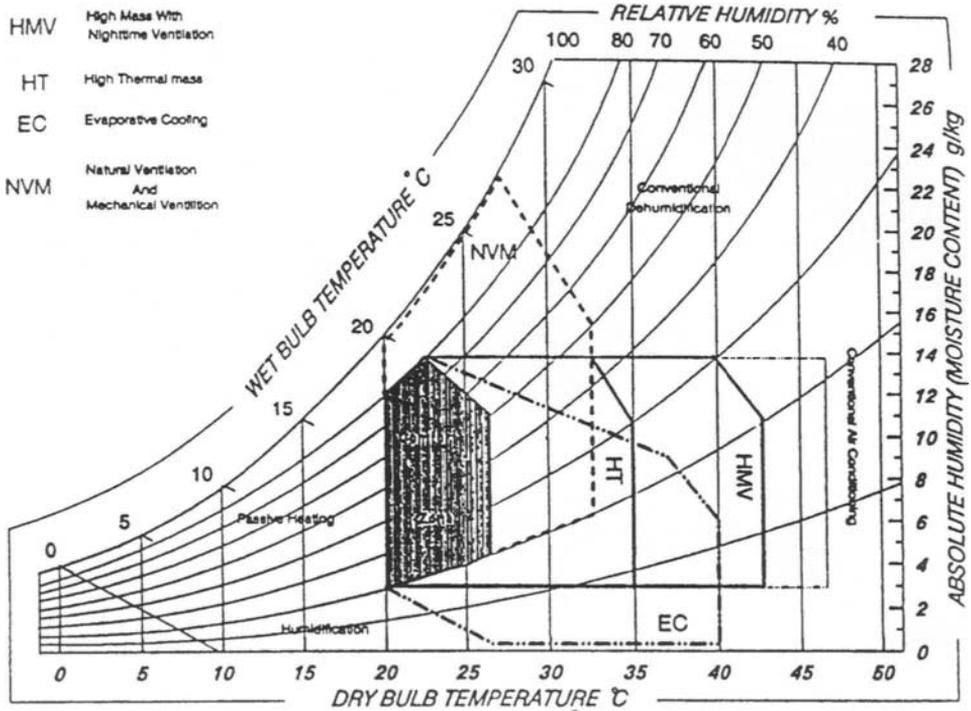


Fig. 5. Givoni's building bioclimatic chart [6].

- (ii) The ventilation upper boundary zone is based on the assumption that indoor mean radiant temperature and vapour pressure are nearly the same as those of the external environment. This necessitates a building of low mass and an exterior structure of medium to high thermal resistance provided with white external paint.
- (iii) The thermal mass effectiveness is based on the assumption that all windows are closed during the daytime, a still indoor air and the indoor vapour pressure is 2 mm higher than the outside.

4.2.2. Applicability of Givoni's bioclimatic chart to Qatar

The chart applied to Qatar is shown in Fig. 6. The chart indicates that high mass building coupled with night time ventilation can effectively restore comfort for the months of April, May, June, October and November. However, for the months of July, August and September, the high ambient temperature and humidity indicate that passive techniques are ineffective and conventional means (dehumidification and air conditioning) are therefore essential to restore comfort in buildings. Furthermore, passive heating can restore comfort from December through March.

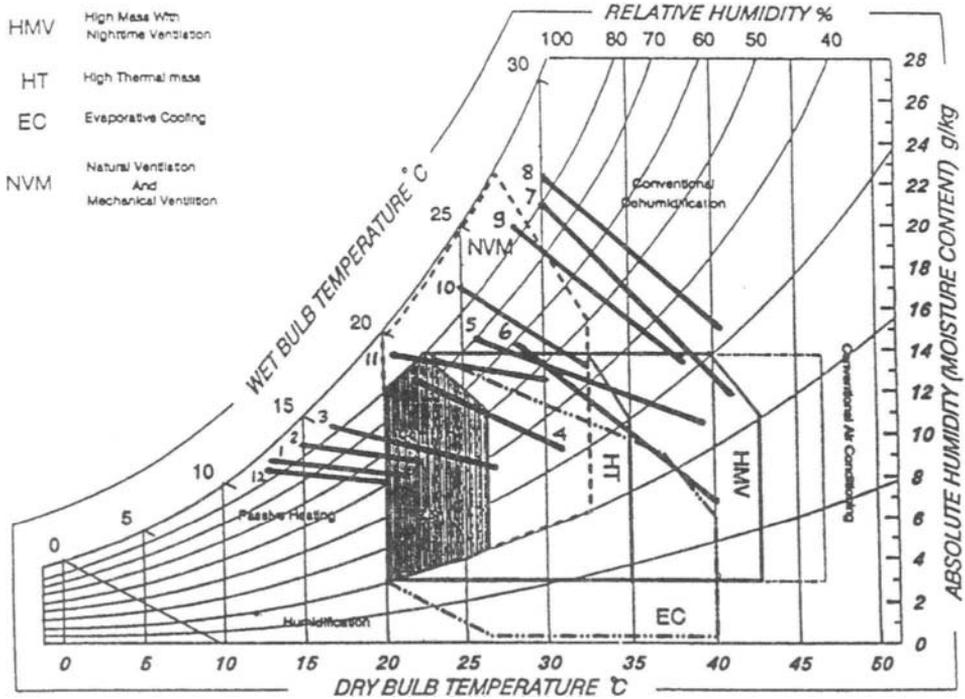


Fig. 6. Givoni's building bioclimatic chart applied to Qatar.

4.3. Szokolay's bioclimatic chart

Givoni, in 1970, published his analysis of the Index of Thermal Stress, which was followed by Humphreys [5] in 1978 and Auliciemes in 1982 with their Thermal Neutrality equations. Szokolay [9] in 1986 brought these separate strands of thought together and developed the concept that, depending on the location and the people of that location, there are, in fact, two comfort zones rather than one, Fig. 7. The zones are based on thermal neutrality correlated to the outdoor mean temperature (T_m) by eqn (8):

$$T_n = 17.6 + 0.31T_m \tag{8}$$

Equation (8) is only valid under the following conditions:

- (i) $18.5 < T_n < 28.5$
- (ii) The width of the comfort zone is 2 K at 50% relative humidity.
- (iii) Humidity boundaries are based on ASHRAE standard 55-81 which set the lower and upper limits at 4–12 g kg⁻¹ moisture content (AH).
- (iv) Relative humidity should not exceed 90% RH curve.

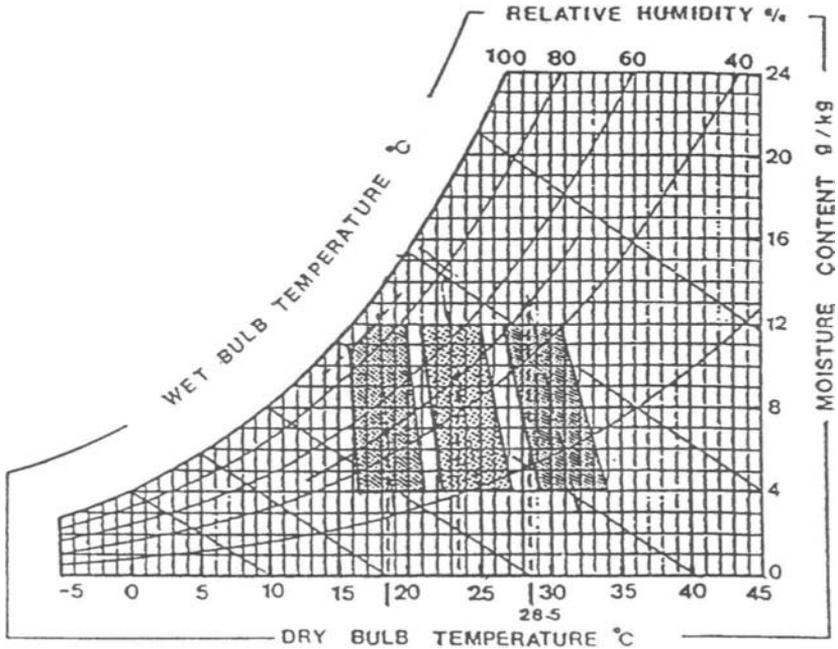


Fig. 7. Szokolay control potential zone chart [9].

4.3.1. Applicability of the control potential zones (CPZ) to Qatar

The control potential zones indicate that the strategies which can be followed to restore comfort in buildings in Qatar are similar to those indicated by Givoni's bioclimatic chart, Fig. 8.

5. Problems impairing the use of the bioclimatic charts

Arens [10] discussed the problems impairing the use of the bioclimatic charts. Such problems include:

- (i) The monthly average of wind, humidity and temperature are a poor representation of the widely varying coincident occurrences of these variables.
- (ii) The result of the graphic method is not a measurable quantity: during some months it will be seen that ventilation is inadequate to provide comfort, but the number of hours in which this occurs during these months cannot be determined.
- (iii) There is no provision for cloth changing and activity levels throughout the day or seasons.
- (iv) The charts do not account for acclimatization. The effect of acclimatization and comfort expectations should be taken into account especially when comfort

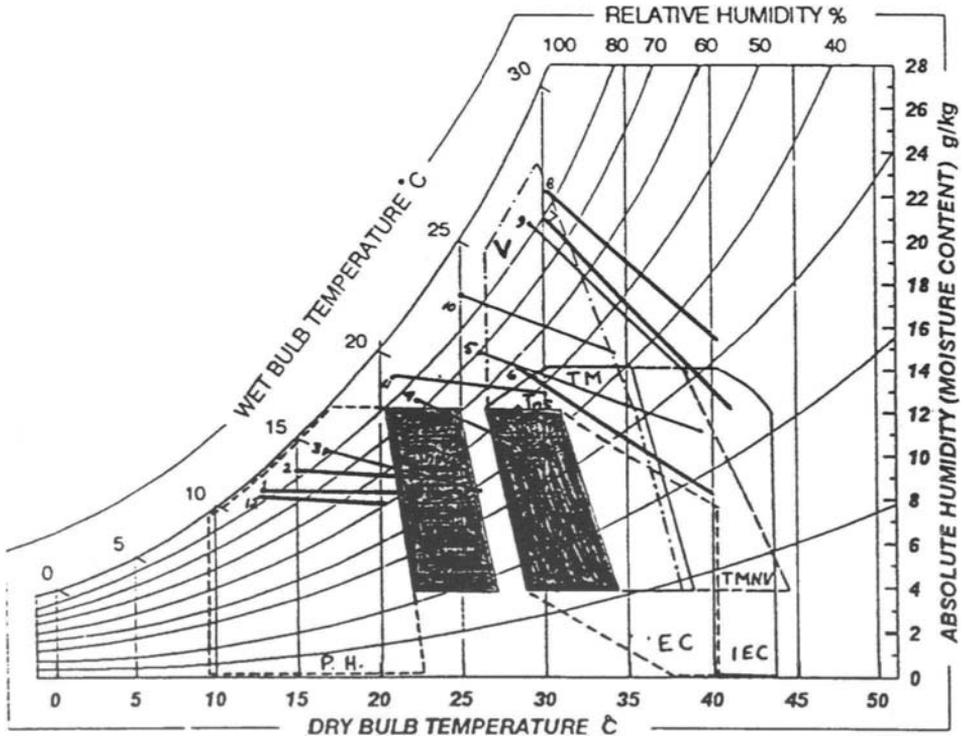


Fig. 8. Szokolay control potential zone applied to Qatar.

diagrams, and buildings design guidelines, are constructed for, and applied in, warm/hot developing countries [11].

6. Mahony tables

The Department of Development and Tropical Studies of the Architectural Association in London developed a methodology for building design in accordance to climate. The proposed methodology is based on three stages of design, the sketch design stage, the plan development stage and the element design stage. For the purpose of systematic analysis during the three stages, they introduced the Mahony Tables. The tables are used to analyse the climate characteristics, from which design indicators are obtained. From these indicators a preliminary picture of the layout, orientation, shape and structure of the climatic responsive design can be obtained. These tables are briefly described below.

6.1. Climatic data

The climatic data such as dry bulb temperature, relative humidity, precipitation and wind are classified into groups as described in Table 4.

Table 4
Climatic data

Mean relative humidity	Humidity group
Below 30%	1
30–50%	2
50–70%	3
Above 70%	4

Similarly the monthly mean maxima and minima of the site in question are compared to the day and night comfort limits for each individual month, according to the annual mean ranges given in Table 8 respectively (i.e., maxima with the day comfort limit and minima with the night comfort limits). The classification is established as follows:

Above comfort limit H
 Within comfort limit —
 Below comfort limit C

The humidity and comfort classifications are compared for each month to establish humidity and arid indicators.

6.1.1. Humidity indicators

- H1 Indicates that air movement is essential. It applies when high temperature (day thermal stress = H) is combined with high humidity ($HG = 4$) or when the high temperature (day thermal stress = H) is combined with moderate humidity ($HG = 2$ or 3) and a small diurnal range ($DR < 10$ C).
- H2 Indicates that air movement is desirable. It applies when temperature within the comfort limit (day thermal stress = —) are combined with high humidity ($HG = 4$)
- H3 Indicates that precautions against rain penetration are needed. Problems may arise with even low precipitation, but will be inevitable when rainfall exceeds 200 mm per month.

6.1.2. Arid indicators

- A1 Need for thermal storage. This applies when a large diurnal range (10 C or more) coincides with moderate or low humidity ($HG = 1, 2$ or 3)
- A2 Indicates the desirability of outdoor sleeping space. It is needed when the night temperature is high (night thermal stress = H) and the humidity is low ($HG = 1$ or 2). It may be needed also when nights are comfortable outdoors but hot indoors as a result of heavy thermal storage (day = H, night = —, $HG = 1$ or 2 and when the diurnal range is above 10 C
- A3 Indicates winder or cold-season problem. These occur when day thermal stress = C.

Table 5
Recommendations for building design in Qatar

Element	Recommendations
Layout	Building oriented on east-west axis to reduce exposure to sun Compact courtyard planning
Spacing	Open spacing for breeze penetration.
Air movement	Rooms single banked Permanent provision for air movement.
Openings	Size: medium openings, 20–40% Position: north and south walls at body height on windward side.
Walls and floors	Heavy external and internal walls.
Roofs	Light insulated roofs.
Outdoor sleeping	Space for outdoor sleeping is required.

Table 6
Air temperature

Temperature (°C)	J	F	M	A	M	J	J	A	S	O	N	D
Monthly mean max.	21.0	22.1	26.3	31.3	38.6	39.7	41.3*	40.6	38.3	33.6	39.8	20.4
Monthly mean min.	12.4†	14.9	16.8	22.0	25.8	28.0	29.7	30.0	28.2	25.0	20.9	12.8
Monthly mean range	8.6	7.2	9.5	9.3	12.8	11.7	11.6	10.6	10.1	8.6	8.9	7.6

* Highest monthly mean; † Lowest monthly mean; AMR = Annual mean range = Highest – Lowest = 28.9; AMT = Annual mean temperature = (Highest + Lowest)/2 = 26.9.

These tables are followed by the sketch design recommendations in which the design requirements of a building can be derived. The recommendations for the form of the building are grouped under the following eight subjects: Layout, space, air movement, openings, walls, roofs, outdoor space and rain protection.

At this stage, recommendations for the various size and protection of openings, layout planning, positioning, glazing, natural light and prevention of glare, along with the type of external walls, roofs and floors, could be indicated.

6.1.2. Application of Mahoney's tables in Qatar

The climatic data of Qatar is Tabulated in Mahoney's Tables 6–11. The recommendations of the climatic analysis for building design are summarized in Table 5.

7. Conclusions

The following conclusions were arrived at:

- (1) The summer neutrality temperature for Qatar is about 28.5°C, whereas in winter

Table 7
Comfort limits

Average R H HG		AMT over 20°C		AMT 15–20°C		AMT under 15°C	
		Day	Night	Day	Night	Day	Night
0–30	1	26–34	27–34	23–32	14–23	21–30	12 21
30–50	2	25–31	17–24	22–30	14–22	20–27	12 20
50–70	3	23–29	17–23	21–28	14–21	19–26	12 19
70–100	4	22–27	17–21	20–25	14–20	18–24	12 18

R H: relative humidity; HG: humidity group; AMT: annual mean temperature.

Table 8
Humidity, rain and wind

R H (percentage)	J	F	M	A	M	J	J	A	S	O	N	D
Monthly mean max. a.m.	87.1	84.8	81.5	74.3	69.7	58.7	79.4	84	83.1	87.6	89	87.7
Monthly mean min. p.m.	49.5	52	38	32.7	24.1	17	25.5	33.3	33	43	48	51
Average	68.3	68.4	60	54	47	38	53	59	58	65	69	70
Humidity group	3	3	3	3	2	2	3	3	3	3	3	3
Rainfall (mm)	6.8	1.3	68.9	12.8	0	0	0	0	0	0	0	21.2
Wind: prevailing	NW	NW	SE	NW	NW	NW	NW	NE	SE	NW	NW	NW
Wind: secondary	NW	N	NW	NE	N	N	N	N	E	N	N	NW

* Total rainfall (mm) 111; R H: relative humidity.

- it drops to about 23°C. Their corresponding comfort zones are 26.5–30.5 and 21–25°C respectively. According to those limits the period from May to September requires either mechanical air conditioning or other passive cooling strategy.
- (2) According to the Olgay method, Fig. 9, ventilation is the most effective strategy that can be used (42%), whereas radiation for heating utilizes about 17 and 21% of the time the condition falls within the comfort zone and requires no strategy. Active air conditioning and/or dehumidification utilizes about 21% of the time.
 - (3) Givoni's method indicates that high mass building coupled with night time ventilation can effectively restore comfort (50%), Fig. 10. Furthermore, dehumidification and passive heating utilizes 13 and 17% of the time respectively, whereas only 17% of the time falls within the comfort zone.
 - (4) Szokolay's method indicates strategies which are similar to those obtained using Givoni's method.
 - (5) Mahony Tables indicate that high mass walls and light insulated roof should be used. The high mass building and outdoor sleeping is an effective strategy (43%).

Table 9
Diagnosis

	J	F	M	A	M	J	J	A	S	O	N	D
Humidity group	3	3	3	3	2	2	3	3	3	3	3	3
Temperature (0°C)												
Monthly mean												
max.	21	22.1	26.3	31.3	38.6	39.7	41.3	40.6	38.3	33.6	29.8	20.4
Day comfort												
max.	29	29	29	29	31	31	29	29	29	29	29	29
min.	23	23	23	23	25	25	23	23	23	23	23	23
Monthly mean												
min.	12.4	14.9	16.8	22	25.8	28	29.7	30	28.2	25	20.9	12.8
Night comfort												
max.	23	23	23	23	24	24	23	23	23	23	23	23
min.	17	17	17	17	17	17	17	17	17	17	17	17
Thermal stress												
day	C	C	—	H	H	H	H	H	H	H	H	C
night	C	C	—	—	H	H	H	H	H	H	—	C

H: above comfort limit; —: within comfort limit; C: below comfort limit.

Table 10
Indicators

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Humid				X						X	X		3
H1 Air movement													
H2 Air movement													
H3 Rain protection													
Arid													
A1 Thermal storage				X	X	X	X	X	—	—	—	—	5
A2 Outdoor sleeping					X	X	X	X	—	—	—	—	4
A3 Cold-season	X	X	—	—	—	—	—	—	—	—	—	X	3

Passive heating is required (25%) during the winter months and only 33% of the time falls within the comfort zone.

- (6) Table 12 compares the different approaches (Olgyay, Givoni, Szokolay and Mahony Tables) for building designs. It lists the appropriate strategy to restore comfort during the day and night independently. The bioclimatic charts and Mahony Tables indicate that in the early summer months (May and June), high mass building with night ventilation and outdoor night sleeping can restore comfort. Moreover, during the peak summer months (July–September) high mass building along with dehumidification and active air conditioning is required.

Table 11
Design recommendations

Indicator total from Tabel (4)			Recommendations		
Humid		Arid			
H1	H2	H3	A1	A2	A3
3	0	0	5	4	3
			Layout		
			0–10		x
			11 or 12	5–12	1. Building oriented on east to west axis to reduce exposure to sun
				0–4	x 2. Compact courtyard planning
			Spacing		
11 or 12					3. Open spacing for breeze penetration.
2–10					4. As 3, but protect from cold/hot wind
0 or 1					x 5. Compact planning.
			Air movement		
3–12					x 6. Rooms single banked. Permenant provision for air movement
1 or 2			0–5		7. Double banked rooms with temporary provision for air movement.
1 or 2			6–12		As 7
0	2–12				As 7
0	0 or 1				8. No air movement required
			Openings		
			0 or 1	0	9. Large openings, 40–80% of N and S walls
Any other conditions			11 or 12	0 or 1	x 10. Very small openings, 10–20%
					11. Medium openings, 20–40%
			Walls		
			0–2		12. Light walls; short time lag
			3–12		x 13. Heavy external and internal walls
			Roofs		
			0–5		x 14. Light insulated roofs
			6–12		15. Heavy roofs; over 8 hours time lag
			Outdoor sleeping		
			2–12		x 16. Space for outdoor sleeping required
			Rain protection		
3–12					17. Protection from heavy rain needed

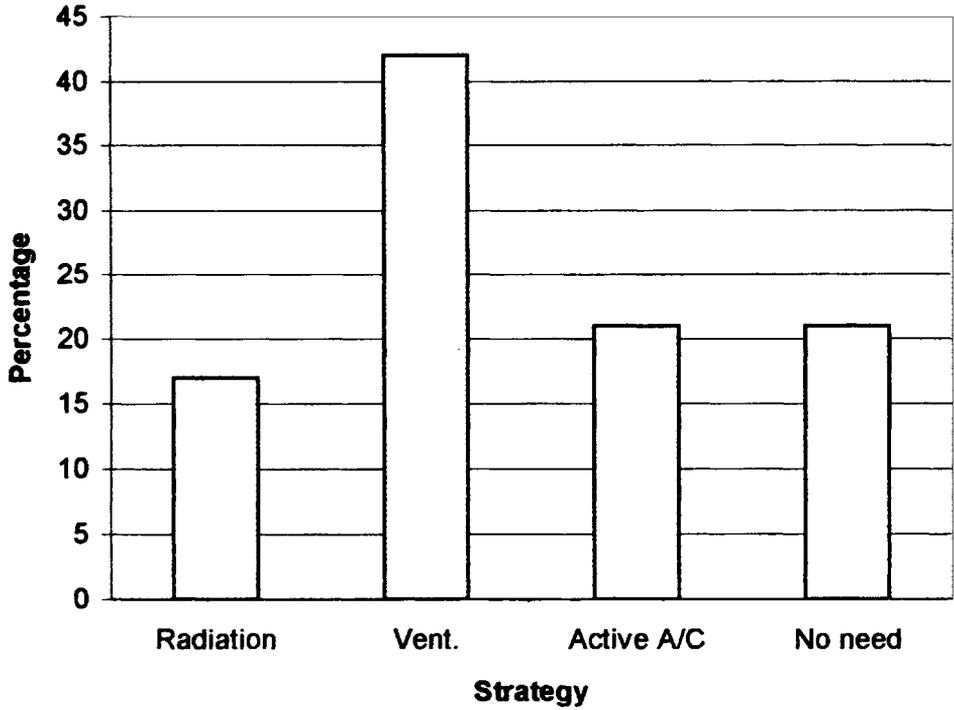


Fig. 9. Application of Olgyay method to Qatar.

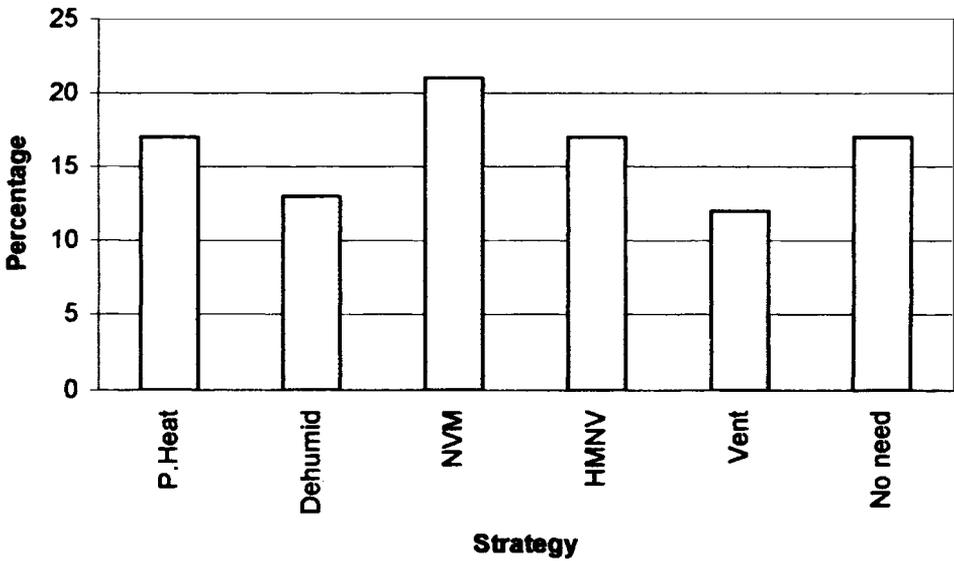


Fig. 10. Application of Givoni method to Qatar.

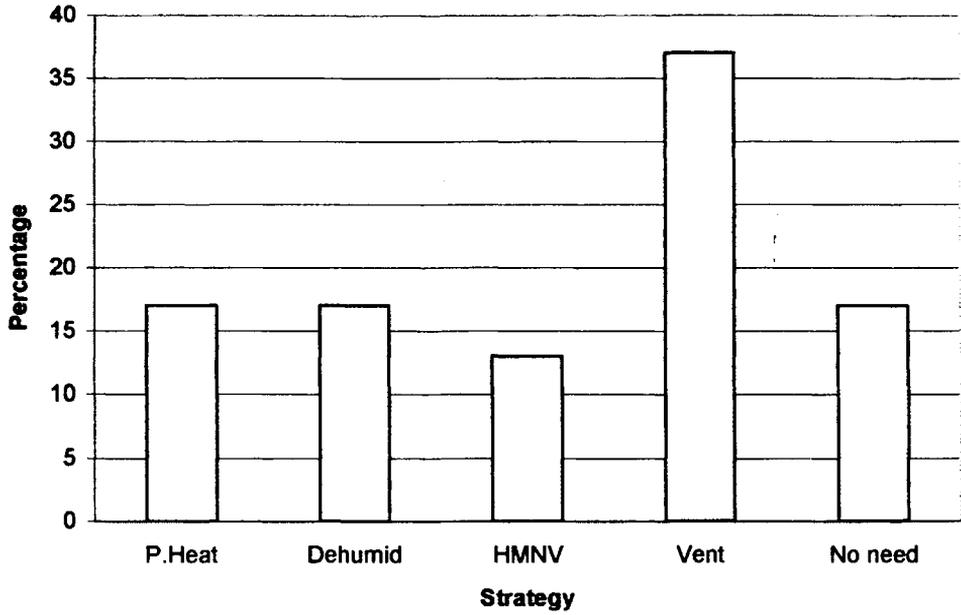


Fig. 11. Application of Szokolay method to Qatar.

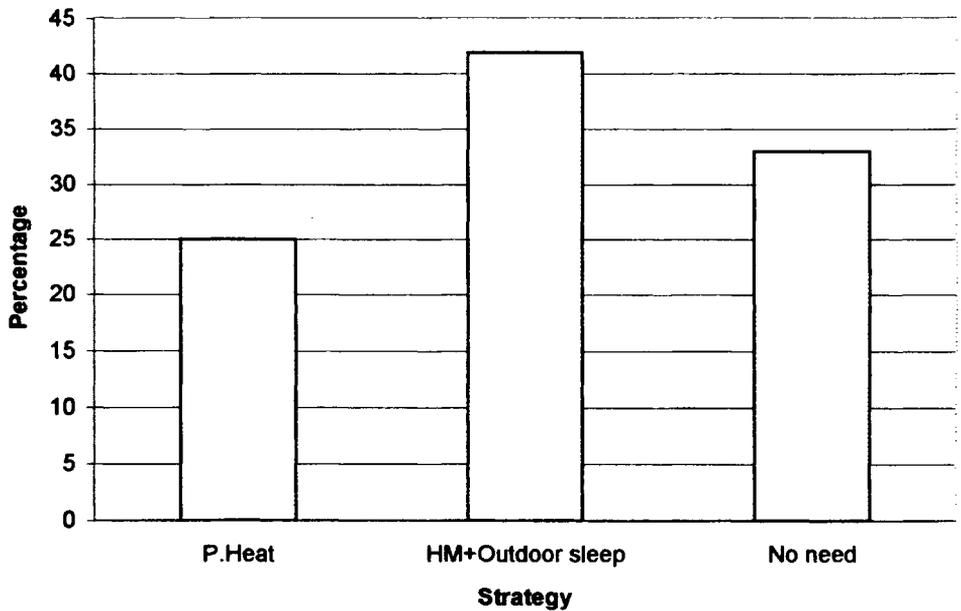


Fig. 12. Application of Mahony Tables to Qatar.

Table 12
Comparison of different methods applied to Qatar

Month	Olgyays	Givoni		Szokolay		Mahony Tables			
Jan	Day	—	—	—	—	—	—	Passive heating	
	Night	C	Radiation	C	Passive heating	C	Passive heating	C	
Feb	Day	—	—	—	—	—	—	Passive heating	
	Night	C	Radiation	C	Passive heating	C	Passive heating	C	
Mar	Day	—	—	—	—	—	—	—	
	Night	C	Radiation	C	Passive heating	C	Passive heating	C	
Apr	Day	H	Ventilation	H	HMNV + Ventilation	—	—	H	Thermal mass
	Night	—	—	—	—	—	—	—	—
May	Day	H	Ventilation	H	HMNV	H	TMNV	H	Thermal mass + Outdoor night sleep
	Night	H	Ventilation	H	Ventilation	H	Ventilation	H	—
Jun	Day	H	Ventilation	H	HMNV	H	TMNV	H	Thermal mass + Outdoor night sleep
	Night	H	Ventilation	H	Ventilation	H	Ventilation	H	—
Jul	Day	H	Ventilation	H	HMNV	H	TMNV	H	Thermal mass + Outdoor night sleep
	Night	H	Active A/C	H	Dehumidification	H	Active A/C + Ventilation	H	—
Aug	Day	H	Active A/C	H	Dehumidification	H	Dehumidification	H	Thermal mass + Outdoor night sleep
	Night	H	Active A/C	H	Dehumidification	H	Active A/C + Ventilation	H	—
Sep	Day	H	Active A/C	H	HMV	H	TMNV + Dehumidification	H	—
	Night	H	Active A/C	H	NVM	H	Ventilation	H	—
Oct	Day	H	Ventilation	H	NVM	H	Ventilation	H	—
	Night	H	Ventilation	H	NVM	H	Ventilation	H	—
Nov	Day	H	Ventilation	H	NVM	H	Ventilation	H	—
	Night	H	Ventilation	H	NVM	H	Ventilation	H	—
Dec	Day	—	—	—	—	C	Passive heating	—	Passive heating
	Night	C	Radiation	C	Passive heating	C	Passive heating	C	—

H: above comfort limit; —: within comfort limit; C: below comfort limit.

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Chapter 2—Vernacular and contemporary buildings in Qatar

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1. Introduction

“The strength of vernacular architecture is that it blends buildings into various settings so that there is a natural harmony between climate, architecture and people. In countries such as Iran, Iraq and Egypt there have evolved buildings which not only demonstrate this harmony and unity between people and their environment but also offer a combination of engineering and architecture which has an aesthetic quality” [1].

In the past, people in Qatar built their houses according to their real needs and in harmony with the environment as well as with optimal utilization of the available local building materials. In spite of the hot long summer with the dry bulb temperature of up to 45°C, human comfort was achieved in those traditional buildings by the utilization of natural energies. This was the result of repeated cycles of trial and error and the experience of generations of builders. It is worth mentioning that builders had to rely mostly on the locally available material to construct the buildings with the exception of timber which was imported from India.

In the 1940s the country's economy flourished as a result of oil discovery, and electricity was introduced. Modern technologies were adopted without studying their suitability with regard to culture and climate. An architectural heritage that survived for centuries because of geometric, technical and constructive principles that work for the society, is being sadly destroyed under the guise of modernization. Traditional buildings are being abandoned as it is perceived that they reflect underdevelopment and poverty.

This chapter is devoted to discussing various passive techniques that has been employed in the traditional buildings and their role in providing comfort especially during the hottest hours of the day.

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2. Vernacular architecture

2.1. Passive techniques employed in traditional Qatari buildings

Vernacular buildings in Qatar have employed some ingenious passive techniques in order to restore thermal comfort within the building particularly during the hottest hour of the day. Such techniques are discussed hereafter.

2.1.1. Town layout

The buildings were joined close to each other. The houses, on the other hand, shared walls and this minimized the surface exposed to the sun. The streets were like a trench. This helped the buildings to shade one another as well as to shade the streets. The only spaces that received a great amount of sunshine were the open spaces such as the courtyards. At midday the courtyard received more solar radiation than the shaded areas. As these heated up, hotter air rose and denser, cool air rushed in automatically. The cool air was drawn from the shaded streets. The streets oriented in the direction of the prevailing wind which created a low pressure area in the open space thus moving the air from the streets into the living spaces.

2.1.2. Massive walls

The walls of traditional buildings were massive with a thickness of about 60 cm (Fig. 1). Various materials were used to construct the walls [2]. Such materials include:

- (i) Mud: This was the only material with sufficient cohesion to form walls. It was stable in dry conditions, and was mixed with straw and sometimes wool to achieve maximum strength.
- (ii) Coral stone: Coral stones were mixed with mud to form stronger and more durable walls. However, stone collecting was labor-intensive and time-consuming.
- (iii) The coral slab ('Frush'): this material underlies the coastal waters; in some places it lies exposed, and in others is covered by several meters of sand or silt. It was mainly used to construct the *Badgir*, (refer to Section 2.1.4.).
- (iv) Gypsum ('Jus'): gypsum was used to plaster the internal walls and only some of the external walls. A thin layer was also used on the rooftop to act as a reflector.
- (v) Lime ('Nurah'): lime was used mainly to pigment the interior of a house with brilliant white. It could also be mixed with indigo to produce a light bluish colour.
- (vi) Timber: dressed timber was used for doors and windows. The windows were unglazed, but were provided with wooden shutters on the outside to ensure privacy and to keep out dust, sun and rain (Fig. 2). Round timber poles ('danjal'), on the other hand, were used to form the framework of the roof and to support the wall above the windows. The *danjal* on the roof is covered with mangrove slats ('yereed') and a woven palm-frond matting ('mangrur'), and then by a mixture of mud and straw (or sometimes wool) (Fig. 3). Table 1 summarizes the properties of common building materials.



Fig. 1. A traditional massive wall.



Fig. 2. A traditional window.



Fig. 3. A traditional roof construction.



Fig. 7. A traditional courtyard.



Fig. 9. Traditional wall air vents.



Fig. 10. A traditional wind tower.



Fig. 11. A modern building with a large area of glazing

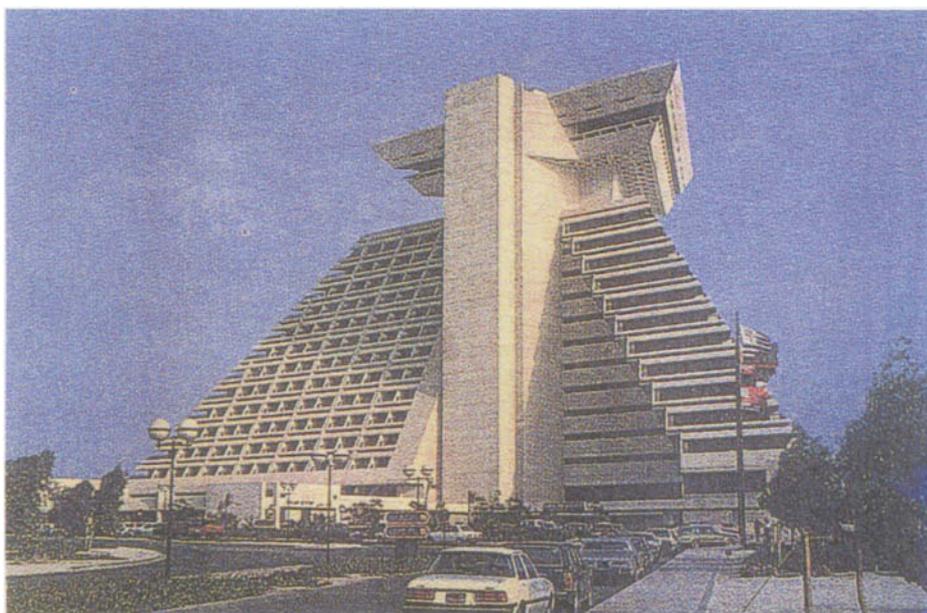


Fig. 12. Sheraton Hotel, Doha—energy wasteful building.



Fig. 13. Qatar University.



Fig. 14. The traditional coffee house of Qatar.

Table 1
Comparison of thermal and physical properties of commonly used materials

Material	Thermal Conductivity (W/m ² °C)	Specific heat (kJ/kg°C)	Density (kg/m ³)	Thermal storage (kJ/m ³ .°C)
Adobe	0.516	1.00	1730	1.73
Stone	1.8	0.92	2451	2.26
Reinforced concrete	1.728	0.96	2400	2.3
Hollow clay block	0.36	0.84	1029	0.86
Hollow cement block	0.6	0.84	1403	1.18
Solid cement block	0.789	0.84	1600	1.34
Thermal insulation mat.	0.0276	0.66	32	0.02

Buildings with high mass structure utilize their thermal storage capabilities to achieve cooling in different ways [3]:

- (i) Damping out interior daily temperature swings
- (ii) Delaying daily temperature extremes
- (iii) Ventilating ‘flushing’ the building at night.

Furthermore, the thick walls, in addition to their insulating properties, act as a heat reservoir. During the hot day, the heat flow from exterior (due to solar radiation) to the inside is retarded and during cooler hours a part of the stored heat in the walls is released to the interior. This results in a minimization of temperature change inside the building (Fig. 4). On the other hand, in winter, heating requirements are reduced due to the heat stored in the walls and which is radiated during the night. In hot climates with large temperature swing (arid regions) daytime temperature is often so high that ventilative cooling is ineffective. On the other hand, the night air becomes low in contact with the thermal mass. Furthermore, night flushing is most effective in buildings occupied during the day, allowing the mass to be more effectively cooled.

Fathy, [4], conducted tests on experimental buildings located at Cairo Building Research Centre, using different materials. The materials used were mud brick walls

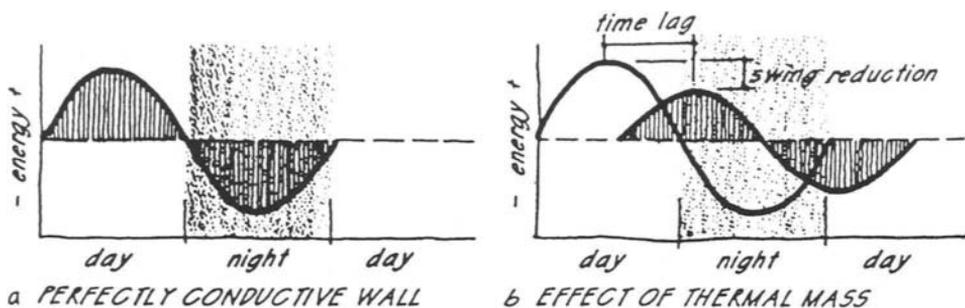


Fig. 4. Effect of thermal mass on interior temperature (Moore, 1993).

and roof 50 cm thick and prefabricated concrete panel walls and roof 10 cm thickness. Figure 5 shows the performance of the two buildings over a 24 h cycle. The air temperature fluctuation inside the mud brick model did not exceed 2°C during the 24 h period, varying from 21–23°C which is within the comfort zone. On the other hand, the maximum air temperature inside the prefabricated model reached 36°C, or 13°C higher than the mud brick model and 9°C higher than outdoor air temperature. The indoor temperature of the prefabricated concrete room is higher than the thermal comfort level most of the day. Moore (1993) reported the temperatures in and around an adobe building (Fig. 6). It indicates that when the average inside and outside temperatures are about equal, the maximum interior temperature occurred at about 22.00 h (about 8 h after the outside peak). Furthermore, the outside temperature swing was about 24°C while the interior swing was about 6°C. The shaded area represents the effect of night ventilation.

2.1.3. Courtyards

The traditional courtyard was surrounded by high narrow rooms having large unglazed windows facing the courtyard (Fig. 7). They were completely opened to the clear sky or partially shaded with overhangs and arcades. They tend to differ in size and shape according to the geographical location and type of climate. For example, in hot-humid regions, large courtyards provide good ventilation, especially when opening on to another courtyard or street such that cross ventilation is promoted. On the other hand, small courtyards provide more protection against hot, dusty winds in hot-arid regions. Some courtyards contain fountains and trees to promote evaporative cooling and provide shade. Courtyards moderate the climatic extremes in many ways:

- (i) The cool air of the summer night is kept undisturbed for many hours from hot and dusty wind provided that the surrounding walls are tall and the yard is wide.
- (ii) The rooms draw daylight and cool air from the courtyard.

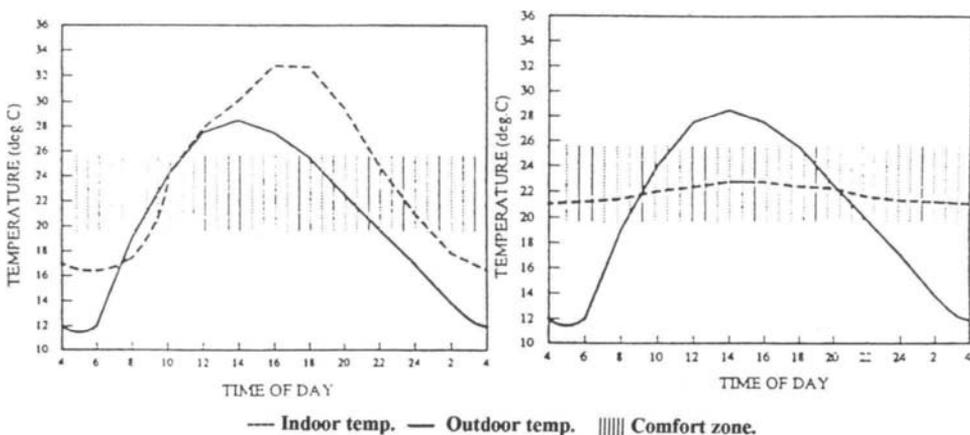


Fig. 5. Comparison of indoor and outdoor air temperature fluctuation within 24 h period (a) for the prefabricated concrete test model; (b) for the mud-brick test model (Fathy, 1986).

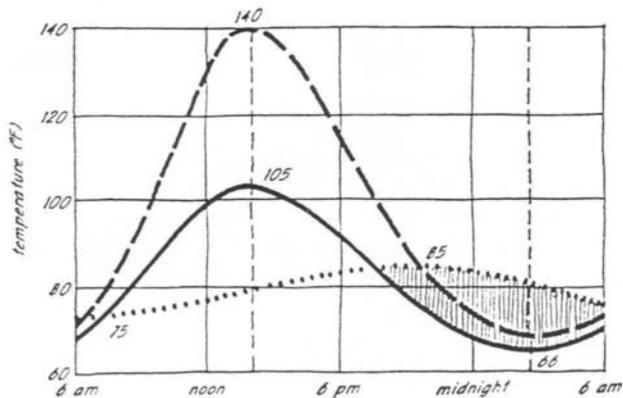
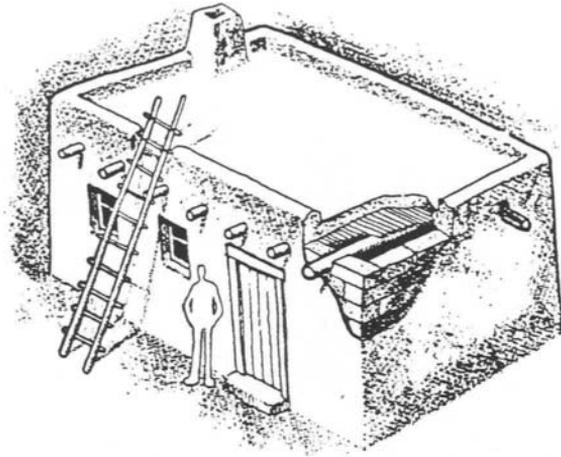


Fig. 6. Temperature in and around an adobe house (Moore, 1993).

- (iii) It enhances ventilation and filter dust.
- (vi) It provides privacy to the family and keep their activities and noise away from neighbours.
- (v) The courtyard with its gentle microclimate provides a comfortable outdoor space to enjoy.

Talib [5], described the functioning of the courtyard during the 24 h cycle (Fig. 8). He subdivided the functions into three phases. In the first phase, cool night air descends into the courtyard and into surrounding rooms. The structure, as well as the furniture, are cooled and remain so until late afternoon. In addition the courtyard loses heat rapidly by radiation to the clear night sky. Therefore, the courtyard is often used for sleeping during summer nights. During the second phase, at midday, the sun strokes

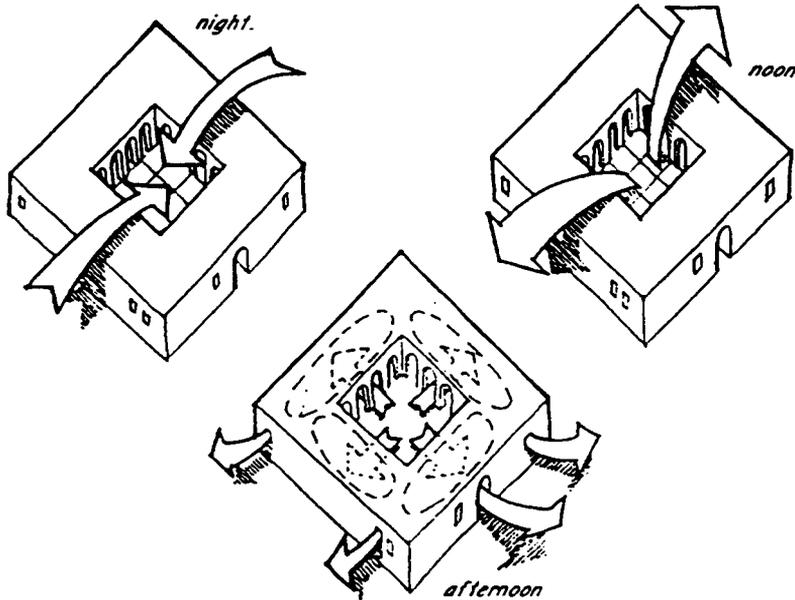


Fig. 8. The function of the courtyard during the 24 h cycle (Talib, 1984).

the courtyard floor directly. Some of the cool air begins to rise and also leaks out of the surrounding rooms. This induces convective currents which may provide further comfort. At this phase the courtyard acts as a chimney and the outside air is at its peak temperature. The massive walls do not allow the external heat to penetrate immediately. The penetration is delayed and depends on the time lag of the walls (up to 12 h). During the last phase, by late afternoon, the courtyard floor and the interior rooms become warmer. Most of the trapped cool air spills out by sunset. After sunset the air temperature falls rapidly (arid regions) as the courtyard begins to radiate rapidly to the clear night sky. Cool night air begins to descend into the courtyard, completing the cycle. It is worth mentioning that the courtyard concept is most effective in arid regions where a large diurnal temperature variation exists.

2.1.4. Wall air vents

This is a complex method of catching the breeze. The air vents are provided in the outer walls of the house (Fig. 9). Between the bearing columns of the house, twin panels of thin coral slabs are set parallel to each other in the wall. A space was left between the slabs, through which the air flows. The outer slab was a little short at the top and the inner slab a little short at the bottom. Thus the breeze enters through the gap at the top of the outer slab, and filters through the gap at the bottom of the inner slab into the room.

2.1.5. The wind tower ('Badgir')

The traditional wind tower construction in Qatar is shown in Fig. 10. It consists mainly of two parts, the catching device and the tower. It is opened into either upstairs

or downstairs rooms and stopped about two meters above floor level. The tower is subdivided by brick partitions to contain several shafts. The wind tower in Qatar is built to an X-shaped design, open on the four sides to catch the breeze from any direction. The operation of the wind tower depends on wind conditions and the time of the day.

2.1.5.1. *Night operation.* When there is no wind blowing at night, the wind tower acts as a chimney. The tower walls which have been heated during the day transfer heat to the cool night ambient air. The heated air is then exhausted through the tower openings. The chimney action of the tower maintains a circulation of ambient air through the building and cools the structure of the building including the tower itself. When there is wind blowing at night, the air circulation will be opposite to that described above and the walls and rooms will be cooled.

2.1.5.2. *Day operation.* When there is no wind blowing during the day, the tower operates as the reverse of a chimney. The hot outside air in contact with the cold walls of the tower (cooled from previous night) is cooled and pulled down through the towers passages. When there is wind blowing, both the air circulation and the rate of cooling are increased, and thus, cooler air is delivered to further position inside the building. the performance of the wind tower is affected, beside its geometrical forms (height, cross sectional plan, tower orientation and location of its outlets), by the climatic conditions. It is most effective in dry arid regions. In such regions the diurnal variation is large and night air temperature is low.

3. Contemporary buildings in Qatar

Contemporary buildings in Qatar are generally built under the combined influence of British and American architecture. Since the generated electricity is subsidized by the government, it was provided to the private sectors at low rates (1 p/kW.h) whereas Qatari nationals receive electricity free. Therefore, the energy consumption each building required was not considered as a design criterion. A major design consideration was the visual impact of the building. Buildings were constructed of materials that are not suitable for the region's environment (steel and concrete). Dwellings constructed as a large enclosed glazed space with no provision for ventilation and protection from the sun (Fig. 11). High rise buildings have a high electricity consumption, as shown in Table 2 [6]. The Doha Sheraton (Fig. 12), for

Table 2
Air conditioning load in some hotels in Qatar (Sayigh, 1985).

Hotel	No. of rooms	Tonnage	Ton/Room
Sheraton	456	3750	8.3
Gulf Hotel	366	1300	3.6
Ramada Inn	302	1080	3.4

example, designed by a Japanese company and is constructed of steel frame. It has 16 storeys arranged in a pyramid shape. The side walls to the outside are totally made of glass panels. The hotel has 456 guest rooms and several meeting halls. It has a hollow pyramid shape with its fresh air intake at the bottom on the side of the prevailing wind. The air exhausts from the top which makes the air conditioning load very high. In summer, the hotel consumes 3750 tons of air conditioning.

In recent years, there has been an increased influence of the traditional architecture in modern buildings. Traditional concepts were adopted for its architectural form and not from an energy stand point. Nevertheless, this has resulted in lowering the cooling load for these buildings.

3.1. *Qatar University*

Dr Kamal Kafrawi, an Egyptian architect, has succeeded, to a great extent, in reconciling modern technology with the traditional elements of Arabic Islamic architecture (Mimar, 1985). Some of the elements utilized by the architect were (1) wind tower (2) protected courtyards (3) Moshrafiya (4) geometric forms (Fig. 13). The use of these elements has helped to control the harsh climatic conditions. The wind tower structures, which are one of the most outstanding features of the university, also provide the cover of the university buildings. The courtyards, both open and partially covered, provide connection and circulation spaces within the university complex. With their gardens and fountains, the courtyards provide pleasant areas of coolness and shade. The octagonal shape of the modular unit was derived from the traditional principles which enhances ventilation through wind towers and provide lighting through indirect sunlight.

3.2. *The traditional coffee house*

The traditional coffee house, designed by architect Shahab Nassim, incorporate many traditional features which creates a pleasant atmosphere within the house (Fig. 14). It is constructed of heavy fired clay brick walls with domes and arches to reduce thermal gain. There are three wind towers situated on three corners of the building. The whole building is situated on the seashore with no walls facing the sea in order to get maximum benefit from the sea breeze. It also contains courtyards, covered verandahs to promote coolness and provide shade.

4. **Conclusions**

The vernacular building form, structure and materials were selected to suit the climatic conditions and achieve a cool and stimulating environment for people using the buildings. Traditional architecture often displays buildings with heavy facades, limited openings on the external elevation and they are well shaded. The basic form of the traditional building employs a combination of mass, shade and ventilation which let the building breathe in harmony with nature and permit the best range of

comfort condition for occupants inside. The enclosed courtyard with trees, plants and fountains which cool the air by evaporation, help to keep dust down, provide shade, visual and psychological relief. The roof of the building receives the highest proportion of solar radiation and is also the surface most exposed to the clear cold night sky. Hence, the light colour of the roof, in the traditional building, is used for its high reflectivity to solar radiation and high emittance in the atmospheric window.

On the other hand, contemporary architecture which has replaced the traditional buildings in Qatar has the influence of western architecture. However, this type of building forms and materials was found unsuitable for the harsh climates of desert regions. therefore, it is important for the architect to understand how to blend lessons from tradition with modern technology in building design.

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Chapter 3—Principles of thermal comfort

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1. Introduction

The human body, considered as a thermodynamic system, produces mechanical work and low temperature heat, using food (fuel) and oxygen as input. This system requires, in healthy conditions, to maintain a constant internal temperature around $37 \pm 0.5^\circ\text{C}$, otherwise the functionality of important organs like liver, spleen, etc, may be severely damaged.† In order to achieve this goal, the rate of heat generation of the body must be equal to the rate of heat loss from it. The job of our thermoregulatory system is to maintain the heat balance, that is a fundamental condition for survival and necessary (but not sufficient) for comfort. Skin temperature, otherwise, is not constant, and it varies according to the part of the body and the air temperature; the absolute maximum and the minimum values, however, are 45 and 4°C (pain thresholds).

2. Heat exchanges man–environment

The energy balance man–environment, per unit body surface area, may be written as follows:

$$S = M - W_k - E_{sk} - E_r - C - R - C_k [\text{W m}^{-2}] \quad (1)$$

where S = instantaneous energy balance of human body; M = metabolic rate, i.e. internal heat production of the body; W_k = external work; E_{sk} = heat loss by evaporation from the skin; E_r = respiration heat loss, latent and dry; C = heat loss by

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† During heavy work it rises by a few tenths of degree; under extreme activity it may rise as high as 39.5°C for short durations; temperatures above 40°C maintained for many hours lead to a breakdown of the thermoregulatory system, causing death. Chilling of internal organs to 36°C is possible without damage; below this, muscular weakness, exposure and then death results. In carefully controlled situations, as in surgical hypothermia, 30°C can be reached.

convection from outer surface of the clothed body to air; R = heat loss by radiation from outer surface of the clothed body to its environment; C_k = heat loss by conduction due to the contact skin/solid object.

All the terms of eqn (1) are expressed per unit area of body surface, thus allowing for people of different size and shape. A good estimate of the body surface area is given by the following expression (Dubois area, A_{DU}):

$$A_{DU} = 0.202 \cdot (w_b)^{0.425} \cdot (h_b)^{0.725} \text{ [m}^2\text{]} \quad (2)$$

where w_b is the body weight (kg) and h_b is the body height (m).

2.1. Instantaneous energy balance

The thermoregulatory system struggles to S fluctuate around zero, with very small swings. When $S < 0$, the body is releasing more energy than it is producing, and its temperature tends to decrease. The first action of the thermoregulatory system is on skin thermal resistance, that is increased by means of the vasoconstriction mechanism; the blood vessels under the surface of the skin constrict. Vasoconstriction leads to a reduction of the blood flow and, consequently, to a reduction in the body surface temperature and in the rate of heat loss.‡

If this action is not sufficient, i.e. if still $S < 0$, our thermoregulatory system starts to act on energy production, by increasing it. First increasing the muscular tension, then, if still not enough, shivering occurs.

On the other hand, when $S > 0$, heat losses are not balancing heat production. The first action of the thermoregulatory system is to induce the vasodilatation; blood vessels expand, skin temperature increases and, with it, the heat loss rate. The overall effect is that of reducing the thermal resistance of the skin.

If the first action is not enough (i.e. still $S > 0$), sweating starts, involving larger and larger fractions of the body's surface area according to the extent of the inequality in the energy balance. Sweating improves evaporative heat losses.

2.2. Metabolic rate

Metabolic rate varies according to the activity performed; it is often measured in met ($1 \text{ met} = 50 \text{ kcal h}^{-1} \text{ m}^{-2}$). In Table 1 some metabolic rates are given.

2.3. External work

External mechanical efficiency η is defined as the ratio W_k/M , and ranges between 0 and 0.2; man, as an engine, is not very efficient. Legs are more efficient than arms.

‡ It is interesting to note that the formation of goose pimples, occurring at the extreme limit of vasoconstriction, is a useless action for today's physical characteristics of man. It was useful when we were very hairy all over the body surface; the raising of hairs was a good way to improve thermal insulation.

Table 1
Typical metabolic heat generation for various activities*

Activity	Heat generation (W m ⁻²)
<i>Resting</i>	
Sleeping	40
Reclining	45
Seated, quiet	60
Standing, relaxed	70
<i>Walking (on the level)</i>	
0.89 m s ⁻¹	115
1.34 m s ⁻¹	150
1.79 m s ⁻¹	220
<i>Office activities</i>	
Reading	55
Writing	60
Typing	65
Filing, seated	70
Filing, standing	80
Walking about	100
Lifting/packing	120
<i>Driving/flying</i>	
Car	60–115
Aircraft, routine	70
Aircraft, instrument landing	105
Aircraft, combat	140
Heavy vehicle	185
<i>Miscellaneous occupational activities</i>	
Cooking	90–115
House cleaning	115–200
Seated, heavy limb movement	130
Machine Work	
Sawing (table saw)	105
Light (electrical industry)	115–140
Heavy	235
Handling 50 kg bags	235
Pick and shovel work	235–280
<i>Miscellaneous leisure activities</i>	
Dancing, social	140–225
Calisthenics/exercise	175–235
Tennis, singles	210–270
Basketball	290–440
Wrestling, competitive	410–505

* Most values are rounded; for example, the accrued value for a person seated, quiet, is 58.15 W m⁻².

2.4. Heat loss by evaporation

Heat loss by evaporation is made up of two terms, E_d and E_{sw} . The former accounts for the heat loss by water vapour diffusion through the skin and it is not controlled by the thermoregulatory system. The latter accounts for the heat loss due to the regulatory sweat secretion from the skin and it is controlled by sweat glands.

E_{sk} is a function of:

- air relative humidity, rh
- air temperature, t_a
- relative air velocity, § v_{ar}
- skin temperature, t_{sk}
- clothing, including thermal resistance and vapour permeability, I_{cl}
- skin wettedness, i.e. fraction of the whole skin covered with a film of unevaporated sweat, w

2.5. Respiration heat loss

When breathing, expired air contains water vapour saturated at internal body temperature; the vaporization heat is taken from the lungs: this is the latent respiration heat loss. The other (dry heat loss) derives from the temperature difference between inspired and expired air. E_r depends on:

- activity level
- air relative humidity
- air temperature

2.6. Convective heat loss

The convective heat flow rate from the body to the environment is given by:

$$C = f_{cl} h_c A_{DU} (t_{cl} - t_a) [\text{W m}^{-2}] \quad (3)$$

where f_{cl} = ratio of man's surface area clothed/nude; h_c = average skin-air convective heat transfer coefficient; t_{cl} = surface temperature of clothing; t_a = air temperature.

C is a function of:

- air temperature
- average temperature of clothed body surface
- kind of clothing
- relative air velocity

§ Relative to the body; for example, for a person walking at 3 km h^{-1} in absence of wind, the relative air velocity will be $3/3.6 = 0.83 \text{ m s}^{-1}$.

2.7. Radiative heat loss

The rate of radiative energy exchange between the human body and its environment may be expressed as:

$$R = 3.96 \times 10^{-8} f_{cl} A_{DU} [(t_{cl} + 273)^4 - (t_{mr} + 273)^4] [\text{W m}^{-2}] \quad (4)$$

where the mean radiant temperature t_{mr} is defined as the uniform blackbody temperature of an imaginary enclosure with which man exchanges the same heat by radiation, as he would in the actual complex environment, and can be calculated as:

$$t_{mr} = \sum t_i F_{p,i} [^{\circ}\text{C}] \quad (5)$$

with t_i = temperature of the generic isothermal surface i seeing the subject (a wall, a window, piece of furniture, another person, etc.) $F_{p,i}$ = view (or angle) factor between the subject p and the surface i ; it may be evaluated by means of the procedure described in Appendix A.

R is a function of:

- average temperature of clothed body surface
- mean radiant temperature
- kind of clothing

2.8. Heat loss by conduction

This is the loss occurring, when seated, as heat is exchanged between the body and the chair, or when standing as exchange between feet and floor. The term C_k is difficult to evaluate: it is usually ignored as a separate item, but taken into account in the clothing thermal resistance.

2.9. Thermal resistance of clothing

The process of heat conduction through the clothing is quite complex, involving transfer through air spaces, conduction through solid material, which varies if wet, radiation exchanges between layers, etc. Because of the difficulties inherent in the handling of so many (and often impossible to determine) parameters, a simplification has been adopted, and the properties of clothing have been included in an overall thermal resistance. The new unit clo has been introduced, which is a dimensionless expression for the thermal insulation of clothing, measured from the skin to the outer surface of the clothes, but excluding the external surface resistance:

$$1 \text{ clo} = 0.155 \text{ m}^2 \text{ } ^{\circ}\text{C W}^{-1}$$

that represents approximately the thermal resistance of a lounge suit with normal underwear.

Values of thermal resistance I_{cl} of some typical clothing ensembles, expressed in

$\text{m}^2\text{C W}^{-1}$ and in clo units, are given in Table 2. For clothing ensembles not included in Table 2, individual resistances of various garments are available in Table 3. The total resistance for the entire clothing ensemble is then determined by the sum ΣI_{cli} and by using the equation $I_{\text{cl}} = 0.82 \Sigma I_{\text{cli}}$.

3. Comfort indices

Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment. Dissatisfaction may be caused by warm or cool discomfort for the body as a whole, but thermal dissatisfaction may also be caused by an unwanted heating or cooling of one particular part of the body (local discomfort).

3.1. Effective temperature

The Effective Temperature ET^* is defined as the uniform temperature of an imaginary enclosure at 50% relative humidity in which a person exchanges the same total heat as in the actual environment; two environments with the same ET^* should evoke the same thermal response even though they have different temperatures and humidity (but same air velocity).

Table 2
Values of typical clothing ensembles

Clothing ensemble	$\text{m}^2\text{C W}^{-1}$	clo
Nude	0	0
Shorts	0.015	0.1
Typical tropical clothing ensemble (briefs, shorts, open neck shirt with short sleeves, light socks and sandals)	0.045	0.3
Light summer clothing (briefs, long light-weight trousers, open neck shirt with short sleeves, light socks and shoes)	0.08	0.5
Light working ensemble (light underwear, cotton work shirt with long sleeves, work trousers, woollen socks and shoes)	0.11	0.7
Typical indoor winter clothing ensemble (underwear, shirt with long sleeves, trousers, jacket or sweater with long sleeves, heavy socks and shoes)	0.16	1.0
Heavy traditional European business suit (cotton underwear with long legs and sleeves, shirt, suit including trousers, jacket and waistcoat, woollen socks and heavy shoes)	0.23	1.5

Table 3
Individual insulation values of men's and women's garments

Men		Women	
Garment	I_{cl} (clo)	Garment	I_{cl} (clo)
Cool socks	0.03	Bra and panties	0.05
Warm socks	0.04	Pantihose	0.01
Briefs	0.05	Girdle	0.04
T-shirt	0.09	Half slip	0.13
Undershirt	0.06	Full slip	0.19
Woven s.s. shirt	0.19	Cool dress	0.17
Woven l.s. shirt	0.29	Warm dress	0.63
Cool s.s. knit shirt	0.14	Warm l.s. blouse	0.29
Warm s.s. knit shirt	0.25	Warm skirt	0.22
Cool l.s. knit shirt	0.22	Cool l.s. blouse	0.20
Warm l.s. sweater	0.37	Cool slacks	0.26
Warm jacket	0.49	Warm slacks	0.44
Cool trousers	0.26	Cool sleeveless sweater	0.17
Warm trousers	0.32	Warm l.s. sweater	0.37
Shoes	0.04	Cool s.s. sweater	0.17

Note—s.s.: short sleeved; l.s.: long sleeved.

3.2. Operative temperature

The combined effects of air and mean radiant temperature can be combined into a single index, the operative temperature. The operative temperature t_o is defined as the uniform temperature (i.e. equal values of t_{mr} and t_o) of an imaginary enclosure in which man will exchange the same dry heat by radiation and convection as in the actual environment. For thermally moderate environments and for $t_{mr} - t_a < 4^\circ\text{C}$, it may be assumed that $t_o = (t_{mr} + t_a)/2$.

3.3. Skin wettedness

The skin wettedness is the ratio of observed skin evaporation loss to the maximum; this index is considered as particularly suitable for predicting discomfort in hot environmental conditions.

3.4. The predicted mean vote

As previously noticed, a necessary condition for thermal comfort is the satisfaction of the energy balance of human body, i.e. the satisfaction of the condition $S = 0$ (see eqn (1)). Thus, taking into account the subjective variables and the environmental

Table 4
Thermal sensation scale used by Fanger

+	3	Hot
+	2	Warm
+	1	Slightly warm
	0	Neutral
–	1	Slightly cool
–	2	Cool
–	3	Cold

ones, the thermal equilibrium of the body is satisfied if:

$$f(M, W, I_{cl}, t_a, rh, t_{mr}, t_{sk}, E_{sw}) = 0 \quad (6)$$

$$E_{sw} = 0.42\{(M - W)/A_{DU} - 58.15\} \text{ [W]} \quad (7)$$

$$t_{sk} = 35.7 - 0.0275(M - W)/A_{DU} \text{ [}^\circ\text{C]} \quad (8)$$

For example, a person seated, relaxed ($M/A_{DU} = 58.15$, $W_k = 0$, see Table 1) will experience comfort condition if [1]:

- thermal balance is satisfied (eqn (6))
- no sweating occurs ($E_{sw} = 0$, from eqn (7))
- average skin temperature is 34.2°C (from eqn (8))

It is very unlikely that subjective and environmental conditions are such that eqns (6)–(8) are simultaneously satisfied and, therefore, perfect comfort is experienced. Most likely sweating rate and/or average skin temperatures will be very close but not coincident with the comfort ones. In this case, how uncomfortable does a person feel?

In order to face this problem, Fanger [1] proposed a comfort index called Predicted Mean Vote (*PMV*). *PMV* is an index that predicts the mean value of the votes of a large group of persons on a seven-point thermal sensation scale (Table 4).

The *PMV* index can be determined when the activity (metabolic rate) and the clothing (thermal resistance) are estimated, and the following environmental parameters are measured: air temperature, mean radiant temperature, relative air velocity and partial water vapour pressure. The *PMV* is given by the equation:¶

$$\begin{aligned}
 PMV = & (0.303e^{-0.036M} + 0.028)\{(M - W) - 3.05 \times 10^{-3}[5733 - 6.99(M - W) - p_a] \\
 & - 0.42[(M - W) - 58.15] - 1.7 \times 10^{-5}M(5867 - p_a) - 0.0014M(34 - t_a) \\
 & - 3.96 \times 10^{-8}f_{cl}[(t_{cl} + 273)^4 - t_{mr} + 273)^4 - f_{cl}h_c(t_{cl} - t_a)\} \quad (9)
 \end{aligned}$$

¶ In the *PMV* index the physiological response of the thermoregulatory system has been related statistically to thermal sensation votes collected from more than 1300 subjects.

where

$$t_{cl} = 35.7 - 0.028(M - W) - I_{cl} \{ 3.96 \times 10^{-8} f_{cl} [(t_{cl} + 273)^4 - t_{mr} + 273^4] + f_{cl} h_c (t_{cl} - t_a) \}$$

$$h_c = \begin{cases} 2.38(t_{cl} - t_a)^{0.25} & \text{for } 2.38(t_{cl} - t_a)^{0.25} > 12.1(v_{ar})^{1/2} \\ 12.1(v_{ar})^{1/2} & \text{for } 2.38(t_{cl} - t_a)^{0.25} < 12.1(v_{ar})^{1/2} \end{cases}$$

$$v_{ar} = v_a + 0.005(M/A_{DU} - 58.15)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 \cdot I_{cl} & \text{for } I_{cl} < 0.078 \text{ m}^2\text{C W}^{-1} \\ 1.05 + 0.645 \cdot I_{cl} & \text{for } I_{cl} > 0.078 \text{ m}^2\text{C W}^{-1} \end{cases}$$

where all terms have been previously defined, except p_a = partial vapour pressure, in pascals.

The *PMV* index is derived for steady state conditions, but can be applied with good approximation during minor fluctuations of one or more of the variables, provided that time-weighted averages of the variables are applied.

It is recommended to use the *PMV* index only for values between -2 and $+2$ and when the six main parameters are inside the following intervals:

$$M = 46 \div 232 \text{ W m}^{-2} \text{ (0.8–4 met)}$$

$$I_{cl} = 0 \div 0.31 \text{ m}^2\text{C W}^{-1} \text{ (0–2 clo)}$$

$$t_a = 10 \div 30 \text{ }^\circ\text{C}$$

$$t_{mr} = 10 \div 40 \text{ }^\circ\text{C}$$

$$v_{ar} = 0 \div 1 \text{ m s}^{-1}$$

$$p_a = 0 \div 2700 \text{ Pa}$$

The *PMV* may be determined either using a digital computer or directly from Appendix B, where graphs of *PMV* values vs operative temperature are provided for different activities, clothing and relative air velocities, with relative humidity kept constant and equal to 50%. The influence of humidity on thermal sensation, however, is small at moderate temperatures close to comfort and may usually be neglected when determining the *PMV* value.

3.5. Predicted percentage of dissatisfied

The *PMV* index predicts the mean value of the thermal votes of a large group of people exposed to the same environment, but individual votes are scattered around this mean value. In order to predict the number of people likely to feel uncomfortably warm or cold the Predicted Percentage of Dissatisfied (*PPD*) index has been introduced. The *PPD* index establishes a quantitative prediction of the number of thermally dissatisfied persons.

When the *PMV* value has been determined, the *PPD* can be found from Fig. 1 or determined from the equation:

$$PPD = 100 - 95 \cdot \exp[-(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2)] \quad (10)$$

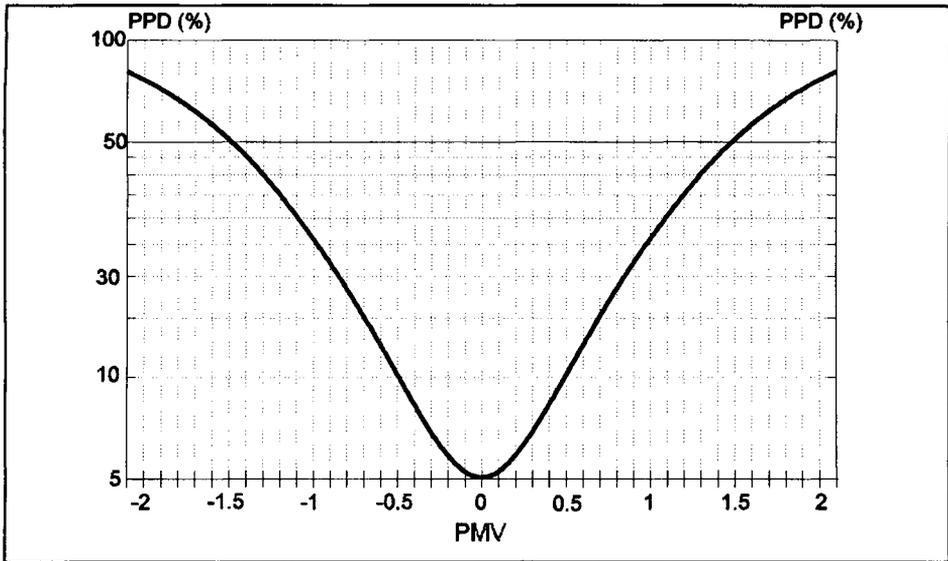


Fig. 1. Predicted percentage of dissatisfied (*PPD*) as a function of predicted mean vote (*PMV*).

Owing to individual differences it is impossible to specify a thermal environment that will satisfy everybody. This is highlighted in Fig. 1, where it is shown that even if the *PMV* is zero, 5% of people are dissatisfied. It is possible, however, to specify environments known to be acceptable by a certain percentage of the occupants. The ISO standard 7730 [2], for example, recommends that the *PPD* should be lower than 10%, i.e. *PMV* within the range $-0.5 \div \pm 0.5$.

4. The adaptation model

There is no significant difference in the thermal sensation of people who usually live in a very cold, hot or temperate climate when they are exposed to the same thermal environment. However, differences have been found in the neutral temperatures^{||} of occupants in buildings around the world. It has been found that comfortable indoor temperatures were related to the outdoor temperature, particularly in free running[#] buildings: the higher the latter the higher the former. This is not due to physiological differences but to differences of expectation. The adaptation model (Fig. 2), which takes into account such factors, may offer an alternative approach for predicting comfort in non air-conditioned buildings. People adapt by changing the physical parameters (environment), their physiology or activity level, their clothing, their

^{||} The ambient temperature found by statistical analysis to most frequently coincide with the central or optimal rating in a thermal comfort study. [#] Without any heating or air-conditioning system.

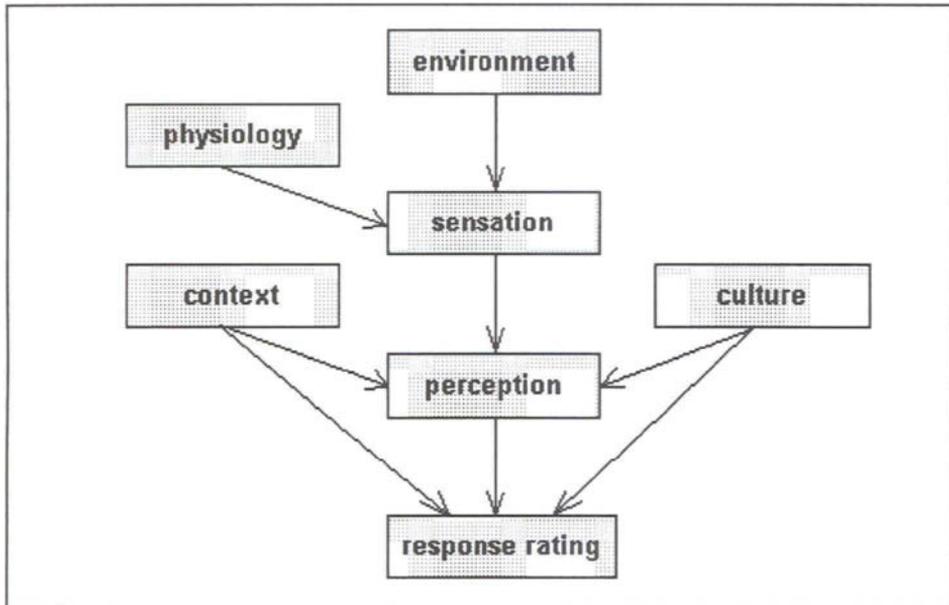


Fig. 2. The adaptation model.

expectations and the way they use rating scales. In simple deterministic terms the environment affects a person's sensation of that environment which in turn alters their perception and finally their assessment using a rating scale.

Appendix A

View factors between a person and an enclosure

The view factor from P to surface α , $F_{P,\alpha}$, can be defined as the fraction of the diffuse radiant energy leaving the surface α which falls directly on P , (i.e. is intercepted by P); this implies that the larger is the apparent size of the surface α , as seen by P , the larger is the view factor (Fig. A1).

Consider a person sitting or standing in a parallelepiped enclosure; with regard to the view factors, this enclosure can be divided in six different geometrical situations (Figs A2 and 3), in such a way that the person sees 24 rectangles as one, α , depicted in Fig. A1. If symmetries are considered, the six situations can be reduced to four, as shown in Figs A4 and A5 for a seated person and in Figs A6 and A7 for a standing person.

To calculate the view factor $F_{P,i}$ from a person P and a surface i , the following simplified and sufficiently accurate procedure can be used, with reference to Figs A4–A7, where:

Table A1
View factors

Refer to	F^*	A	B	C	D	E
Fig. A4	0.118	1.21590	0.16890	0.71739	0.08733	0.05217
Fig. A5	0.116	1.39569	0.013021	0.95093	0.07967	0.05458
Fig. A6	0.120	1.24186	0.16730	0.61648	0.08165	0.05128
Fig. A7	0.116	1.59512	0.12788	1.22643	0.04621	0.04434

$$F_{P,i} = F^*(1 - \exp[-(a/c)/\tau]) \times (1 - \exp[-(b/c)/\gamma]) \quad (\text{A1})$$

$$\tau = A + B \frac{a}{c} \quad (\text{A2})$$

$$\gamma = C + D + \frac{b}{c} + E \frac{a}{c} \quad (\text{A3})$$

The values of the parameters F^* , A , B , C , D and E are given in Table A1 for seated and standing persons.

Since an additive property can be applied to view factors, in the case of a window, the view factor $F_{P,efgh}$ can be calculated as (Fig. A8):

$$F_{P,efgh} = F_{P,abcd} - F_{P,jgmd} - F_{P,keid} + F_{P,jhid}$$

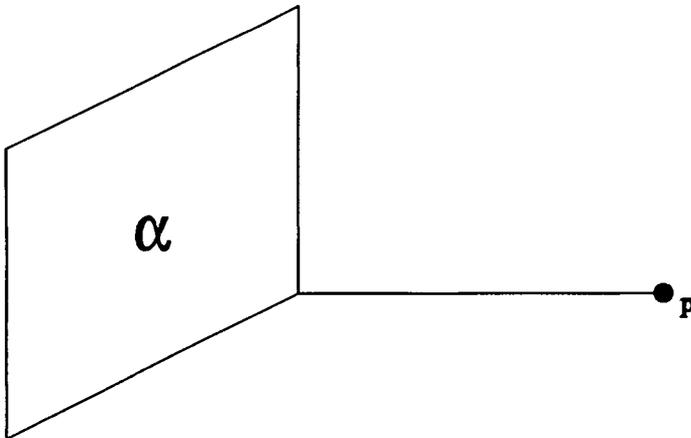


Fig. A1

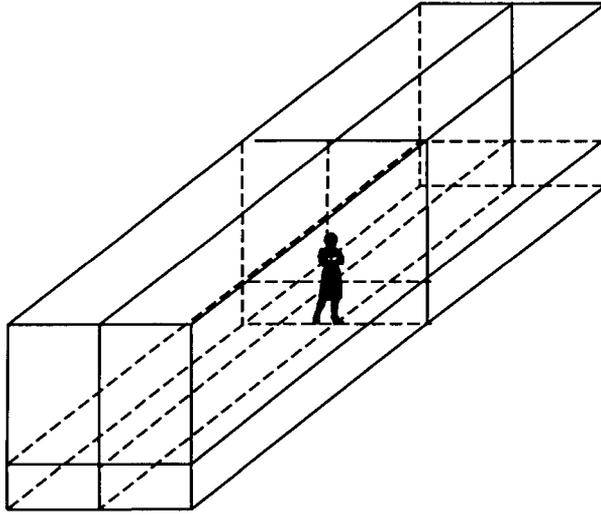


Fig. A2

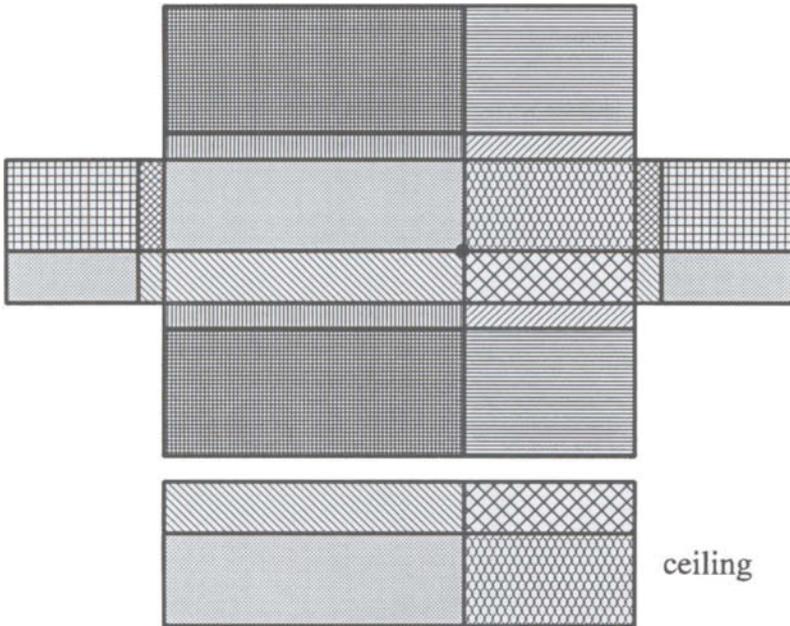


Fig. A3

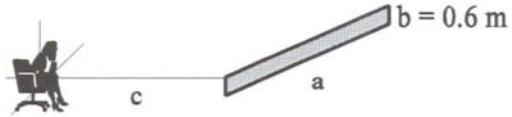
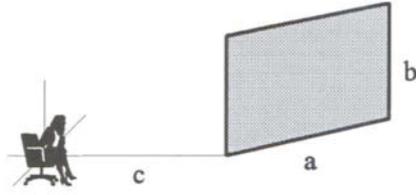


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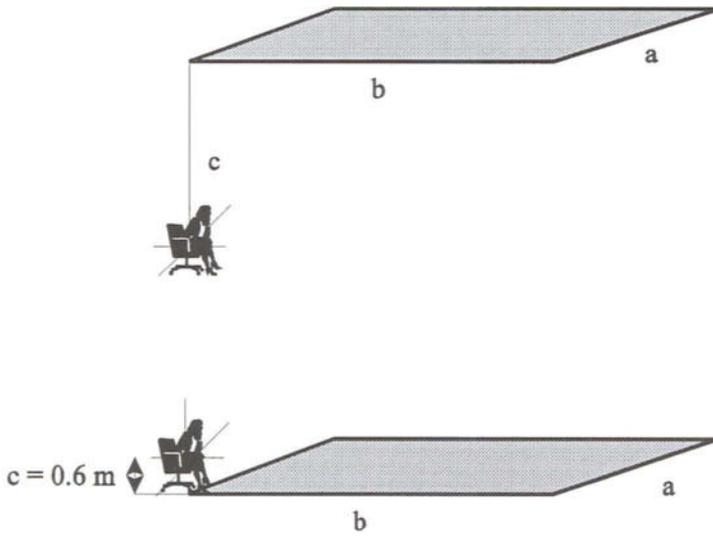


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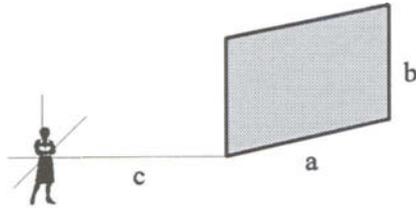


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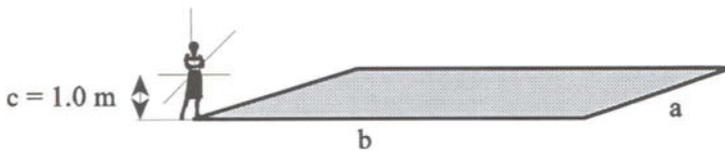
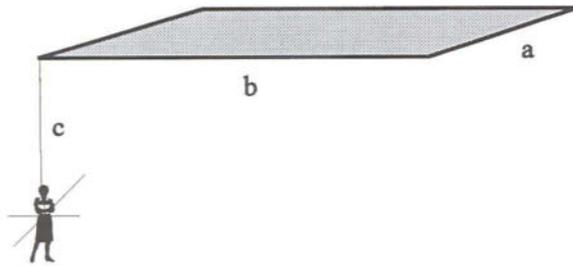


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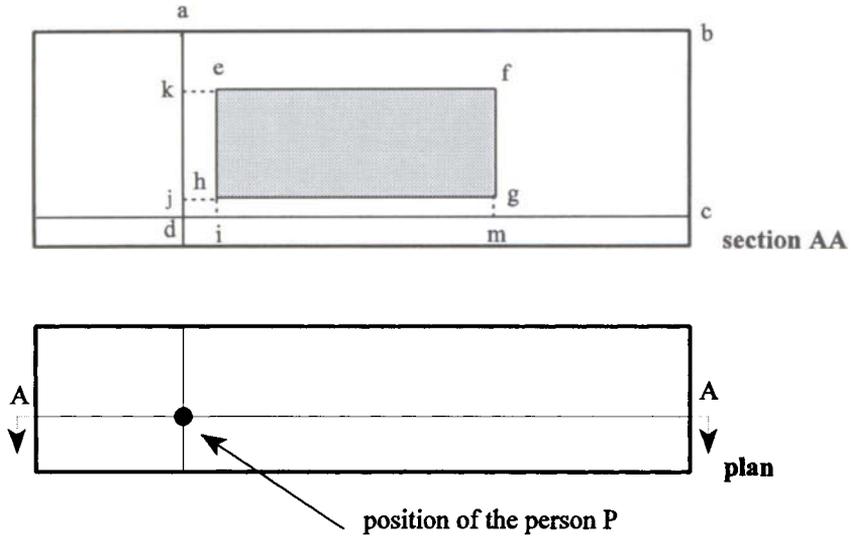


Fig. A8

Appendix B

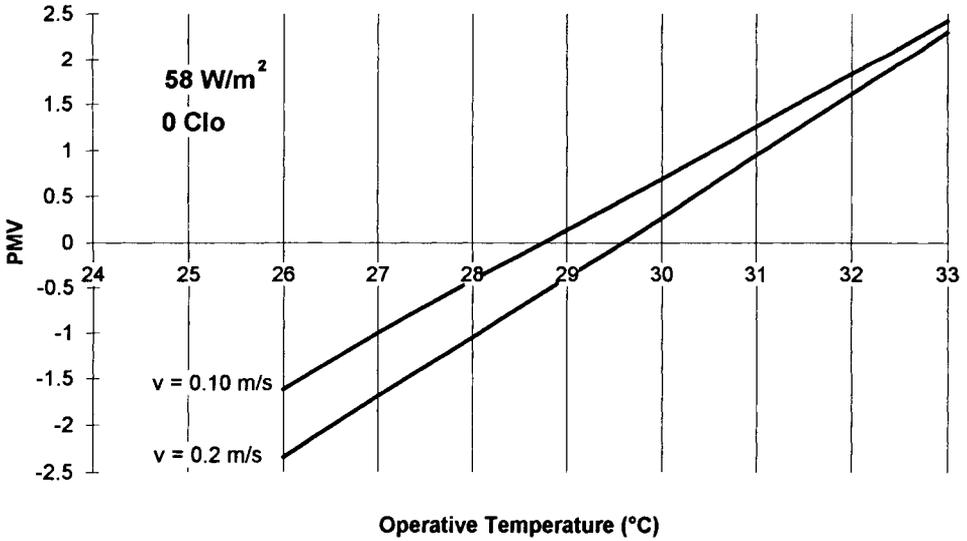


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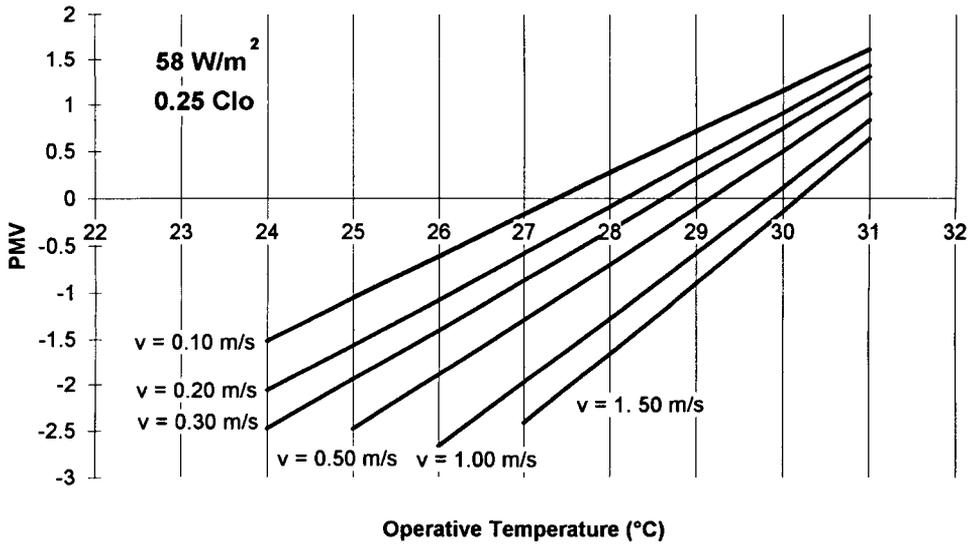


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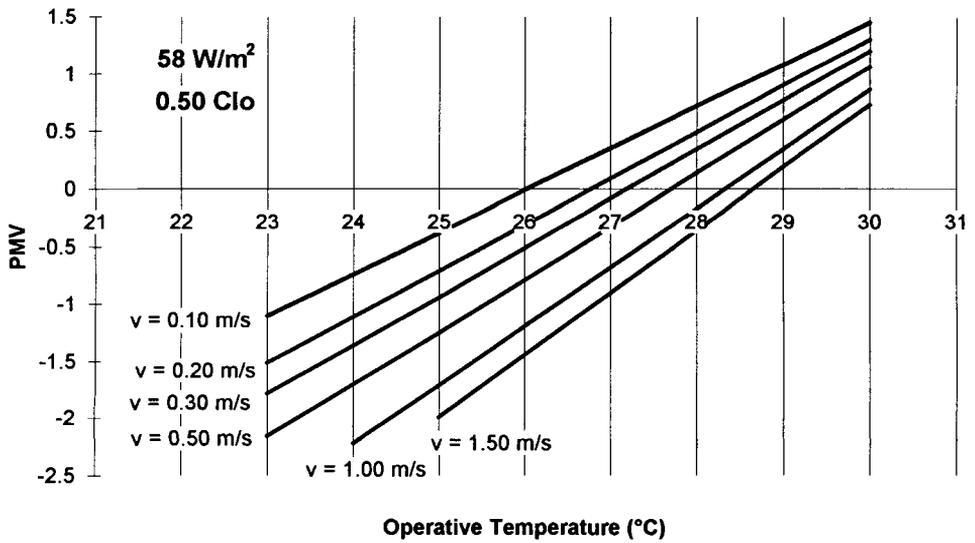


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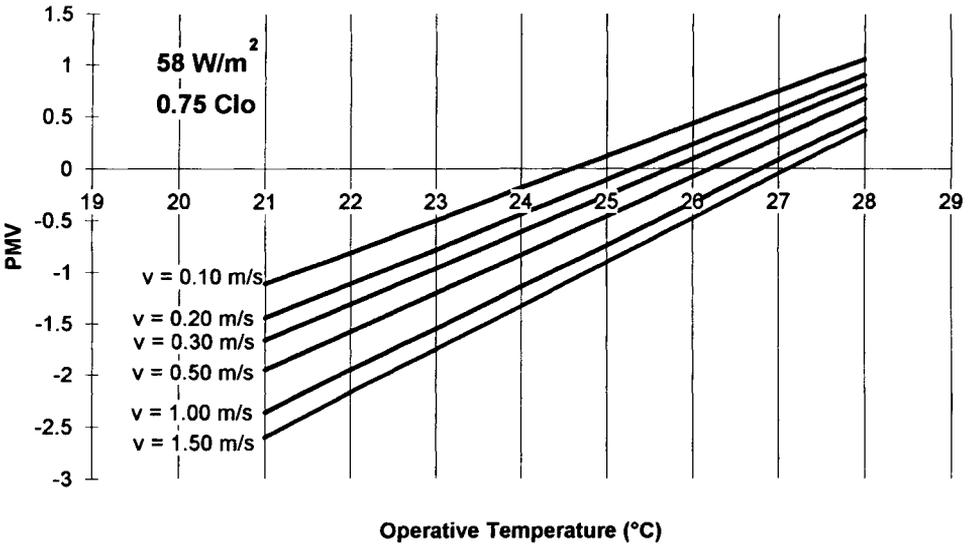


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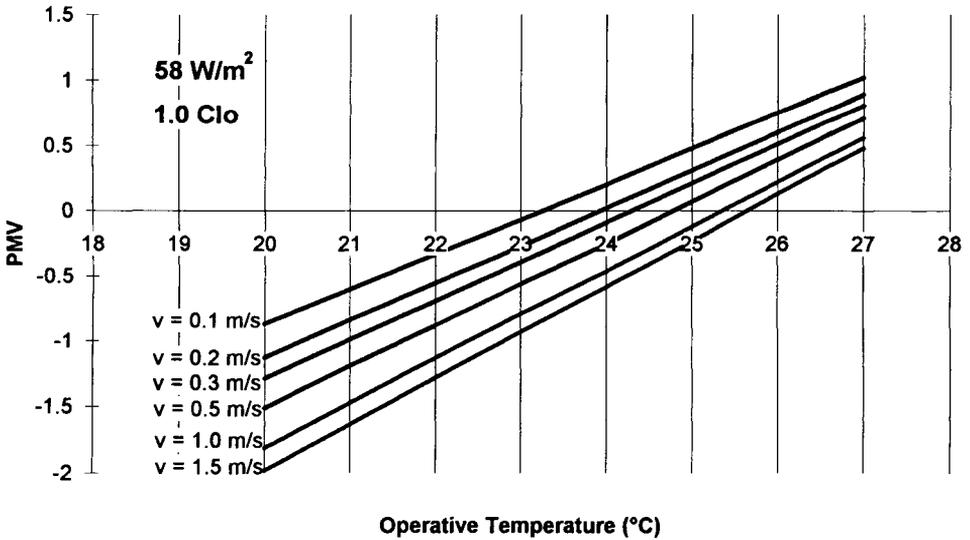


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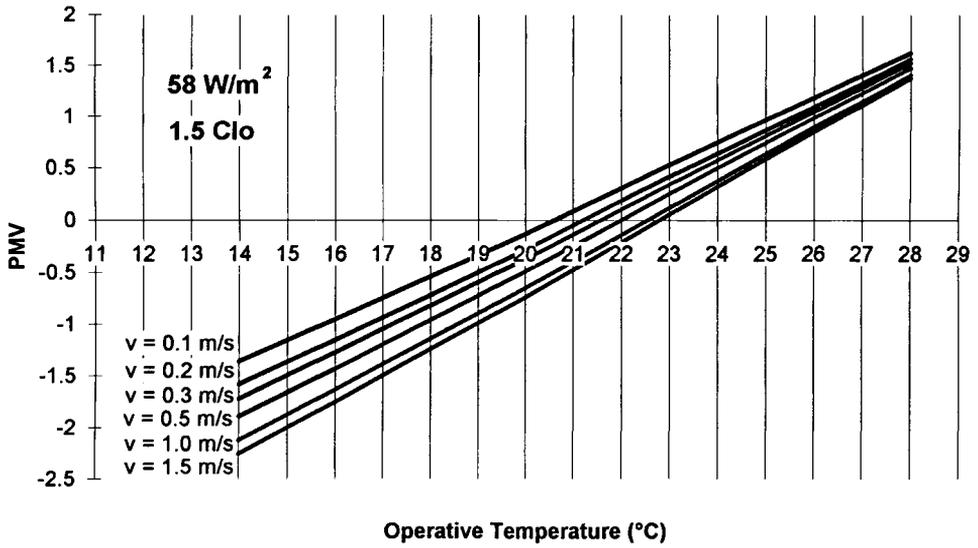


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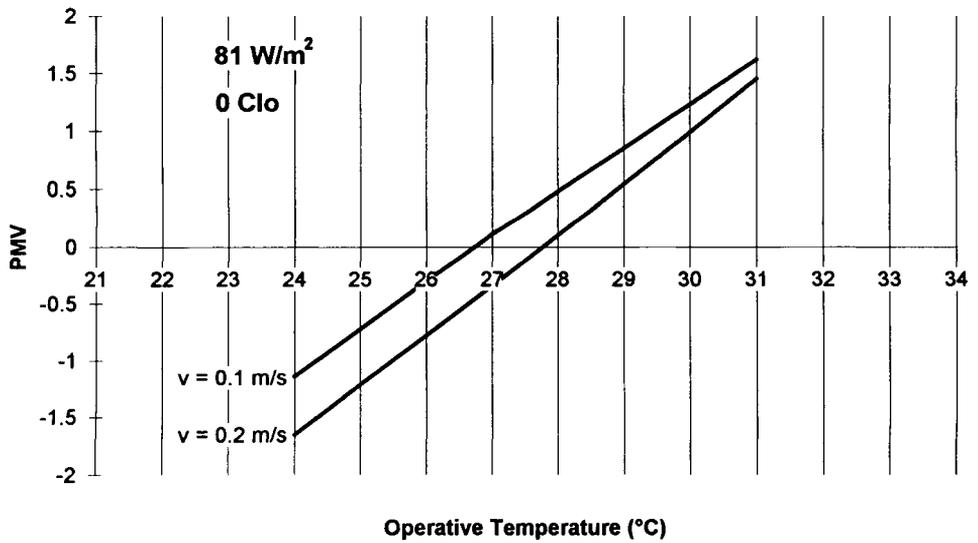


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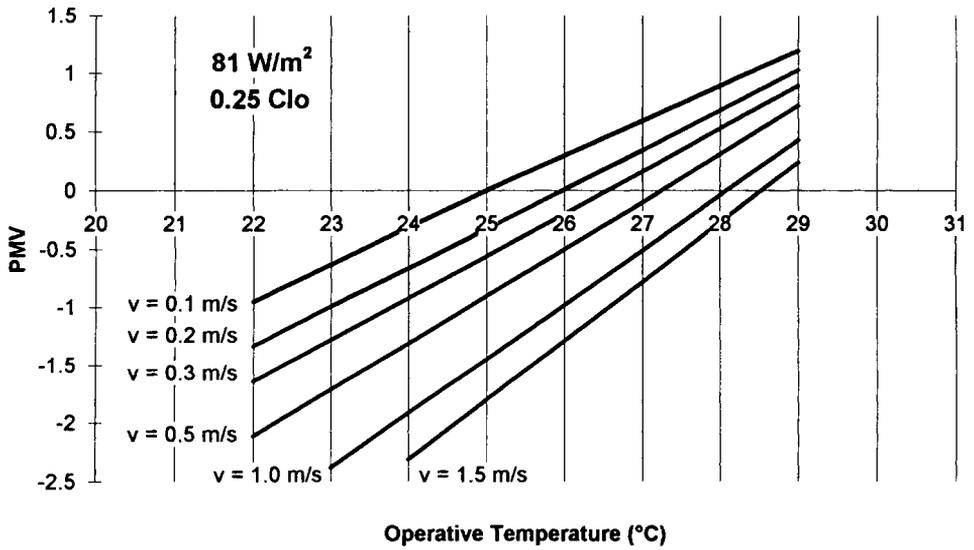


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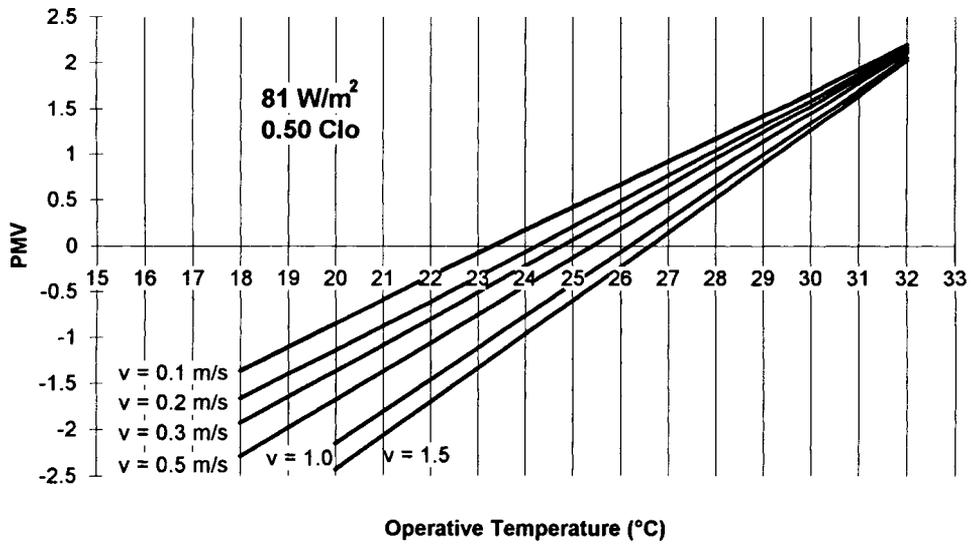


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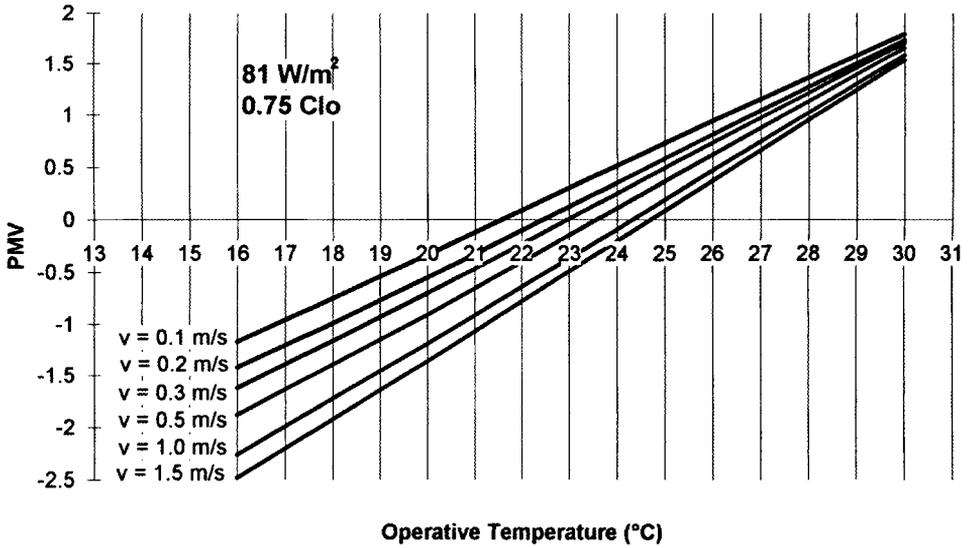


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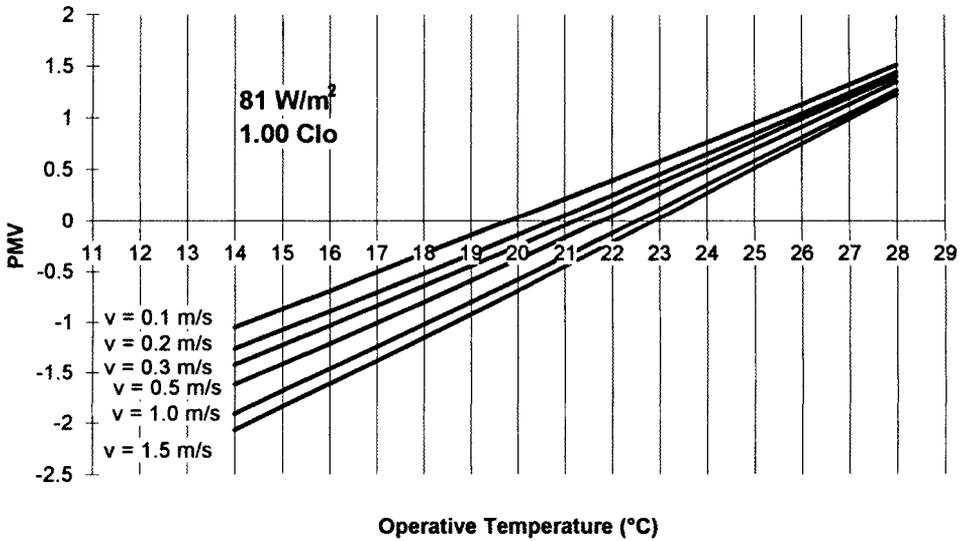


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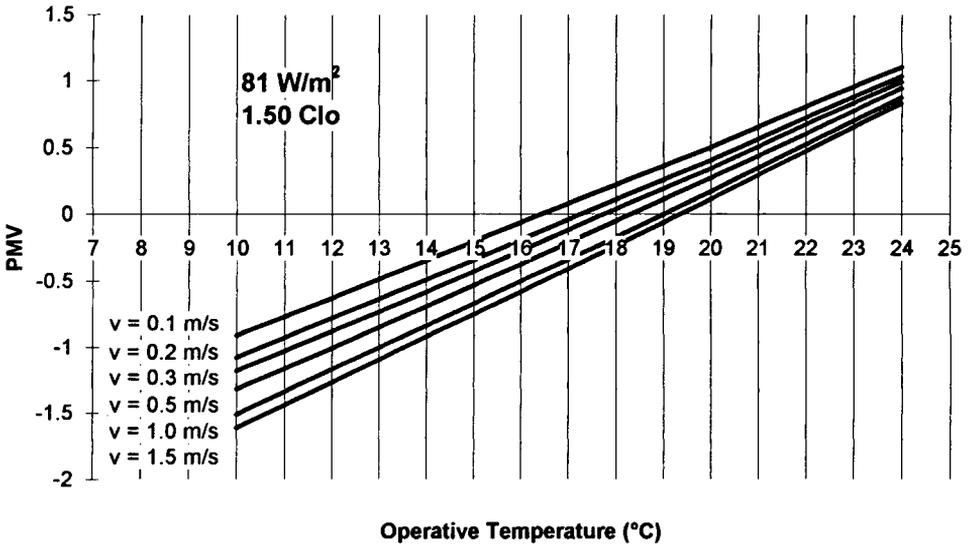


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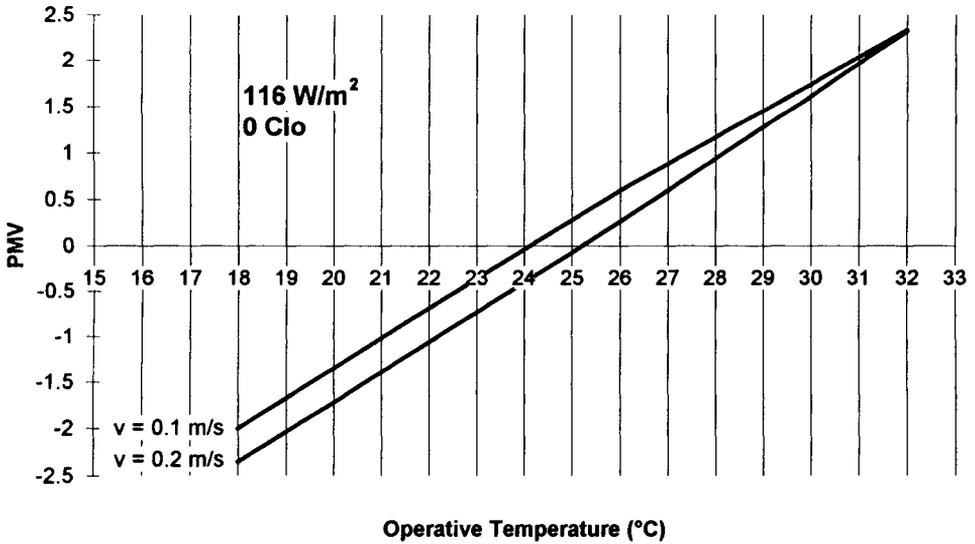


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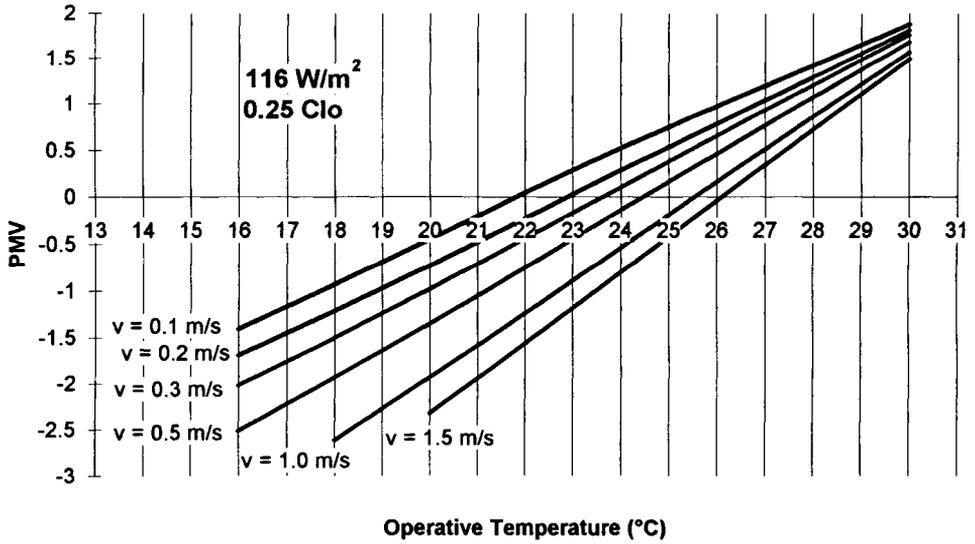


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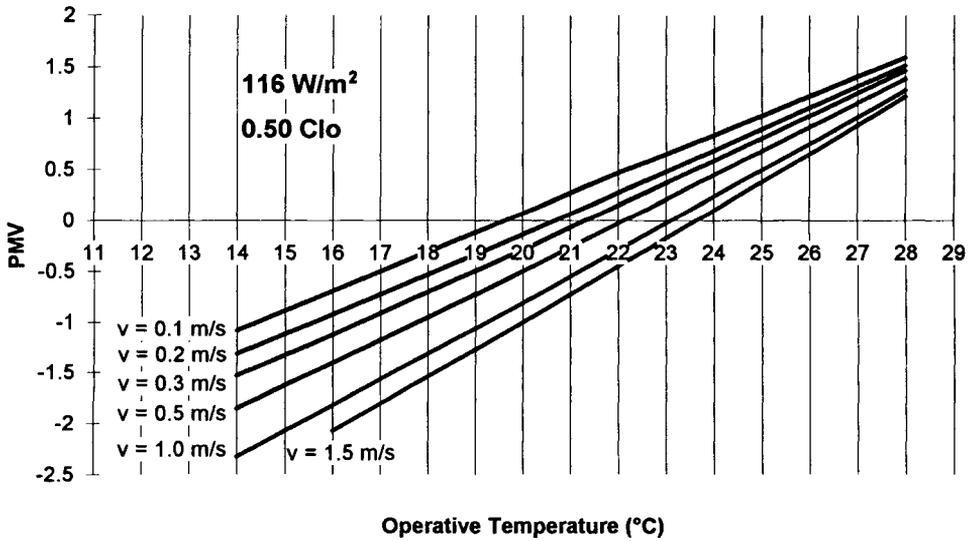


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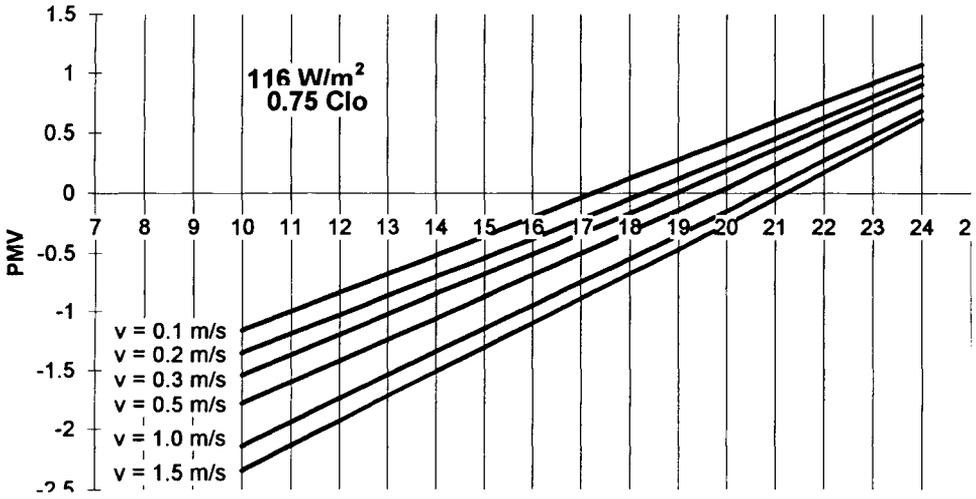


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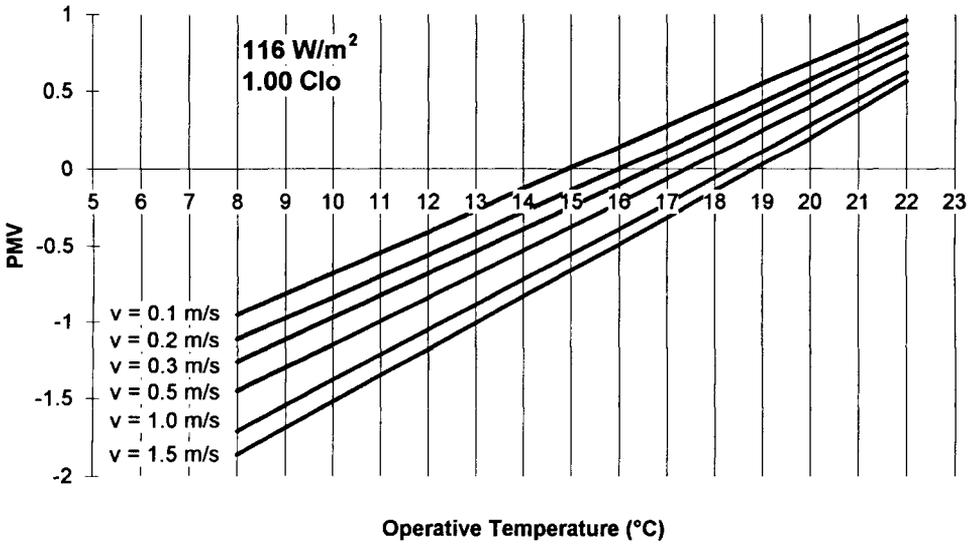


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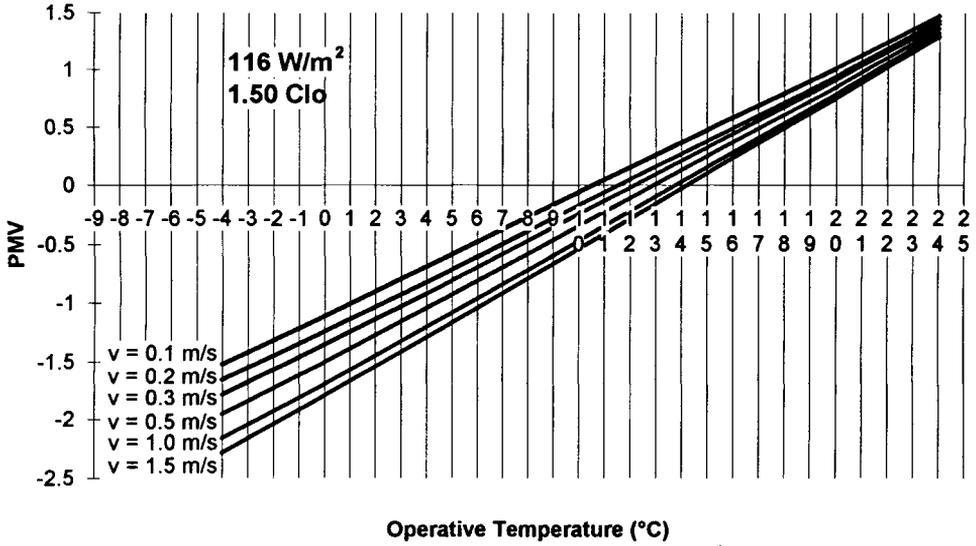


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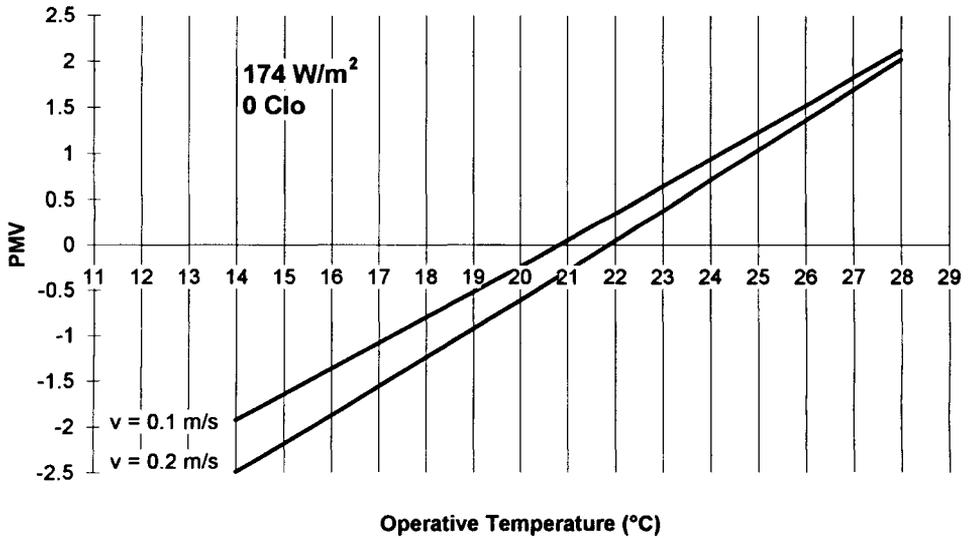


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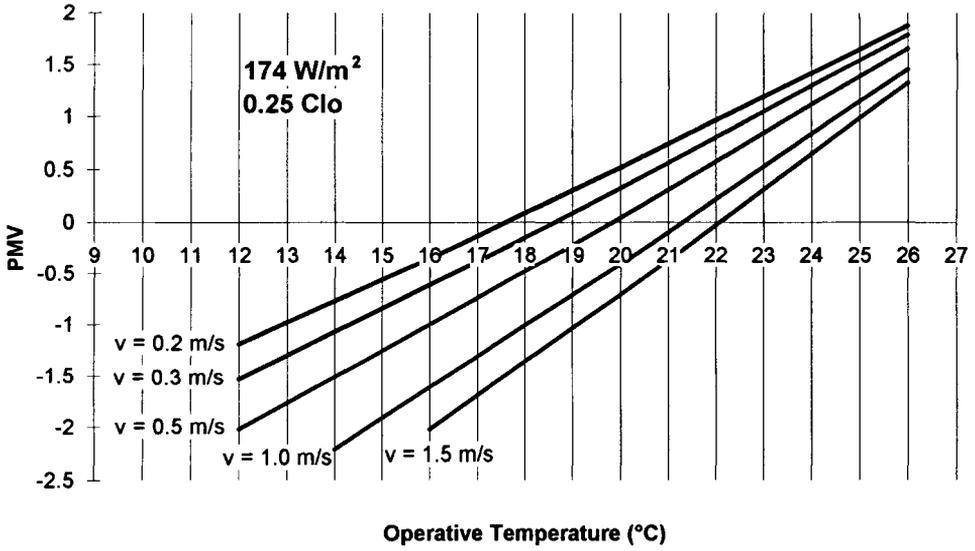


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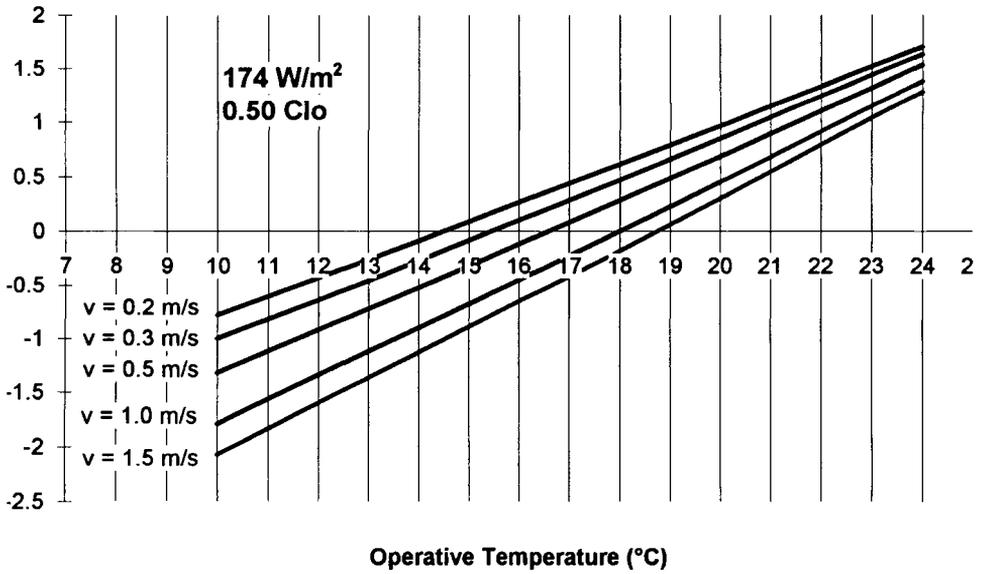


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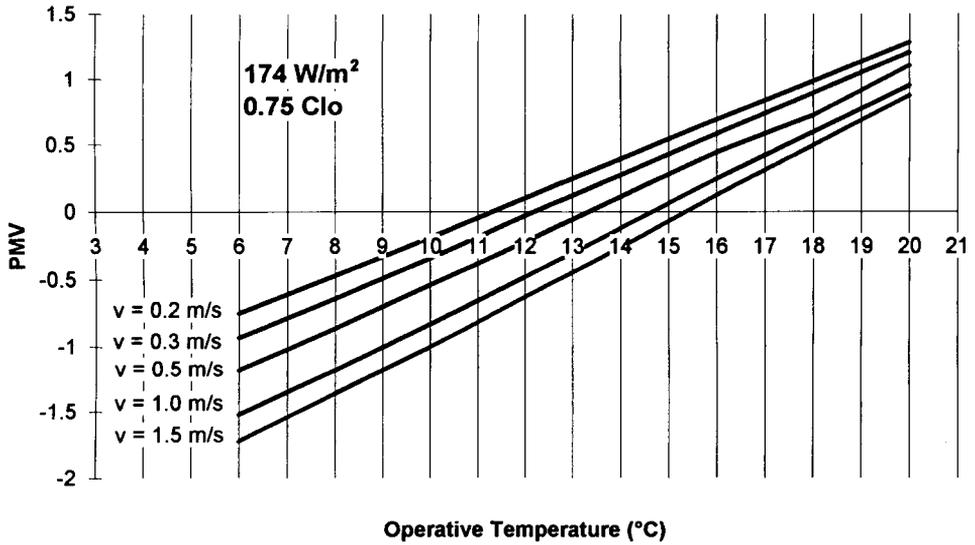


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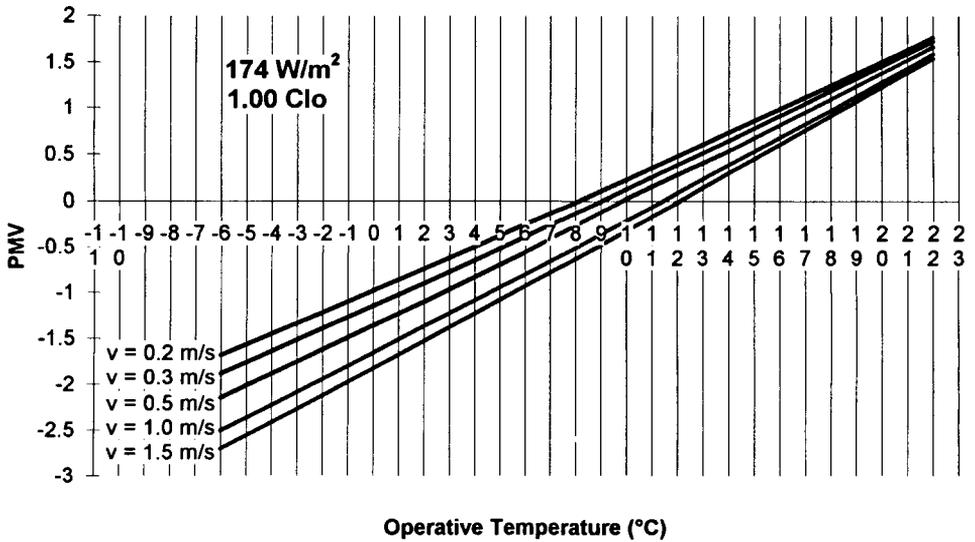


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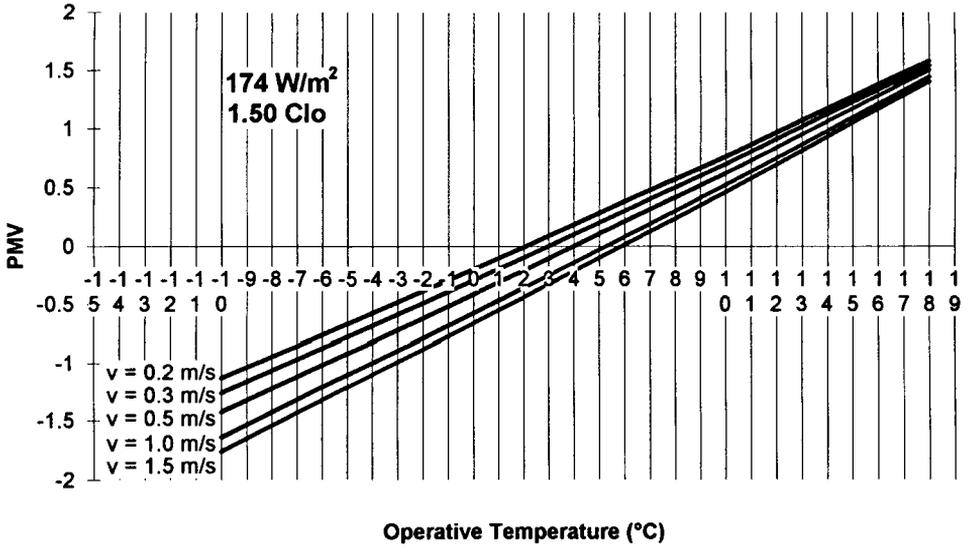


Fig. B24

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**RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS**

Chapter 4—Bioclimatism in vernacular architecture

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1. Vernacular architecture vs Representative architecture: the role of energy

Any analysis of the role played by energy in architecture is faced with serious limitations due to the lack of studies in the architectural bibliography, especially studies of popular architecture. An awareness of these limitations will allow us to understand better why architects have paid little attention to the interaction of form and energy, and to the bioclimatic approach in contemporary architecture in general.

The first limitation stems from the very essence of bioclimatic analysis; energy is immaterial, difficult to represent in images, changing in time and wrongfully left out of the architectural literature. This is why it is difficult to find a basic knowledge of the functional aesthetic possibilities of bioclimatism in the cultural experience of present-day architects.

The second limitation to this knowledge, even more important than the previous one, is the low value given to the more anonymous 'popular architecture' as opposed to 'representative architecture'. The latter is the kind of architecture built by established power, which attempts to impress the observer and clashes with, dominates, and often destroys the natural environment. This style of architecture is crammed with theoretical aesthetic concerns, which would rather create artificial environments than be integrated in the natural milieu. To sum up, it is the architecture undertaken by well-known authors, found in 'important' buildings, which have been commented and widely appreciated by architecture critics throughout history.

Nowadays, representative architecture can be said to describe the architecture found in large office buildings, which embody the legacy of such works from the history of culture as the pyramids, classic shrines, medieval castles and large Gothic cathedrals, baroque and Renaissance palaces, etc. These modern buildings, clad in glass as a symbol of their modernity, are incongruously dark and require artificial lighting during the day, while the flimsy casing separating them from the outside

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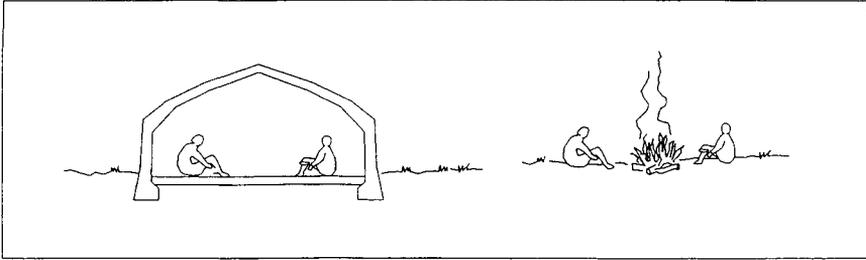


Fig. 1. Architectonic views: constructive or energetic.

makes it necessary to use air conditioning all year round, even when outside conditions are pleasant. We can well affirm that these buildings are so wrong that they ‘work worse than the climate’.

In comparison with this type of representative architecture, we find popular architecture, performed by the people as a direct response to their needs and values. These buildings show a greater respect for the existing environment, whether natural or artificial. They do not reflect theoretical aesthetic pretensions and use local materials and techniques as far as possible, repeating over and over again the course of history models which take the constraints imposed by the climate fully into account.

Our popular architecture—so often forgotten in official circles—may well be the kind which can best teach us today how to assimilate the bioclimatic approach in the practice of architectural design. However, we should not consider these solutions to be models to copy in current architecture. Our technical capacity and our cultural grounding prevent us from returning to these obsolete architecture forms, but what may be of use as a lesson and a source of inspiration is the attitude of the builders of this popular architecture, which recovers a relationship to the environment which has been lost in the more official architecture of the 20th century.

2. General principles of the relationship between form and climate

Although it seems that any contemporary architectural design can solve its problems of environmental control by means of artificial systems, this is not completely true in our culture. Furthermore, in many other cultures buildings have been built (and are still being built) with an acute awareness of the limitations imposed by the climate in which they are located. Builders with few technical resources are forced to design their buildings in close relationship to their usefulness as a barrier against the climate. In our modern buildings, on the other hand, the unrealistic faith in artificial systems leads to designs which disregard the climate and turn out buildings that are both physiologically and psychologically inhospitable.

To study the relationship between climate and popular architecture, we should first of all classify the different types of climate found on the planet. If we make a simplified overall analysis, temperature can be considered to be the most representative parameter, both in its average values and in annual and daily variations. We consider



Fig. 2. Popular architecture and representative architecture.

humidity to be indirectly indicated by such thermal variations, since the greater the variation the greater the continentality of the climate, and thus the lower its humidity.

Looking at the most critical factors which affect the climate we will observe:

As regards the mean temperature, **THE LATITUDE**, with lower temperatures in places of greater latitude.

As regards temperature variation, **CONTINENTALITY**, which involves an increase in thermal variation and in the dryness of the climate.

Secondary factors, which modify the action of the previous ones, are:

ABSOLUTE HEIGHT above sea level, which as it rises entails a fall in the average temperatures and normally an increase in temperature variation and a fall in humidity.

TOPOGRAPHIC RELIEF, with countless microclimatic variations in its relationship to the sunshine and prevailing winds.

VEGETATION and **HUMAN ACTION**, which modify the results foreseeable according to the above factors, acting as a rule in opposite directions: greater thermal stability and humidity with the presence of vegetation and greater temperature variation and less humidity with the development of the natural land in human settlements.

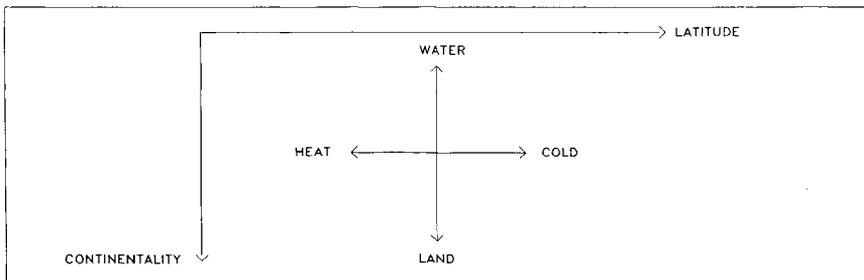


Fig. 3. Climate general classification.

The ensemble of all these factors means that there are marked local variations in the climate. There are also seasonal variations which can lead to the climate changing in a given place between extreme cases from the general field of possibilities during the year.

In spite of this, in order to be able to make a general analysis of the climate as regards its influence on the forms and solutions of popular architecture, we simplify the more complex reality by classifying climates into certain basic types which enable us to draw simple conclusions from architectural analysis. From this point on we will understand that any real climate is a weighted mixture of these basic types.

This simplified classification will let us observe that the most extreme cases of climate are those which have a clearer architectural solution, while the architecture found in temperature climates paradoxically turns out to be more complex, since the buildings have to adapt to changing conditions, and do not permit single solutions.

The foregoing allows us to distinguish three basic types of climate:

- (a) **COLD CLIMATES**, typical of high latitudes or great heights in medium latitudes, with very low temperatures, seasonal variation with the changes of winter-summer sunshine levels, an always pleasant solar radiation and aggressive winds when they come from the direction of the corresponding pole.
- (b) **DRY WARM CLIMATES**, typical of deserts close to the Equator, with high average temperatures and high temperature variations in the daily cycle, very low humidity and very directional solar radiation, no cloud cover and practically no rainfall, and dry winds which are warm, heavy with dust, and also very aggressive.
- (c) **WET WARM CLIMATES**, typical of subtropical coastal regions, with high average temperatures and little day-night and seasonal variations, high humidity and heavy rainfall, high and relatively diffuse solar radiation, and variable winds which can easily be of hurricane strength.

To these three basic types, two further quite exemplary cases can be added:

- (d) **WINDY CLIMATES**, which are found along with any of the previous cases with the presence of intense and frequent winds, or in temperate climates in which wind can become the main factor in the design of buildings.
- (e) **COMPLEX CLIMATES**, as a rule temperature climates displaying, though with less intensity, the conditions of the previous cases in their variations throughout the year. In this case the greatest problem of architecture is its capacity to adapt to these changes by means of flexible solutions.

The solutions provided by popular architecture to the problems raised by the climate and its variations are interesting to analyze, as they make us aware of the fact that there are several ways to solve environmental problems, according to the influence of different cultures. These solutions have the special value that they reach a state of balance with nature that is never attained by representative architecture, perhaps as a result of making full use of limited technical resources. This has given rise to architectural cultures which have withstood the advance of many generations of users thanks to the basic correctness of their designs.

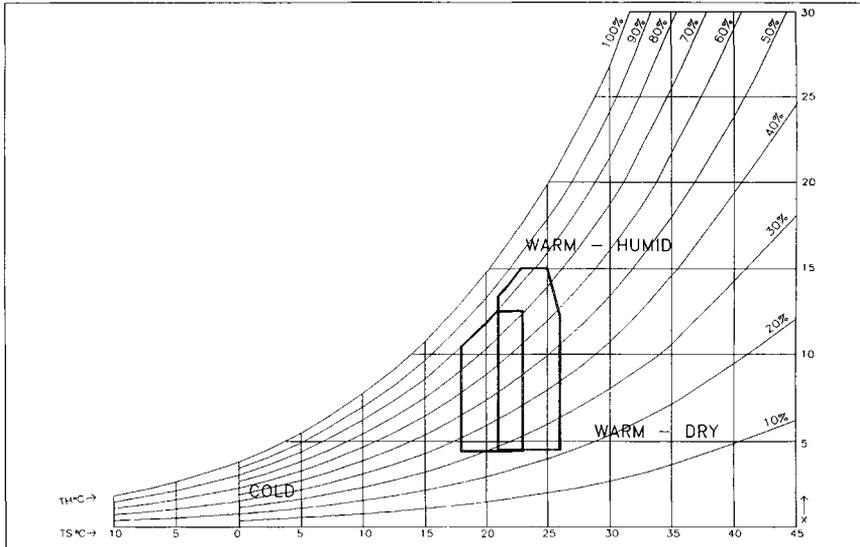


Fig. 4. Basic climates.

3. The richness of vernacular architecture

In popular architecture the climate is simply one more of the different forces (whether social-cultural, economic, defensive or religious, or involving the availability of materials, technical and constructive resources, etc.) that generate the forms of architecture. It is in conditions of low technology that the climate plays the main role and becomes the dominant force in the solutions used.

The more severe the climatic conditions, the more limited and rigid the solutions are. According to this principle, in very extreme conditions we should find unique solutions, the most useful, efficient and economic ones. However, reality does not work in this way, and in one and the same zone, with a given climate and conditions, we often find several solutions which solve the same climatic problems by different methods.

This is the case with deserts, in which the underground architecture of some settled peoples contrasts with the lightness of the shelters and tents of other nomadic peoples. In one case the heat from powerful solar radiation is fought by means of thermal inertia and darkness, and in the other with multiple screens against the sun and subtly controlled ventilation. Even in the most extreme climatic cases there are actually other factors apart from the climate which determine the solutions chosen.

In spite of this plurality of solutions, always limited by the basic constraints of the climate, it is interesting to observe how practically identical architectural models are developed in similar climates with highly different cultures and very distant geographical locations. This is what has led in many cases to the belief in the inflexibility of the connection between climate and popular architecture, to the point of converting it into a caricature of the real situation.

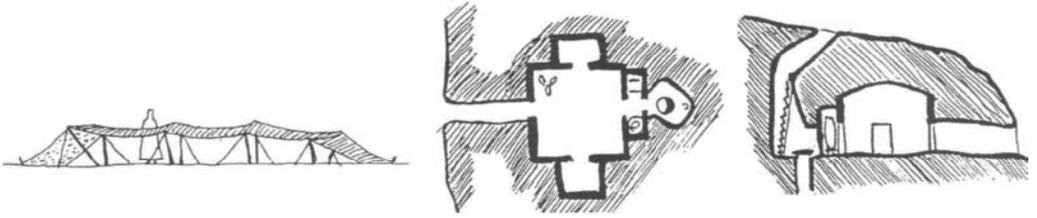


Fig. 5. Tuareg tent. *Mopti* Cave, West Sudan.

When underground dwellings very similar to Tunisian ones are found in Chinese deserts, or when the Malay longhouses prove to be practically identical to those built in the Amazonian jungle, we can start to believe, though wrongly, that the climate leads to typical building models that are limited in their economy of resources.

In any event this is not the case, and we have already seen how identical problems are solved in the same zone by different alternatives, something which enriches popular architecture extraordinarily. But there are also other points upholding the same arguments. It is even more interesting to find special architectural solutions that transcend from one place to other and from one culture to another, and are used with subtle variations to solve very different climatic problems.

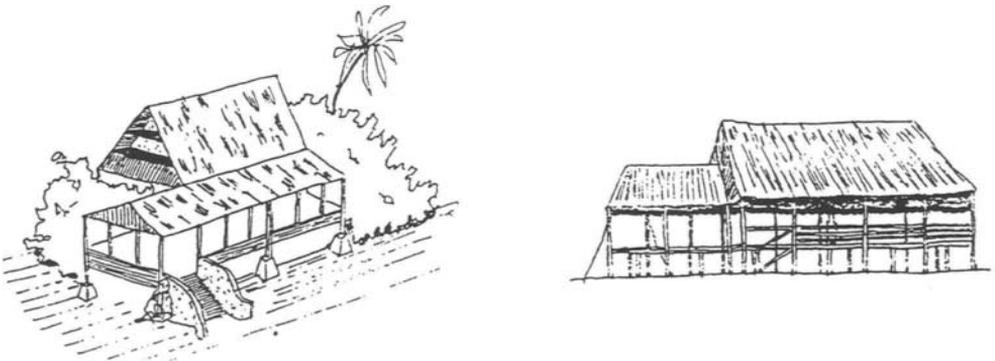


Fig. 6. *Yagua* house (Amazon). *Malaysian* house.

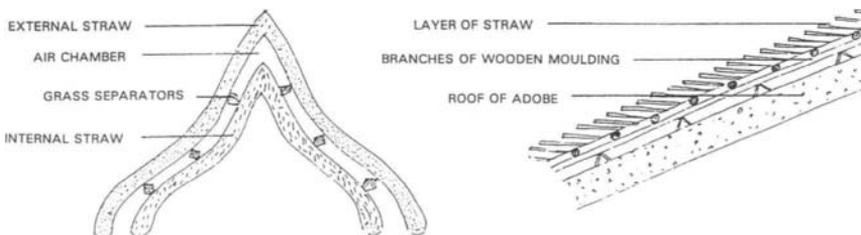


Fig. 7. Double roof: *Masa* housing (Cameroun), and *Orisa* housing (India).

This is the case of intermediate spaces in general and of the central courtyard in particular, as we will see below. We use the term intermediate spaces to mean those areas which do not strictly belong to the interior or the exterior of the building. Some examples of this type are porticos, balconies, galleries, vestibules and porches, in addition to the courtyards already mentioned.

All these spaces often fulfil important climatic functions, but they also have a strong symbolic role associated with them, outwardly expressing the feeling of their owners as well as having a flexible and diffuse utilitarian aspect which makes them multi-purpose areas and last resorts for any activity that does not have its own particular space in a building. Thus, over and above the climate, these spaces are used by everyone, demonstrating their marvellous capacity for adaptation.

The case of the courtyard is perhaps the most exemplary of all. The model of the house-courtyard as a detached residence or in dense urban situations is found in very diverse climates, changing its form and proportions to fulfil its climatic functions better in each case. The courtyard thus sometimes becomes a shady redoubt, protected from the wind and refreshed with the humidity of fountains and vegetation in warm-dry climates. It is also used to ventilate central zones of the building in wet climates, becoming a 'solarium' sheltered from winter winds in colder climates. And it is included within representative architecture in any climate as an ornamental element that reproduces the patterns of light and darkness of domestic architecture on a different scale.

This example, like others which we could put forward, once again demonstrates the mistake of considering the solutions of popular architecture to be limited. The great wealth of this kind of architecture lies precisely in the flexibility and adaptability of its solutions, which without ostentation attempt to express this wealth with the daily simplicity of the resources it uses.

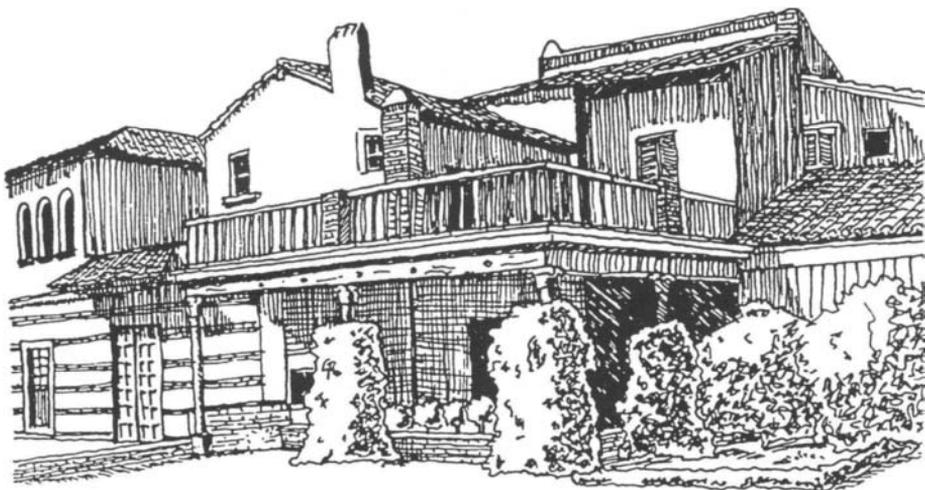


Fig. 8. Intermediate spaces between interior and exterior ambiances.

4. A singular solution—changes of location

This is a kind of solution which has had in the past, and may continue to have, special importance as a resource of environmental control.

There are many examples in the popular architecture of emigration or seasonal changes of residence. Normally connected with nomadic peoples that follow their herds in their annual search for fresh grazing land, these changes of residence are also linked to a desire to follow more favourable climatic conditions during the year. In this way the constructions can be simpler, adapted only to the climate of one part of the year, without needing to be adapted to the most extreme conditions which are avoided by moving.

The Paiuta Indians thus wintered in huts of a conical structure with a central oven and a hole for the smoke to get out, built with branches, wood and tree bark, and covered with branches or cane or grass fabrics. In summer their settlements were square without walls, with flat covers held up by four sticks, or more often they built shelters in a circular or semicircular shape, made with stakes or scrap of any kind, against which sand was swept up from the outside, with a fireplace and alcoves to sleep leaning against the wall inside.

In winter the shepherds of Siberia and Central Asia use tents covered with skins and snow piled up outside up to half their height, whereas in summer they use lighter leather tents. Sometimes they substitute the tents used in summer for cabins made of stone, wood and grass and in winter for semi-underground rectangular constructions, with the fireplace located opposite the entrance, walls and roofing a metre thick in earth, with grass for insulation and small windows made of animal gut.

The Mongolians have the ingenious solution of their typical yurt, built in such a way that it can easily be dismantled and transported on horseback. Its covering is made with a different number of layers of felt according to the season of the year.

The Kazaks of Central Asia, with a similar climate to the Mongolians, pitch their tents in the mountains in summer and gather in winter in towns located at the bottom of the valleys close to the forests, to protect them from the cold winds.

Similar systems, such as those used by certain American Indians or the ones used by the Japanese in the Neolithic age, consist in using light tents in summer and semi-underground dwellings in winter.

This long list of cases of seasonal changes of residence should not surprise us if we take into account the custom of changing residence in summer so widely found in our own bourgeois society. It is, however, interesting to see that in these examples there is often a marked change in the type of building according to the time of the year, whilst in our case this no longer happens, at least as far as differences in climate are concerned.

Another type of migratory solution, also forgotten in modern architecture, is that of a change in the use of spaces within the same building according to the time of year, or even from day to night. This was very frequent, and it still is in countries on the mediterranean coasts, where the very complexity of the climate makes this type of solution worthwhile. Though this system requires greater constructed volumes than in typical modern apartments, it permits an improvement in the flexibility of the

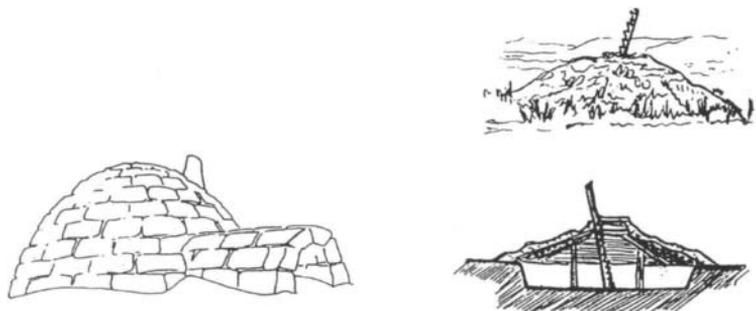


Fig. 9. Eskimo igloo, cold design. *Salish* shack (Canada).

architecture which makes it much more comfortable. Furthermore, it is indirectly more independent of artificial systems of environmental control, and therefore more economical with energy.

This concept is seen in many urban dwellings in Arab countries, where in summer they sleep on the roofs at night and take refuge in underground spaces during the day, while in winter the more conventional central spaces are occupied. In colder areas the zones of the dwellings used in winter are reduced as far as possible, leaving a whole series of intermediate spaces whose only purpose is to act as a supplementary thermal barrier against the outside weather. In summer or in the intermediate seasons, these intermediate spaces regain their full capacity for use in daily life.

This type of ‘dual housing’, with examples in the history of all the Mediterranean countries, normally had two kitchens, the winter one being in the innermost part of the dwelling to keep it warm, and the summer one outside to prevent heating of the cooler spaces inside. Dining rooms, studies and even different bedrooms, were similarly used in winter and in summer.

One of the challenges still pending for modern architecture is perhaps the recuperation of this concept of flexible occupation of buildings, and its transfer to other types of use apart from housing. In public buildings and office blocks this variable occupation and the intelligent development of intermediate spaces could well permit a more efficient use of architecture.

5. Typologies depending on the climate

5.1. Cold climates

In cold regions, the most important factor for the habitability of the buildings is keeping the heat trapped inside. This leads directly to a preference for compact built forms, with as few surfaces exposed to the outside as possible to reduce heat loss. In the most extreme case the forms of architecture become semi-spherical, seeking the maximum volume for the minimum shell surface, while in other cases the building is set underground, seeking the greatest possible protection. It is clear that these solu-

tions reduce the possibilities of ventilation and lighting in the interior, but once again the most critical condition of the architecture—in this case the cold—takes preference over the others in the definition of its general volumetry.

As a complement to the above features, popular architecture in these climates attempts to obtain the maximum possible insulating power of the enclosure walls, at the same time as a high level of airtightness to avoid draughts. Since in primitive technologies it is not easy to find insulating materials and hermetic openings, the result tends to be buildings in which the apertures are few and small, thus increasing still further the darkness inside. As it is difficult to obtain good insulation in opaque wall faces, complex and sometimes very ingenious strategies are used to improve the defence against the cold. Typical solutions found in these climates are the following:

- Using heaped snow on the roofs and walls of the buildings to benefit from its insulating power.
- Using granaries and lofts as heat barriers, storing straw in them to increase their insulating power.
- Using the heat produced by the kitchen, locating it in the interior of the building in a central position or in the coldest orientation of the house.
- Using the heat given off by the cattle, by locating the stables under the inhabited zone.

In addition to these specific solutions, which are common to most buildings in these zones, there are strategies of a more general nature for improving on unfavourable initial heat conditions.

The locations that tend to be chosen are hillsides facing the sun. The buildings are constructed in groups, seeking a compact formation in towns to obtain mutual protection against the cold winds, even though this is achieved at the price of lower access of solar radiation to the openings.

In most examples of popular architecture in cold countries, the collection of solar radiation for the purpose of heating is forfeited in exchange for better insulation. This voluntary loss of the possibility of solar heating and lighting has a proper justification which is sometimes hard to understand from our technological and cultural standpoint. The use of translucent or transparent materials in very low technology situations is very rare so, without the possibility of using the greenhouse effect of glass, the additional losses caused by an aperture are much greater than the gain in solar energy that could be obtained.

The Eskimo habitat can be considered as the most representative and exaggerated example of popular architecture in cold climates. In this case, the strategy of the use of openings to pick up solar radiation is approached through enclosure walls made of blocks of ice that allow a certain amount of radiation to get through. They are covered with opaque skins when the radiation is not of interest and improved insulation is sought.

Because of the constant and intense cold, and the intense winds of the zones close to the North Pole, the Eskimos typically live in igloos. These semi-spherical ice constructions have a raised floor inside in the occupied sector in order to use thermal stratification. The Eskimos cover the inside of the walls of this living space with skins,

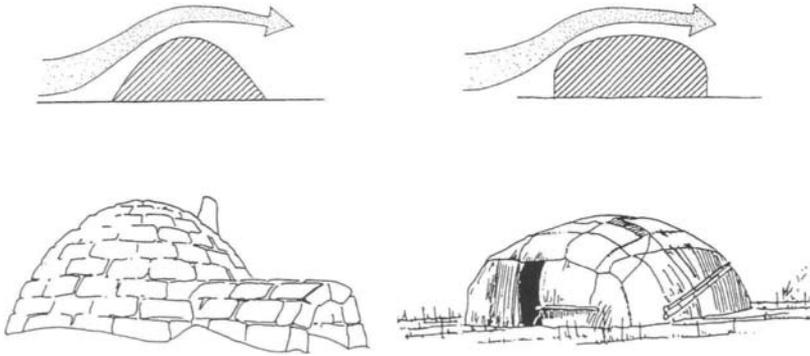


Fig. 10. Wind adaptation eskimo igloo and mongolian yurt.

creating air spaces that improve the insulation. In the centre of the space a small lamp burning seal oil is enough to keep the place warm.

In the summer, which is also cold, the Eskimos use partly buried dwellings. These are also circular in shape, with stone and earth walls up to a height of a metre and a half, and a narrow underground entrance. The floor inside is also on a higher level to that of the entrance, to cause a thermal siphon effect as in the igloo. The wooden beams are arranged in a radial pattern, and leave a central opening for the smoke to get out. They are covered and joined together by a double layer of seal skins filled with moss, thus achieving quite good insulation.

These Eskimo solutions are used with slight variations in the different zones inhabited by this race, though the underground habitat, less spectacular than the igloo, is sometimes used all year round with good heat efficiency. Another variation of the Eskimo habitat is the one found in Siberia, where in some cases they build rectangular cabins that have a wooden structure covered with a thick (1 m) layer of earth mixed with grass, which provides quite good insulation.

Aside from all the modalities of the Eskimo habitat, there are many more representative examples of dwellings in cold zones, with diverse variants of the general characteristics that we have defined above. Other examples of original cases could also be given, such as the outdoor covered corridors for communication between New England barns, the streets lined with porticos in the cities of northern Japan and Switzerland, the underground communication tunnels between Eskimo igloos, and so on. In these examples we find a curious parallel with the shady streets of certain zones of Arab cities or the underground connections in troglodyte districts of Turkey. All these are cases in which the environmental control goes beyond the scale of the building and reaches the urban scale.

5.2. *Hot dry climates*

In the regions with this type of climate an attempt is normally made to take advantage of the great temperature variation during the day-night cycle, delaying the

penetration of heat as far as possible so that it reaches the interior at night, when it is least bothersome. For this purpose materials of great thermal inertia are used, such as clay in the form of adobe bricks or mud walls, thick stone and all the possible combinations of these solutions.

Houses in these climates are frequently arranged in compact patterns, one very near to another, leaving small separations in the form of alleys or courtyards. Thus, the surfaces exposed to solar radiation are reduced and the built weight per unit of volume occupied is increased, which raises the thermal inertia of the ensemble. The generation of shade between neighbouring buildings reduces the warming of their walls by radiation and at the same time enables them to be cooled by contact with the fresh air at night.

In these buildings with great thermal inertia, the way their openings are handled is of vital importance: windows should be totally closed during the warmest hours of the day, not letting in either the light or the hot air from outside. At night these windows should be fully opened to use the cooling effect of nocturnal ventilation.

In some special cases in which thermal inertia cannot be relied on, such as the Tuaregs' tents in the desert, this independence of the internal air from the outside air is forfeited, and direct radiation is fought by being reflected and re-emitted through sophisticated barriers, with fabrics that are sometimes of dark colours and are cooled



Fig. 11. Somalian village.

under the sun by the effect of the accelerated circulation of air that occurs within the fabric, preventing the re-emission of radiation toward the interior.

In the dwellings found in these climates the kitchen is located outside, thus avoiding adding heat to interior spaces which could worsen their living conditions. The outside of the buildings is painted white or in light colours that reflect the radiation as much as possible. The openings facing the exterior are few and of a small size, often set in the highest part of the walls to reduce the radiation on the ground, to help hotter air in the house to get out, and to obtain the best possible lighting with the minimum penetration of radiation.

In these regions the presence of water is very important, and for this reason an attempt is always made to retain rain water, protecting it from evaporation through storage in underground tanks below the dwelling. These tanks also increase the thermal inertia of the building and sometimes cool it through the evaporation effect which, though small, provides some continual damping and cooling for the floors of the houses.

Other resources used to reduce the effects of the sun on buildings are eaves, blinds and lattices in the openings, vegetation to protect from the radiation on the walls or on the paving of outside spaces, etc. Larger scale solutions are public spaces such as streets or squares, and even entire towns, covered with immense barriers against radiation by means of canvases, cane meshes, etc.

Another type of solution found all over the world is the construction of underground dwellings by digging caves where the land permits, seeking the temperature stability that is always found at a certain depth under ground level and creating much more inhabitable interiors.

Another element typical of the architecture of these climates, though it is also present in other environments, is the courtyard. The cooler damp night air is retained in these areas, keeping conditions pleasant during the day because the yard is protected

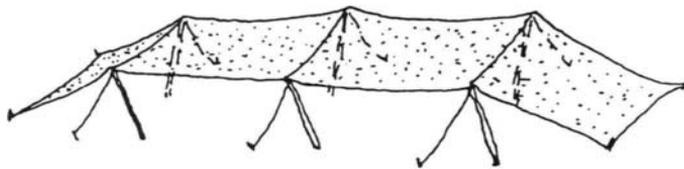


Fig. 12. *Tuareg* tent.



Fig. 13. *Yokurt* settling, collective protection.

from solar radiation, dry winds and sand storms. With the complement of water and plants, these yards become refreshing wells in the heart of the building.

In certain cases, especially in Arab countries, wise use is made of a combination of two courtyards, one in shade and the other sunny, to create a natural air flow from the cooler courtyard to the warmer one, creating an especially pleasant environment in the intermediate premises. In other cases, as in the Moroccan mountains, very high and narrow courtyards are built in buildings several storeys high, acting as inverted chimneys that ventilate the innermost zones of the building.

The basic design of the courtyard-house, which can be found in all types of cultures and climates, thus finds in warm-dry regions its best operating conditions and its greatest usefulness as a system of climatic improvement of architecture.

In the warm-dry climates of different zones of the Earth we often find similar buildings forms. For example, it is typical to use heavy enclosure wallings, adobe or mud walls or roofs of very great thickness. These are often justified by their structural function, but basically fulfil a climatic function, as is shown by the cases in which they act simply as a covering for load-bearing wooden structures.

Another typical solution in these regions is that of the double roof or double wall with a ventilated inner space. This is normally found in climates that are warm and dry for the greater part of the year but have a rainy season during which conditions approach those of warm-wet climates. In this case it is common to build enclosure wallings combining the use of straw and clay, with the following consequences:

- (1) The straw layer, that has to be renewed annually, protects the lower clay layer from the water during the rainy season.
- (2) the same straw protects most of the roof from the direct effects of the sun, avoiding heat storage and the indirect warming of the interior by radiation re-emitted during the dry period.

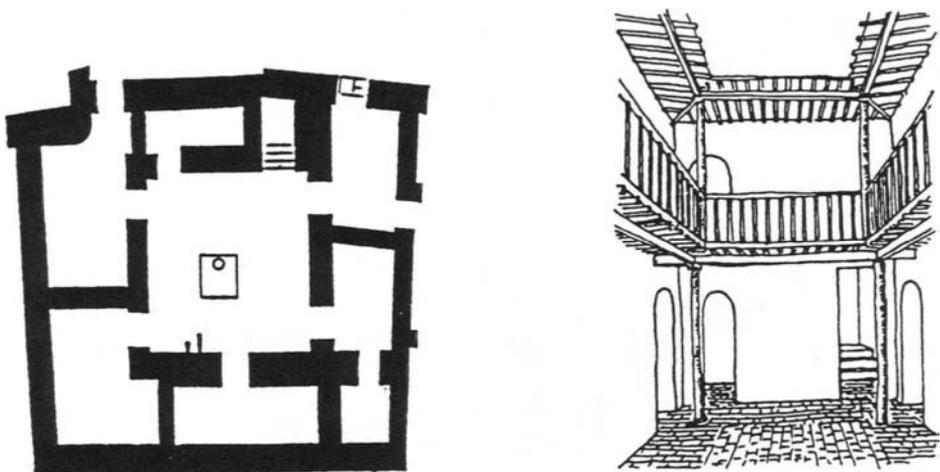


Fig. 14. Layout and courtyard of a housing in *Ur* (Mesopotamia).

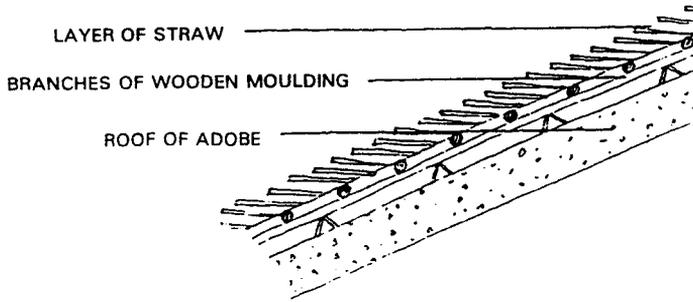


Fig. 15. Orisa housing (India).

- (3) The empty space between the two layers offers additional insulation on very warm days and the clay layer, with its thermal inertia effect, regulates the inside repercussions of outside temperature variations.
- (4) The inertia of the interior space is improved since the straw layer acts as an outer insulation for the wall faces, a situation that is theoretically the most favourable for thermal stability in permanently occupied buildings.

5.3. Hot humid climates

In this type of climate the thermal inertia of the buildings offers no advantage, since the variations in the outside temperature in the daily and annual cycle are very small. Furthermore, because the radiation is very intense, it is vital to obtain the maximum possible protection against its effects by attempting to stop not only direct, but also diffuse radiation, which is of importance in these climates.

On the other hand ventilation is also very important in order to dissipate the heat in the interior and to reduce the humidity of interior spaces. For this reason, the buildings have large openings protected from the sun, while the typical implantation of buildings uses long narrow forms that are independent and distant from each other, attempting not to create barriers for the breezes between the different buildings.

To make air circulation reach the whole interior space in these climates, apertures occupying the whole wall face are used to allow the air to circulate, with protection from radiation and onlookers by means of lattices, blinds, etc. In spite of these devices this solution logically entails problems of privacy and a total lack of protection from noise.

In traditional dwellings in these zones the roof is a very important element, since it has to act as a parasol and umbrella at the same time. In some cases the roofs are broken down into a great number of overlapping roofs, one shading the other, among which the air can circulate, thus avoiding overheating.

Also typical in these zones are roofs with a steep slope to drain off the frequent rains. They favour the thermal stratification of hotter air at the top, where openings are made to let this air out. The very accentuated eaves afford protection from radiation and from the rain. They also offer ventilation and sometimes form porches

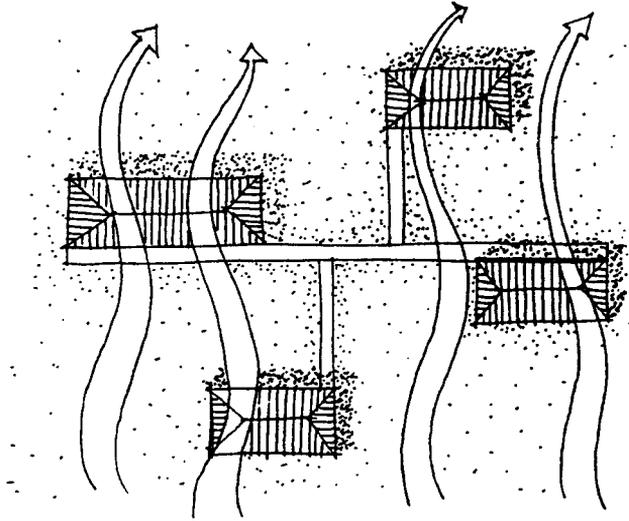


Fig. 16. Hot humid layout of buildings.

or open galleries, generating shady intermediate spaces by day and spaces protected from the cool damp air at night, which makes it possible to rest or sleep on very hot days.

In nearly all cases the roofs are light in order to avoid heat storage from radiation, with a composition that permits a certain 'breathing' of their strata to avoid condensation inside and favour cooling by air circulation. The floors of the buildings are raised in many cases, to obtain better exposure to the breezes, protection from floods in the event of storms, and protection against insects and small animals. These raised floors are built so that they are also permeable to the air, thus completing the ventilation facility of the whole envelope of the house.

A typical environmental solution of these climates, which we could consider to represent the minimal habitat, is the hammock. Used for sleeping or rest, these

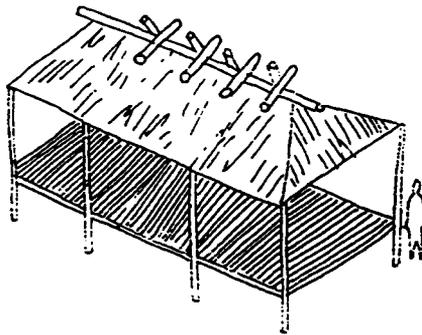


Fig. 17. Seminola house (Florida).

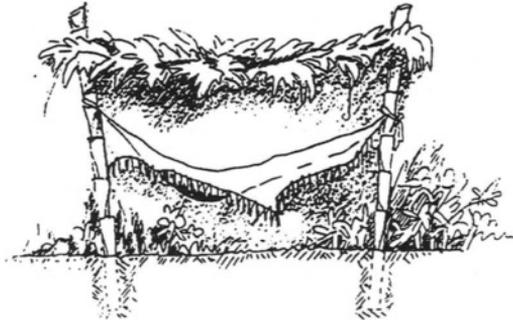


Fig. 18. Colombian hammock.

permit air circulation in all directions, and the swinging motion produces the relative movement of the air with minimum of effort. The hammock does not have any thermal inertia, as opposed to mattresses, which are uncomfortable in these climates. A complete example of this solution would be the typical Colombian 'habitas', made up of a roof of leaves on a structure that also serves as a support for the hammock and for baskets or sacks containing foods, water, etc.

To sum up, in these climatic zones the role of protection that we normally attribute to the building results in the most immaterial architectural constructions.

In these warm-wet zones, natural light can become much more bothersome than in warm-dry zones, since the sky produces a very intense brilliance in all directions, easily causing dazzling effects. For this reason, the openings are often covered with dark coloured cane meshes that reduce the brightness penetrating the interior from the surface of the openings. The ceilings are painted white to distribute the light as evenly as possible in the interior. This same function is performed by the lattices and grilles found in Arab countries and the galleries and balconies that act as areas of shade and protected extensions of the indoor area towards the public space.

In the zones where the damp heat is only seasonal, housing design can become relatively more complex. Sometimes in urban zones very high ceilings are used, where the hot air is stratified and the air in the lower part of the rooms, which is the occupied part, is cooler. In other cases, in the event of changing from wet to dry heat, houses are built with a light structure covered with canvases or awnings, which in the dry season contract and allow air to circulate among their fibres, and which dilate in rainy conditions to form almost waterproof, compact meshes.

5.4. *Windy climates*

Air movement is connected with the sensation of heat, thus becoming a positive factor for comfort in warm-wet climates and a clearly negative one in cold climates. However, excessively strong winds are unpleasant in any type of climate, and can in extreme cases become the main conditioner of the forms of popular architecture.

The simplest and most primitive system of controlling the effects of wind is found

in the simple windbreaks, built with branches, straw or grass, that are found as a primary model in all cultures that take their first steps towards civilization. Shelters of this type are still found in the 20th century as a habitat of Australian aborigines.

The basic form of these windbreaks is an inclined plane that is located in the direction of the wind and provides protection for people and for the fire used by them, whilst also giving some protection against rainfall.

Other primitive peoples also use more or less sophisticated shields for shelter from the wind, as in Samoa or in South Africa, where the Khoisan move large screens about to close up the walls, raising or lowering them according to the direction and the intensity of the wind.

Another more elaborate example of controlling the effects of wind is the case of the Arab tent, which is erected only to a limited height and is protected from the wind by mobile barriers anchored in the sand.

Different peoples that lives in zones with intense winds, such as the Eskimos or the Siberian Mongolians, make their buildings with rounded forms close to semi-spherical shapes, which are the ones that offer the least resistance to wind.

When choosing locations for their igloo settlements, Eskimos also seek sites protected from the wind by cliffs, with the entrance to their dwellings facing the beach. These entrances are built in the shape of a curved tunnel to prevent the direct entry of the wind. The mouth is set transversely to the dominant direction of the wind and is protected with a wall of compressed snow blocks.

Another sophisticated habitat solution that controls the action of the wind is that of the American Indians' tepees, which with two large flaps on the upper part of the tents, worked with two long sticks from ground level, direct the opening in the most suitable direction according to the weather conditions.

If we seek examples closer to the European culture, there are many buildings from popular architecture whose form is clearly influenced by the presence of a dominant wind. This is the case of Norman farms, in the northwest of France, whose cane and



Fig. 19. *Bushman windbreaks (Austral Africa).*

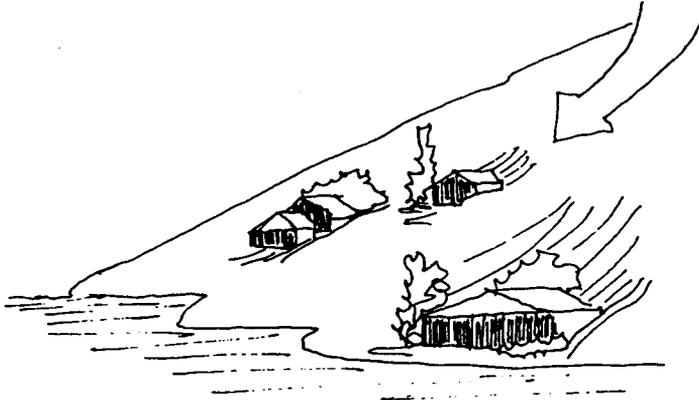


Fig. 20. Switzerland houses.

straw roofs have shapes similar to the hull of a ship, with the prow facing the hostile Atlantic wind and the stern extended to create a protected zone toward the east.

In Italy, in the village of Pescontanzo in the Abruzos mountains, the houses set between partition walls have very pronounced eaves, that are supported on the prolongations of the divided walls, thus covering and protecting from the intense wind of the zone not only the outdoor staircases, but also the small windows and doors set into the facades.

Finally, in many other zones with intense winds, such as French Provence or the Swiss valleys, houses are dug into the hillsides of the mountains facing north, helping to divert the wind over the roofs and creating a protected zone on the southern side.

5.5. *Complex climates*

As we have already mentioned above, temperature climates often have very variable conditions throughout the year, which force popular architecture to use much more complex solutions than in the case of the more extreme climates. This complexity is made manifest in the use of flexible systems, with elements or combinations of elements of the building that can easily change their environmental action according to the weather conditions. The most typical of these flexible systems are:

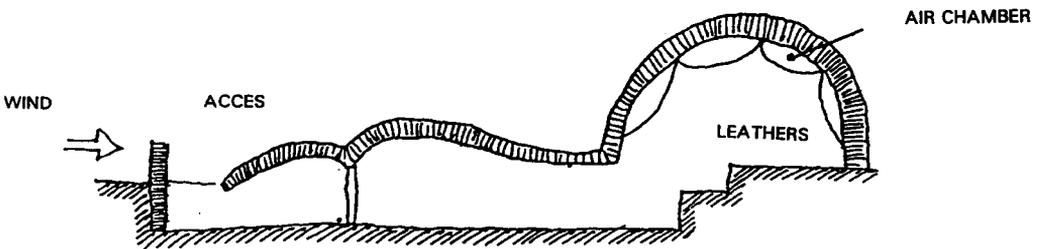


Fig. 21. Section of an igloo.

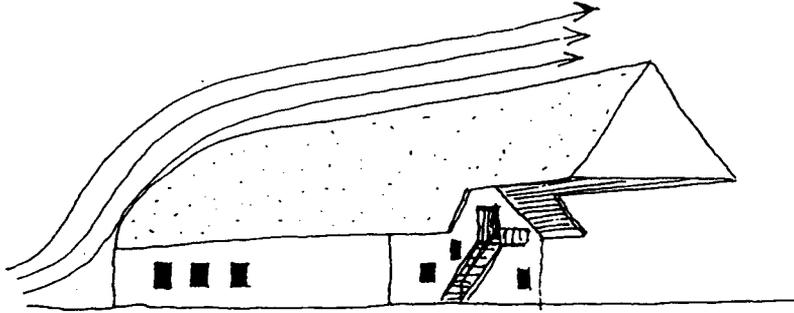


Fig. 22. Normand farm.

- Mobile shade systems, such as the typical louvre blind that allows the entry of radiation and ventilation to be controlled simply and conveniently.
- Mobile insulation in the openings, shutters, curtains, etc., which enable the flow of heat and light to be regulated, above all in winter.
- Apertures that can be completely opened, permitting maximum control of ventilation and allowing the free passage of air and sunlight when appropriate.
- Intermediate spaces between indoor and outdoor areas, which can generate favourable microclimates, as has already been mentioned above. These can also be occupied at different times of day and seasons of the year, thus adding to the building's functional possibilities.

With this great number of resources, the popular architecture of temperate climates in general, and the Mediterranean climate in particular, solves the difficult problem of using one sole architectural form to resist differing climatic conditions that, though to a lesser extent, reproduce the characteristics of the extreme climates analyzed above.

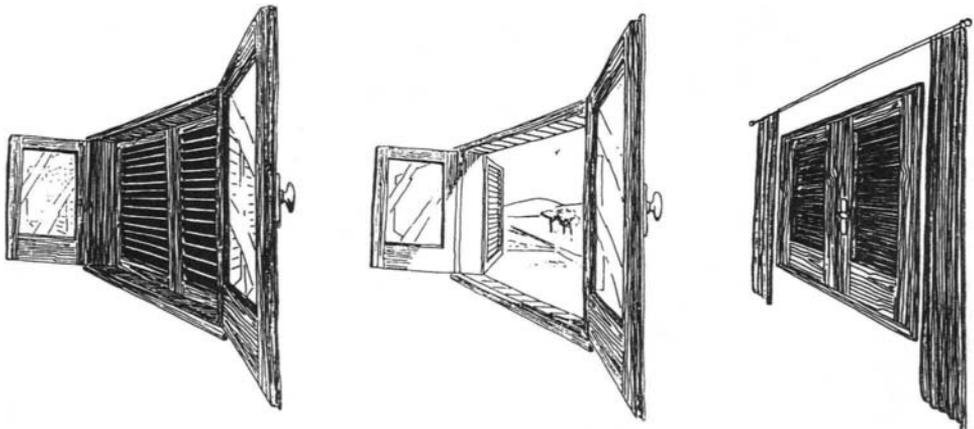


Fig. 23. Movable shading systems, movable insulation and completely practicable openings.

These climates have the problem of cold in winter, which can be dry or wet; though this distinction was of no importance in very cold climates, it involves different solutions here. They can also be very hot in summer, with high or low humidity, at times with the same intensity as the examples dealt with above, though these weather conditions last for shorter periods. Finally, there is the problem of the intermediate seasons, spring and autumn, where in short periods of time the climatic conditions can change from one extreme to another.

Though all these situations may not be critical separately, taken as a whole they have given rise to this complexity and wealth of solutions in popular architecture in these climates, which in fact makes it more complicated than that of more extreme environments.

When challenged by climatic changes, architectural solutions become more complex, seeking in the relationship between interior and exterior an energy operation that we call a 'filter' between different environmental conditions, instead of using most solutions of the 'barrier' type that we have found in simpler and more aggressive climates.

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Chapter 5—The utilization of microclimate elements

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1. Introduction

In architectural design the knowledge of microclimate elements is important: wind and local breezes, sun and shadows, humidity and vegetation, etc if well utilised, can strongly contribute to the thermal well-being of the inhabitants. If these elements are manipulated by the creativity of the architect they often inspire new architectural shapes: therefore an accurate knowledge of local climate factors and of the thermal characteristics of construction materials must be part and parcel of the architect's background information and a source of inspiration in the creative process.

2. The wind

Wind is an important element in the design of a bioclimatic house: two typical elements of the oriental architecture, the wind-towers and the 'malqaf' are significant examples. Wind towers, originated in Iran around the 10th Century, and are also called 'baud geers' (the Persian word means literally 'wind catcher'). A wind tower is made by a kind of large chimney vertically slit in its upper part by several brick baffles. During night time the tower cools off; the air coming in contact with the tower also cools off, becomes heavier and descends the interior of the tower, thereby penetrating the building. On windy days this process is further enhanced. The air enters the side of the tower exposed to the wind, descends and goes through the building, exiting from the doors that face the central hall and the basement. The pressure created by the cool air pushes hot air out of the building through doors and windows.

During day time the tower absorbs heat, which is then transmitted to the air at night, thereby creating an uplift current; when there is need for further cooling, this current can be employed to suck in the building the fresh air of the night. When the night is windy, the air flows down the side of the tower which is exposed to the wind

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and is warmed by the contact with the masonry, while an upward current is generated in the leeward section of the tower. By appropriate opening or closing of the various sections of the tower and/or of the building, the tower will cool off different sections of the building as needed. Wind towers are often used in conjunction with curved roofs or domes, which constitute other elements of environmental comfort during the summer heat.

In fact, hot air tends to raise to the vault above the living area; furthermore, while a curved roof receives the same amount of radiation as a flat roof of comparable area, the former offers a greater surface to transfer heat (by radiation and convection) to the exterior during night time. A round hole placed in the upper section of the dome further improves the circulation of the air. When it is windy the passage of the air above the external curved surface of the dome causes a point of depression at the apex of the dome. This depression sucks away the hot air which accumulated on the interior of the dome. The eyelet at the peak of the dome is usually covered by a cap pierced by several small openings which deflect the wind and increase the suction of the hot air. Usually the opening on the vault is placed over the living area. Sometimes domes are used in conjunction with wind towers; other times, especially when the wind carries a lot of sand, the domes are used without wind towers. Often, in areas where the winds blow most of the time in the same direction, the dome is substituted by a barrel vault whose longitudinal axis is perpendicular to the wind.

The most efficient natural cooling systems found in traditional Iranian architecture make use of water. These systems exploit the cooling effect caused by the evaporation of water. Warm air when blown over a water surface, or a damp wall, transfers part of its heat to the water, causing a partial evaporation. This cooling effect is achieved by the Iranians through various means; sometimes they use the natural dampness of the underground portion of the wind tower, or of the underground ducts connecting the tower to the house. These underground ducts were traditionally used for food conservation before the coming of modern refrigerators. A water basin and a fountain placed in the basement of the wind tower or in the room connected to the duct coming from the tower can supply further cooling by evaporation. In other cases, the air coming from the wind tower at a high velocity sucks the cool and damp air from these. A particularly efficient water cooling system uses a combination of several wind towers (four or more) and a cistern. This cistern is dug into the ground to a depth varying from 10–20 m. It is then covered by a dome surrounded by several wind towers. This system utilizes the seasonal temperature variations of the desert area, and also the insulating characteristic of the ground, which maintains a constant temperature throughout the year. The cistern is partially filled with cold water in winter. In summer time the constant air current created by the wind towers carries away the surface layer of the water, after its evaporation. In this way the external heat cannot penetrate the lower levels of the reservoir, and large amounts of water remain cool during the whole summer, even in the middle of the desert.

To satisfy the need for ventilation alone, the ‘malqaf’, or wind-catch, was invented. This device dates back to very early historical times: it is represented in Egyptian wall paintings of the tombs of Thebes, which date from the Nineteenth Dynasty (1300 B.C.). The malqaf is a shaft rising high above the building with an opening facing the

prevailing wind. It traps the wind from high above the building where it is cooler and stronger, and channels it down into the interior of the building. The size of the malqaf is determined by the external air temperature. A large size is required where the air temperature at the intake is low, and a smaller size where the ambient air temperature is higher than the limit for thermal comfort, provided that the air flowing through the malqaf is cooled before it is allowed to circulate into the interior.

In some designs, the drafts from the malqaf outlet are cooled by passing over water in the basement. However this method is not very effective, and some other device is required to provide air cooling, at increased rates of airflow, sufficient to meet the conditions of both hygiene and thermal comfort. By increasing the size of the malqaf and suspending wetted matting in its interior, the airflow rate can be increased while providing effective cooling. People in Iraq hang wet mats outside their windows to cool the wind flowing into the room by evaporation. The matting can be replaced by panels of wet charcoal held between sheets of chicken wire. Evaporation can be further accelerated by employing the Bernoulli effect or Venturi action with baffles of charcoal panels placed inside the malqaf. The wind blowing down through the malqaf will decrease the air pressure below the baffle, which increases airflow and thus accelerates evaporation. Metal trays holding wet charcoal can be advantageously used as baffles. Air can be directed over a *salsabil*, a fountain or a basin of still water, to increase air humidity. The baffles are also effective in filtering dust and sand from the wind.

The malqaf is still today incorporated into new architectural designs. The value of the malqaf is even more obvious in dense cities in warm humid climates, where thermal comfort depends mostly on air movement. Since massive buildings reduce the wind velocity at street level and screen each other from the wind, ordinary windows are inadequate for ventilation. This situation can be corrected by using the malqaf. Actually, a great advantage of both the malqaf and the wind tower is that they solve the problem of screening resulting from the blocking of buildings in an ordinary town plan. Several research centers have been working to develop the best configuration for locating blocks of buildings, while avoiding screening of blocks by those upwind; but after six or seven blocks no configuration will solve the problem of screening. The malqaf and the wind tower, however, being smaller in size than the buildings themselves, do provide an effective solution.

Another example of cold air utilisation in buildings comes from Italy: a group of six villas built in the 16th century near Vicenza was equipped with a remarkable system of underground air conduits that provided air-conditioning during the hot Mediterranean summer. The system includes natural cavities and manmade passages tunnelled through the hill on which the villas stand. The temperature of the air in the cavities is practically constant at 11–12°C all year round. During the summer, when the outdoor air is hotter than the air underground, a natural circulation system is created. Hot outdoor air is drawn into the underground cavities and flows out, now cool, into the cellars of the villas and thence into the rooms above through adjustable stone or marble grates set in the floor.

In the same century the work of Raphael, the Italian painter and architect, indicates that this Master was well aware of bioclimatic issues and of the main winds of the

local microclimate. In one of his letters, Raphael describes the Villa Madama, just commissioned by Pope Alexander VII, in bioclimatic terms. The terms ‘sirocco’ (the south-east of the sea wind from that direction) and ‘libeccio’ (south-western wind), are used not only to explain the orientation of the rooms, but also to show how the layout of the rooms was coherent with the external climatic influences. This letter puts into evidence the sound knowledge Raphael had of the bioclimatic question, and the care he gave to environmental comfort. Raphael writes

“... In order to expose the villa (Madama) to healthier winds, I have oriented it lengthwise Sirocco and Mistral (north-west wind), taking care not to have any of the living area windows facing Sirocco, but only those windows that need heat” [1].

In the exedre of the Villa Madama (Rome) the windows are oriented by 15°C east in respect to the east-west solar axis, in consideration of the asymmetrical course of the sun in respect to the hours of the day. The exedre windows so designed would have looked somewhat incomplete (while correct from a solar point of view) out of balance in respect to the final arch. Raphael therefore built two blank windows with the purpose of protecting the eastern windows from the uncomfortable western sun. But when the wind is not a strong element of microclimate, it has to be created for a passive cooling in architecture. It is important for an architect to know how airflows can be developed; the Egyptian master Hassan Fathy wrote:

“Another science to which architecture is indebted is aerodynamics. The methods of investigating airflow around the wings and bodies of aircraft are now being used to study airflow through, over, and around buildings. Scaled and full-size models can be tested in wind tunnels to determine the effect of the size, location, and arrangement of openings on the airflow through individual buildings, as well as the nature of wind patterns and forces between groups of buildings” [2].

The French architect Laszlo Mester de Paraijd utilises very well the airflows in the plans and sections of his buildings in Africa to give physiological well-being and cool; slanted and ventilated counterwalls are used extensively in the Arlit and Agadez courthouse and the Court of Appeals building in Niamey (see Figure). He writes:

“When air can circulate freely between a cool open space and a hot open space, a natural flow is created from the colder to the warmer space. Based on this principle, natural cold-air flows were created to cool the various parts of the building, circulating from one inner courtyard to another and from the courtyards to the outdoors, according to the amount of sunlight and the kind of ground covering” [3].

At the Faculty of Philosophy of the University of Iannina in Greece, a row of PVC pipes of 25 cm in diameter have been laid at 1.5 m under ground level. Their purpose is to precool the air entering the building during the summer before it flows to the University libraries. The same system has also been experimented in an agricultural

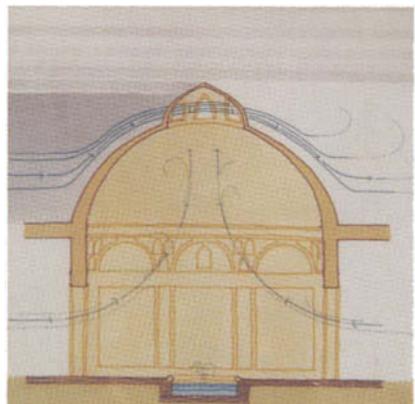
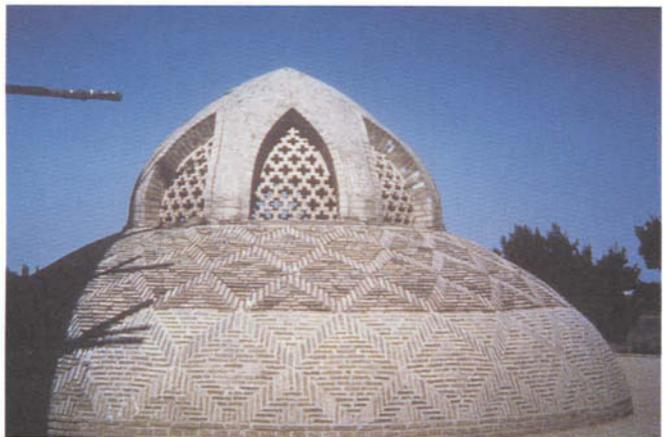
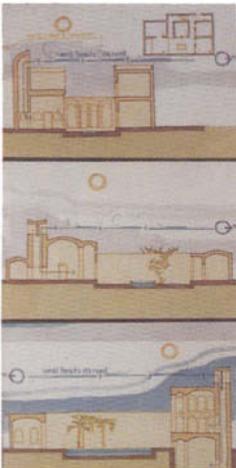
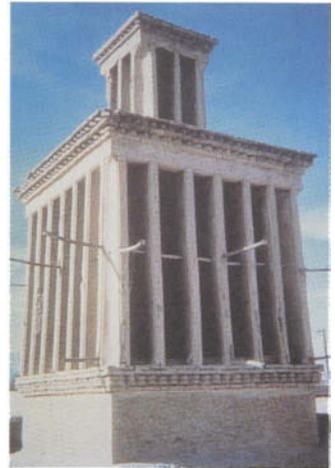
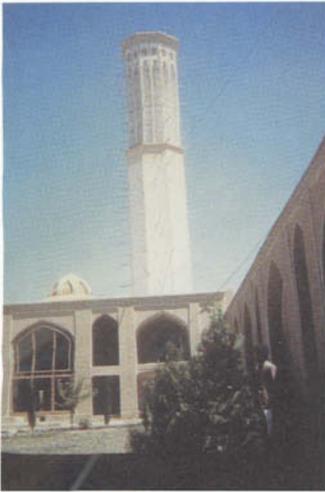


Fig. 1 (top left). Yazd (Iran)—Tower of the wind. Fig. 2 (top centre). Section of a tower of the wind. Fig. 3 (top right). Tower of the wind. Fig. 4 (middle left). Sections of the tower of the wind. Fig. 5 (middle right). Yazd (Iran). Fig. 6 (right). Yazd (Iran).

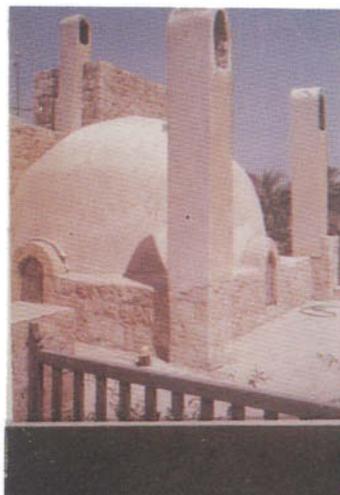
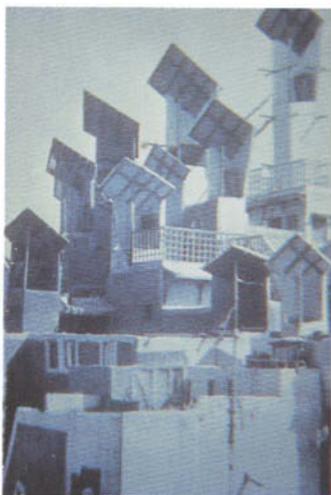
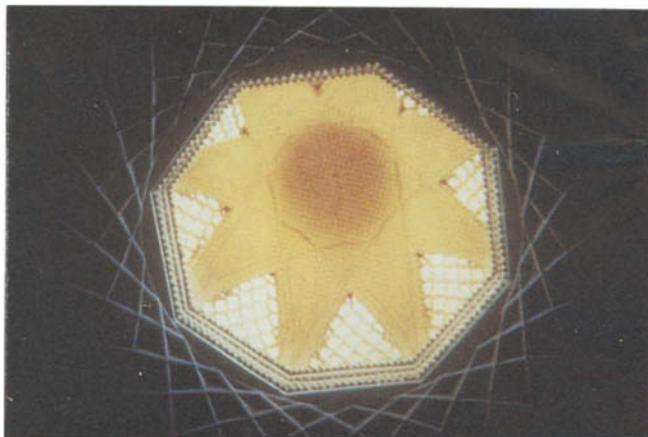


Fig. 7 (top). Yazd (Iran).
 Fig. 8 (middle left). Sind (Pakistan): malqaf. Fig. 9 (middle right). 'Mit Rehan', Shabramant, Egypt (1980), qa'a dome and chimneys.
 Fig. 11. L. Mester de Parajid, Cour d'Appel Niamey (Niger).

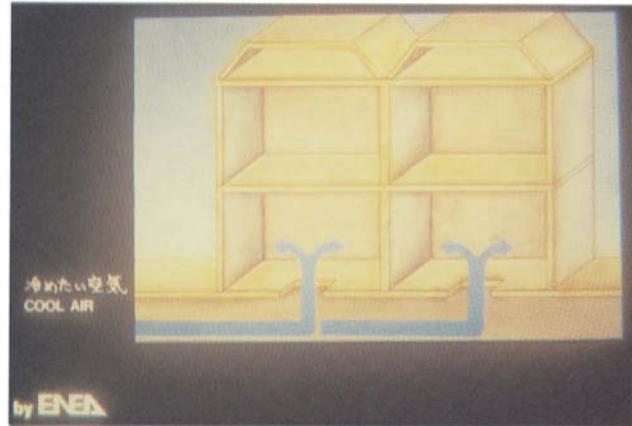
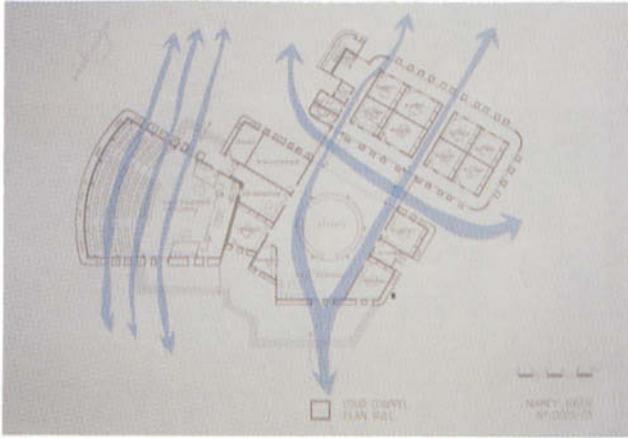


Fig. 12 (top left). L. Mester de Parajid, Cour d'Appel Niamey (Niger). Fig. 13 (top right). The Villas of Costozza, Italy. Fig. 14 (left). The Villas of Costozza, Italy. Fig. 15 (right). The Villas of Costozza, Italy.

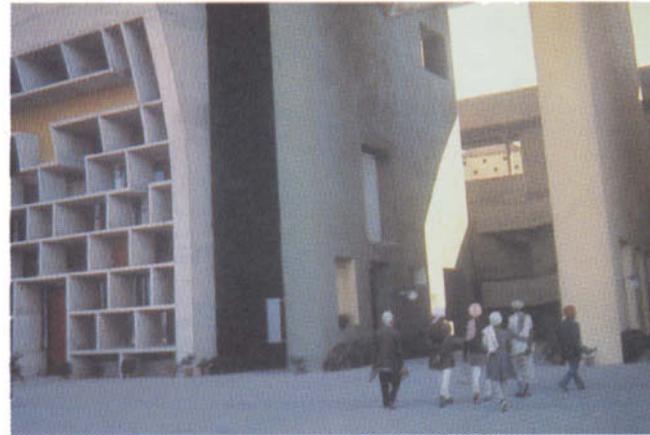
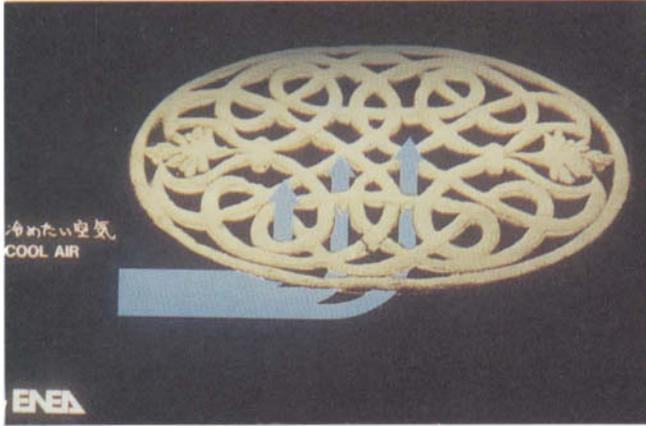


Fig. 16 (top left). The Villas of Costozza, Italy. Fig. 17 (top right). Villa Madama of Raphael, Rome, Italy. Fig. 20 (left). Le Corbusier—Monastery of 'La Tourette', L'Arbresle (Lyon), France. Fig. 21 (right). Le Corbusier—Buildings in Chandigar (India).

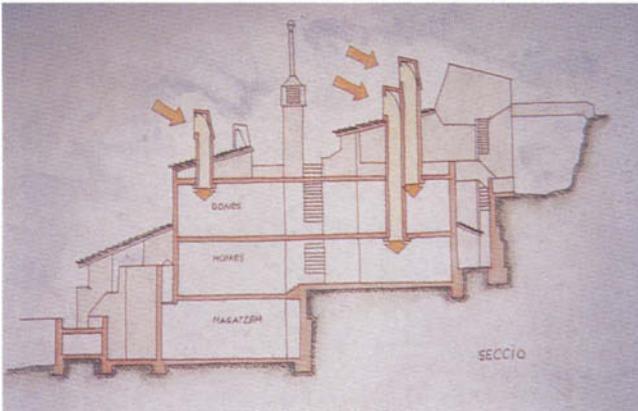
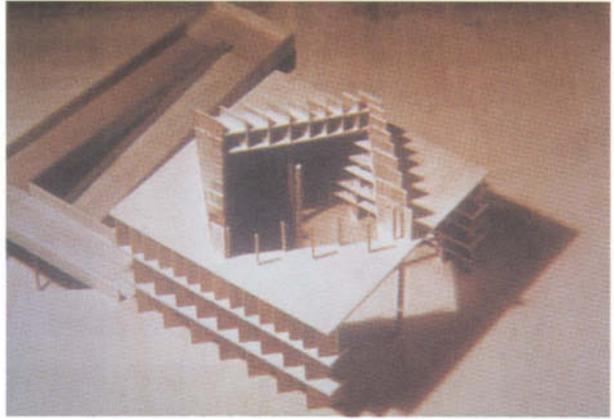


Fig. 22 (top left). Le Corbusier—Buildings in Chandigar (India). Fig. 23 (top right). Le Corbusier—The Tower of Shadows (maquette). Fig. 25 (above). R. Serra—Sport Centre in Barcelona (section). Fig. 27 (right). Hohenheim (Germany)—H. Schmitges, Student housing.

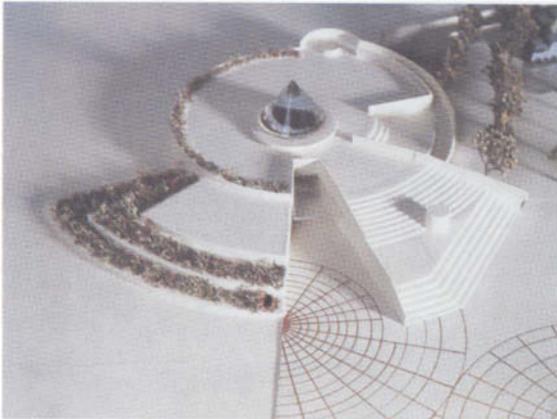
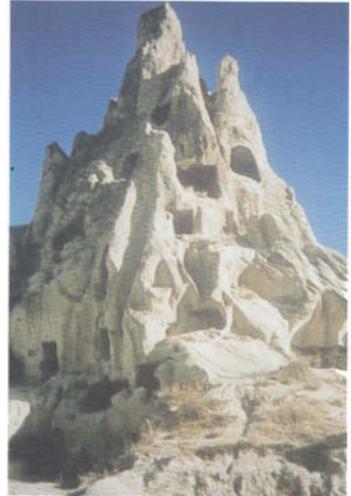
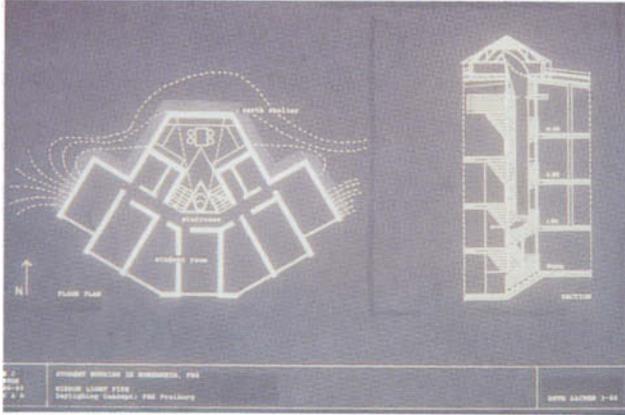


Fig. 28 (top left). Student housing: section. Fig. 29 (above left). Student housing: a yellow fluorescent truncated cone of the Fluorescent Planar Concentrators. Fig. 30 (above right). Cappadocia (Turkey): underground dwellings. Fig. 32 (left). Building for exhibition space (architect Gallo–Prof. Silvestrini): maquette.

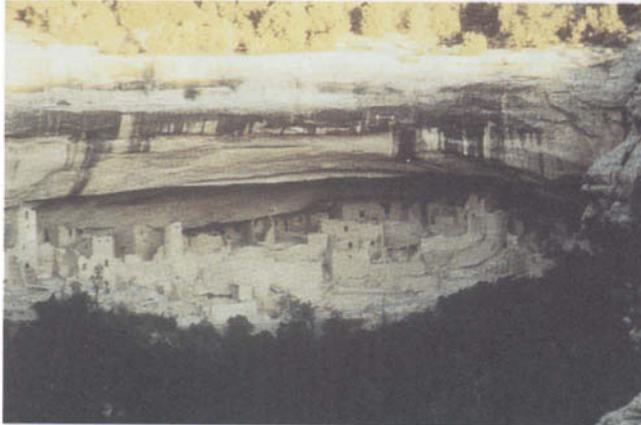


Fig. 36. Mesa Verde (Colorado, U.S.A.): the Anasazi Indians settlement.



Fig. 37. Apulia (Italy): the Trullo.

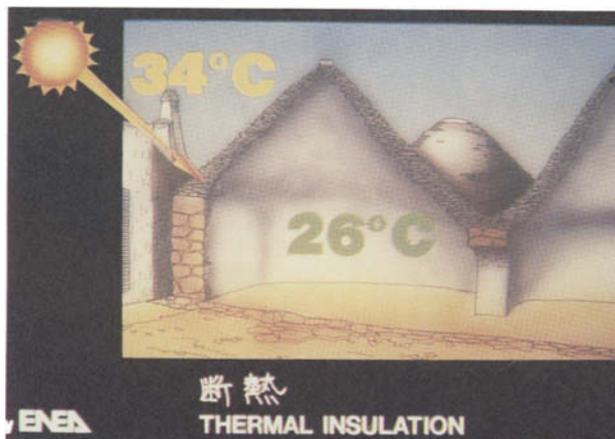


Fig. 38. Apulia (Italy): the Trullo.

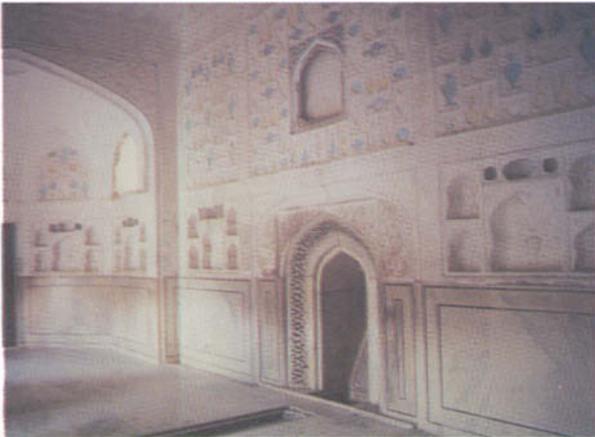


Fig. 39 (top left). The Spanish Pavillon in Sevilla Expo '92 (Spain). Fig. 40 (top right). The Spanish Pavillon in Sevilla Expo '92 (Spain). Fig. 41 (middle). The Spanish Pavillon in Sevilla Expo '92 (Spain). Fig. 42 (above). The Maharaja Palace in Amber (India).



Fig. 43. The Maharaja Palace in Amber (India).



Fig. 44. Lahöre (Pakistan): the tents in the open space of the Mosque.



Fig. 45. Lahöre (Pakistan): the tents in the open space of the Mosque.



Fig. 46. The Holy Mosque of Medina.



Fig. 47. The Holy Mosque of Medina.

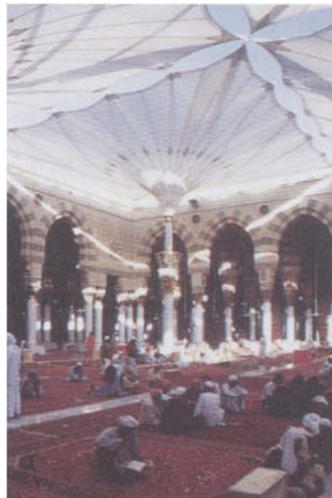


Fig. 48. The Holy Mosque of Medina.

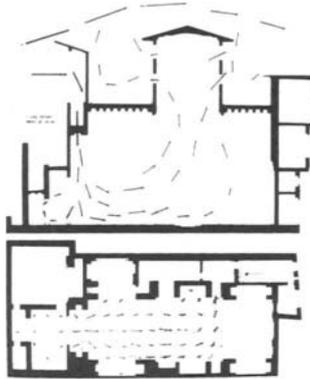


Fig. 10. House of the Muhibb Al-Din Muwaggi, survey showing air movements through the building (measurements were made by scholars from the Architectural Association School of Architecture in London, in 1973).

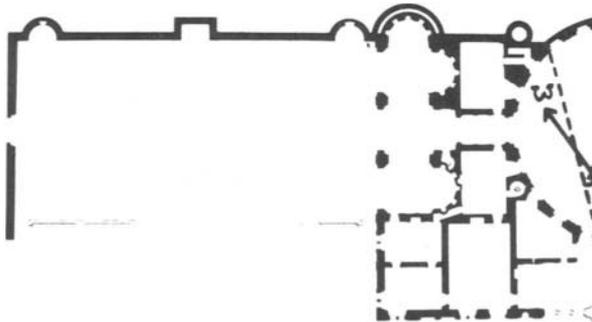


Fig. 18. Villa Madama of Raphael, Rome, Italy.

firm: differences of temperature of the air entry and exit points have even reached 20°C.

3. The sun

The knowledge of the course of the sun during the day and the seasons is another essential element of the architect's background information: solar charts show the sun direction at any time of the day for each latitude, by having a diagram that enables us to easily locate the position of the sun in a given place at a given time. By consulting these charts, one can determine what methods to use to keep the windows shielded at all times. First of all, it is best to give all windows a northern or southern

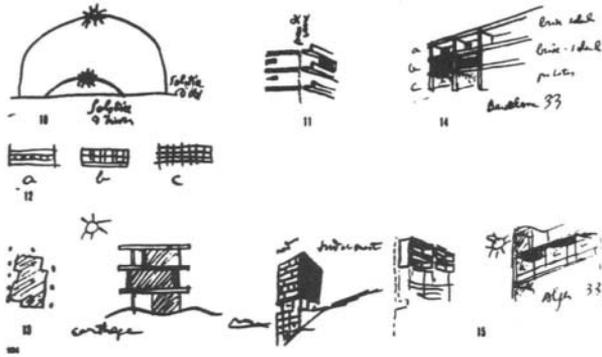


Fig. 19. Le Corbusier—Studies for the 'brise-soleil'.

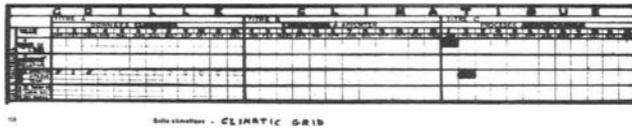


Fig. 24. Le Corbusier—The climatic grid.



Fig. 26. Hohenheim (Germany)—H. Schmitges, Student housing.

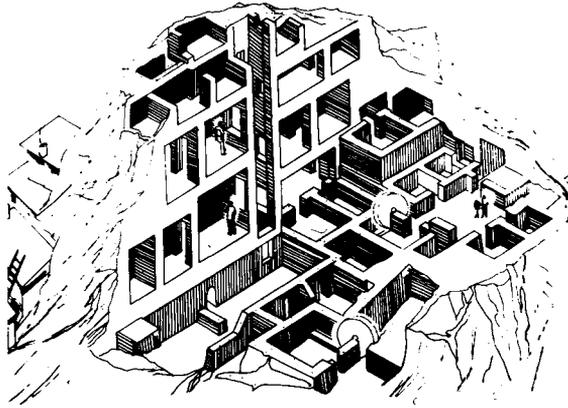


Fig. 31. Cappadocia (Turkey): underground dwellings (section).

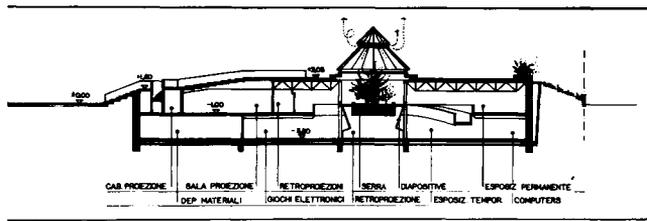
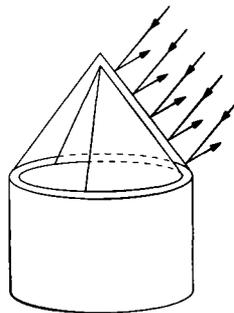
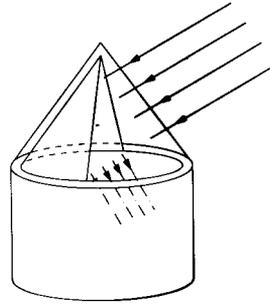


Fig. 33. Building for exhibition space (architect Gallo–Prof. Silvestrini): maquette.



schema di funzionamento della campana in assetto estivo

Fig. 34. The Silvestrini bell: performance in summer.



**schema di funzionamento della
campana in assetto invernale**

Fig. 35. The Silvestrini bell: performance in winter.

exposure; it is relatively easy to shield glass facing in these two directions because the sun here is always high in the sky. The situation is different to the east and the west, where the sun is low on the horizon and can penetrate deeply into the rooms. After the windows have been properly oriented, the next step is to set them back in order to keep them shaded at all times. Screening used as an energy conservation device during winter time can generally be used also as a screen against undesired solar radiation in summer time. There are many interesting screening solutions: more or less technologically sophisticated venetian blinds, double glass windows with a gas or small polyurethane pallets in the cavity, several types of membranes applied to the glass surfaces in order to modify its optical properties, spectrum selective windows, electrochromatic appliances etc.

An interesting solution is represented by a type of venetian blind placed between two layers of glass, operable from the interior of the building. The blades are covered on one side by a dark insulating material, and are silver-colored on the other side. This solution presents the widest choice of combinations: all open, intermediate position, silver screening on the outside (summer time), silver screening on the inside (night-time in winter), etc. There is also an ingenious proposal for an automatic screening system. It, too, is a kind of venetian blind with silver colored blades of larger dimensions. The movement of the blades is controlled by two small communicating containers filled with freon gas. In the summer, the containers are placed so that the solar radiation, by hitting the external one causes the expansion of the gas, making it flow inside the interior container. In this way the added weight makes the blind close. In winter, the position of the containers is inverted, so that the blades open during the day and close at sunset. There are also several types of membranes to be applied to the glass surfaces in order to modify its optical properties. Of particular merit among these is the 'heat reflector', a very thin metallic membrane with the characteristics of an extreme transparency to solar radiation and a high capacity for reflecting infrareds.

In the best solutions these elements become architectural plastic elements: the 'brise-soleil' is an important term of Le Corbusier's architectural vocabulary, in Geneva,

in Barcellona, in Algier, to control . . . “the conditions of the exposure to the sun”—he writes—“the beneficiary entry of the sun in winter and the catastrophic entry of the sun in summer time. . . .” [4].

During the winter solstice, the sun is low on the horizon, and its rays are welcome in the dwelling where they warm it physically as well as psychologically. The in-between seasons, spring and autumn, gratify the human being with a mellow sun, but the summer solstice and the heat-wave, with its intolerable temperature, transform our friend, the sun, into a pityless enemy.

“In the Clarté building in Geneve . . . we have been instinctively enticed by jobs which bring us closer to the *Brise Soleil*” [5].

Le Corbusier stated:

“I design the floors and they extended themselves beyond the glass panel with a balcony one and a half meters deep, with a parapet. Sliding shutters were added in front of the parapets because of the summer heat, thereby casting a first shadow and establishing a very satisfactory condition of sun penetration in winter (the sun being low over the horizon) and of sun barrier in the summer (when the sun is high)” [6].

In the Tower of Shadows in Chandigar (India), the sun is an architectural tool. The tower of shadows is placed on the edge of the Capitol, between the Hall of Justice and the Parliament. It is a tall and shady open hall. Its dark atmosphere invites meditation. The orientation of the building is north-south, making a deliberate break with the symmetry of the huge esplanade, the northern side is completely open, while the other three sides are equipped with brise-soleil. The course of the sun during all seasons has been very carefully studied and annotated at the Atelier Le Corbusier in order to determine the location and orientation of the various brise-soleil.

In fact, when looking at the model built expressly for the observation of the effects of the sun light with the alternation of the seasons, we can clearly see how the southern elevation is always in shade during the hottest periods, while being hit by the sun that penetrates the rooms in winter. The shadow pattern can be photographed on the model, but can also be computed from geometrical considerations. The relative methodology is fully developed: the following diagrams can be used for a graphic rendering of the shadow pattern. This is clearly a space designed to induce a sense of freshness, coolness in its interior during the hot Indian days, and to become, thanks to the physiological comfort experienced by the visitor, a place of encounter, reflection, meditation. But the sun, the great determinant of the design of the facade, is also an instrument of light and shadow, therefore of Architecture.

The Climatic Grid elaborated at the Master’s Atelier in Rue de Sevres in Paris at the beginning of the 20th century, is still today a correct methodological approach for architectural design. The Grid is a visual tool for a correct design approach: it allows us to enumerate, coordinate, and analyze all climatic data of a specific place with the purpose of orienting, directing, and guiding the design process towards solutions in accord with human biology. All the excesses of an extreme climatic

condition should be regularized, and specified so as to provide, through an architectural solution, the necessary conditions for comfort.

3.1. *Setting up the Grid*

There are four horizontal divisions supplying the data for the environmental conditions. (The vertical divisions scan the time sequence). They are divided into three subsequent compartments:

- (A) Conditions of the environment
- (B) Corrections according to comfort
- (C) Architectural solutions

3.1.1. *Conditions of the environment*

Also a representation of the environment considered. Every climate could be usefully represented by four basic elements:

- (a) Temperature
- (b) Air humidity
- (c) Air movements (wind or currents, droughts)
- (d) Thermal radiation of the objects under consideration.

The four horizontal sections of the Grid visualize the variations of the four factors mentioned above, during the lapse of time considered (day, year, etc.). The time is expressed by the vertical divisions according to the unit chosen: moments, days, seasons, years, etc., in the typical points such as, solstices, equinoxes, monsoon, etc. A red line indicates the annual range of the temperature. A blue hard line indicates the hygrometric curvature of the air on the second sector. The third sector shows the various directions and intensities of the winds throughout the year. Finally, the fourth sector supplies the thermal radiation of the walls and roofs of the design under consideration. In this way, all the conditions of the environment are graphically represented. The conditions of the environment constitute the first panel of the Grid.

3.1.2. *Corrections according to comfort*

The necessary corrections and biological modifications to ensure proper comfort are listed on the chart. The reading of the first sector has revealed the critical conditions under which man suffers. The second sector of the Grid follows the first one, and has the same horizontal and vertical divisions. The physician–biologist then inserts in some of those compartments the opportune modifications or corrections. Consequently, the reading of the second panel of the Grid will already represent, in essence, the program at the basis of the architectural design.

3.1.3. *The architectural solution*

The third sector of the Grid follows the second one, and has the same divisions of the previous two. A stamped seal, in each square compartment, corresponding to those

of panel 2, in which the changes and corrections of biological nature were shown, indicates the existence of a special plate, with the appropriate architectural solution. The stamp also shows a 'D' meaning that at this point of the grid there is a design. Two white squares under the 'D' enclose the point of reference that enables us to relate the document in question to its exact location in the 3rd sector of the Grid, and also to the date of its execution.

These graphic documents represent the architect's solution to the problem. A fairly easy manual operation can make section 3 of the Grid an extremely efficient tool; inside the summentioned squares, in the space left empty by the stamp 'D', a schematic plan of the drawing corresponding to it should be drawn. Thanks to this graphic visualization, the use of the Grid will be simplified [7].

To give physiological comfort means to create in rooms a high quality of life: the right temperature, no noise, good lighting. This is the purpose of the research on the best utilisation of daylighting (certainly to limit artificial lighting is also a good energy saving).

Of interest in this field is the research on light pipes to bring day-lighting in underground or internal rooms of the building, that normally utilize only artificial light: the light pipes are horizontal or vertical ducts, with highly reflective walls which transmit light from the external surfaces to the inside of buildings.

In the Sport Centre in Barcelona designed by Rafael Serra, the internal zones of this three-story building are lit by natural light provided by 'sun-ducts'. These are vertical ducts, with specular walls, one or two storeys high. Sunlight penetrates into them through 'sun-catchers' placed on the roof, and is reflected downward, until it reaches the areas to be illuminated.

In the student housing in Hohenheim (Germany, design: H. Schmitges; built in 1985) each of the six four-storey buildings has a glass pyramid on top of the staircase, providing light to the kitchen/dining rooms. Two components are used: 'light-pipes' and Fluorescent Planar Concentrators (FPC). Light-pipes are triangular vertical wells, with high reflectance (0.95) mirror walls, aimed at increasing the amount of daylight into the first-floor dining rooms. FPCs collect light in a yellow fluorescent truncated cone; the light is then guided down, within the 0.6 cm thickness of a 30 cm diameter transparent pipe, and is reflected by a mirror into the kitchen.

The quality of the working environment would be greatly improved by letting natural light reach and affect as much of the floor area as possible. Basically the problem can be stated as follows: how to effectively and economically bring natural light to those parts of large commercial buildings that are located far from the external envelope, where daylight is available, without causing discomfort.

First of all, it is important to obtain an optimal diffusion of the sunlight in the rooms: two interesting steps in this research are the prismatic surfaces and holographic films. The prismatic surfaces increase the sensitivity of the transmission factor to the angle of incidence, so that it is possible to reflect direct sunlight and transmit and re-direct skylight, as a function of the angle of the sun. Holographic films intercept sunlight and diffract it in another direction. Although under clear sky conditions a large amount of light is offered for day-lighting, it is often necessary to switch on the artificial light when shading devices are closed. By lightguiding building components

with holograms this unsatisfactory situation can be improved, directing the solar radiation to the ceiling, from where it is distributed evenly to the working level without glare effects. By means of vertical and horizontal adjustment of the direct radiation, room illumination can be achieved by comparatively small, clear window areas. Since the thermal resistance of glass is smaller than that of the opaque walls, this helps to minimize thermal losses while ensuring adequate internal lighting. To obtain a still more energy-wise result the use of solar energy should be coupled with a reduction of heat losses, essentially by insulating the walls and the windows. The extreme step in the direction were the underground dwellings; today we have testimony in many sites of the world characterised by border line weather conditions: Matmata in Tunisia, Cappadocia in Turkey, Honnan in China.

Sometimes a physics principle—the low heat dissipation of the cylindrical shape—can inspire the basic idea of an architecture.

In this building project of exhibition space (design: architect C. Gallo with Prof. V. Silvestrini) the shape and the siting of the building were studied so as to minimize thermal losses. The cylindrical shape, the partial earth coverage and the admission of light through a central conical light well reduce heat losses to very low values, even though the constructional solutions that have been chosen are not exaggerated in terms of thermal insulation (the heat conduction coefficient assumed for the outer walls is $1.5 \text{ W m}^{-2}\text{C}$). Under these conditions, heat loss is dominated by the contributions due to ventilation. The unconventional skylight (the Silvestrini bell) was designed to optimize the collection of solar energy. Inside the conical glass cover, there is a rotary segment; its inner surface is white, so as to reflect solar radiation toward the inside of the building (the winter garden). This central structure, which provides for the natural lighting of the whole building, results in very low heat loss because of its geometry. On sunny winter days, it receives an amount of solar radiation comparable with the overall energy requirements of the building. During the summer, the same conical segment that reflects light inside during the winter is rotated so as to shade the winter garden. The air conditioning load is thus reduced essentially to that necessary to remove excess humidity from the new air brought into the building by ventilation.

The scientist Vittorio Silvestrini writes about the ‘round house’ of Mario Botta:

“Mario Botta is not an expert in solar energy: he is simply an architect. But like all good architects, he must take into account the problem of comfort and consequently of a rational use of energy in the projects he designs. In his projects for private houses there is a recurring characteristic pertinent to the question of energy, and that is the fact that his houses are ‘introverted’ so to speak. The external shell is particularly compact and closed: the forms, cylindrical and cubic, reduce to a minimum the dispersion of energy, and windows are also kept to a minimum. These forms both correspond to a requirement of energy conservation, that of reducing thermal dispersion and to a perfectly architectonic need, that of offering a controlled view of the surroundings. The source of light and heat is a central nucleus which we could call the ‘energy heart’ of the house. This nucleus generally receives

energy by means of a skylight placed on top of the building. Botta's houses also make use of a temperate micro-climate, but this climate is realized in an internal rather than external space. The advantages are evident. The external shell can now be extremely well insulated, there is no obligatory orientation, climate control is simple even during the summer, and costs are moderate. The houses of Mario Botta are real homes, not mere accidents of experimental technology" [8].

The Master of contemporary architecture, Louis Kahn, observes about his Management Training School at Ahmedabad in India:

"The orientation of the houses follows the direction of the winds; all the walls are parallel to this direction. The walls are traced diagonally around a court in order to define it, while keeping the regularity demanded by the layout . . . it will be noticed that I have inserted a light well in the school building. I believe that, in a certain way, this device is superior to the one I had invented in Luanda. There I had built a wall to screen the sun and to modify its reverberation, while here the solution has become an integral part of the composition . . . This could be called an inside-out bow window" [9].

In the houses of Ghardaia, Algeria, the light well is formed by the 'chebeq', a square hole in the ceiling that makes up for the total absence of windows and provides air-conditioning as well as light. The indoor is cooled by the air flow created between the chebeq and a number of openings in the walls beneath. In this climate zone, known as 'the desert within the desert', the houses are built adjacent to each other, with thick stone walls, so that the living quarters are shaded. The stone slows heat penetration during the day and releases the heat during the night.

4. Thermal mass

In the past, the thermal mass of walls was always an element to minimize temperature oscillations and to protect the rooms from the external heat or cold.

"The Indian settlement of Mesa Verde (ca 1200) in Colorado represents a perfect example of exploitation of natural resources for survival. The settlement is located in a horizontal cut of the rock with a southern exposure, sheltered from the summer sun, but not from the winter one. The immense rock that the Indian settlement leans against provides a very large mass of thermal inertia, thereby guaranteeing a nearly constant comfort level throughout the year" [10].

In Mesa Verde the combination cave/buildings provide a kind of energy collector that is over 50% more efficient in the winter than in the summer. In winter, the sun rays—because of the lower angle of incidence—have free access to the cavity in the rock. The heat from the solar radiations, well absorbed by the rock itself and by the

adobe of the buildings, is slowly released to the environment after sunset, thereby providing a constantly comfortable microclimate (as compared to the extremely cold winters and hot and dry summers). The daily life of the Anasazi Indians took place at the interior of the 'kiva', a covered circular space, heated by a central open fireplace. A natural ventilation system provided the air change. The hot air heated by the fire went out from a hole in the roof, while a cold air inlet at the floor level provided cold air that was deflected by a low wall in front of the fireplace, forcing its circulation around the 'kiwa'.

Two other interesting examples of 'spontaneous' bioclimatic architecture in Italy are 'dammuso' and 'trullo'. Both buildings feature very thick walls and minimal openings, allowing for a comfortable microclimate inside. Dammuso, the typical dwelling of the island of Pantelleria, represents an example of spontaneous architecture of bio-climatic inspiration. The climate of the island presents a high temperature, ranging from 34°C in August to 10°C in January. There are low levels of rainfall and strong winds, and consequently the main purpose of the Dammuso is to provide protection from the summer heat and the winds. There are several thousand Dammusi in the island of Pantelleria. This type of dwelling evolved many centuries ago as a response to the need for a temporary shelter for vineyard workers and a tool shed and storage for produce. The roof of the Dammuso is made by a barrel vault externally waterproofed, and shaped to collect rainwater to be stored in an underground cistern. There is only one door to the dwelling and no windows to speak of, except two or three small openings in the walls for the sole purpose of ventilation. The walls of the original Dammuso vary in thickness between 80 cm and 2 m. They are made by an outer and inner wall of large dry-set stones and the central cavity is filled with smaller stones. This construction provides such a good insulation from the exterior that, during the past two centuries (once the danger from outside invasions had ceased) they have become the permanent residence of the islanders. Measurements taken on the interior of a typical Dammuso during the month of August, show a fairly constant temperature of 26°C, during both night and day.

The hot climate of Apulia calls for climatization. The traditional answer to that has been the Trullo, a stone shelter whose large masonry walls mass act as some sort of thermal regulator, by absorbing the radiation heat during the day and releasing it slowly at night, thereby levelling the temperature variations, and making the interior temperature several degrees lower than the exterior one during the day time. The internal thermal behaviour of the Trullo has been verified by a comparison of the results of a simulated test, using a thermal grid code developed by the Laboratorio Progettazione Ambientale (Environmental Design Laboratory), and the results of a weekly temperature survey done during the summer. The simulated data and the collected ones correspond, and show that there is an internal thermal variation of 4°C in correspondence of an external variation of 10°C.

Thus we examined various ways to create passive cooling in architecture: to reduce heating, to cool the hot air by other cold air, water or earth...

Another aspect of the problem is open public spaces in hot countries.

5. Open public spaces

5.1. *Vegetation*

Vegetation around a building is important: this means choosing a site rich in greenery or else creating vegetation where there was none. The role of the microclimate, and of its possible breezes and currents is fundamental in determining the conditions for well being in a built environment. Besides creating shade, vegetation transpires water and thus provokes natural cooling through evaporation. A recently published review [11] quotes reductions of temperature through evaporation of 2–3°C. It seems well demonstrated that joint evaporation and transpiration of a single tree can save from 1–24 MJ of electricity in terms of air conditioning per year; a lawn can cool a sunny lot by 6–8°C, while the evaporation of a hectare of grass corresponds to more than 125 MJ per day.

In one of its works [12], the Rocky Mountain Institute compares the reduction of the thermal load due to vegetation in three cities: Sacramento (34%), Phoenix (18%, dry climate), Los Angeles (44%). This data seems to indicate that vegetation works more effectively in a damp climate, where it can, however, lead to a rise of humidity.

In dry climates vegetation can influence the dry bulb temperature. In the many bioclimatic systems realised in Bioclimatic Rotunda in Sevilla Expo '92 by Spanish architects, very effective coolers in a hot and dry climate, the vegetation is essential: in the plan the proportion between green and buildings is 60/40. The vegetation refreshing effect consists of temperature mitigation, solar radiation's reduction, relative humidity increasing, wind mitigation and direction (regulation). The main difference between refreshing effects from vegetation and from structures built by man is that an inorganic material has a limited refreshing capacity, based on thermal characteristics of the materials; a plant on the contrary is a living organism that will regulate its branches and leaves to utilise most of the solar radiation.

In Sevilla, other key-concepts of passive cooling are utilised. Besides the ventilation, the utilisation of earth mass, there are water jets, fountains, water films and water floors: water runs beneath pavements made of porous material that allows water to evaporate. Micronizers increase the evaporation during the hottest period, and running water and cold air coming from underground pipes give their contribution to thermal well-being.

Running water, together with a cold air current, is the cooling system that was utilised in the Maharaja Palace of Amber, near Jaipur, built in the 16th century: a room with one side entirely open towards the courtyard is cooled by a waterway crossing it, bounded by two stone sides which are pierced to admit air.

6. Shading devices

In Bioclimatic Rotunda in Sevilla Expo, a focal point is the generation of shadows on public spaces: but it is important that these sun protective systems are movable

and they can be removed during the night to make possible the heat dissipation by long wave-length radiation to the sky.

The same system is utilised for example in the open space of oriental mosques: the big tent for solar protection during the day are removed at the evening. In the Holy Mosque of Medina, twelve umbrellas with a diagonal span of 24 m, installed in groups of six, immediately answered any doubts one might have had as to the possibility of solving the climatic problem of Middle-Eastern historic buildings without incurring a heavy environmental impact. The twelve shading mechanisms are the invention of the Bodo Rasch Jr, the natural successor of Frei Otto, inventor of the tensile structure, as a technologically advanced lightweight system of coverage. The extension and retraction of the membranes is regulated by a computerized system in which local climatic data have been recorded in conjunction with the spatial configuration of the Mosque and its courtyards, so that efficient functioning is guaranteed in all atmospheric conditions. Generally speaking, the principle adopted prescribes opening the membrane cover during the day in summer as protection from the strong sunlight that raises the temperature to 45°C in the shade, while its closure at night permits the evacuation of heat absorbed during the day by the thick walls. In winter, the procedure is reversed, so that the umbrellas are closed during the day, allowing the mild sun to warm the marble paving and walls, whose thermal inertia is preserved at night by opening up the membrane to prevent extreme cooling. Lastly, the convertible structures are equipped with a windspeed monitor which automatically prevents opening and closing operations when speeds exceed 36 km/h. Each umbrella has four lamps integrated into the claddings above the column capital to illuminate the courts at night, and air outlets located in the base and capital of the lower column which are linked to the building's air-conditioning system.

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RENEWABLE
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Chapter 6—Daylighting

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1. On natural light

To talk of architecture is to talk of light, and above all of natural light. It is not just a physical means enabling us to see the exterior and interior material form of buildings; rather, it provides architecture with its main energy component, necessary for the existence of a rich, integrated duality of matter and energy which, beyond mere usefulness, generates an aesthetic sensation in the users.

It is for this reason that great architecture has always been associated with natural lighting, generating it with and within itself. From the categorical eloquence of the single opening of the Pantheon to the magical complexity of the Germanic baroque, via the increasingly finely wrought Gothic cathedrals, natural light has been a deciding factor in the quality of space. In spite of this, the role played by light in architectural aesthetics is often ignored, great works being analysed with parameters that are concerned purely with style and geometric form. In the narrower sense of architectural quality, the aesthetic power of light is what differentiates architecture from mere construction when we visit a building. Such it has been described by the great commentators on architecture, from Vitruvius to Bruno Zeni, when they speak of light with the enthusiasm that art alone can arouse.

Yet when we attempt to analyse the role of light in contemporary architecture, we find a huge vacuum. Today's representative buildings almost totally neglect the important part natural light could play in their interiors. Excessive use is made of artificial systems, and architecture is conceptualized as glass geometry, with paradoxical curtain walls that instead of communicating with the exterior, create impractical barriers. A point is thus reached where the interior environment, which is theoretically controlled, frequently becomes more inhospitable than the exterior. In such cases, architecture works 'worse than the climate'.

Today, it is essential for the architectural profession to recover the systematic use of natural light. To this end, designers should be made aware of how spaces work in conjunction with light, and the best way to do this is not by way of elegant or sophisticated technical solutions. It is sufficient to be acquainted with certain basic principles, which can be divided into two well-defined areas: the physics of light and the physiology of vision. These basic principles can lead to the practice of natural

light in design with greater efficiency than would be the case with the technology of particular solutions and systems.

The physics of light allows us to understand how this electromagnetic radiation behaves in architectural space. By knowing its basic laws and its interaction with the surfaces that reflect, absorb and transmit it, we can control the effect of light on buildings and its distribution in interiors.

The physiology (and psychology) of vision facilitates understanding of human reactions in lit spaces. By knowing the basic principles of perception and comfort, as we design buildings we can control the relationship between light and the users of their exterior and interior environments, and in this way define the lighting aesthetically and functionally from the very start of the project.

Finally, providing a building with natural light is more than just the solution of a problem of energy consumption; more, even, than an aesthetic resource easily incorporated into the architecture. Natural light in architecture must be part of a more general philosophy that reflects a more respectful, sensitive attitude in human beings towards the environment in which they live.

2. Basic physical principles

Various phenomena affect man's environment: radiation, air vibrations, temperature and so on. All these manifestations of energy are to some extent of human senses, although in the case of light the part of the phenomenon which is perceived is very small in comparison with the phenomenon's total field (electromagnetic radiation).

2.1. *The physical principle of electromagnetic radiation*

Electromagnetic radiation is a form of energy transportation by means of periodic variations in the electromagnetic state of space, and can also be interpreted as the movement of immaterial particles (photons).

The wide field of electromagnetic radiation is classified according to its wavelength (l) or its frequency (f) into a number of zones of what we call the radiant spectrum, which is equivalent to doing so according to its technologically perceptible effects. In this spectrum, visible light occupies an extremely narrow band (Fig. 1).

It is important to bear in mind that the wavelength and the frequency of the propagation of a vibratory movement are related to the speed of propagation (c) thus: $l = c/f$.

Electromagnetic radiation is caused by variations in the atomic structure of bodies, when the orbital situation of the electrons is altered; on returning to their original position they cause photons to be emitted, the excess energy thus being eliminated in the form of radiation.

There are two main types of radiant sources, discharge and thermal sources, although for the purposes of natural light it will suffice to consider the latter.

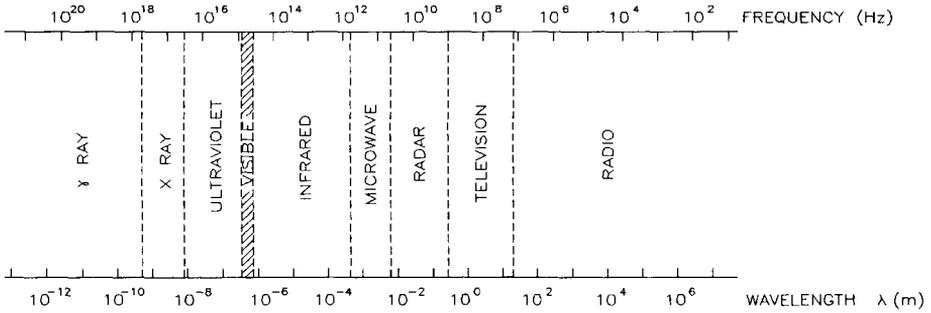


Fig. 1. Radiant spectrum.

Thermal sources emit radiation as a result of the thermal agitation of matter, and display a characteristically continuous spectrum in the field of wavelengths they cover (Fig. 2).

Under normal conditions, thermal sources emit mostly infrared radiation, but as the temperature of the emitter rises, not only does the amount of energy increase but also the maximum value of emission moves towards increasingly shorter wavelengths. In this way, as the radiation temperature increases it moves further into the visible band of the spectrum, until, at a temperature of around 6500 K, the maximum is located in this zone. It is no coincidence that this temperature is approximately that of the surface of the sun; the field of activity of human sight is adapted to the highest values of radiation in its planetary environment (Fig. 3).

2.2. Units and fundamental equations of light as energy

In lighting, four main units are used to describe light and its effects.

Luminous flux measures the amount of light per unit of time, and is abbreviated as Φ . Its unit of measurement is the lumen (lm).

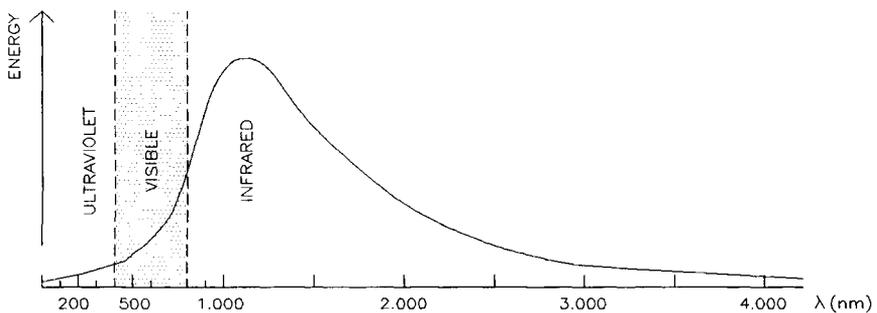


Fig. 2. Energy/wavelength curve for a thermal source.

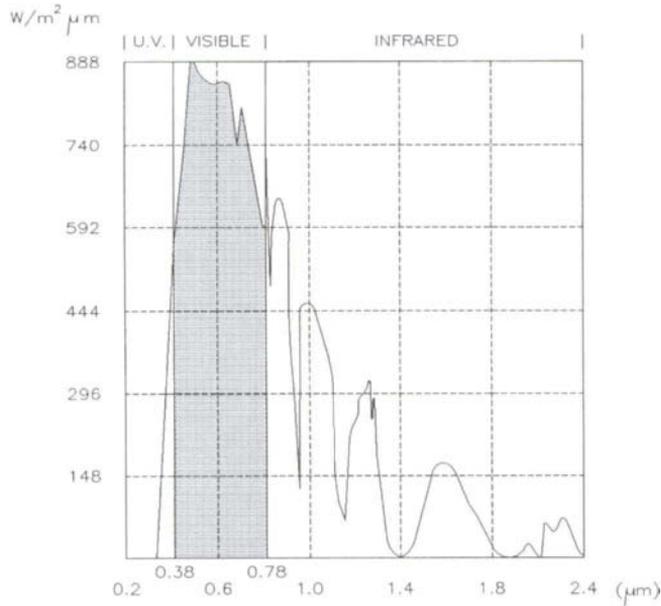


Fig. 3. Spectrum of solar radiation.

Luminous intensity measures flux in a given direction, and is abbreviated as I . Its unit of measurement is the candela ($\text{cd} = \text{lm sr}^{-1}$) (sr: unit of solid angle in which the surface subtended on a sphere is equal to the square of the radius).

Luminance indicates the lightness of an emitting surface for an observer, and is abbreviated as L . Its unit of measurement is the candela m^{-2} (cd m^{-2}).

Finally, illuminance measures the flux reaching a given surface, and is abbreviated as E . Its unit of measurement is the lux ($\text{lx} = \text{lm m}^{-2}$) (Fig. 4)

In any light phenomenon it can be observed that the light originating from an emitting source expands through space, and as it moves away from its source the illuminance that it produces on a surface decreases by the square of the distance. Equally, if the surface is not orthogonal to the incident beam, the illuminance decreases by the cosine of the angle of deviation, resulting in the following:

$$E = (I/d^2) \cdot \cos \alpha \quad (1)$$

In the case of direct solar radiation, given the great distance of the emitting source, variation due to distance is negligible on the Earth's surface and the beams are considered parallel, which means that $E = I \cdot \cos \alpha$.

2.3. The visible spectrum

Light not only transports energy but also has colour, as a result of the distribution of energy over the different wavelengths of the visible spectrum; a specific colour

Φ = flux
 I = Intensity
 E = Illuminance
 L = luminance

r = reflection coefficient
 S = illuminated surface

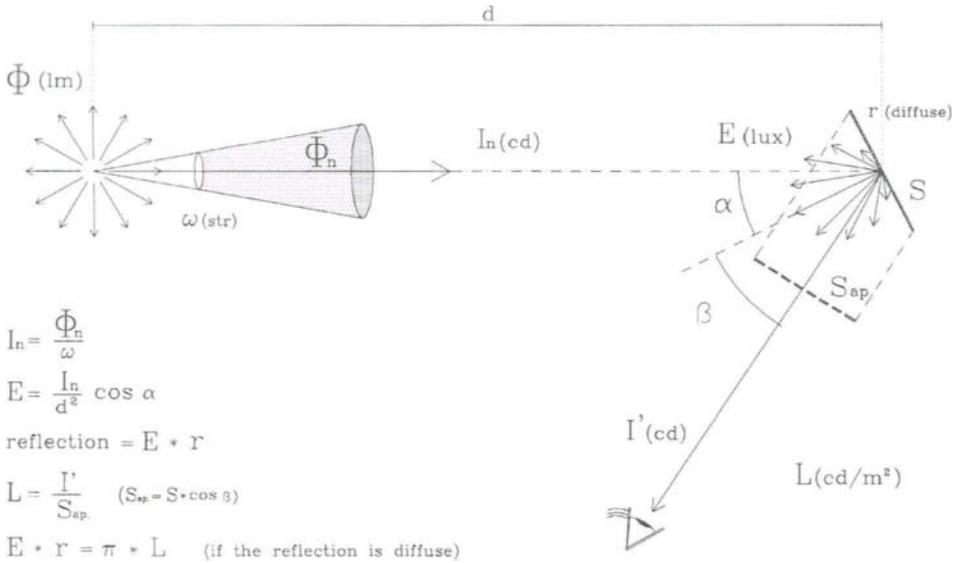


Fig. 4. The four units.

corresponds to each wavelength, as in the colours of the rainbow. Sunlight covers all the zones of the spectrum (Fig. 5).

In the field of lighting technology specific units are used to indicate the chromatic characteristics of light, thus:

The colour temperature (T_c) expresses the colour of a source of light by comparing it

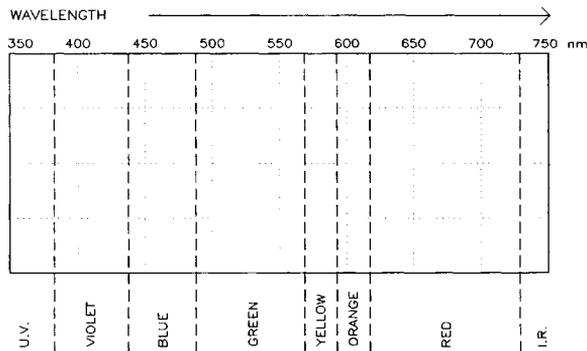


Fig. 5. Spectral colours.

with that of the light issued by a black body at a given absolute temperature, its unit being the kelvin (K). As the black body changes spectrum according to temperature, at around 3000 K the light is reddish, in the region of 5000 K the distribution cancels out, and at higher temperatures it is bluish. T_c is defined as the temperature to which a black body must be heated for the light it emits to be of a similar colour to the light being measured. In the case of natural light we note that its colour temperatures are in the order of 6000–6500 K, in keeping with the real temperatures of the surface that emits this light (the sun's corona).

The colour rendering index expresses the reproductive capacity of light on the colour of the objects that it illuminates. It is abbreviated as R , and is expressed as a percentage. In order to have good chromatic reproduction, light must have energy on all wavelengths, as is the case with sunlight, which is, moreover, the type with which we are most familiar. In practice, the R of natural light is 100%.

2.4. *Light and the limits of space*

Light is propagated through space at a speed that for architectural purposes can be regarded as instant, but on encountering a material obstacle is partly reflected and partly absorbed by the surface (being transformed into heat). Some of the light may also be transmitted to the other side of the obstacle. The coefficients of reflection (r), absorption (a) and transmission (t) give respective ratios for the incident light that is reflected, absorbed and transmitted by a given surface. The sum of the three coefficients will always yield unity: $r + a + t = 1$.

The phenomena of the reflection and transmission of light from surfaces are very important for the understanding of the behavior of light in architectural spaces. As energy can be reflected qualitatively in a different way depending on the type of surface, we shall consider the different possible types from both the spectral and geometric viewpoints.

- (a) from the spectral viewpoint, surfaces can display different behaviour for the different wavelengths within the visible zone. In this way, natural light can take on various colours, on being reflected or transmitted by coloured surfaces.

This is the specific reflectance or transmittance (r_1 or t_1), which determines the behaviour of a given surface for light of a given wavelength (with its associated colour). The mean weighted value of r_1 or t_1 for a given radiation (in this case sunlight) will give us the value of the reflection coefficient of the surface.

As a rule, the radiation reflected or transmitted by a surface reproduces the spectrum of the incident radiation, modified by the values of the various specific reflections or transmittances (r_1 or t_1) (Figs 6 and 7).

- (b) from the geometric viewpoint, the finish and the internal structure of bodies can affect the geometry of the transmission or reflection. As long as the material irregularities are of a similar order of magnitude to the wavelength of the light, the light will be diffused. If these irregularities are significantly smaller, regular reflection or transmission will occur, with no modification of the geometry of

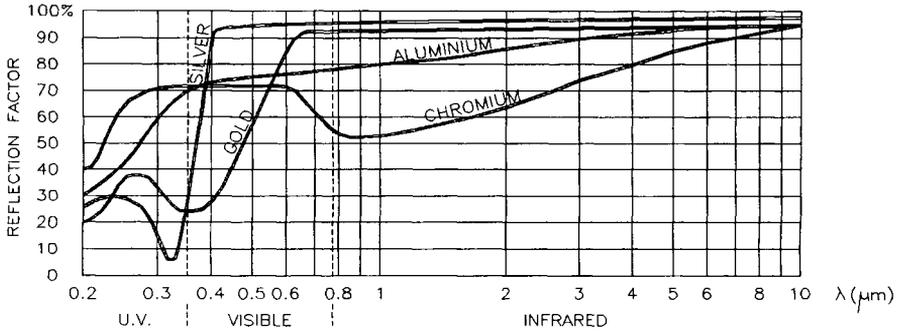


Fig. 6. Spectral reflectances, of different materials.

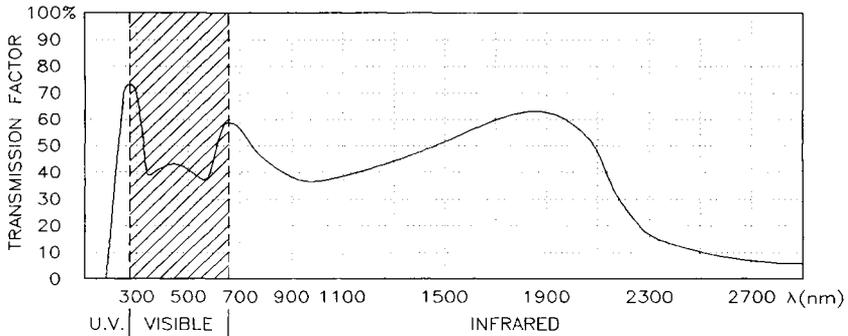


Fig. 7. Spectral transmission through a glass.

the incident light. In practice, three basic types of geometric behaviour can be distinguished (Figs 8 and 9).

As the wavelength of light radiation is very small, most surfaces with which we work in architecture present reflection of a diffuse type, and light does not pass through them. Only highly polished surfaces and those with an ordered internal molecular structure (crystals) display regular behaviour regarding reflection and transmission.

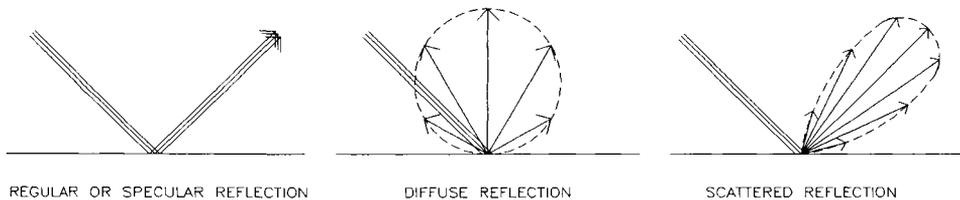


Fig. 8. Reflection—geometric behaviour.

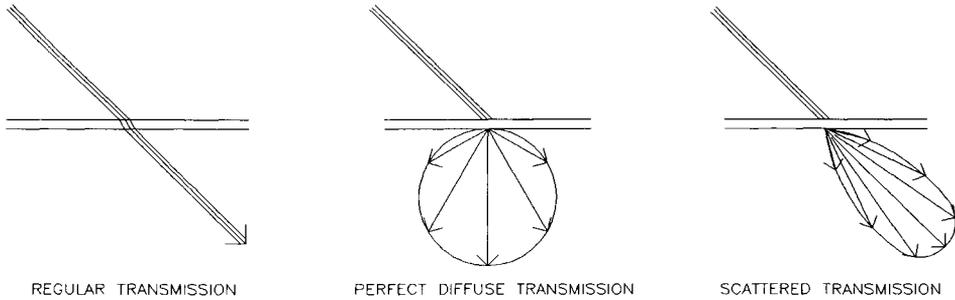


Fig. 9. Transmission—geometric behaviour.

In the case of diffuse reflection or transmission, the resulting distribution of the light is such that the luminance L of the surface, observed from any direction, is constant and has the value:

$$L = (E \cdot r)/\pi \quad \text{or} \quad L = (E \cdot t)/\pi \quad (2)$$

This formula, in combination with the one in Section 2.2. above, makes it possible to assess the behaviour of natural light in architectural spaces (see Section 6).

In architecture, where most surfaces have diffuse reflection, this behaviour tends to distribute natural light more uniformly around interior spaces. Surfaces with regular (or specular) reflection can be useful for reflecting light, especially the direct radiation of the sun, in particular directions which are considered appropriate. Equally, transmitting surfaces are normally regular or transparent, thus allowing the entry of direct sunbeams without varying their geometry and at the same time a view, usually considered a favourable effect. Nevertheless, when it is sought to diffuse light entering an interior, or to avoid the visual discomfort of a patch of direct sunlight, or even to preserve visual privacy, diffusive materials or systems are used which avoid the regular transmission of light to the interior.

2.5. Absorbed light

In both reflection and absorption processes, some light is absorbed by the obstacle and its energy is converted into heat. This disappearance of energy from the world of light can have important technical consequences that are often neglected in the design of buildings.

Direct sunlight has a relatively high energy density, in the region of 1000 W m^{-2} . Because of this, light shining into an interior, especially when it surpasses visual needs, can cause overheating. This effect, which can be positive in winter and at high latitudes, becomes hazardous in hot and temperate climates. For this reason, it is just as important to be able to regulate strong external solar radiation shining in as it is to provide appropriate interior lighting in circumstances of poor natural light.

3. The physiology of vision

Light in general and natural light in particular act upon human beings when perceived by our sense of sight, and this action can be considered to have two main consequences. The first and more general of these is our perception of the world, which is conducted by means of sight and provides our brain with information about our surroundings. This perception is also important aesthetically, and is very important in architecture for both reasons. The second consequence is more specific and consists of the discomfort light can cause our sense of sight, particularly the distribution of luminances in the field of vision, which affects the users' comfort and is therefore also decisive in the design of spaces. As both architectural consequences depend directly on the physiological functioning of sight, we shall begin by studying the human eye.

3.1. *The eye and sight (visual perception)*

The sense of sight is based on the functioning of a highly specialized organ, the eye. This organ features the pupil, which regulates the amount of light entering the eye by means of an opening the surface area of which can be adjusted in a ratio of 1 : 16. The more closed the pupil is, the less energy enters, but the vision is sharper and with a greater depth of field. The crystalline lens changes shape to regulate the focus, maximum deformation occurring with near vision. From the crystalline lens, the light crosses the vitreous humour that fills the eyeball and so strikes the retina, where the images focused by the crystalline lens are formed. This retina is a 'particle', sensitive to the amount of light by means of cells called rods, and to the amount and the colour (wavelength) of the light by means of other cells called cones. In the centre of the retina there is a small concavity called the fovea centralis, containing only small, tightly packed cones, which is the region providing sharp vision (Fig. 10).

This visual system is able to detect both the amount of energy falling on the eye and the spectrum of the light to which it is sensitive. Between certain limits, it also has the capacity to regulate various effects, such as the amount of light that enters or the focussing of the images on the retina.

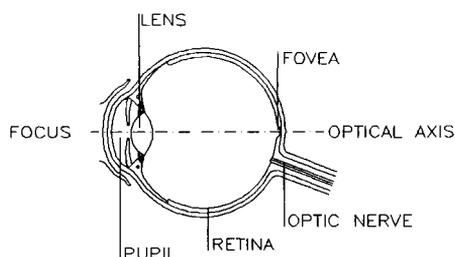


Fig. 10. Structure of the human eye.

From the retina, where the light photons affect the sensory cells and generate nervous impulses, the signals are sent to the brain along the optic nerve and are interpreted as images.

The human eye responds to the amount of energy it receives with sensations that do not correspond linearly to the stimulus. As is also the case with the other human senses, sight follows an approximately logarithmic law according to which equal increases in the stimulus do not imply equal increases in sensation; rather, the latter are smaller when energy levels are high than when they are low. Consequently:

$$S = K \log E + B \quad (3)$$

(where S = sensation, E = stimulus, and B and K = constants)

This type of reaction permits the human senses to take in wider fields of energy levels, but also means that when assessing the effects of light, a given increase has a different value depending on the level of departure. Thus, an increase of 1 m^2 in a light opening has a huge effect if the previously existing opening measured 1 m^2 , whereas an increase of 1 m^2 in a space already possessing 10 m^2 of opening results in very little sensation of increased light in that space.

In addition to this basic sensory mechanism, sight can adapt to different energy levels using other systems. We have already seen how the pupil varies the surface area through which light enters in a ratio of 1 : 16 by means of a retroactive mechanism. In addition to this, the cells of the retina work in various fields; the rods are the only cells that register luminances below 10 cd m^{-2} , just as only cones respond in conditions above 300 cd m^{-2} ; between these limits, the two types of cells work together.

The cones allow the perception of colour; sensitivity is greatest in the yellow–green region, gradually fading until it fails completely at the two ends of the spectrum. This vision by means of the cones is called photopic vision. In vision using the rods, known as scotopic vision, colour is not registered, and maximum sensitivity is located in a zone with a short wavelength (blue), the so-called ‘Purkinje effect’ (Fig. 11).

The sensitivity curve of the eye with photopic vision can be used to define the units

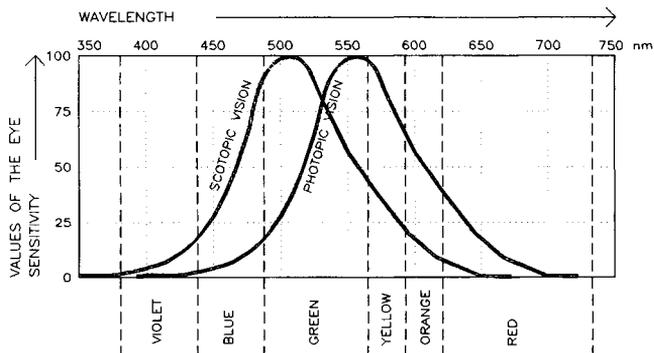


Fig. 11. Sensitivity curves of the human eye.

discussed in Section 2.2. The luminous flux results from affecting the total radiant flux by the sensitivity coefficient of the eye for each wavelength.

$$F_l = F_r \cdot V_{(l)} \cdot 680 \quad (4)$$

(where F_l = luminous flux in lm, F_r = radiant flux in W, and $V_{(l)}$ = sensitivity coefficient)

3.2. *Temporal sensitivity of vision*

The human senses tend to adapt constantly to stimuli and to be sensitive according to the mean energy values of their perceptual field. In the case of sight we have already discussed the basic mechanisms of adjustment to change: the pupil, the cones and rods and the general sensitization of the retina.

In order to adapt to a change in the conditions of mean luminance of the visual field, the eye needs a period of time which varies according to whether the change is from light to dark or vice versa. More than 30 min is generally considered to be necessary for good adaptation when changing from light to dark conditions, compared to just 30 s or so to adapt from darkness to light. In fact, they should be thought of as adjustment curves of a logarithmic type, with rapid response at the beginning but tapering off as time passes. Perfect adaptation from light to dark is a matter of hours, but the first instants are the most noticeable.

This phenomenon is important in architectural design, especially considering that correct perception depends more on the balance of luminances in the field of vision than on the absolute level, since sight possesses capacity for adaptation in an extremely wide field of energies, with correct rendering from mean luminances as low as 50 up to 25,000 cd m⁻². For this reason, the absolute value of light levels in architectural spaces is often less important than it is for the user to be able to move gradually between different light levels and thus adapt.

3.3. *The spatial perception of the human eye*

The human eye has an approximately semispherical field of vision (2π steradians), with a narrow, central solid angle of precise vision, corresponding to the location of the cornea in relation to the retina. Towards the edges of the visual field, vision is blurred, the perception of shapes rapidly being lost, while that of movement remains more intact (Fig. 12).

Our eyes are usually in constant movement, switching our precise vision from one area to another of the visual field that is under the global control of the periphery of the retina. The movement of the head complements our capacity for the visual perception of our environment, but there always remains an eclipsed area at our rear which we neither perceive nor control with our sight and which requires the aid of our sense of hearing if we are to feel in control of our surroundings. For this reason, the position of people in relation to the space they occupy can be important, especially in interiors with acoustic difficulties.

Our sense of sight also allows us to pinpoint the direction of the objects that

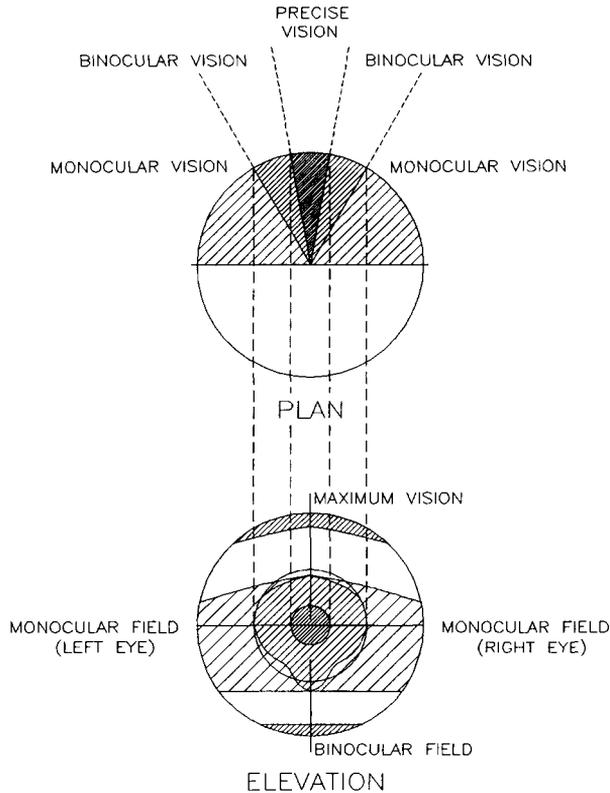


Fig. 12. Plan and evaluation of visual field.

surround us, basically by directing the head and eyes towards that which we are observing. The action of the muscles informs the brain of the direction in relation to our body, to a large extent on the basis of experience.

Judging distance is more complex, and involves a number of mechanisms. Firstly, there is the deformation of the crystalline lens as it focusses the image, which makes it possible to judge very short distances. Furthermore, binocular vision, with the difference between the image that each eye perceives, enables us to recognize the relative location of the objects in our field of vision, while at the same time the convergence of the eyes assists us in judging short distances. Finally, it is the learning process that contributes most to informing us how far away objects are located, as we simply weigh up their apparent size on the basis of previous experience. The only drawback to this is that it is an unreliable system in novel environments or ones with a different scale to normal, an effect which has frequently been used as an architectural device to produce special sensations in the observer.

3.4. *Visual comfort*

When we talk of comfort we mean well-being or lack of discomfort in a given environment. Several different causes may be involved in this concept, since all the senses are receiving stimuli simultaneously, in addition to which, other more difficultly recognizable factors are also present. Nevertheless, comfort is traditionally analysed independently for each of the main senses, including sight.

On the subject of comfort we make a distinction between comfort parameters, assessable values of the energy characteristics of the environment, and factors, which depend on the user and influence the appreciation of the parameters. Comfort depends on the relationship between the two, and although architectural design essentially effects the parameters, the factors of the user (age, type of activity, etc.) must be taken into account in order to ensure that the design fulfils its objective.

Visual comfort depends, as is logical in a basically informative sense, on how easily we can perceive that which interests us. As a result, the primary requirement is that there must be the right amount of light (illuminance) for our visual acuteness to distinguish the details of what we are observing. In accordance with this, the first parameter is illuminance (L_x), with recommendable values that vary depending on the circumstances and the glare conditions (which constitute the second parameter to be considered in visual comfort).

Glare, considered as a comfort parameter, is the unpleasant effect caused by an excessive contrast of luminances in the visual field. As a rule, this effect is due to the existence of a small surface of great lightness (luminance) in a field of vision with a considerably lower mean value, normally as a result of a lamp or a window.

Physiologically, we distinguish two types of glare. 'veil glare' is that produced by a bright spot on a very dark background, such as a streetlight or a star at night. As the beam of light enters the eye it causes a degree of diffusion in the vitreous humour, which makes us see the point of light as being enveloped in a veil or producing rays in the shape of a cross or a star. The other type, called 'adaptation glare', is more important in architectural design, and is caused when the eye adapts to the mean luminance of a visual field where there is a great variation in luminance values, with extremes that are outside the capacity for visual adaptation and are therefore not seen.

Glare can also be classed according to the incidence on the eye of the excessive beam of light. When it strikes the fovea centralis it is called direct glare, or incapacitating glare, since practically nothing is visible. If the incidence is elsewhere on the retina it is called indirect glare; this type can hinder vision without actually preventing it, and is also called disturbing or perturbing glare. It should be borne in mind that in many cases the same terminology (direct/indirect) is used to define and distinguish the glare produced directly by a source of light from that produced by a reflection on a glossy surface (such as a glass-topped table) (Fig. 13).

Glare is a phenomenon which it is difficult to evaluate, although this can be achieved by analysing the various different luminances present in the field of vision. As a first approximation, the following values are recommended as suitable for a work environment: contrasts of 1–3 between the observed object and its immediate back-

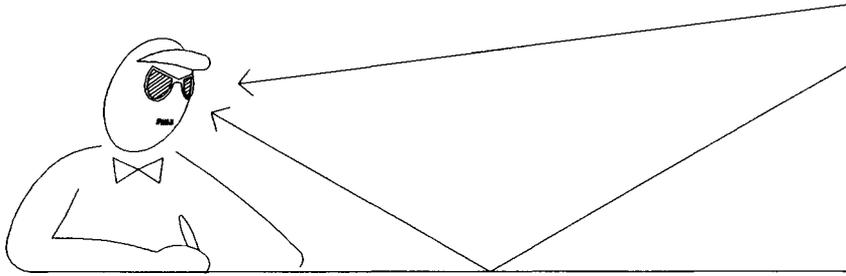


Fig. 13. Direct/indirect glare.

ground, 1–5 between it and the work surface as a whole, and 1–10 between it and other surfaces in the field of vision. In a more accurate analysis, the following concepts are brought into play:

$$g = \frac{L_s^a \omega^b f(\theta)}{L_B} \quad (5)$$

where:

L_s = luminance of the light source

ω = solid angle of the source from the eye

$f(\theta)$ = function of the direction from which the light arrives (value 1 if it arrives perpendicularly to the eye and value 0 if it arrives laterally)

L_B = luminance of the background to the light source

a and b = coefficients with typical values 1.8 and 0.8

The sensation of glare grows as the value of this glare constant g increases. As, subjectively, growth in discomfort due to glare approximately follows the logarithmic law of sensation, the glare index (G) is defined thus:

$$G = 10 \log_{10} g \quad (6)$$

When the value of the index G exceeds 10 the glare is noticeable, from 16 to 22 it is bearable, from 22 to 28 it is uncomfortable, and for higher values, intolerable.

A third parameter for visual comfort is the colour of the light; derived from the concepts of colour temperature and colour rendering index, discussed above, the colour of the light is not only a quality factor as regards perception but an element of comfort or discomfort to be taken into consideration. In connection with this, the Kruithof graph establishes a relationship between the colour temperature of the light and the illuminance, and defines a field of compatibility between the two values.

In the case of natural light, the colour of the light will have little influence on comfort, since its chromatic characteristics are taken as the theoretical ideals. Nevertheless, it should not be forgotten that, as the colour temperature in this case is very high (around 6500 K), in the case of low lighting levels the sensation can be excessively cold, and therefore unpleasant. The reflection or transmission of light to shift its spectrum towards warmer tones can improve the users' visual comfort in such cases.

Considering all the above and always bearing in mind the relative value of these data, we can state typical values for light parameters in relation to the factors of the user (Tables 1–5).

4. Daylighting in architecture

The analysis of light on both physical and psychological levels provides us with the theoretical base for understanding how natural light interacts with architecture, and it is this knowledge that must be used to plan the functioning of light in buildings as a basic part of the project; it should never be postponed as a technique applicable to a previously defined project. Consequently, in our analysis we consider first and foremost the importance of light in fairly general design plans, relegating specific

Table 1
Light definers

Illuminance (general values)	
Activities with very high eye strain: precision drawing, jewellery etc.	1000 lux
Short-duration activities with high or very high eye strain: reading, drawing, etc.	750 lux
Short-duration activities with medium or high eye strain: work in general, meetings, etc.	500 lux
Short-duration activities with low or medium eye strain: storage, movement, social activities, etc.	250 lux

Table 2
Modifying factors for the general illuminance values

× 0.8	× 1	× 1.2
Age < 35 years	Age 35–55 years	Age 55 years
Activity unimportant	Activity important	Activity critical and unusual
Low difficulty	Normal difficulty	High difficulty

Table 3
Luminance values (with corresponding illuminances)

Visual code	Luminance (cd m^{-2})	Horizontal illuminance (lux)
Human face hardly visible	1	20
Face fully visible	10–20	200
Optimum for normal work	100–400	2000
Surfaces with reflection > 0.2 well lit	> 1000	20,000

Table 4
Glare

Glare indices (G)	
Highly critical conditions with difficult work, dangerous situations, etc.	Imperceptible: < 13
Conditions with long-duration work of normal difficulty, with rest periods, etc.	Low: 13–16
Conditions with short-duration work or light work, with long breaks, etc.	Medium: 16–19
Conditions below critical, with short work periods, movement, etc.	High: 19–22
Conditions without visual requirements, in which glare is not a problem	Very high: > 22

Table 5
Colour of the light

Type of space	Condition	R (%)	T_c (K)
Spaces where colour is very important	Work	> 85	4500–6000
	Rest		2500–4000
Spaces where colour is important but not critical	Work	70–85	> 4000
	Rest		< 4000
Spaces where chromatic recognition is unimportant	Work	< 70	> 4500
	Rest		> 4500
Space without chromatic vision		40	Indifferent

Characteristics recommended according to use

systems and components of natural lighting to a secondary position, since they are often no more than forced solutions to problems that could have been solved more effectively at a previous stage in the project.

4.1. *Indoor and outdoor light*

Architecture is basically a contraposition of indoors and outdoors, sheltered space and exposed environment, confidence and vulnerability, privacy and society. During the day, natural light reveals the entirety of the exterior, filling all its corners and crudely showing the skin of buildings, their size, their shape and all their details (Fig. 14).

In these buildings, clearly visible in the intense natural light, openings are seen as dark holes that give few clues as to what is hidden indoors. In daylight hours, when light rationalizes the complex reality of our inhabitable environments, this same light renders the interior spaces of architecture invisible, private and mysterious. Even when the openings are covered with glass or whole façades of buildings attempt to reproduce the hard aesthetics of precious stones, being totally glazed, the interior of the architecture refuses to be observed during the day and the hard reflections of the glass defend the mystery of its interior.

In short, architecture is darkness during the day; only by penetrating its interior,

adapting our vision to indoor conditions (recall the slow adaptation when moving from light to dark), can we once again appreciate the architecture's interiors (Fig. 15).

On our wanderings around the interior spaces, the openings become powerful magnets, attracting our gaze towards the outside world, which seems more real and powerful than the dark interior in which we stand. As part and parcel of the attraction exerted by the view, we are dazzled by the high luminances of the exterior and no longer able to appreciate the details of the interior (Fig. 16).

For this reason, when light is used wisely in architecture it enters from outside the visual field of the observer, through high openings often located above the entry to the space. This restoration of an interior light of its own, from an unidentified source, exerts a rather magical effect. It renounces the external view in exchange for the reorganization of the interior space, which ceases to be secondary.

This whole situation changes radically at night, when the roles of the interior and the exterior are inverted. This is not the object of this work, although at this point two brief comments can be made on the use of artificial and natural light in architecture.

- (1) Both architecture and we who inhabit it are different by day and by night, therefore it makes no sense to try to imitate the effects of natural light with artificial light; the results will always be mediocre.
- (2) It is always difficult to combine the two kinds of light, due to their different chromatism and the fact that when the eye is accustomed to natural levels of light it finds artificial light poor and gloomy, whereas at night it seems ideal.

Returning to natural light as energy passing from the exterior to the interior of the building, it should be borne in mind that the way in which it enters is conditioned by its origin, which can be threefold (Fig. 17):

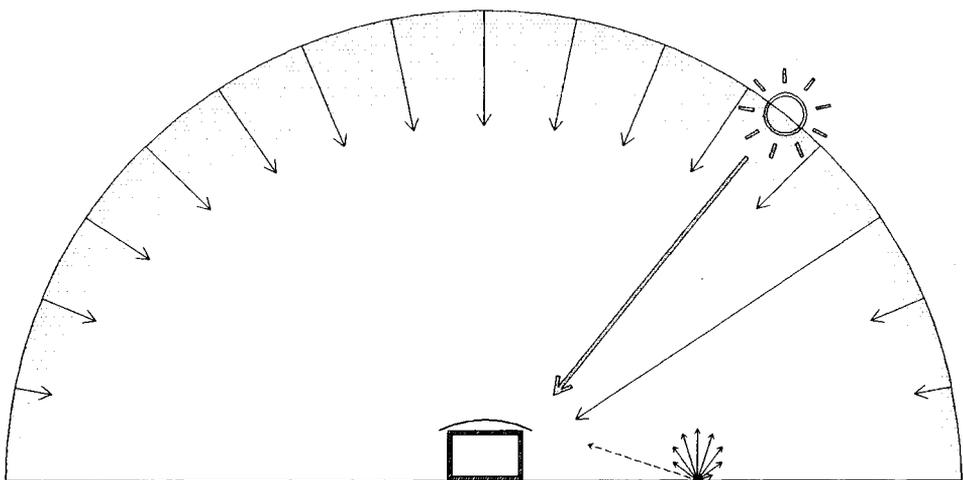


Fig. 17. Sky dome and building, showing three incidences: direct sun, sky dome and albedo.

- Direct sunlight is frequent in Mediterranean climates (see Section 6.1.), and strikes with parallel beams of high energy density (as high as $100,000 \text{ cd m}^{-2}$). Indoors it generates clearly defined patches of light that change as the sun moves across the sky dome. This type of light therefore creates uncomfortable interior visual conditions caused by excessive contrast, and easily results in overheating in interiors. Its thermal effect and its unique distribution of luminances, which imparts a feeling of cheerfulness, are desirable in winter and in cold climates and undesirable in summer in hot climates.
- Sky dome light is associated with an overcast sky (though it is also the case in clear skies for directions facing away from the sun), and is the most usual light in Atlantic and northern climates. Its lighting intensity is 10–20% weaker than direct sunlight and is also distributed in a more diffuse way, as it does not come from one single direction. This is the light which is often used as a minimum condition, but one must also consider that, in hotter climates, its entry into the building, even when direct radiation has been eliminated, can cause overheating problems.
- Reflected or albedo light from external surfaces becomes important when the other two types lack intensity, either because they are eradicated to avoid overheating or because the conditions of the premises or building do not allow direct access to skylight. In these circumstances, and when the external surfaces (the ground and neighbouring buildings) have relatively high reflectances, albedo light can generate useful interior lighting, although it should always be considered that since the light is not coming from above it has a greater tendency to cause glare.

Finally, bearing in mind the diffuse nature of both sky dome light and albedo light, in the absence of direct sunlight any opening behaves as if it were an emitting surface of diffuse light for the interior, since the luminances of the exterior can be considered to be transferred to the plane of the opening without any error of physics, the only correction necessary being the transmission coefficient of the glass, if present (Fig. 18).

4.2. *The perception of light in architecture*

When an architect imagines the architecture that he is beginning to design, he pictures in his brain the forms of the building he is creating, from overviews of the building to specific details of its façades. If he is sensitive to interior space, he will also imagine how the interior forms of its building will be when it is inhabited, thus becoming much more closely involved in the future architectural experience. Very few architects, however, are sensitive enough to imagine and design in their mind the light being planned for these spaces.

If we look at the works of the great masters of architecture, both ancient and modern, it is clear that in most cases natural light was present from the very first images of the projects they conceived. This conceptual presence of light is manifested not only in the results in the finished building, but can often be recognized as early as in the initial drawings that precede the actual result.

It is interesting to observe the different approaches architects have to natural light.



Fig. 14. Photograph of buildings from the exterior.



Fig. 15. Photograph of an interior, with dazzling windows.



Fig. 16. Photograph of an interior with 'hidden light', showing the light but not the opening.



Fig. 18. Photograph of entry of light through a window in two cases: direct sunlight/diffuse light.



Fig. 19. Photograph: light as a fluid.



Fig. 20. Photograph: light beams.



Fig. 21. Photograph: light as an impressionistic game.



Fig. 30. Photograph: intermediate lighting spaces.



Fig. 31. Photograph: interior light spaces.



Fig. 32. Photograph: lateral pass-through components.

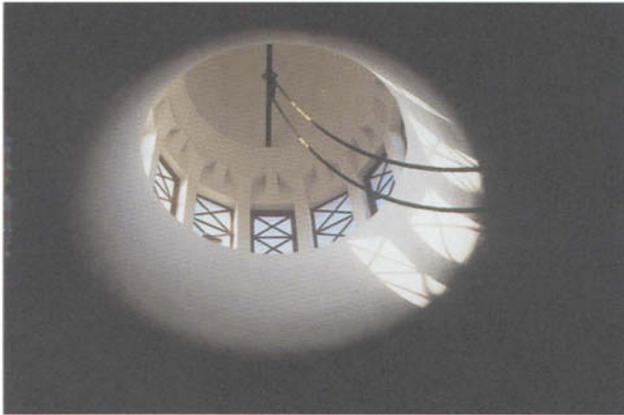


Fig. 33. Photograph:zenithal pass-through components.

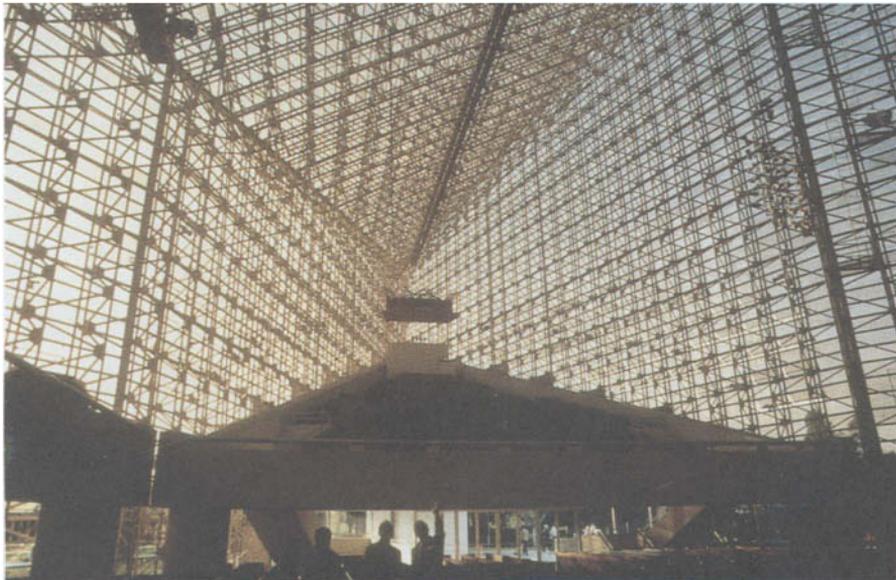


Fig. 34. Photograph: global pass-through components.

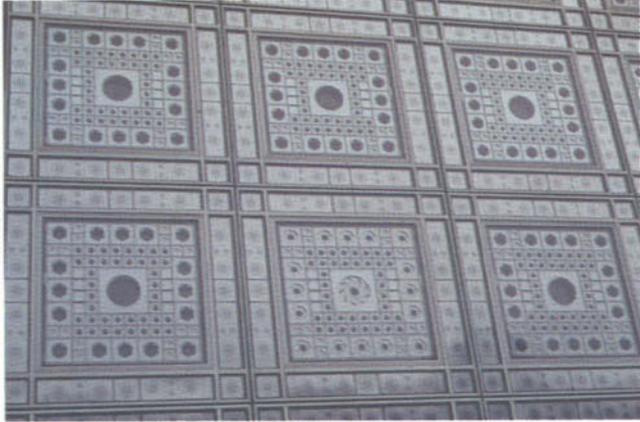


Fig. 35. Photograph: separator surfaces.



Fig. 36. Photograph: flexible screen.



Fig. 37. Photograph: rigid screens.



Fig. 38. Photograph: solar filters.



Fig. 39. Photograph: solar obstructors.

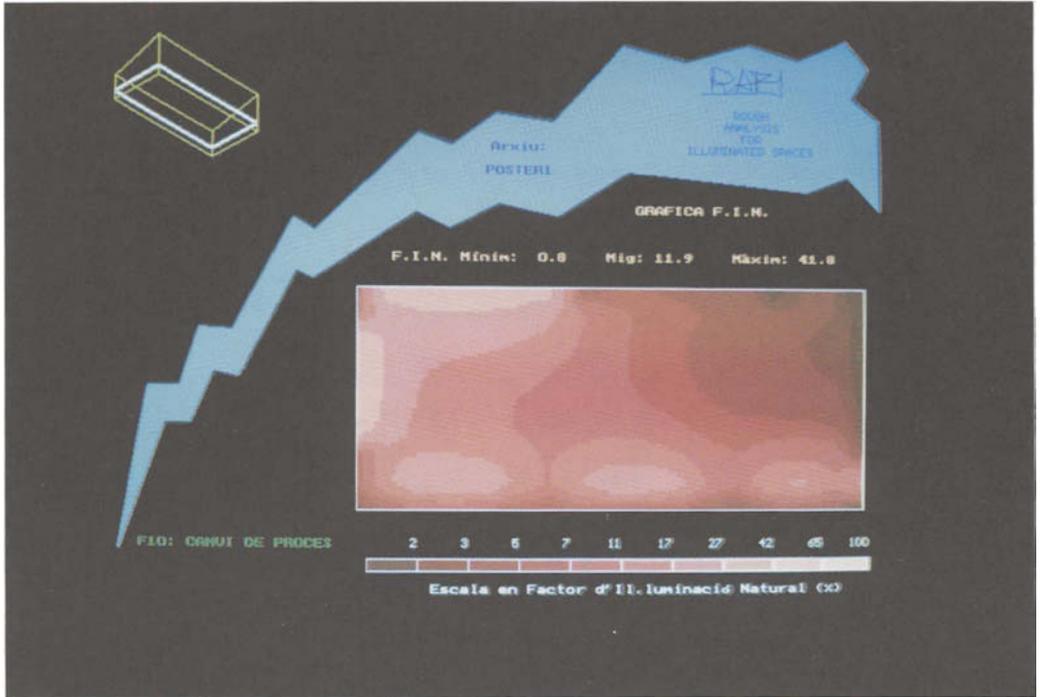


Fig. 40. Photograph: screen with isoDL graph.



Fig. 41. Photograph: scale model.

Quite apart from the greater or lesser knowledge they may have of the basic principles of lighting and even without assessing the efficiency of the results obtained, it appears that each one of them intuitively conceives the phenomenon of light differently, and this is reflected in the way in which light defines and shapes the spaces of their architecture (Fig. 19).

In many cases light is imagined as a fluid, liquid or gas that occupies all external space and spills or expands (according to how it is conceived), through the light openings and into the interior space. Faint patches of light define volumes, and transitions between spaces gives subtle meaning to the light that fills them. The lightness (i.e., luminance) of the surfaces are flat and undegraded, and only proximity to the openings reveals that the light fluid is entering with some lighter patches (Fig. 20).

In other cases light is understood as beams, in an almost mythological image of celestial force travelling through space, penetrating the interior and bouncing off surfaces, thus imbuing them with reality. Low-angle lighting therefore re-creates the material nature of construction elements and gradation shows the fatigue light suffers as it travels towards interior space (Fig. 21).

On other occasions natural light enacts an impressionistic game in an interior, independent patches of light only coming together to form a whole in the brain when the space is perceived globally. In such cases colour is decisive, and wall surfaces change the tone of the light they receive. Furthermore, shade takes on a value of its own, and the play of the absence of luminance can be more decisive than that of the actual light.

This analysis could unearth many other keys to the perception of light in architecture. Streams of light, silhouettes, rhythms of light and shade between spaces, the visible entry of light and the mystery of concealed entry, the magic of zenithal light, and so on. Whatever, it is clear that there is no such thing, nor should there be, as a single recipe or system for imagining light. The important thing is to nurture the will and the effort to imagine it; only in this way will architecture develop its full aesthetic potential.

4.3. *Lighting in peripheral and core zones*

The first point to tackle when considering the use of natural light is its entry into interiors that would otherwise be dark, due to the fact that they are separated from the exterior by a façade. Only the creation of openings in the shell of a building will allow the entry of natural light, in an inevitably limited yet controllable way.

In any building, two separate problems can be distinguished: the lighting of the peripheral zones or premises, which have contact with the skin of the building and therefore the possibility of direct access to the light outside; and that of the interior zones or premises, without contact with the shell, where the only access to natural light is by means of some system of transportation. These two problems, that of the peripheral zones and that of the core zones of the building, each have their own peculiarities, and they will be treated separately when considering possible solutions (Fig. 22).

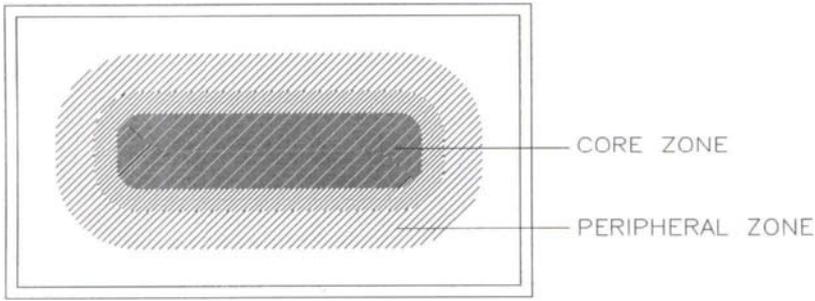


Fig. 22. Peripheral zone and core zone of a building.

However, before dealing with specific systems applying to the periphery or the core, we shall consider some general aspects of the project which affect its interrelation with light.

One initial point to consider is the compactness of the building, which establishes the relationship between the outer shell of the building and its volume, i.e., the degree of concentration of the interior spaces (Fig. 23).

Logically, less compact buildings will have greater possibilities of natural lighting, as the core zone, where the entry of light is more difficult to achieve, is correspondingly smaller.

Another aspect to be taken into account is the porosity of the building, which refers to the existence within its global volume of empty spaces and points of communication with the exterior, such as courtyards (Fig. 24).

A high degree of porosity indicates the possibility of creating an access for light (and also ventilation) in the core zones of the building. Although lighting by means of a courtyard will never be so effective as direct contact with the exterior, if the courtyard is suitably designed it can be very useful.

A further general aspect to consider is the transparency of the skin of the building to light, which varies from totally opaque buildings to totally glazed ones. Although greater transparency increases light in the peripheral zone, good lighting depends more on the appropriate distribution of light than on quantity. Often the effects of glare make lighting by means of large openings inadvisable.

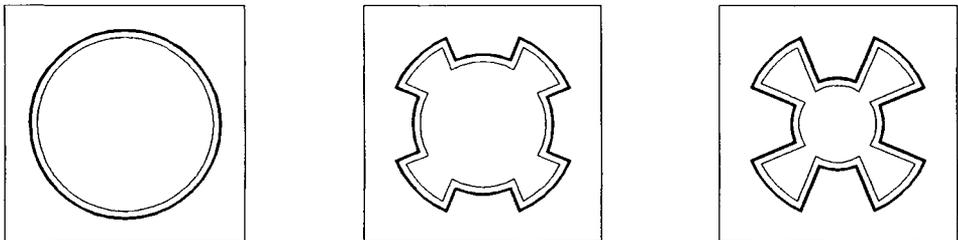


Fig. 23. Degrees of compactness of a building.

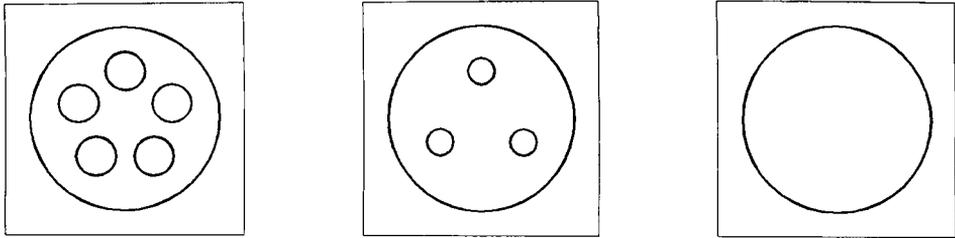


Fig. 24. Degrees of porosity of a building.

Other aspects to take into account are the geometric characteristics of the interior spaces. Premises can thus be analysed according to size, shape, proportions and possible differences in floor level.

The size of a building does not in principle have any influence on the distribution of light in its interior; areas of identical shape but different size and with their openings to scale with their size will have the same interior light distribution. Since radiant phenomena generally and light in particular do not change with size, the study scale of these phenomena can be accurately studied. The only point that should be borne in mind is that spaces with large surface area will have a dark central zone unless they preserve their proportions by having a higher ceiling (Fig. 25).

The shape and proportions of a building are important for its natural lighting, depending on the location of the opening. As a rule, irregular or elongated spaces with light entering at the end have a rather irregular light distribution (Fig. 26).

It should be taken into account that the lateral entry of light into a space causes a rapid decrease in light (i.e., illuminance) the further we are from the opening, due to the fact that the angle of vision of the sky (the main source of light) is soon lost. This results in peripheral zones and premises easily being badly lit, even if the total amount of light present is sufficient. The entry of zenithal light, on the other hand, tends to be more suitable (Fig. 27).

Finally, differences in the floor level have repercussions on both lighting and the view. If the floor drops towards the middle, the light distribution improves but the view is reduced, and vice versa (Fig. 28).

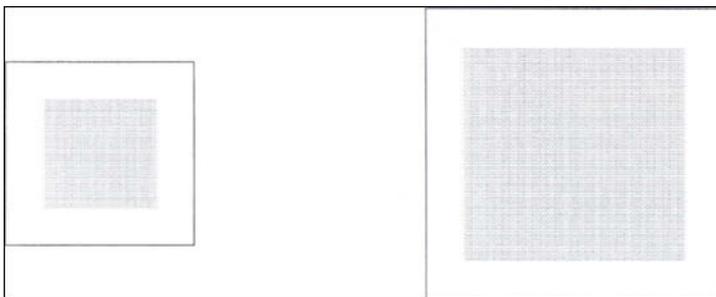


Fig. 25. Central zone in spaces with a large surface area.

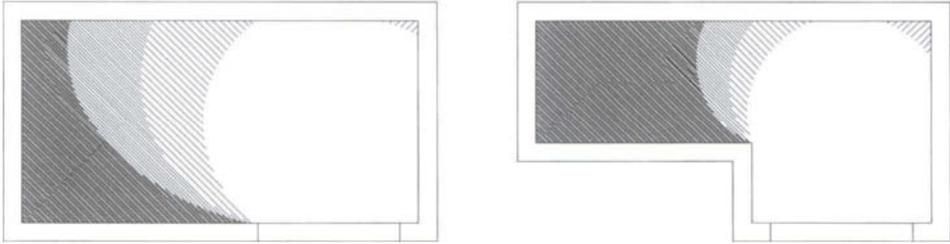


Fig. 26. Relationship between shape and light distribution.

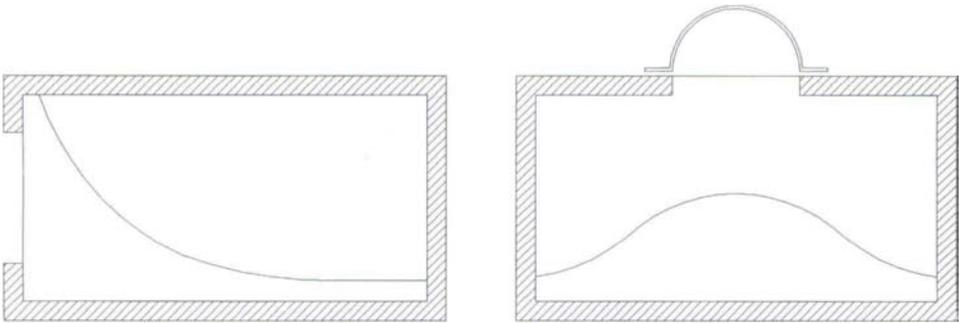


Fig. 27. Lighting levels with lateral and zenithal openings.

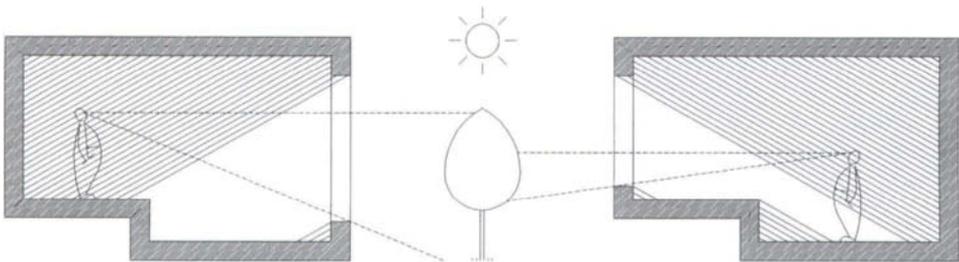


Fig. 28. Variation of light and views in stepped premises.

5. Daylighting improvement in buildings

Working from the basis of the considerations in the above sections, we shall now attempt to analyse natural lighting systems, considering them as a complementary strategy to the general lighting design of buildings.

Natural lighting systems are components or sets of components of a building the chief purpose of which is to improve the natural light of inhabitable spaces, optimizing the distribution of light in peripheral zones and attempting to bring as much natural light as possible into interior zones with no direct contact with the exterior. Among

the components of natural lighting we make a distinction between pass-through components and conduction components.

Conduction components are those which take natural light from the exterior towards interior zones of the building. They are frequently connected, forming continuous series.

Pass-through components are devices designed to allow the passage of light from a given light environment to one located next to it.

From this analysis, any combination or succession of pass-through and conduction components can be established, and we can interpret a building in lighting terms as a series of pass-through components placed between conduction components which connect them. In this way it is possible to schematize any complex system for the entry of natural light towards interior spaces (Fig. 29).

Pass-through components for natural light can be highly complex; so in order to analyse them we consider them as being composed of a set of control elements through which light passes. These control elements which make up the pass-through components correct the light reaching them and send it on to the neighbouring conduction component in a controlled way.

5.1. Conduction components to the core of the building

These are spaces that are located beyond an initial pass-through component which captures natural light from the exterior. They collect the light captured by the pass-through component, convey it to the next pass-through component and so on. Their shape is very important, since their capacity to conduct the light they receive depends to a large extent on the geometric characteristics of the conducting space.

The characteristics of the finish on their surfaces are also important, as this is where the natural light strikes. Different finishes cause components to act differently according to whether they are reflecting, specular, diffuse, absorbent or whatever.

Conduction components can be classed into two groups depending on their location in the building. They can be located between the external light environment or perimeter of the building and the interior spaces they are designed to illuminate, in

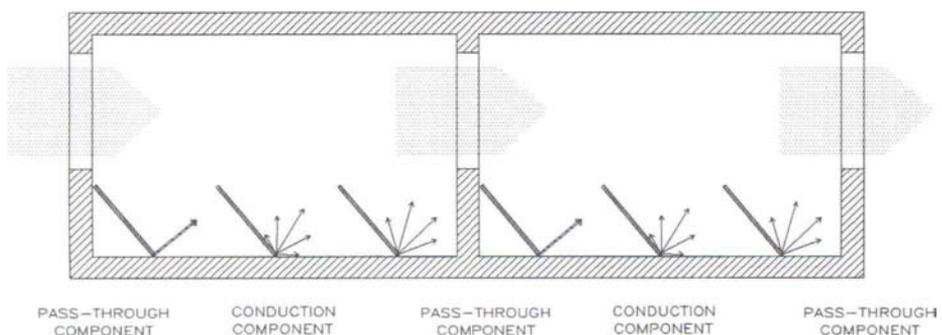


Fig. 29. Natural lighting components: conduction components and pass-through components.

which case we will call them intermediate light spaces. However, there are also conducting spaces that form part of the interior space of the building, relatively far from the periphery, and these we will call interior light spaces.

5.1.1. *Intermediate light spaces*

These are located in the peripheral zone of the building, between the external environment and the inhabitable spaces. They can act as regulatory filters between the internal and external environmental characteristics; they guide and distribute the natural light that reaches them from the exterior to the interior. They are sealed with transparent or translucent materials and can incorporate control elements to regulate light passing through. The most typical example are galleries, porches and greenhouses (Fig. 30).

They supply a low light level with little contrast with the interior, which they protect from the direct sun and the rain. Typically, they are one or two storeys high and 1–5 m deep.

5.1.2. *Interior light spaces*

These form part of the interior zone of a building, guiding the natural light that reaches them to interior inhabitable spaces that are far from the periphery. Within this group are courtyards, atria and all types of light-ducts and sun-ducts (Fig. 31).

They create light conditions that are intermediate between the interior and the exterior, and allow a degree of natural lighting in the interior zones of the building, which are connected by means of pass-through components.

Their size is very variable, although they are usually higher than they are wide. A light-coloured finish to their surfaces improves their performance, and a lining of mirrors converts them into sun-ducts.

5.2. *Peripheral components*

These are devices or sets of elements that connect two different light environments separated by a wall containing the component. They are defined by their geometric characteristics, namely, their size in relation to that of the wall in which they are set, their position in that wall (central or lateral, high or low) and the shape of the opening. Their composition depends on the elements they incorporate to control and regulate the lighting, visual and ventilation phenomena.

These components can be divided into three groups, according to the direction of incidence of the light in the inhabitable spaces. The three groups are: lateral pass-through components if the light enters the space to be lit on a vertical plane, zenithal pass-through components when the light tends to reach the interior from above and global pass-through components if the light comes into the interior space from both directions at once.

5.2.1. *Lateral pass-through components*

These are located in vertical enclosing surfaces, either in the skin of the building or in internal partition walls, between two environments with different lighting characteristics, and permit the lateral entry of light to the receiving area. Typical lateral

pass-through components are windows, balconies, translucent walls and curtain walls (Fig. 32).

They allow the lateral entry of light and direct solar radiation if they are in external façades, and often a view and natural ventilation. They greatly increase the light level near the window, but the distribution of light in the space is irregular.

Their dimensions are variable, from small windows measuring 0.1 m^2 to large glazed surfaces usually between 1.2 and 2.8 m high. They can be incorporated into all types of control elements.

5.2.2. *Zenithal pass-through components*

These are located in horizontal enclosing surfaces in the roof or the interior of a building, between two different light environments, and are designed to let zenithal light into the receiving environment below. Typical zenithal pass-through components in architecture are clerestories, monitor roofs, north-light roofs, translucent ceilings, skylights, domes and lanterns (Fig. 33).

They allow the entry of light from the sky dome and either protect or redirect the direct solar radiation towards the space below. They can also permit natural ventilation without an external view, and generate high lighting levels in the interior environment, usually with diffuse light, thus avoiding excessive contrasts.

The size of the openings is variable; they sometimes occupy a large proportion of the surface area of the ceiling over the space that it is intended to illuminate. They are seldom smaller than 2 m^2 .

5.2.3. *Global pass-through components*

These form part of the enclosing surfaces of a built structure, and are made of transparent or translucent material. They totally or partially surround the environment and permit the global entry of natural light.

The most typical component of this type is the membrane, with translucent or transparent surfaces, which surrounds the whole of an interior environment. It allows overall entry of light and generates a high, uniform light level in the interior, similar to external conditions (Fig. 34).

These components can easily cause problems of excess radiation in hot or moderate climates, especially in summer, when the sun's path is higher in the sky.

For this reason it is advisable to complement these components with radiation control elements to protect their whole surface. Furthermore, movable openings should be provided at their highest points to enable hot air to escape.

The surface area of these global components is usually greater than the ground plan of the space surrounded by the membrane. The materials commonly used for the enclosing surfaces are plastics (acrylic polycarbonates or glass fibres) supported by an aluminium or steel structure. In many cases, these pass-through components define the volume of peripheral conduction components such as greenhouses or atria.

5.3. *Control elements*

These devices are specially designed to enhance and/or control the entry of natural light through a pass-through component.

Among their general characteristics, we should consider their position in relation to the pass-through component that they are regulating, their mobility or possible regulation by the users of the spaces, and their optical properties, such as transparency, diffusion and the reflection of light.

In addition to their behaviour with regard to light, these control elements can serve other environmental purposes for the pass-through components, for instance, ventilation, the possibility of a controlled view, the thermal protection of the interior space or the safety of the building.

We shall classify the control elements in five general groups according to the way in which they control the incident light: separator surfaces between two different light spaces, screens in flexible materials, rigid screens or screens in rigid materials, selective filters for a particular characteristic of solar radiation and total radiation obstructors.

5.3.1. *Separator surfaces*

These are surface elements of transparent or translucent material, incorporated into a pass-through component that separates two different environments. They enable radiation, and sometimes the view of the exterior, to pass through, but block the passage of air. Among the numerous types of separator surface in existence in the field of architecture, there are conventional transparent ones, those with chemically or mechanically treated surfaces, those that follow a particular geometrical pattern and active enclosing surfaces (Fig. 35).

Conventional divisions are made of glass or transparent plastic. Treated divisions include all kinds of coloured glass, mirrored glass, translucent glass, and recently, glass incorporating thermochromic or holographic films. They are useful for the way they modify the characteristics of the light that passes through them, varying according to given geometric or thermal parameters. Geometric divisions are formed by sheets of a plastic material with optical properties due to its geometry, and redirect the incident light in a given direction. Finally, active divisions are manufactured with high-technology materials incorporated into their surface, and regulate the light that passes by means of electrical phenomena that modify the optical properties of the division.

5.3.2. *Flexible screens*

These are elements that partially or totally prevent the entry of solar radiation and make the light that shines through them diffuse. Depending how they are placed, they can allow ventilation and provide visual privacy. They can be retracted, rolled up or folded away to remove their influence when so wished. The commonest types of flexible screens are awnings and exterior curtains (Fig. 36).

Awnings and curtains are made of materials that are either opaque or serve to diffuse light. They can be placed over the external surface of a pass-through component, so as to selectively prevent radiation passing prior to entry or, by placing them over the interior of separator surfaces, control the radiation that has already entered the pass-through component and is illuminating the interior.

5.3.3. *Rigid screens*

These are opaque elements that redirect and/or block the direct solar radiation that strikes a pass-through component. Normally, they are fixed and unadjustable, though there may be exceptions to this. Their main variable is their position with relation to the opening they protect. Among the various possible types we shall put special emphasis on overhangs, light-shelves, sills, fins and baffles (Fig. 37).

Screens can be specifically placed in any position, where they are intended to block or reflect the sun's rays coming from particular directions.

5.3.4. *Solar filters*

These are surface elements that cover all, or nearly all, of the outer face of a pass-through component, protect it from solar radiation and allow ventilation. They can be fixed or movable (so that they can be removed and the opening left free), and adjustable if the orientation of the louvres of which they consist can be changed. Those most used in architecture are the various types of blinds and jalousies (Fig. 38).

They are very widely used in architecture, in many different climates and cultures. This explains the great variety of possible forms and materials available for this extremely popular mechanism.

5.3.5. *Solar obstructors*

These are surface elements composed of opaque materials, and can be attached to the opening of a pass-through component in order to completely seal it. They are normally called shutters and can be located either on the exterior or on the interior of a glass separator surface (Fig. 39).

The effect they have on the entry of light into inhabitable interior spaces is heightened by their effect on visual control and thermal insulation. They act as barriers to all effects, at times when users wish to neutralize interactions between the external environment and the interior through the pass-through components which they modify.

6. **Conditions of the sky**

6.1. *The luminance of the sky*

The luminance of the sky is a basic characteristic to be taken into consideration when studying the pre-existing conditions of a site, and the local climate, with its associated degree of cloud cover, is a decisive factor in this.

There are several different possible models for the luminance of the sky to take into account as a pre-existing environmental condition in a given place. As a rule, an overcast sky is taken to be the most unfavourable case, and this alone is studied. This is logical in northern climates, but not in temperate ones, where the cases of cloudy and clear skies should also be considered, as should the position of the unobstructed sun, protection from it and the exploitation of its radiation both requiring attention.

Table 6

The values for the mean luminance of the sky dome for latitude 40°, with different climatic conditions and times of year

Winter solstice			Equinoxes			Summer solstice		
08:00	10:00	12:00	08:00	10:00	12:00	08:00	1:00	12:00
16:00	14:00			16:00	14:00		16:00	14:00
1750	3200	4700	3200	4600	6200	6000	7600	8600
4600	21,000	24,000	22,000	28,000	30,000	27,000	31,000	32,000

The values in the first row correspond to mean luminance with an overcast sky, while the second row is for a clear sky. The minimal case at Mediterranean latitudes is taken to be an overcast sky with 3200 cd m⁻², which is equivalent to some 10,000 lux on a horizontal plane without obstructions.

It should be borne in mind that Mediterranean climates have direct sunlight much more frequently (70% of the time) than more northern climates (30% of the time); this is often neglected when studying the natural lighting of buildings.

6.1.1. Uniform overcast sky

This is the main model used in natural lighting studies, with constant luminance in all directions and heights. The relationship between the mean luminance of the sky and the illuminance of a horizontal plane without any obstruction will be:

$$E_h = \pi L \quad (7)$$

where:

E_h = illuminance on horizontal plane (lux)

L = mean illuminance of the sky (cd m⁻²)

The values for the mean luminance of the sky dome for latitude 40°, with different climatic conditions and times of year are in Table 6.

6.1.2. CIE overcast sky

This is the model for the standard overcast sky, which provides a better fit with reality, since luminance varies with height, to the extent that the sky is considered to be three times lighter at the zenith than at the horizon.

This relationship is defined with the Moon–Spencer formula:

$$L_x = L_z \left(\frac{1 + 2 \sin \alpha}{3} \right) \quad (8)$$

where:

L_x = luminance at a height with angle α above the horizon

L_z = luminance at the zenith

In this case L_z can be considered to be 9/7 of the (uniform) mean luminance of the sky.

Another correcting factor to be taken into account in this analysis is the variation of the luminance of the sky depending on direction, not only with a cloudy or clear sky but also with an overcast one.

This variation in the luminance can be expressed, for luminance at the horizon, as a 20% increase in the direction of the equator and likewise a 20% decrease in the direction of the pole of the hemisphere concerned. These variations diminish with increasing height, finally disappearing at the zenith.

The Moon–Spencer expression, duly corrected to allow for this variation, would be:

$$L_{x,\beta} = L_z \left(\frac{1 + 2 \sin \alpha}{3} \right) (1 + 0,2 \cos \beta) \quad (9)$$

where:

$L_{x,\beta}$ = luminance of the sky for a height β in the direction of the equator
 L_z = luminance at the zenith

6.1.3. Clear sky

For the case of a clear sky the best strategy is to consider only the direct incidence of the sun, with an intensity in the order of 100,000 cd m⁻² and the position corresponding to the time of the year and day.

We will also consider, as indirect sources, the rest of the sky dome and reflection from other surfaces on the ground or other external elements (albedo).

For the case of a clear sky dome, luminance decreases as we move away from the sun, with values varying between 2000 and 9000 cd m⁻².

For the case of the albedo, the typical luminance value is taken as the result of applying the following expression:

$$L_a = E_h r / \pi \quad (10)$$

where:

L_a = luminance of albedo
 E_h = illuminance received by the surfaces (estimated at 100,000 lux for a clear sky)
 r = reflection coefficient of the surfaces (typical value of 0.2, or as high as 0.7 on light surfaces)

6.1.4. Cloudy sky

In the case of a cloudy sky, intermediate between a clear and an overcast sky, hypotheses must be made which correspond to a situation somewhere between those considered in the above cases. Nevertheless, if the two extremes are known, it is not necessary to study this type of sky beyond ascertaining its frequency for each time of year.

6.2. *Compilation of data*

Compiling data on this topic is difficult, but often meteorological services give percentages of clear, cloudy and overcast days for each month of the year, and this information can be used as a good approximation of the conditions of the sky that can be expected in a given place.

7. **Daylighting evaluation in architecture**

The aim of a natural lighting dimensioning method for a project or building is to ascertain the amount of light in the interior environment, together with its distribution.

In natural lighting there is so much variability in the factors that generate the environment that evaluation systems are inexact. Calculations provide us with knowledge of interior conditions in relation to exterior ones which we know to be changing. Because of this, results are expressed as percentages of the exterior level, and are called daylighting factors (*DL*):

$$DL = 100 \times E_i(\text{interior})/E_e(\text{exterior}) \quad (11)$$

Generally speaking, natural light calculation systems fall into one of the following categories: predimensioning methods, point-by-point methods and computer-assisted exact calculation. there are also evaluation systems that use scale models.

The first of these shows approximately how much light will enter the space and from this enables us to deduce the resulting mean illuminance on a working plane. The problem with this method is that, since the distribution of light in an interior tends to be irregular, the mean value reached gives little information about the resulting light environment. Only in the cases of diffusive zenithal systems or comparative general evaluations can this system be considered useful.

Point-by-point systems give the light distribution within the premises by means of the repetitive calculation of the light arriving from the openings at each point in a theoretical network or mesh covering the working plane in question. This system provides a better evaluation of the resulting environment and can be used to produce graphs of relative illuminance value, but its precision is low, since it fails to consider the effect of light reflection on the interior walls.

Computer systems not only permit point-by-point calculation but also take interior reflection into account. The results they yield are highly accurate, their only weak point being the lack of reliability of data on outdoor light, which can only be improved with detailed statistics on the average conditions of the sky.

The resulting system for the representation of light is very important. It can be derived from any method that gives point-by-point values. Using the mesh of points which represents the premises, 'isolux' or 'iso*DL*' curves can be drawn joining points of equal illuminance value, for fixed values every 50 or 100 lx, or every 2, 5 or 10 *DL*. These curves, similar to those drawn on a topographic map, provide very good visual information on the distribution of light in the space (Fig. 40).

7.1. Predimensioning method

The most commonly used lighting predimensioning method, both for its simplicity and the relative accuracy of the values it gives considering the time needed to make the calculations, is the flux method.

The result given is the mean illuminance on a working plane situated just above the floor in an interior space. The formulation is as follows:

$$E_i = \frac{E_e S_{\text{pas}} v t u}{S_i} \quad (12)$$

where:

E_i = interior illuminance, in lux

E_e = mean exterior illuminance on a horizontal plane, in lux

(Normal figures in the calculations are 10,000 lx per overcast day in winter and 100,000 lx per clear day in summer.)

S_{pas} = total surface area of openings for light to pass through, in m^2

v = opening factor, or solid angle of sky seen from the opening as a proportion of the total solid angle of the sky (2π), over 1 (on a vertical plane, 0.5)

t = transmission factor of the enclosing surface as a whole, over 1 (normally under 0.7)

u = utilization coefficient, or ratio between the flux reaching the lit plane and the flux entering the premises through the opening, over 1 (value of 0.2–0.65)

S_i = surface area of the premises, in m^2

7.2. Point-by-point calculation method

This method calculates the resulting illuminance for each of the points chosen, which together form a metre-square mesh, and for each of the openings, considered as diffuse emitting surfaces. The basic formulae applied are:

$$E = \frac{I \cos \alpha}{d^2} \quad (13)$$

where:

E = resulting illuminance, in lux

I = intensity reaching the point, in candelas

α = angle at which the light arrives from the opening

d = distance from the centre of the opening to the point, in m

$$I = L S_o \quad (14)$$

where:

L = illuminance of the opening, in cd m^{-2}

S_o = surface area of the opening, in m^2

$$L = \frac{E_o}{\pi} \quad (15)$$

where:

E_o = illuminance emerging from the opening

$$E_o = E_c vt \quad (16)$$

where:

E_c = mean exterior illuminance on a horizontal plane, in lux

v = opening factor, or solid angle of sky seen from the opening as a proportion of the total solid angle of the sky (2π), over 1

t = global transmission factor of the enclosing surface, over 1

There exist tables and graphic abaci that can be used to calculate the opening factor v and the mean exterior illuminance on a horizontal plane E , depending on the geometric situation of the openings in relation to the exterior and the lit point.

7.3. Computer calculation methods

These make use of the powers of computer calculation to integrate the results of the light reaching each point from openings and interior reflections alike. In fact they apply the point-by-point system with all the necessary iterations to obtain great accuracy.

7.3.1. Evaluation methods using scale models

The use of scale models in architecture to evaluate natural lighting has a long tradition. Physical models reproduce in miniature the building that it is intended to build, their strength residing in the fact, mentioned above, that radiant phenomena are stable despite scale changes in space, basically as a result of the short wavelength of light in comparison with the size of spaces.

Model buildings must mimic the exact form and the finish of surfaces, including colours. Likewise, the openings for the entry of light should reproduce those in reality, with materials for the enclosing surfaces that behave identically to those planned for the building.

Scale models make it possible to evaluate complex configurations and shapes which are difficult to reproduce in computer models, and have the further advantage that the resulting light in the space being designed can be visualized easily. The behaviour of the building with regard to light can be tested in different ways:

The simplest process is to use the real sky, but this depends on climatic conditions, and a great number of experiments are needed to evaluate the results for different times of year.

With artificial skies, the procedure is costlier, but the fact of working in a laboratory allows greater input control. Various types of devices can be used with these methods;

mirror chambers can easily render overcast sky conditions, shading tables make it possible to study the effects of direct sunlight cheaply, and finally, the more expensive hemispheric sky simulator can make a global reproduction of the natural sky in any circumstance (Fig. 41).

Nevertheless, it should be borne in mind that evaluation systems, whether they be manual, computer-assisted or using scale models, are no substitute for a sound approach to the project, and this depends above all on the attitude of the designer, which should be based on a good understanding of the physical and physiological principles of light and vision.

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Chapter 7—Ventilation

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1. Introduction

1.1. *Historical background*

Building ventilation is necessary for supporting life by maintaining acceptable levels of oxygen in the air, to prevent carbon dioxide (CO₂) from rising to unacceptably high concentrations and to remove odour, moisture and pollution produced internally. Although CO₂ is not considered a harmful gas, nevertheless a high CO₂ concentration (e.g. above 5000 ppm) is synonymous with deficient oxygen levels in the air.

In the past, ventilation has been applied to buildings to remove excess heat in hot climates. In the Middle East wind towers were developed during the first millennium to scoop the cool wind into the building, which was sometimes made to pass over water cisterns to produce evaporative cooling and a feeling of freshness. In temperature climates, such as in Middle and Northern Europe, ventilation was mainly used to remove smoke produced by hearths, rather than to provide fresh air for breathing [1]. In the 18th and 19th centuries ventilation of particularly small dwellings became a social problem in Europe and, consequently, scholars and medical professionals started to assess the need for providing fresh air to buildings in terms of quantity and methodology. Until Pettenkofer in Germany showed in 1862 that CO₂ is harmless, it was always perceived as the cause of ‘bad air’. In England, Barker [1] advocated 1000 ppm of CO₂ as an appropriate concentration which was thought to be sufficient to render odour unnoticeable. This corresponds to a fresh air supply rate of about 7 l s⁻¹ per person.

The concentration of CO₂ was considered by many as the criterion for admitting fresh air into a building. However, some have doubted the suitability of CO₂ concentration as an index of air quality. More recently, research has shown [2] that, in modern buildings, other pollutants can be more important in terms of quantities produced and their impact on human health.

Over the years, ventilation guides have revised the recommended fresh air supply

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rates to building occupants. Figure 1 [3] shows the changes in recommended fresh air rates in the USA during the last 160 years. If anything, this figure shows our lack of knowledge, even today, of the optimum fresh air rate that a designer is required to provide a building with. This is partly due to design changes, technological development, changes in lifestyle and also to the relative cost of energy during any one period of time when these ventilation rates were specified.

More recently, the identification of Sick Buildings (SB) and the coining of the phrase Sick Building Syndrome (SBS) has again focused attention to the method used in ventilating a building, i.e. whether air-conditioning or natural ventilation should be used, as well as the quantities of fresh air supplied to a building. Some studies [4] have found a link between the occurrence of SBS and ventilation although other factors were also found to have an influence. It is suggested that lack of fresh air is a contributory factor but not necessarily the main cause of SBS. So we now find ourselves, as was the case throughout the last three centuries, in a position where we know that ventilation is a necessity but we are not sure about what a building, or an occupant, requires for health and comfort. We do not claim that an answer to this question will be found in this chapter, but the intention here is to discuss the problems involved and provide the means to quantify ventilation rates that meet certain usage and requirements of buildings and their occupants.

1.2. *What is ventilation?*

In the last two decades, ventilation and energy conservation have been the main themes of building system design. Ventilation has become a science among building

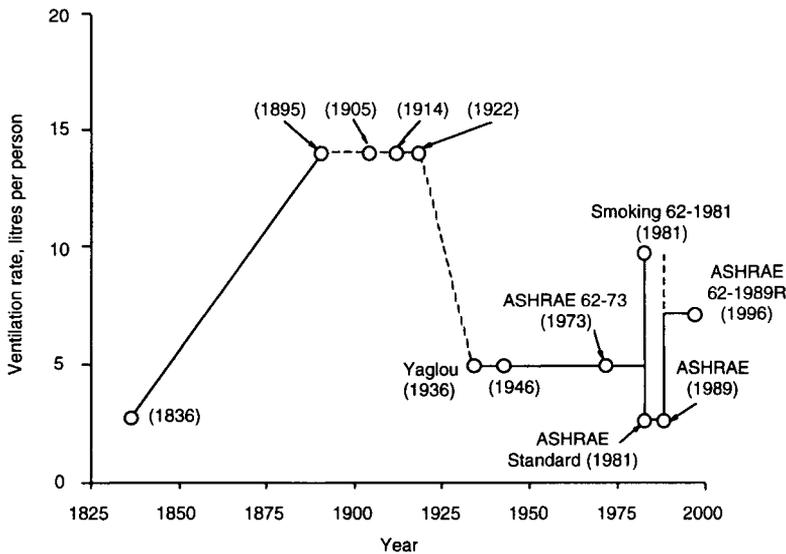


Fig. 1. Changes in the minimum ventilation rates in the USA.

system designers, scientists and engineers, who are concerned with the well being of the building occupants. Major international conferences which are dedicated to this topic, e.g. Roomvent, Indoor Air, Healthy Buildings etc., have been held periodically over the last two decades.

As a result of the increasing interest in the subject, new concepts have emerged covering wide aspects of ventilation. It is not sufficient now just to assume that ventilation air can be introduced from any convenient opening in a room at a rate taken from some design guide because there are many parameters which can influence the perceived air quality indoors. For example, the method of air distribution is so important in influencing not only the air quality in the occupied zone but also the cooling or heating energy requirement for the space. New terms such as ventilation effectiveness, ventilation efficiency, air quality index, age of air, etc., have all become important indices for assessing the ventilation process [5]. It is no longer sufficient just to specify $X \text{ l s}^{-1}$ of fresh air to the space, as this will have little meaning unless it is assessed in the context of these ventilation indices. So, nowadays we consider ventilation as the process of providing fresh air to the building occupants, rather than the buildings themselves, in order to sustain a good standard air quality with minimum capital cost and environmental impact. The need for ventilation is still the same as it has been over many decades, namely to provide oxygen for breathing and removing the internally produced pollution. What is changing, however, is the means of achieving this need.

1.3. *Ventilation requirements*

As mentioned earlier, ventilation is required for breathing and the removal of internally produced pollution. Before a ventilation rate can be specified, it is first necessary to estimate the rate of production of all known pollutants, viz. body bioeffluents, carbon dioxide, tobacco smoke, volatile organic compounds (VOCs), ozone, particulates, radon, water vapour, etc. Because it is not known how the aggregate of all such pollutants affect the air quality, these are normally considered separately, i.e. a ventilation rate is estimated for each known pollutant and the largest value is used for design purposes. If the air is to be heated or cooled, then it may be necessary to recirculate some of the room air but this component is excluded from the ventilation rate because it is already polluted. The pollution concentration levels that can be tolerated in buildings are found in guides and standards, such as ASHRAE Standard 62-1989R [6] and the UK Health and Safety Executive (HSE) guidelines [7]. HSE specifies two exposure limits: the long term exposure limit (LTEL) and the short term exposure limit (STEL) for dealing with different exposure periods to various pollutants.

Another factor which is often ignored but is very important in determining ventilation rates is the ventilation effectiveness (ϵ_v) which is defined as:

$$\epsilon_v = (c_o - c_i)/(c - c_i) \times 100(\%) \quad (1)$$

where

c_i = pollution concentration in the supply air, ppm or mg m^{-3}

c_o = pollution concentration in the exhaust air, ppm or mg m^{-3}

c = mean pollution concentration in the occupied zone, ppm or mg m^{-3} .

The value of ε_v depends on the ventilation strategy used, i.e. location of air supply and extract openings, the momentum and turbulence of the supply air and the room heat load and its distribution. Values of ε_v can only be obtained by measurements or simulation of the air movement using computational fluid dynamics (CFD), or may be found in handbooks or guidelines for certain air distribution strategies. As an example, a typical value of ε_v for high level mixing ventilation might be around 70%, whereas for floor displacement ventilation it is somewhere in the region of 120%. Hence, theoretically at least, based on these values a displacement system should require only about 58% of the ventilation rate of a high level system. Further information on air distribution in rooms is given in Section 7 and ref [8].

2. Indoor pollutants

There are many pollutants present in room air at any one time, some of which exist at such low concentrations that they are considered harmless to the occupants, whereas others can be at high concentrations. An estimation of the main pollutants is necessary to calculate fresh air rates. It is not possible in this chapter to describe all known internal pollutants and, therefore, only some of the most common pollutants which are known to be present in room air are described.

2.1. Odour

Odour is a bioeffluent associated with occupancy, cooking, bathroom activities and waste. Although the experience of odour is not pleasant, it does not normally affect health. Body odour is emitted by sweat and sebaceous secretion through the skin and by the digestive system. The results of the tests which were carried out by Yaglou et al. [9] on people in a ventilated test chamber some 60 years ago are still in use today. Yaglou's work showed that the air supply rate is dependent on the occupation density of the space in m^3 per person, i.e. as the volume increases the air supply rate required to achieve an acceptable odour intensity is reduced. However, more recent research by different investigators has failed to find a correlation between room volume and the required fresh air rate.

It is generally accepted that a minimum fresh air rate of 3 l s^{-1} per person will be required to dilute body odour [6]. This is in addition to the ventilation rates required to dilute pollution from buildings, their contents and any HVAC system that may contribute to indoor pollution.

2.2. Carbon dioxide

The main source of CO_2 indoors is the building occupants. The rate of production of CO_2 by respiration is directly proportional to the metabolic rate through the relationship:

$$G = 4 \times 10^{-5} M A$$

where

G = CO_2 production rate, $l s^{-1}$

M = metabolic rate, $W m^{-2}$

A = body surface area, m^2

An average sedentary adult produces about 5 ml s^{-1} (18 h^{-1}) of CO_2 by respiration.

Most ventilation standards recommend that the CO_2 concentration should not exceed 0.5%, or 5000 ppm. However, more recent studies have indicated that this limit is far too high for human comfort. At this concentration, the occupants can experience headaches and lethargy and 1000 ppm is now widely accepted as a limit for comfort. Using eqn (2), it is possible to estimate ventilation rates based on CO_2 emission if one assumes that an average outdoor CO_2 concentration is about 400 ppm which could vary depending on whether the building is an urban, suburban, or rural location.

2.3. Tobacco smoke

The risk to health from tobacco smoke is widely publicized and the odour from smoke constitutes irritants to the eyes and the nasal passages, such as acrolein, tar, nicotine and carbon monoxide. British Standard 5925 [10] recommends 8, 16, 24 and 36 l s^{-1} per person of fresh air for rooms with no smoking, some smoking, heavy smoking and very heavy smoking respectively. Because of the additional flow rate required, an estimate of the smoking population should be made at the design stage. For this purpose, statistical data on the smoking population in the country should be used where available.

2.4. Formaldehyde

Formaldehyde (HCHO) is a chemical that is commonly used in the manufacture of building materials, furnishing, cosmetics, toiletries, food packaging, etc. The inexpensive urea-formaldehyde (UF) resin is the most commonly used adhesive in the production of plywood, wood chipboard, hardboard, plaster board and as a binder in the production of fiberglass insulation. Formaldehyde polymers are also used in the manufacture of wallpapers, carpets and textiles. Unvented combustion appliances are also a source of formaldehyde indoors and so is tobacco smoke.

Formaldehyde can enter the body through inhalations, ingestion or adsorption. It is a strong irritant and genotoxic, i.e. once in the body formaldehyde rapidly reacts with tissues containing hydrogen and damages them. Although not conclusive, there is a belief that formaldehyde poses a carcinogenic risk to humans.

The emission rate of formaldehyde in buildings depends, among other things, on the age of the material. Peak emission rates are produced by new products due to the presence of free formaldehyde molecules. For a formaldehyde source of a given age, the emission rate to room air depends on the area of emitting surface, total air volume,

Table 1
Typical formaldehyde emission rate

Material	Emission rate ($\text{mg h}^{-1} \text{m}^{-2}$)
Woodchip boards	0.46–1.69
Compressed cellulose boards (e.g. hardboard)	0.17–0.51
Plasterboards	0–0.13
Wallpaper	0–0.28
Carpets	0
Curtains	0

air change rate and other parameters, such as temperature and humidity. The steady state unsuppressed emission is expressed by:

$$C = AE/(\rho NV)$$

where

C = formaldehyde concentration, ppm

A = area of emitting surface, m^2

E = net emission rate from surface, $\text{mg m}^{-2} \text{h}^{-1}$

ρ = density of air, kg m^{-3}

N = air change rate, h^{-1}

V = room air volume, m^3

If the emission is suppressed, such as for very low air change rates, then the formaldehyde concentration in room air will increase and the emission rate will continuously decrease until it falls to zero at zero air change rate. Typical formaldehyde emission rates from common building materials and furnishings are given in Table 1.

Most current ventilation guides and standards recommend a maximum exposure limit to formaldehyde of about 0.1 ppm. Even though this conception has been found to be excessive for individuals who are sensitive or sensitizable, this limit has been found to be exceeded for several type of dwellings, particularly those insulated with UF foam insulation.

2.5. Ozone

Ozone (O_3) is naturally present in outdoor air, but its concentration is dependent on altitude and climate. It is also produced indoors by electrostatic appliances and office machines, such as photocopiers and laser printers. It has the potential for adverse acute and chronic effects on humans if present in high concentrations. The World Health Organisation (WHO) recommends a maximum concentration of $100 \mu\text{g m}^{-3}$ (50 ppb) for an 8 h exposure and ASHRAE Standard 62-1989 R [6] suggests $235 \mu\text{g m}^{-3}$ (120 ppb) for a short term exposure of 1 h.

Table 2
Classification of VOC exposure-effects [11]

Concentration range ($\mu\text{g m}^{-3}$)	Description
< 200	Comfort range
200–3000	Multifactorial exposure range
3000–25,000	Discomfort range
> 25,000	Toxic range

2.6. Volatile organic compounds (VOCs)

Volatile organic compounds (VOCs) are produced indoors from a variety of sources. There is, however, no clear definition of the classes of VOCs present in indoor air, though researchers define these as compounds having boiling points between 50 and 260°C. Although formaldehyde is considered a VOC it is usually dealt with separately because it requires different measuring techniques than those used for most other VOCs. In indoor air measurements VOCs are often reported as total volatile organic compounds (TVOCs). These are usually given as the sum of the concentrations of the individual VOCs. Research on the health effects of VOC is relatively new and there is little information available on the long term exposure to most known VOCs. There are, however, some exceptions such as formaldehyde whose health effects are better understood. In most buildings the concentration of VOCs is not sufficiently large to be able to establish their health risk. Field studies in some European countries did not find a positive correlation between measured indoor air TVOC concentrations and sick buildings syndrome (SBS) prevalence. There are, therefore, no established LTEL or STEL limits for TVOC in indoor air, although Molhave [11] conducted laboratory studies of the responses of human subjects exposed to controlled concentrations of 22 VOCs mixture. As a result of these studies we may be able to classify the exposure effect of VOCs as shown in Table 2. However, the concentrations in most buildings are usually much lower than those given in the table.

2.7. Radon

Radon is a radioactive gas which is present in small amounts in the earth's upper crust. The gas itself is harmless but for the alpha particles emitted by short lived decay 'daughters'. These particles normally have small penetration depths and they only form a health risk if inhaled; damage to the lining of the lungs could occur posing the risk of cancer.

The concentration of radon in the atmosphere is measured in picocuries per litre (pCi l^{-1}) or becquerels per m^3 (Bq m^{-3}), where $1 \text{ pCi l}^{-1} = 37 \text{ Bq m}^{-3}$. The concentration of radon daughters is measured in terms of the working limit (WL) which is the equivalent to alpha particle emission of $1.3 \times 10^5 \text{ MeV per l}$, i.e. $1 \text{ WL} = 100 \text{ pCi l}^{-1}$.

The concentration levels of radon in buildings depends on the geological history of the site, hence there is a wide variation in concentration levels even in one country. Unless high concentrations of radon is known to exist in the locality of a building, no special treatment is needed. In high risk areas the most effective way of reducing radon concentration indoors is by extracting air from underneath the ground floor of the building. A radon concentration value of 0.01 WL is usually used as a limit for calculating ventilation rates.

2.8. *Particulates*

Particulates suspended in air (aerosols) form a major source of indoor air pollution. Depending on their size and room air movement, aerosols can deposit on a surface within minutes or remain airborne for weeks. The constituent of aerosols can be dust, dander, fibrous, pollen, fungi, moulds, mites, bacterial, viruses, etc. Dust particles smaller than about $0.5\mu\text{m}$ can accumulate in the lung lining, causing blockages to the respiratory tubes. Biogenic particles can transmit disease or allergy. The most effective way of reducing the concentration of aerosols is by air filtration.

2.9. *Water vapour*

Water vapour exists in outdoor air and is also produced in buildings by occupants activities and certain processes. Water vapour itself does not represent a health risk. Recent research has shown that the lower the humidity is the better the perceived indoor air quality becomes. However, it is generally believed that low humidity levels contribute towards increased risk of infection of the respiratory tract and high humidity levels can cause discomfort, due to the inhibition of sweat. Furthermore, certain types of buildings require precise control of humidity to sustain its content or the processes being carried out. It is, therefore, necessary in some buildings to control the humidity of the air by means of an HVAC system.

3. **Ventilation strategies**

3.1. *Ventilation rates*

The ventilation rate required for a given room or a building is determined to satisfy both health and comfort criteria. The health criterion should take into consideration the exposure of the occupants to indoor pollutants which will involve the identification of the pollutants, their sources, source strengths and a knowledge of the short term exposure limit (STEL) or long term exposure limit (LTEL) for the pollutants. These limits are used to estimate the ventilation rate required to obtain the pollutant concentration that can be tolerated. Where the location of the pollution sources can be identified, the preferred approach would be for the removal of such pollutants at source.

The comfort criterion, however, will produce ventilation rates that can minimise

the effect of odour and sensory irritants from occupants' bioeffluents, occupants' activities and pollutants emitted from the building, the building systems and furnishings. This is usually used in domestic buildings, office buildings, public buildings, etc. and the health criterion is applied to industrial buildings. Despite their different chemical composition and sensory effects, studies have shown that pollutants can have additive impact called 'agonism' both in terms of smell and irritation. However, details of how agonism can be assessed are not available and as an approximation it is suggested that all source strengths (due to people and buildings) be added for the calculation of a design ventilation rate.

ASHRAE Standard 62-1989R gives two methods of determining ventilation rates: the prescriptive procedure and the analytical procedure. In the prescriptive procedure, tables of ventilation rates required to dilute the pollution produced by people and buildings are given for different types of buildings. In the analytical procedure, the ventilation rates are calculated using data for pollution sources and the effectiveness of the ventilation system. Details of these two procedures are given in ref. [6].

The European CEN pre-standard pr ENV 1752 [12] proposes the use of three categories A, B, C of buildings and recommends a ventilation rate accordingly. An air supply rate of 10 l s^{-1} per person which corresponds to 15% of the occupants predicted dissatisfied (PD) for category A; 7 l s^{-1} per person which corresponds to 20% PD for category B; and 4 l s^{-1} per person for a category C building which corresponds to 30% PD.

The expression below can be used to calculate the ventilation rate, Q , required to maintain the concentration of a particular pollutant within a desired value:

$$Q = G / \{\varepsilon_v(c_i - c_o)\} \times 10^6 \text{ m}^3 \text{ s}^{-1} \quad (2)$$

where

- G = pollutant generation rate, $\text{m}^3 \text{ s}^{-1}$ or kg s^{-1}
- c_i = indoor concentration that can be tolerated, ppm or mg kg^{-1}
- c_o = outdoor concentration of the pollutant, ppm or mg kg^{-1}
- ε_v = effectiveness of ventilation system.

3.2. Energy implications of ventilation

In modern and retrofit buildings, ventilation is probably the greatest component of the total energy consumption. This is usually in the range of 30–60% of the building energy consumption. The large proportion of ventilation energy is due to three main reasons. Firstly, modern buildings are generally well insulated and, therefore, the heat gain or loss through the fabric is low. Secondly, modern building materials and furnishings emit large amounts of VOCs and TVOCs and so it becomes necessary to dilute their concentration by supplying greater ventilation rates to these buildings. The third cause is as a result of the recent concern regarding the sick building syndrome and other building related illnesses which have influenced HVAC designers to improve the indoor air quality by specifying greater quantities of fresh air supply.

As a result of these factors, the contribution of energy required for heating or cooling ventilation air to the total energy consumption for the building has increased.

There are, however, practical means of reducing the ventilating air energy requirement, some of which are briefly described below.

3.2.1. *Room temperature*

Both ventilating air and fabric energy consumption can be reduced if the set point temperature in the building is reduced during the heating season and increased during the cooling season. For the UK climate, it has been estimated that a reduction of 1 K in internal temperature from that recommended by ISO 7730 [13] will reduce the energy consumption by 6% [14]. Similar reductions have been estimated for Finland [15]. Field studies of thermal comfort have shown that up to 2.4 K reduction in indoor temperature from that specified in comfort standards can be tolerated by the building occupants without adverse effects on comfort. This is due to the fact that current standards, e.g. ISO 7730 [13] and ASHRAE Standard 55 [16], recommend indoor temperatures which are based on laboratory studies but, in real buildings, clothing habits and activity levels are known to be different from those under ideal test conditions.

3.2.2. *Ventilation system balancing*

Improper balancing of mechanical ventilation systems can result in increased fresh air rates to some zones and a reduction in others. This could not only cause discomfort due to draught in over ventilated zones and poor air quality in under ventilated zones, but could also increase the ventilation energy consumption. It is, therefore, important to check the actual delivery of fresh air to different zones of the building during commissioning and routine maintenance to ensure optimum operation of the ventilation system. Another source of energy wastage is leakage from ventilation ducts. This can also be reduced by specifying better ducts and exercising quality control during installation.

3.2.3. *Heat recovery*

In mechanically ventilated buildings, heat recovery from ventilation air is the single most important means of reducing ventilation energy consumption. Many different types of heat recovery systems are available for transferring energy from the exhaust air to the supply air or vice versa. The most commonly used systems are the regenerative type (thermal wheel), plate heat exchanger and the run-around-coil. Heat recovery of up to 70% can be achieved depending on the system used and the enthalpy or temperature difference between supply and exhaust air.

3.2.4. *Demand controlled ventilation*

Demand controlled ventilation (DCV) is a method of controlling fresh air supply to a room according to the pollution load present in the room. Although there are many pollutants that could be produced in a room due to building materials, furnishing, equipment and people's activities, it is impractical to use all these different pollutants to control the amount of fresh air supply to the room. Usually the concentration in

the room of a few types of pollutants are controlled by the DCV system. These are carbon dioxide (CO₂), TVOCs, smoke and moisture, but for most buildings the CO₂ concentration in the room is used to control the quantity of fresh air supply using CO₂ sensors which control the fresh air dampers. By controlling the fresh air supply to achieve a maximum allowable CO₂ concentration (e.g. 1000 ppm), it would be possible to reduce the ventilation rate during low or no occupancy, thus saving energy.

Although considerable amounts of research results on DCV have been accumulated, there is still a lack of experience in the installation and operation of DCV systems. Another drawback of DCV is the fact that usually only one source of pollutant (CO₂) is used for controlling fresh air rate but in normal buildings there is usually a combination of pollutants produced at different rates depending on the activities within the buildings.

3.2.5. *User control ventilation*

When designing a conventional heating and ventilation system, the energy and the air change rate requirements are normally based respectively on a heat and pollution concentration balance over the whole space for a 'typical' day. However, there is evidence to suggest that the neutral or comfort temperature for occupants can vary substantially within the same building depending on clothing and activity of the occupants. Therefore, maintaining a whole building at the same temperature and the same fresh air supply rate can be energy wasteful. A substantial saving in energy may be achieved by individual and automatic control of the local environment by providing personalized or task-conditioning systems which can be controlled by a single user according to his or her needs. Although the capital cost of such systems is currently higher than conventional systems, this may be outweighed by the improved comfort and increased productivity of the occupants, in addition to energy saving for heating, cooling and ventilation.

4. Air flow principles

4.1. *Fluid forces*

A fluid particle in motion obeys the same laws of mechanics as a solid body, i.e. the force acting on the particle can be predicted from Newton's law of motion. Hence, the inertia force F_i acting on a moving particle is given by:

$$F_i = m \partial v / \partial t$$

where m is the mass of particle (kg), v is the velocity (m s⁻¹) and t is the time (s). In addition to inertia forces, fluids in motion also experience viscous forces due to the viscosity of the fluid. The shear stress τ is given by Newton's law of viscosity, which is:

$$\tau = \mu \partial v / \partial y$$

where μ is the dynamic (absolute) viscosity of the fluid (Pa s^{-1}) and y is the distance normal to the flow direction. The shear force (F_s) is:

$$F_s = A\tau = \mu A \partial v / \partial y$$

In a moving fluid, both of the forces F_i and F_s are significant to different degrees. The ratio F_i/F_s is a non-dimensional number called the Reynolds number, viz:

$$Re = \rho v y / \mu \quad (3)$$

where ρ is the fluid density (kg m^{-3}). For small values of Re the viscous forces are dominant which restrict the movement of the fluid particles to follow the main flow direction, such a flow is called laminar flow. As Re increases, however, the inertia forces acting on the fluid particles dominate the weak shear forces and the flow is said to be turbulent. The transition between laminar to turbulent flow is identified by the value of Re corresponding to the nature of flow and geometry of the object if present in the flow. In practice, for flow in a smooth straight pipe an $Re \leq 2000$ usually suggests laminar flow but for a higher Re a transition range is usually defined followed by a fully turbulent flow for $Re > 4000$.

The momentum of a fluid particle is:

$$M = mv$$

If there were a change in momentum (or velocity) of the moving particle, then the force which causes this change is given by:

$$F = \partial M / \partial t = \partial(mv) / \partial t = \dot{m} \partial v$$

where \dot{m} is the mass flow rate (kg s^{-1}). This equation shows that the force is the rate of change of momentum with respect to time.

4.2. Continuity of flow

In the absence of nuclear processes, matter is conserved. In fluid flow, the law of conservation of mass means that:

$$\begin{aligned} &\text{mass of fluid entering a control volume per unit time} \\ &= \text{mass of fluid leaving a control volume per unit time} \\ &+ \text{change in the mass of fluid in the control volume per unit time} \end{aligned}$$

i.e.

$$(\partial m / \partial t)_{\text{in}} = (\partial m / \partial t)_{\text{out}} + V \partial \rho / \partial t$$

where V is the control volume (m^3) and ρ is the fluid density.

For incompressible flow, i.e. when changes in fluid density are small, which is the case for air flow in buildings, the flow continuity gives:

$$\dot{m} = \rho_1 v_1 A_1 = \rho_2 v_2 A_2$$

and since $\rho_1 = \rho_2$ for incompressible flow, then:

$$Q = v_1 A_1 = v_2 A_2 \quad (4)$$

where \dot{m} is the mass flow rate (kg s^{-1}), Q is the volume flow rate ($\text{m}^3 \text{s}^{-1}$), v_1 and v_2 are the inlet and outlet velocities (m s^{-1}) and A_1 and A_2 are the inlet and outlet areas normal to the velocity direction (m^2).

4.3. Pressure

Pressure is the normal force exerted by a fluid per unit area. At any point in the fluid the component of pressure in any direction is constant, which is the static pressure of the fluid at that point. Since a fluid has a density, the pressure within a static column of a fluid will increase with depth due to gravity acting on the mass of fluid in the column. The variation in static pressure, p_y , vertically is given by:

$$\delta p_y = -\rho g \delta y \quad (5)$$

Hence, the difference in static pressure between two horizontal planes at positions y_1 and y_2 is:

$$p_2 - p_1 = -\rho g (y_2 - y_1)$$

Hence, the static pressure at any horizontal plane (p_y) is:

$$p_y = p_o - y \partial p / \partial y$$

where p_o is the static pressure at a reference plane, y is the vertical distance above the reference plane.

For a constant increase in temperature with height $\partial T / \partial y$, i.e.

$$T = T_o - y \delta T$$

where T_o (K) is the temperature at a reference point, T is the temperature at a height y measured above the reference point and δT is the increase in temperature per m (K m^{-1}), there will be a corresponding decrease in pressure. Using eqn (5) and the gas law $p = \rho RT$, the vertical variation in pressure due to a uniform increase in temperature becomes:

$$\partial p / \partial y = -\rho_o g T_o / T \quad (6)$$

where ρ_o is the fluid density at a reference temperature T_o . The pressure difference between two vertical points 1 and 2 at temperatures T_1 and T_2 separated vertically by a distance y is given by:

$$p_2 - p_1 = \rho_o g T_o y [1/T_2 - 1/T_1] \quad (7)$$

The pressure in a moving fluid has a static component and a kinematic component, i.e. the total pressure p_t of a moving fluid particle is:

$$p_t = p + p_s$$

where p_s is the static pressure and p is the kinematic (velocity) pressure which is $1/2 \rho v^2$. The total pressure of a moving fluid can be measured using a pitot tube with the

static pressure measured using a static pressure tap with the opening parallel to the flow direction.

4.4. Bernoulli's equation

The energy balance of a fluid flow without a change in temperature (isothermal) is represented by Bernoulli's equation, viz:

$$p_1 + 1/2\rho_1v_1^2 + \rho_1gy_1 + \Delta p_{in} = p_2 + 1/2\rho_2v_2^2 + \rho_2gy_2 + \Delta p_f \quad (8)$$

where

p_1 and p_2 are the static pressure at inlet and outlet, Pa

v_1 and v_2 are the velocities at inlet and outlet, $m\ s^{-1}$

ρ_1 and ρ_2 are the fluid densities at inlet and outlet, $kg\ m^{-3}$

y_1 and y_2 are the heights of inlet and outlet from a datum, m

Δp_{in} is the pressure rise due to a fan or a pump, Pa; and

Δp_f is the pressure loss in the system due to friction and flow separation, Pa.

5. Building air leakage and natural ventilation

5.1. Flow characteristics of openings

The air flow openings in buildings are of two types: adventitious openings and ventilation openings. Adventitious openings are present in every building to a different degree depending on the method of construction and installation of services. They range from gaps at wall/ceiling and wall/floor joints to openings associated with electric, water, gas services, etc. Operable building components such as doors and windows can also allow air penetration through interfaces and gaps. Ventilation openings are purposely installed to provide air supply or extract through the building, such as openable windows, air vents and stacks.

The flow through small openings, such as cracks and joints, is either laminar or transitional and that through large openings, such as ventilation openings, is usually turbulent.

For very small openings where the flow is laminar, the pressure drop is represented by the Couette flow equation, viz:

$$\Delta p = 12\mu LQ/(bh^3) \quad (9)$$

where

L is the depth of openings in flow direction, m

Q is the flow rate through the opening, $m^3\ s^{-1}$

b is the width of opening, m

L is the height of opening, m; and

μ is the dynamic viscosity, Pa s

If the flow is transitional, i.e. neither fully laminar nor fully turbulent, the following power law equation can be used:

$$\Delta p = [Q/(kL)]^{1/n} \quad (10)$$

where

k is a flow coefficient, which is dependent on the geometry of the opening, $\text{m}^3 \text{s}^{-1} \text{m}^{-1} \text{Pa}^{-1}$

L is the length of opening, m; and

n is a flow exponent dependent on the flow regime.

For a laminar flow $n = 1$, for a turbulent flow $n = 0.5$ and for a transitional flow n is usually between 0.6 and 0.7.

For turbulent flow through large openings, the pressure drop is given by the following equation:

$$\Delta p = 0.5[Q/C_d A]^2 \quad (11)$$

where A is the physical area of the opening and C_d is the discharge coefficient which depends on the sharpness of the opening and the Reynolds number, Re . For a sharp opening $C_d \approx 0.6$, which is independent of Re .

5.2. Wind and buoyancy pressures

5.2.1. Wind pressure

The time-mean pressure due to wind flow on to or away from a surface is given by:

$$p_w = 0.5C_p \rho v^2 \quad (12)$$

where

C_p = static pressure coefficient with reference to the static pressure upstream of the opening

v = time-mean wind speed at datum level (usually height of building or opening), m s^{-1}

ρ = air density, kg m^{-3} .

C_p is usually obtained from wind tunnel measurements using a scaled model of the building or using CFD. It can have a positive (e.g. windward face) or a negative (leeward face) value.

The wind speed is a temporal and a spatial varying quantity as a result of wind turbulence and the effect of natural or man made obstructions. For a given location and at a given instant the wind speed increases with height above ground where it is essentially zero. The wind speed profile is usually expressed by:

$$v/v_r = cH^a \quad (13)$$

where

v = time-mean speed at height H above the ground, m s^{-1}

Table 3
Terrain factors

Terrain	c	a
Open flat country	0.68	0.17
Country with scattered wind breaks	0.52	0.20
Urban	0.35	0.25
City	0.21	0.33

v_r = time-mean wind speed measured at a weather station normally at a height of 10 m above the ground, m s^{-1} ; and

c and a are factors which depend on the terrain.

Values of c and a are given in Table 3.

Values of v_r which represent hourly mean wind speeds which are not exceeded 50% of the time can be usually obtained from a local weather station or from wind contour maps for the country.

5.2.2. Stack pressure

Using eqn (7), the stack pressure difference between two vertical openings separated by a vertical distance h becomes:

$$p_s = \rho_a g T_o h [1/T_e - 1/T_i] \quad (14)$$

where

T_e = external air temperature, K

T_i = internal air temperature, K.

5.3. Flow through openings

To estimate the amount of air flow through an opening, it is necessary to know the pressure difference across the opening and its effective flow area. The pressure at an opening can be due to wind, as well as buoyancy and it is, therefore, determined by the location of the opening in the building, as well as the internal and external environmental parameters such as wind velocity, wind turbulence and inside and outside air temperatures. The buoyancy pressure is given by eqn (14). However, the wind pressure is usually a fluctuating force which induces time-mean flow through an opening and a fluctuating (pulsating) flow through it. These two components are normally treated separately because they require different methods of calculation. The time-mean flow through an opening due to wind or buoyancy is given by either eqn (10) or (11) depending on the type of opening. Usually, eqn (10) is used for small adventitious openings and eqn (11) is used for ventilation openings. In both equations time-mean pressure differences across the opening due to buoyancy and wind is required.

Alternatively, a quadratic summation of the flow rate due to wind and buoyancy may be made using:

$$Q_t = \{Q_w^{1/n} + Q_s^{1/n}\}^n$$

where n has a value of $2/3$ for cracks and $1/2$ for large openings.

For a fluctuating wind pressure the resulting flow through an opening can be very complex, where inflow and outflow can occur either simultaneously or alternately depending on wind turbulence, opening geometry and internal pressure. The physics of this flow are explained in Etheridge and Sandberg [5] and the effect of a pulsating flow through windows is discussed in Section 5.4.

For ventilation (large) openings the total flow rate Q_t taking into consideration wind, buoyancy and mechanical ventilation due to a fan can be calculated using:

$$Q_t = \{Q_w^2 + Q_s^2 + Q_{mu}^2\}^{1/2} \tag{15}$$

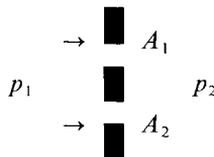
where Q_w , Q_s and Q_{mu} refer to the flow rate due to wind, stack and unbalanced mechanical ventilation (i.e. supply or extract fan).

If there is more than one opening through which air is flowing, then the effective flow area will depend on the position of the openings in the flow direction. If the openings are on one surface which is exposed to the same pressure then the effective area of the openings is given by:

$$A_{eff} = A_1 + A_2 + A_3 + \dots \tag{16}$$

and the pressure difference across each opening is

$$\Delta p = p_1 - p_2 \tag{17}$$

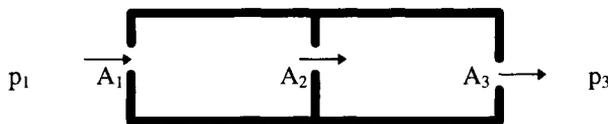


On the other hand, if the flow openings are in series, see figure below, the effective area is obtained using:

$$1/A_{eff}^2 = 1/A_1^2 + 1/A_2^2 + 1/A_3^2 + \dots \tag{18}$$

and

$$\Delta p = p_1 - p_3 \tag{19}$$



The flow rate through multi-openings can be calculated by substituting eqns (16–19) into eqns (9), (10) or (11), depending on the flow regime.

5.4. Single sided ventilation

The air flow through a large single ventilation opening, such as a window, in a room which is otherwise air tight is bi-directional. The effect of buoyancy is such that cooler air enters at the lower part and warm air leaves at the upper part of the opening. The wind pressure has a mean and a fluctuating component due to turbulence. For a large opening, both the mean and the fluctuating pressure components may not be uniform over the opening. A further complication is the effect of compressibility of room air. An analytical solution of this problem is not yet available. However, air change measurements for flow through open windows carried out by de Gids and Phaff [17] on site for various wind speeds, produced the following empirical expression for the effective velocity, v_{eff} :

$$v_{\text{eff}} = \{c_1 v_r^2 + c_2 H \Delta T + c_3\}^{1/2} \quad (20)$$

where

c_1 = dimensionless coefficient depending on the window opening ≈ 0.001

c_2 = buoyancy constant ≈ 0.0035

c_3 = wind turbulence constant ≈ 0.01

v_r = mean wind speed for the site measured by a weather station, m s^{-1}

H = height of opening, m

T = mean temperature difference between inside and outside = $T_i - T_o$, K

The flow rate through the opening is:

$$Q = 0.5 A v_{\text{eff}} \quad (21)$$

where

A = effective area of open window, m^2 .

For a single-sided ventilation BRE Digest 399 [18] recommends a window area of about 1/20 flow area and maximum room depth of 2.5 times the ceiling height, Fig. 2.

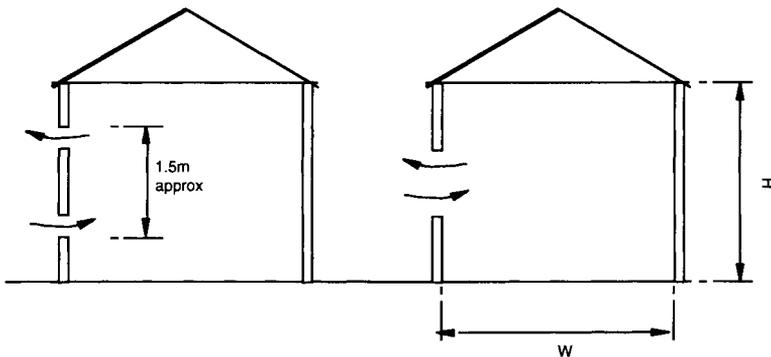


Fig. 2. Single-sided ventilation.

5.5. Cross ventilation

Two-sided or cross ventilation occurs when air enters the room or building from one or more openings on one side and room air leaves through one or more openings on another side of the room or building. The flow of air in this case is due to wind and buoyancy pressures. The types of openings that are used for cross ventilation can be small openings such as trickle vents and grilles, or large openings such as windows and doors. Because the air flow ‘sweep’ the room from one side to the opposite side, it has a deep penetration. This method is, therefore, more suitable for ventilating deep rooms. The position of openings should be such that some are placed on the windward facade of the building and others placed on the leeward facade so that a good wind pressure difference is maintained across the inflow and outflow openings. Internal partitions and other obstructions can affect or disturb the airflow pattern in the room and the air penetration depth.

The air flow rate due to cross ventilation may be estimated using eqn (11). The pressure difference across the opposite openings Δp is calculated for the combined effect of wind and buoyancy. The effective area in eqn (11) is calculated using eqn (18) and the discharge coefficient C_d depends on the type of opening. If no value for C_d is given for the opening, a value of 0.65 for a sharp-edge orifice should be used.

For cross ventilation BRE Digest 399 [18] recommends a maximum room depth of 5 times ceiling heights in a room with few obstructions, Fig. 3.

5.6. Stack ventilation

Buildings which require ventilation rates greater than those achievable using either single-sided or cross ventilation may be ventilated using stacks. In this case, buoyancy is the main driving force and, therefore, the height of the stack becomes significant. The stack pressure which will be determined by the difference between the internal and external temperature and the height of stack, is given by eqn (14).

Depending on the position of air inlet and outlet in the building, the wind pressure

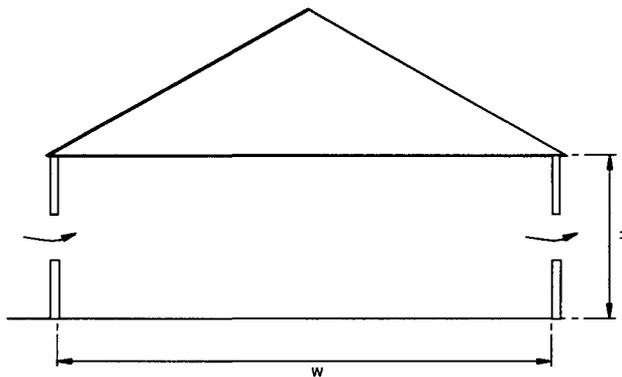


Fig. 3. Cross ventilation.

could assist the stack pressure, reduce its influence or indeed reverse the effect, i.e. by forcing the air through the outlet. Therefore, careful considerations are needed when stacks are incorporated in the building design to avoid these adverse effects occurring. This usually requires either a wind tunnel investigation of a scaled model of the building and the stack or CFD analysis of the flow around and within the building. The effect of buoyancy cannot be modeled in a wind tunnel but it can be taken into account in a CFD simulation of the air flow.

In buildings which have atria attachments, the stack is most conveniently incorporated with the atrium for two main reasons. Firstly, the solar gain in the atrium causes an elevation of the air temperature and hence there will be more effective stack flow. Secondly, the atrium will act as a buffer zone between the building and the external environment which can reduce heat losses from the building in winter.

6. Solar-induced ventilation

Natural ventilation systems are usually designed on the basis of a buoyancy-driven flow to provide a margin for variation from the expected environmental conditions. In situations where the wind assist the buoyancy flow, there should be little difficulty in providing the required air flow rate to the building. However, in the cases where the normal buoyancy pressure (resulting from the difference between the internal and external air temperatures) is not sufficient to provide the required ventilation rates then solar-induced ventilation can be a viable alternative. This method relies upon the heating of part of the building fabric by solar irradiation resulting into a greater temperature difference, hence larger air flow rates, than in conventional systems which are driven by the air temperature difference between inside and outside.

There are usually three devices which can be used for this purpose:

- Trombe wall
- solar chimney
- solar roof

These devices are governed by the same physical principles and are based on the same fluid flow and heat transfer equations. They are described here after the underlying principles of these devices are presented first.

6.1. *Sizing of solar-induced ventilation systems*

Solar-induced ventilation is buoyancy-driven by the use of a solar air collector and, therefore, all the equations derived earlier for buoyancy pressure, eqn (14), and flow rate through large openings, eqn (11), also apply here. However, the external temperature in eqn (14) is replaced by the exit temperature of the collector. In addition, there will be pressure losses through the collector as well as pressure losses at the inlet and outlet openings.

For an air collector which is equipped with a flow control damper the pressure losses are given by the expression below:

$$\Delta p = \{4fH/D_h + K_i(A/A_i) + K_d(A/A_i) + K_e(A/A_e)\} 1/2\rho_m v_m^2 \quad (22)$$

where

A = cross-sectional area of ventilation channel, m^2

A_i, A_d, A_e = area of inlet, damper and exit openings respectively, m^2

K_i, K_d, K_e = pressure loss coefficients for inlet, damper and exit openings

H = height between inlet and outlet openings, m

f = friction factor for the channel

D_h = hydraulic diameter of channel, m

v_m = mean air speed through channel, $m\ s^{-1}$

ρ_m = mean air density, $kg\ m^{-3}$

The hydraulic diameter is given by:

$$D_h = 2wd/(w+d) \quad (23)$$

where

d = channel depth, m

w = channel width, m .

For a narrow channel ($w < 10d$):

$$D_h = 2d \quad (24)$$

The exit temperature, T_e of the collector is given by [19]:

$$T_e = A/B + [T_i - A/B] \exp\{-BwH/(\rho_e C_p Q)\} \quad (25)$$

where

$A = h_1 T_{w1} + h_2 T_{w2}$

$B = h_1 + h_2$

h_1 and h_2 are the surface heat transfer coefficients for the internal surfaces of the channel and T_{w1} and T_{w2} are the temperatures of the corresponding internal surfaces of the channel.

T_i = inlet air temperature of collector, $^{\circ}C$

Q = volume air flow rate, $m^3\ s^{-1}$

ρ_e = air density at exit, $kg\ m^{-3}$

C_p = specific heat of air, $J\ kg^{-1}\ K^{-1}$

The heat transfer coefficients h_1 and h_2 are usually obtained using

$$Nu = 0.1 Ra^{1/3} \quad (26)$$

where

$Nu = hH/k$ = Nusselt's number

$Ra = PrGr$ = Rayleigh number

$Pr = \mu C_p/k$ = Prandtl's number

$Gr = g\beta H^3(T_w - T_i)/\nu = \text{Grashof's number}$

$\mu = \text{dynamic viscosity of air, Pa s}$

$k = \text{thermal conductivity of air, W m}^{-1} \text{ K}^{-1}$

$\nu = \text{kinematic viscosity of air, m}^2 \text{ s}^{-1}$

$\beta = \text{cubic expansion coefficient of air } \approx 1/T_i, \text{ K}^{-1}$

Equation (26) applies to vertical and moderately inclined surfaces ($<30^\circ$ from the vertical) for a Ra range $10^{13} > Ra > 10^9$.

Equations (22), (25), (14) and (11) are all interconnected and to estimate the air flow rate produced by the device, Q , it is necessary to solve these four equations by iteration using a computer. In eqn (11) Δp is the difference between the stack pressure given by eqn (14) and the pressure losses in the collector given by eqn (22). Further details are given in refs [19, 20].

6.2. Trombe wall ventilator

A Trombe wall collector consists of a wall of moderate thickness (thermal mass) with a lower and an upper opening covered externally by a pane of glass. A gap of 50–100 mm between the glass and the wall allows the heated air to rise. Trombe wall collectors have traditionally been used for space heating by allowing air from the room to enter at the bottom of the wall which is heated by the collector and then returned back to the room at high level, see Fig. 4.

The arrangement shown in Fig. 4 is for the winter situation where the Trombe wall is used to heat room air. However, by putting a high level external opening on the glazing and closing the top opening to the room this device can be used for cooling the room by drawing outdoor air from another opening into the room and the warm

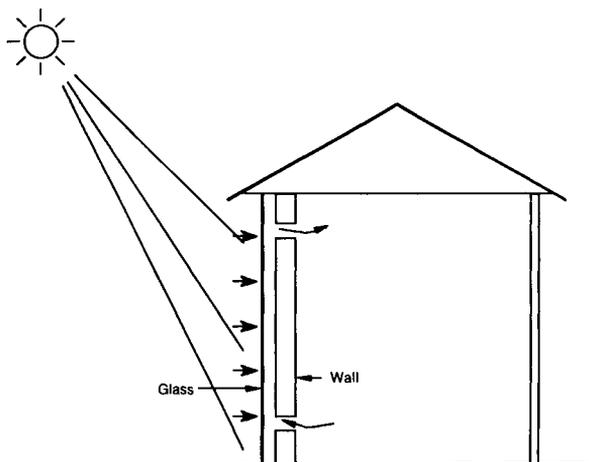


Fig. 4. Trombe wall collector for heating.

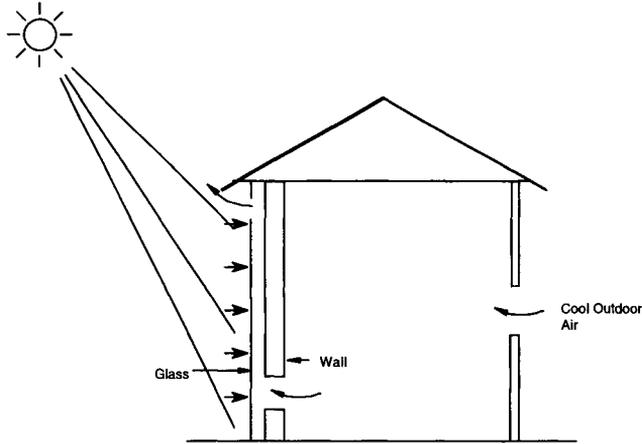


Fig. 5. Trombe wall ventilator.

air is extracted out through the Trombe wall, Fig. 5. To be effective, the wall needs to be placed in a south or south-west facing position in the northern hemisphere.

To calculate the air flow rate through the collector the method described in the previous section is applied. However, an estimate of the wall and glazing temperature will be required and these can be estimated from a knowledge of the solar gain, thermal mass of wall, emissivity of glass and wall, etc. For this purpose the reader should refer to publications on the design of Trombe walls [21, 22].

6.3. Solar chimney

A solar chimney attached to south/south-west facing wall is heated by solar irradiation and the heat stored in its fabric can be utilised for ventilation, Fig. 6.

The heated external surface of the chimney generates a natural convection current by drawing air from the building and extracting it at the top. Outdoor air enters the building to replace the warm, stagnant air inside.

The method described in Section 6.1. also applies here but usually only the external surface of the chimney is heated. In this case, eqn (25) may be simplified to:

$$T_c = T_w + (T_i - T_w) \exp \{ -hwH/(\rho_c C_p Q) \} \quad (27)$$

where T_w = the inside wall temperature of chimney, °C.

In designing a solar chimney particular attention should be given to the depth, i.e. the gap between the chimney and the building. As the gap increases, the air flow rate increases but when the gap exceeds a certain value the flow rate starts to decrease slightly. In an experimental facility in which two surfaces of the chimney were heated the optimum gap was found to be 200 mm [23].

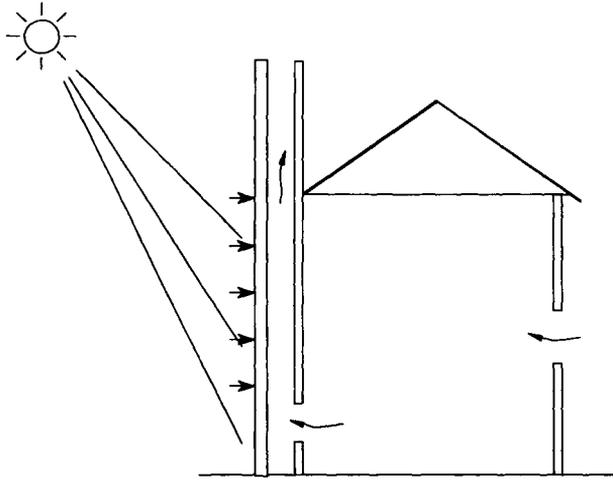


Fig. 6. Solar chimney.

6.4. Solar roof ventilator

In climates where the solar altitude is large, a Trombe wall or a solar chimney may not be very effective collectors of solar energy and, therefore, the ventilation rate that can be achieved with these devices may be limited. In this situation, a sloping roof collector can be more effective in collecting solar energy but because of the sloping surface the height of the collector will be small. A solar roof ventilator is shown in Fig. 7.

The advantage of a roof collector is that a large surface area is available to collect

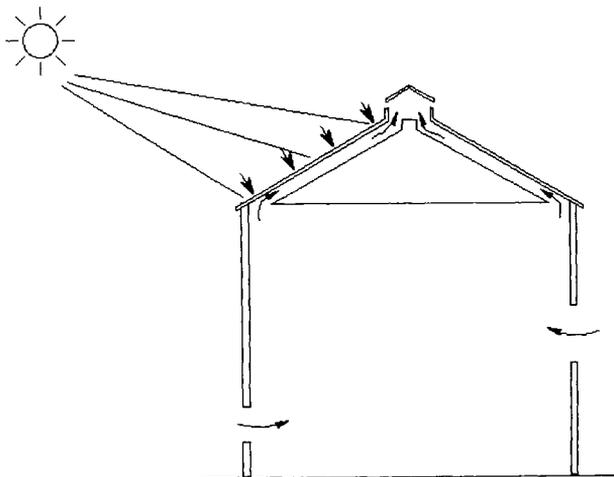


Fig. 7. Solar roof ventilator.

the solar energy and hence higher air exit temperatures can be achieved than that for a Trombe wall or a solar chimney. As a result, a roof ventilator could achieve ventilation rates close to a solar chimney or even higher depending on its design and the climate.

The estimation of the flow rate is carried out using the method given in Section 6.1. Here the height, H , is taken as the vertical distance between the inlet and outlet to the roof and not the length of the roof.

7. Mechanical ventilation

Mechanical ventilation is the provision of outdoor air or extraction of room air by the use of one or more fans. Unlike natural ventilation this form of ventilation offers the ability to control the air flows within a building according to requirements and it is essentially independent of the external weather conditions.

There are two types of mechanical ventilation systems: unbalanced systems and balanced systems. In unbalanced systems the air is either supplied to the building, or extracted from it using a fan. In a balanced system the air is supplied and extracted simultaneously using fans.

In the mechanical extract system, fans remove the air from various locations within the building through ducts and the air which is extracted is replaced by air leakage through windows, purpose-provided openings or cracks in the building envelope. This type of system is effective in removing the pollutants at their points of generation. However, as a result of the depression (negative pressure) created within the building, back flow from flues, sanitary vents, etc. could be induced. Heat recovery from the exhaust air can be achieved using a heat pump to heat water for domestic or central heating use. These systems are also suitable for extracting moisture in domestic buildings, such as from kitchens and bathrooms.

In a mechanical supply system, a positive pressure is created within the building and indoor air is forced to leak out through openings and cracks in the building fabric. This system allows the cleaning and filtration of the supply air and prevents the ingress of outdoor air through adventitious openings and is suitable in areas where the outdoor air is polluted such as in large towns. This system, however, does not allow the use of a heat recovery device because indoor air leaves the building from many locations. It is used in larger buildings where a balanced system or an air conditioning system is considered too costly to install.

Balanced systems provide both mechanical supply of outdoor air and mechanical extract of indoor air. These systems can also be used as air cleaning and heating systems by the use of air filters and pre-heaters. They are most suited to heat recovery where heat from the exhaust air is used to heat the supply air using a variety of air-to-air heat recovery devices. These systems can provide a good control of air supply and extraction to a building and they should ideally be only installed in airtight buildings. They can also be used in conjunction with a separate heating system such as a hot water radiator system. By slightly pressurising the building (i.e. a lower extract rate than the supply rate) only treated air will enter the building. However,

these systems are rather expensive and have a relatively short life cycle (typically 15–20 years) compared with the life cycle of the building. Furthermore, they require regular maintenance to ensure correct operation and good air quality in the building.

In all systems involving mechanical air supply, the indoor air quality is not only influenced by the quality of air supply but to a great extent it is also influenced by the air flow pattern in the room. The latter is determined by the type of air distribution system used for supplying the air to the ventilated space. The most widely used mechanical air distribution systems are briefly described in the coming section. However, a fuller account of these systems are given in Awbi [8] and Etheridge and Sandberg [5].

7.1. Air jets

Outdoor or processed air delivered to a room always enters the room as a jet. A jet of air is the flow resulting from the interaction of the fluid issuing from an opening with the surrounding fluid. This process is called entrainment of the secondary fluid (fluid surrounding the jet) by the primary fluid (the fluid issuing from the opening). If the jet continues to flow unobstructed, it is then called a free jet and if it is attached to a surface it is called a wall jet. The development of the two types of jets is different because of the influence of the boundary layer next to the surface on the jet and also because that side of the wall jet will not entrain the secondary fluid. The momentum of a jet will ideally be conserved in the flow direction, whereas the mass flow increases as a result of entrainment. In practice, the momentum usually decreases due to the dissipation of turbulence energy and also surface friction in the case of a wall jet. However, for a confined jet there could be situations where the momentum actually increases with distance [24]. The velocity across a jet is zero at the boundaries and reaches maximum at the centre of a free jet, or close to the surface for a wall jet. Because the mass flow increases, the maximum velocity of the jet decreases with distance from the outlet.

7.1.1. Free jet

For a free jet, four regions may be identified where the flow has a distinct characteristic (see Fig. 8):

- (i) In Zone I the maximum jet velocity, U_m is the same as the velocity at the outlet, U_o . This extends to about 6 outlet diameters.
- (ii) In Zone II the maximum velocity here is given by:

$$U_m \propto 1/x^n$$

where n is an index whose value is in the range 0.33–1.0 depending on the aspect ratio of the opening.

- (iii) Zone III represents the fully developed flow zone which extends up to about 100 outlet diameters depending on the shape of the outlet opening. Here, the maximum velocity decays inversely with distance, i.e. $U_m \propto 1/x$.

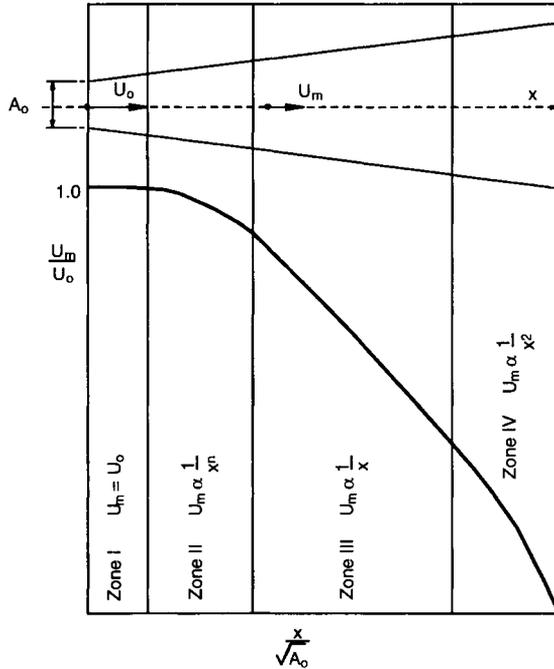


Fig. 8. Zones of air jet.

(iv) Zone IV is called the terminal zone where the velocity decays very rapidly. The maximum velocity decays with the square of the distance, i.e.

$$U_m \propto \frac{1}{x^2}$$

For a free circular jet, Zone II is small but Zone III is the most extensive zone where the maximum velocity may be represented by:

$$U_m/U_o = K_v/(x/d_o) \tag{28}$$

where K_v is called the throw constant which is in the range 5.8-7.3.

For a plane (two dimensional) jet, i.e. a jet issuing from a very long rectangular slot, Zone II is significant in which the jet velocity is given by:

$$U_m/U_o = K_v/\sqrt{(x/h)}$$

where h is the height of the opening and K_v is about 2.5.

For jets issuing from rectangular openings, the extent of Zones II and III depends on the aspect ratio of the opening. However, after about $50 \sqrt{A_o}$, where A_o is the area of the opening, the maximum velocity decay will be given by eqn (28) for a circular jet by replacing d_o by $\sqrt{A_o}$.

7.1.2. Wall jet

A wall jet is most common in mixing ventilation systems (see Section 7.5) in which case a jet is directed over the ceiling. Depending on the aspect ratio of the opening, the resulting jet is either a plane wall jet from a very large aspect ratio (<40) opening or a three-dimensional wall jet from a finite aspect ratio opening. For a plane wall jet, there are two main zones, in addition to the terminal zone. The length of the first zone is about $7h$ where h is the height of the slot opening. The maximum velocity in the second zone, which is the most extensive zone for a plane wall jet, is given by:

$$U_m/U_o = K_v/\sqrt{(x/h)}$$

where K_v is about 3.5.

For a three-dimensional wall jet there are three main zones, not including the terminal zone. The extent of the second zone depends on the aspect ratio of the opening, which can be up to $30\sqrt{A_o}$ from the opening. The velocity decay in the third zone is expressed by:

$$U_m/U_o = 14/x^{1.15}$$

In the previous discussion the jets are assumed to be isothermal (i.e. jet and room temperature are the same). If the jet is non-isothermal (i.e. hotter or cooler than room air) the development of the jet will be influenced by the Archimedes number, Ar viz:

$$Ar = g\beta d_o \Delta T / U_o^2 \quad (30)$$

The treatment of non-isothermal jets is given in [5, 8].

7.2. Air terminal devices

Ventilation openings are usually fitted with a device for controlling the jet and sometimes for aesthetic purposes too. Such a device is usually referred to as an air terminal device (ATD). There are many types of ATDs in use but ISO 5219 [25] classifies these according to the geometry of their openings, thus:

Class 1: Devices from which the jet is essentially three dimensional, e.g. nozzles, grilles and registers.

Class 2: Devices from which the jet flows radially along a surface, e.g. ceiling diffuser.

Class 3: Devices from which the jet is essentially two dimensional, e.g. linear grilles, slots and linear diffusers.

Class 4: Devices for generating buoyant flows, e.g. low velocity air terminals.

The flow within modern ATDs can be very complex and the jets which they produce may not behave in the same way as those jets produced by simple openings which were described earlier. The selection of ATDs should be based on the data available for each particular ATD (nomograms) normally supplied by the manufacturer. ATDs are usually tested in accordance with the procedures laid out in ISO 5219.

7.3. Fans

A fan is a rotary, bladed, machine producing a continuous flow of air by the aerodynamic action of the blades on the air. The performance of a fan is described by fan characteristic graphs supplied by the manufacturer. Typical fan curves would be similar to those shown in Fig. 9. To select a fan for a particular application it is necessary to know beforehand the system characteristics, i.e. the pressure losses of the system for a given flow rate. These two quantities can then be plotted on the fan characteristic graph to determine the desired duty point A, see Fig. 9.

In general, the fan curve will not pass through A and a system curve can be plotted using:

$$p/p_A = (Q/Q_A)^2$$

The point of intersection B gives the operating point, i.e. the flow rate which the fan delivers to the system. If the two points A and B are far apart, then a change in the system pressure losses will be required or a change in fan speed or a different fan is selected. Nowadays, with the availability of speed controllers, there is more flexibility in fan selection. For each speed, a different fan pressure curve is obtained. However, to operate the fan at optimum efficiency, Point B must correspond to the maximum point on the efficiency curve which is M in Fig. 9.

There are many different types of fans which suit a variety of applications in ventilation [26].

7.4. Localized ventilation systems

These systems supply the conditioned air directly where it is required, i.e. to the occupants. The air supply terminals are placed in the vicinity of each occupant, such as on a desk, a seat, etc. In some such systems the user has full control over his/her

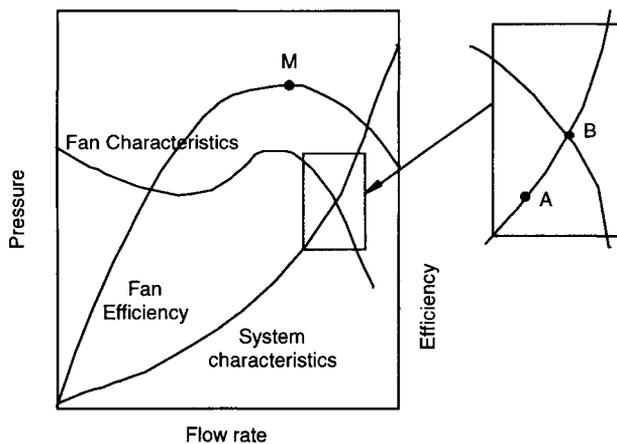


Fig. 9. Fan characteristic curves.

local environment by the ability for controlling the air flow rate, temperature, flow direction etc. Air is extracted from the occupied zone either locally or centrally. Such systems can be more energy efficient and more responsive to the needs of the individual occupant but are more costly to install and maintain. They are used in offices, theatres, hospital operating rooms and certain industrial buildings.

The air supply rates used in localized ventilation systems depend on the application. In office rooms for example the rate is determined by the fresh air requirement for the occupants and this is well documented in ventilation standards, e.g. ASHRAE Standard 62-1989R [6]. Because the fresh air is supplied directly to the occupants, generally these systems require lower air supply rates than other ventilation systems.

7.5. Mixing (dilution) ventilation

A mixing or dilution ventilation system aims to mix the indoor air pollutants with the supply air to achieve a uniform concentration of pollutants. This requires the supply of an air jet in addition to other forms of air movement such as plumes, convection currents, etc. produced by heat sources and room surfaces. Air is usually extracted from the room at high levels.

In most mixing systems, a wall jet is supplied over the ceiling or from a window sill opening to provide a vortex motion in the room such that high velocity air in the jet is kept within regions close to the ceiling and walls, whilst at floor level and in the centre of the room, the air velocity is sufficiently low (e.g. $<0.25 \text{ m s}^{-1}$).

Mixing ventilation has been in use for a long time and there is a wealth of information on the design of these systems, see for example Awbi [8]. Unlike displacement ventilation (see below) mixing ventilation can be used for heating and cooling as well as providing fresh air. However, because the aim here is to provide uniform mixing of the supply air with room air, the heat emitted from internal sources such as people and equipment is fully taken into consideration when the air flow of the system is determined. The same principle also applies to the internally produced pollution. The ventilation effectiveness of mixing ventilation system (ϵ_v) is usually <1.0 .

7.6. Displacement ventilation

Unlike in mixing ventilation, where the supply air is mixed with room air to dilute the pollutants, displacement ventilation tends to displace the pollution and heat in one direction, hence giving a ventilation effectiveness (ϵ_v) >1.0 . The direction of air flow can be from the ceiling down, from the floor up, from a wall to a wall, or from a wall to the floor then up to the ceiling. Because the buoyancy effect from occupants and other heat sources causes most pollutants to rise, the ceiling supply method is less common. What is becoming more popular recently is the use of low velocity units for supplying air from a wall terminal over the floor and allowing the air to rise as it warms up by internal sources and the air is extracted from the ceiling. Such a system is shown in Fig. 10.

This type of ventilation is energy efficient because the air in the room is allowed to stratify (i.e. the air temperature increases with height) which produces the desired

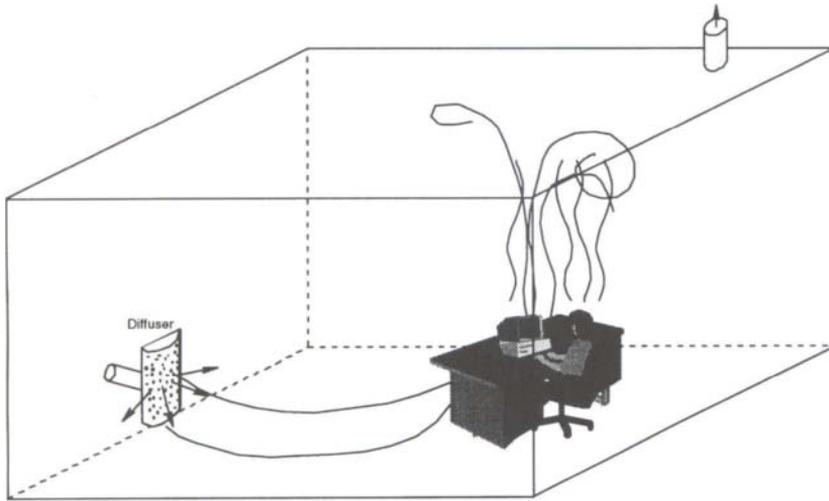


Fig. 10. A typical office room displacement system.

temperature in the occupied zone but the extract air temperature is higher. However, in a normal mixing system the extract air temperature is almost the same as the room temperature because of the mixing effect. In practice, this means supplying fresh air at low velocity (typically $<0.5 \text{ m s}^{-1}$) near the floor directly into the occupied zone with a temperature only a few degrees (up to 5 K) below the room temperature. However, because the supply air temperature is not normally allowed to be lower than about 18°C (for comfort purposes), the cooling capacity of such a system is limited. In comparison, in a mixing system the supply temperature can be as low as 10°C which will have a higher cooling capacity than the air supplied in a displacement system. In order to overcome this limitation, some displacement systems are supplemented by chilled beams or chilled ceiling devices. A chilled beam is essentially a finned pipe carrying cold water hanging from the ceiling, whereas a chilled ceiling consists of a panel attached to a serpentine pipe containing cold water.

A major drawback with this type of displacement ventilation is that it is not suitable for heating and for this purpose a separate system is needed. Guidelines for the design of displacement systems are given in BSRIA TN 2/10 [27].

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**RENEWABLE
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Chapter 8—Technology for modern architecture

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The instinctive attention to how humankind interacts with the environment underwent a brusque inversion with the advent of the Industrial Revolution, when the generally more widespread availability of energy and the evolution of techniques and materials supported the Positivist illusion that technology could dominate nature and open the way to a series of transformations that would somehow be worked independent of environmental conditions and the possibilities for rational use of resources; and today, in the industrialized economies, this link with the environment almost always works in one direction only: nature as object, the field of application for the building industries, and only rarely as a planning parameter in and of itself and a term of comparison for an ethical as well as architectural judgement of the results of this activity.

We are well aware that there exists a pressing need to improve the performance and the quality of buildings; and in this sense, great progress has been made in the field of energy limitation from both the theoretical viewpoint and as regards testing and the reliable performance of components.

Buildings are increasingly more complex, especially from the standpoint of infrastructures and the services that relate to them, and as a result professional figures, who traditionally intervened in the building process only at later stages, are now involved even during the design phase: today's building customer requires consultants who are experts not only on architectural issues but also as regards infrastructures, energy, environment and the management of the building process itself. One could say that in the aftermath of the energy crisis and the information revolution, the relationship between the formal aspect of architecture and those related to energy has been reinverted, and that in many cases the latter aspects are those that lead project development as well as those which define its visible form.

This may be efficiently achieved if our approach to design is multi-disciplinary and as such permits the control, from inception, of each of the various project components, through integrating the contributions of the different techniques that form the overall

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conception, each as regards its specific field of application. The result of such integrated cooperative work approaches the holistic concept of the phenomenon of transformation and can generate a product that is somewhat more complex than merely the simple sum of its components.

This chapter presents new technologies and innovative building elements in contemporary architecture. By means of introductory comments and the use of realised and projected examples there is an attempt to demonstrate the role which technology plays in modern architecture. These examples range from residential buildings to research centres and office complexes to religious buildings, and display not only the technical but also the philosophical, aesthetic and environmental issues encompassed by the realm of modern technology.

1. Ventilated roofs

The major part of the summer sun's heat falls on the roof of a building, due to its position with respect to the sun and has frequently to be protected to avoid overheating the spaces beneath. However, in the summer it is also the surface of the building which releases most heat through radiation to the night sky and these two characteristics are those which can be utilised to improve the internal microclimate.

The idea of the ventilated roof is certainly not new, as is the case with most architectural solutions; and numerous examples of its application are to be found in traditional buildings. In hot and temperate climates roofs in clay tiles, which because of the pitch with which they were made, were effective in keeping water away from their wooden structures beneath whilst at the same time reducing overheating for the occupants within. In nordic countries, solutions were developed to satisfy the need to isolate the interior from contact with the snow-covered roof which involved the use of ventilated air spaces.

Many contemporary architects, including Ralph Erskine, have adopted these solutions whilst utilising advanced technology and non-traditional materials. The typology of the double roof can, moreover, perform numerous functions other than that of sheltering the building from the sun's rays: the positioning of ventilation openings on opposite sides, or a system of forced ventilation can succeed in dissipating a large part of the built-up heat, especially if combined with evaporative cooling techniques. During the winter the option of closing the ventilation openings augments the insulation capacity of the roof and reduces heat losses.

The roof, since it receives such a high level of solar radiation must provide adequate insulation with the minimum mass possible so that it, in itself, is not a thermal mass which is capable of absorbing heat and thereby transmitting it to the spaces beneath. Moreover the roof comprises other physical characteristics which may be exploited for natural climatisation: during the night horizontal surfaces radiate heat to the sky and this constitutes a good method of thermal dispersion. The possibility of varying the external layers (with mobile insulation panels, reflective elements, movable roof elements, etc.) is an effective way to exploit the climatic variations in order to improve the energy behaviour of the building.

The optimal position for an absorption system on a roof is naturally the south-facing side. In the lower latitudes the winter sun has a sufficient elevation to give adequate solar absorption even on a horizontal plane; for higher latitudes the optimal configuration of the collector should be inclined, since the path of the sun is lower in the sky. In order to augment the solar advantage of a horizontal thermal mass, reflective surfaces in inclined positions may also be used. This may be obtained by utilising stepped south-facing planar surfaces and the use of movable elements which in the open position function as reflectors. Another solution consists of the application of movable insulation-reflection panels and function as a large reflective mirror which opens due south.

In a different way to solar absorption, the optimal configuration for cooling involves exposing a horizontal thermal mass to the night-sky. If the cooling load is greater and/or the climatic conditions are not ideal, the external surface may be sprayed with water, in this way the heat loss due to conventional nocturnal radiation has the added considerable cooling effect of evaporation; a thermal mass may, by evaporation, lose two or three times the heat lost through radiation.

The roof typology with a movable structure, although conceptually similar presents many different applications between them varying from large scale solutions, such as the Skydome stadium in Toronto where entire sections of the space-framed roofs open like enormous sails until the entire playing field is uncovered, to small buildings which utilise a simple opening and ventilation system for the assembly spaces, to experimental residential designs which are sheltered beneath a retractable roof.

The study of roofs and their possible utilisation in bioclimatic terms assumes a particular importance in industrial and commercial structures: the most common typology in this category is that where the roof is the dominant feature covering a single storey as opposed to residential and office buildings. The possibility of direct high-level internal illumination of buildings such as museums, factories and supermarkets presents interesting possibilities which have also, in the past, received the attention of many famous architects, from the Le Corbusier project for the Venice Hospital, the churches of Alvar Aalto, to the Menil museum of Renzo Piano.

The contemporary possibility of placing the bearing structure of a building on the outside has made possible uninterrupted internal space, allowing the utilisation of vertical and horizontal load-bearing elements as supports for the fixed or mobile shading components helping to avoid summertime overheating by reducing the direct radiation on the glazed elements. The presence of an external structure also allows the utilisation of different construction systems in the interior of the same building as in many of the projects by Hopkins, from the Schlumberger Research Centre, to the roof of the Mountstand cricket stadium where the bearing columns of the platform also provide the restraining points for the tensile structure of the roof.

The roof typology may be modified for applications in different climatic contexts, according to the prevailing problems. In temperate or hot climates one seeks to reduce the transparent part and augment that which is opaque, giving particular attention to the possibility of natural ventilation as, for example, in the supermarket by Mario Botta in Florence, the office building at Montecchio by Renzo Piano or the Danish Pavilion at the Seville Expo. In temperate-cold climates the roof constitutes a barrier

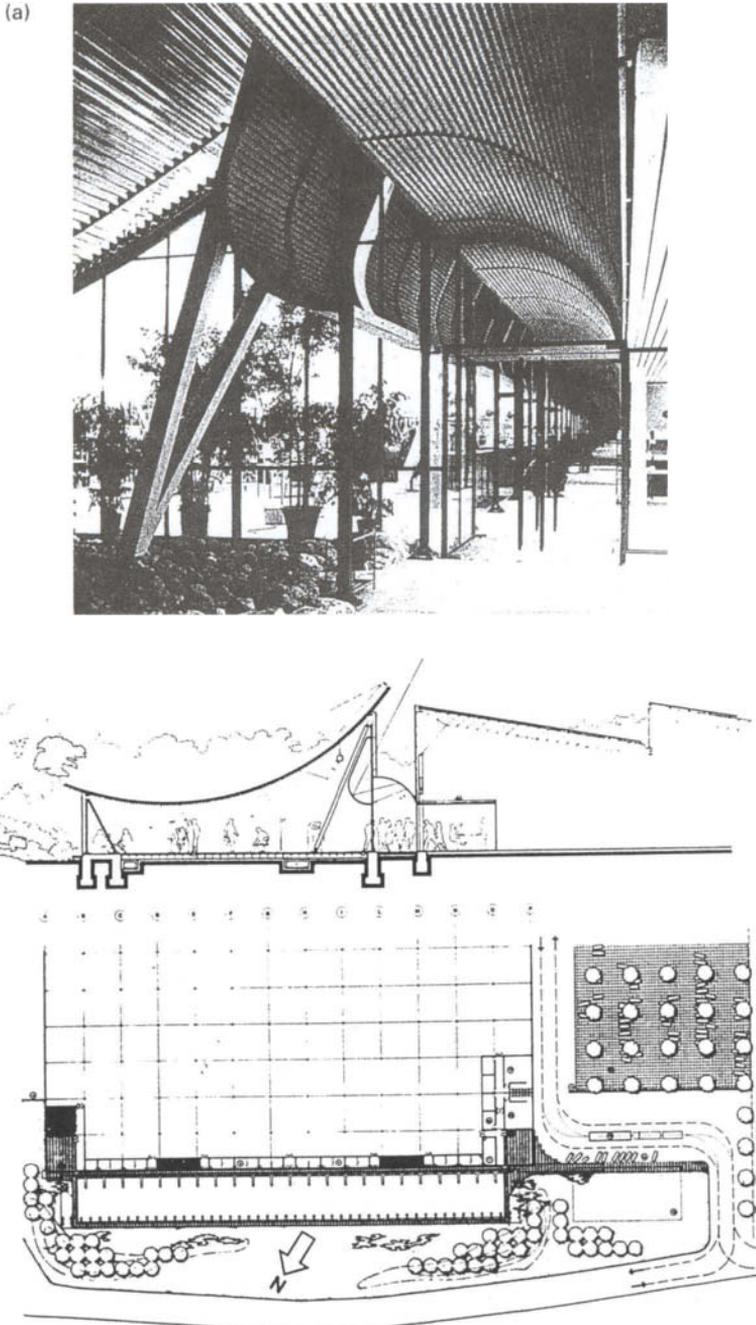


Fig. 1. *Office building, Montecchio, Italy* (Renzo Piano, Architect). (a) The curved roof cladding has a constant section and it is constituted by steel frames with a thick complementary concrete layer and insulation. (b) Plan and section of the project.

(c)

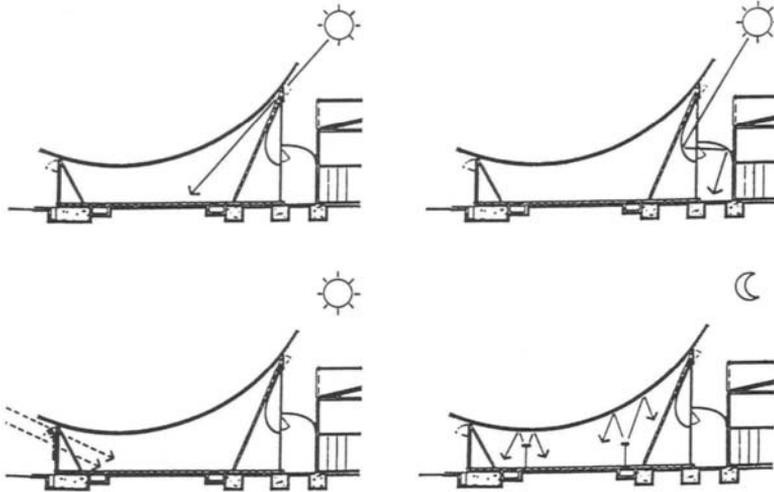


Fig. 1(c). Bioclimatic schemes.

Schlumberger Research Laboratories, Cambridge

Michael Hopkins and Partners

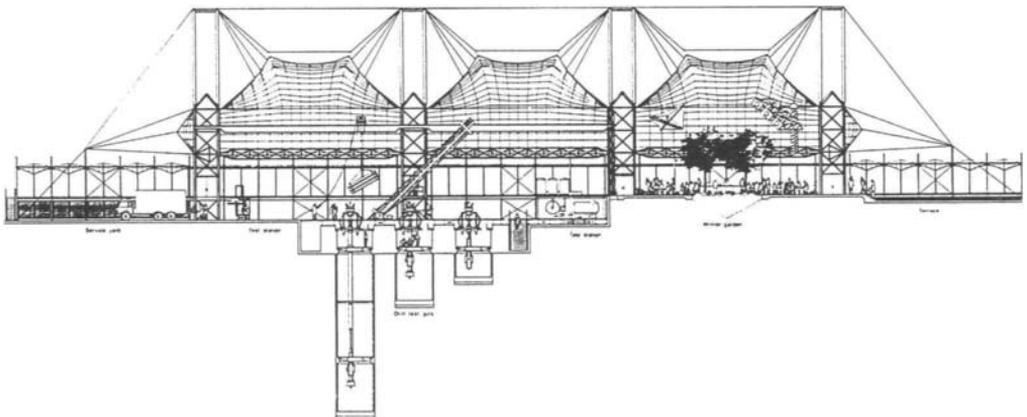


Fig. 2. Schlumberger research centre, Cambridge, U.K. (Michael Hopkins Association). (a) Section.

against heat loss and as a source of natural light, with devices to eliminate thermal bridges and maximise energy gains.

1.1. *Office building, Montecchio, Italy (Renzo Piano architect)*

The building is developed off a central spine passage-way, dividing the offices from the service areas that act as a buffer to the nearby factory. The supporting structure for the roof is formed by paired asymmetrical trestles in I-profiles with hinge joints to the curved beams and to the fixings set into the concrete floor. The curved roof of the building is in profiled metal with impervious and insulating layers. The perimeter panels are completely glazed and allow a transparency between inside and out and office and factory. The distribution of natural light to the interior is assisted by the curved reflective screens which utilise the higher part of the roof sail as a light collector.

1.2. *Schlumberger Research Centre, Cambridge, UK (Michael Hopkins Assoc.)*

The building houses a research centre for petrochemical platforms; in plan it takes the form of a H with offices to either side, the research areas, experimental laboratories and testing hall in the centre, and the entrances on the sunken sides. A large glasshouse on the south wall houses a restaurant and meeting space. The roofs of the offices are made up of trusses whilst the central part is covered by a large translucent glass-fibre membrane, coated in Teflon and suspended from steel cables which form an external structural web. This structure is tied back to pylons in tubular steel, carrying a triangular section truss spanning 19.2 m. The semi-transparency of the roof allows the occupants an idea of the time of day and the weather. The membrane was fixed on site to the trusses.

2. Active curtain wall

Energy-conscious design is but one of the responsibilities of the modern designer requiring an understanding of the building envelope as a layer which has a variable dimension and whose active role is defined by the harshness of the climate in which the building is placed. A large section of contemporary research is directed towards innovations in the field of active curtain walling with the aim of producing automatically controlled intelligent facade components capable of monitoring the internal and external climatic conditions and then reacting in the appropriate manner. This may be used in conjunction with a general energy reduction philosophy to provide a comfortable indoor environment at low energy and environmental cost. This new architectural emphasis has generated a high degree of advanced technological design in contemporary building which may be seen in built-up areas: the intelligent building is a reality to which we must become accustomed since it involves the reconsideration of alternative energy.

The development of curtain walling was a natural progression of the historical understanding of a facade as a wrapping for a building with the dual function of

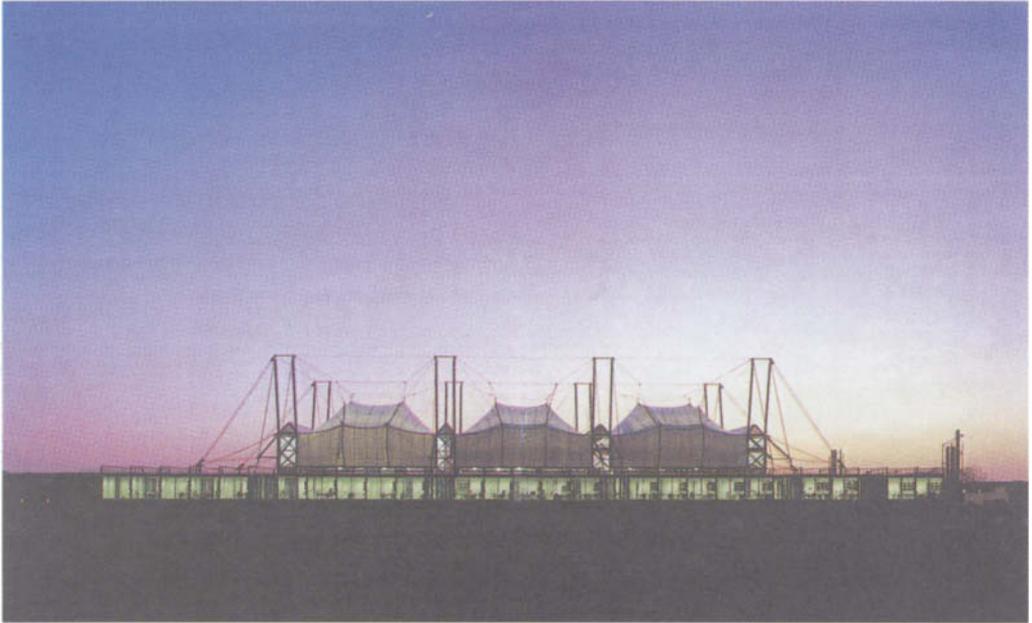
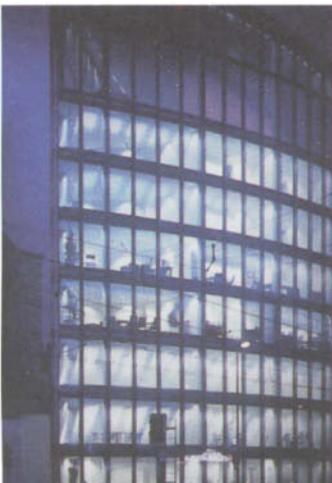


Fig. 2(b). Fabric roofs stretched by wires held by steel pylons.

(a)



(c)



Fig. 3. *Business Promotion Centre, Duisburg, Germany (Sir Norman Foster and Partners)*. (a) The seven-storey Business Promotion Centre is a landmark building which hopes to regenerate business and promote growth in the Ruhr area. (c) The triple layered cladding system uses computer controlled blinds.

(a)



(b)

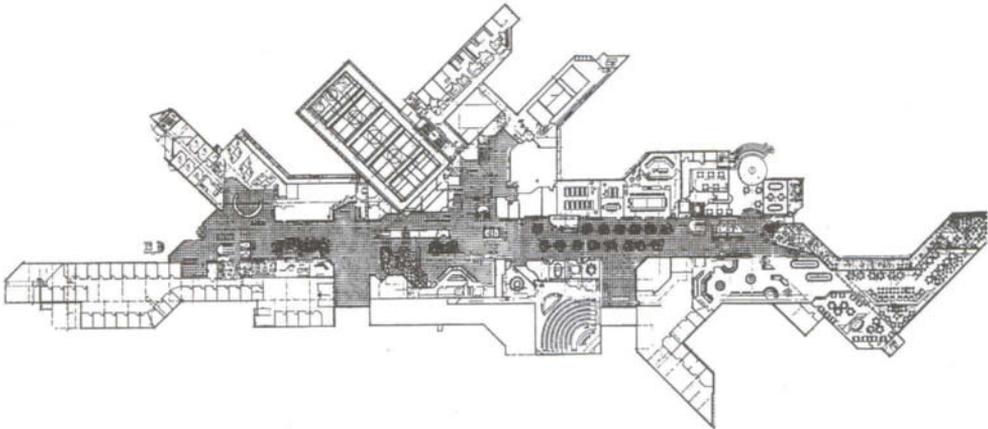


Fig. 4. *S.A.S. head office, Frosundavik, Sweden* (Niels A. Torp). (a) Instead of projecting the building into the seashore zone to create a feeling of contact with the water, the seashore itself was drawn in towards the building in the form of a small “lake”. (b) Plan of the project. The main idea was to give the impression of a new dimension, that the curtain wall “hovers” in front of the building. (c) The SAS Administration Building is intended as a kind of village which, together with the SAS employees, will make up a small living community in its own right. (d) In the street area variations and contrasts are created by the play of incoming daylight from sunrise to sunset and evening.

(c)



(d)



Fig. 4. Continued.



Fig. 5. *Domilens laboratories, France* (Del Sud Associates). (a) The interior veranda housing the large garden with natural light from the glazed surfaces. This glasshouse effect allows the environments to be enjoyed to the full, as well as offering particularly favourable working conditions.

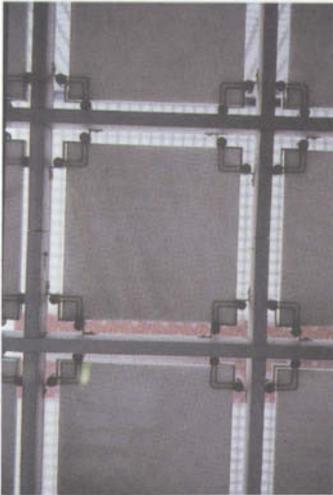
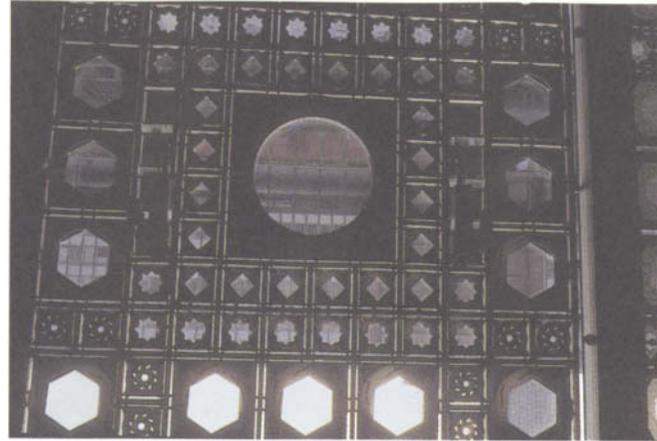


Fig. 6. *The Institute of Arabian Affairs, Paris, France* (Jean Nouvel). (top left) The south side that echoes Arab architectural features. (top right) The view from the inside is screened by a variable pattern based on the principle of the camera diaphragm—the aperture is regulated by means of photo-electric cells to control the amount of light filtering into the room. (left & right) The transparencies, the superimposition of frames and materials follow a technical pattern without excess, perfectly mastered.



Fig. 8. *Belgian Pavillion, Seville, Spain* (Driesen–Meersman–Thomaes). (a) The Belgian pavilion may be considered as a large courtyard, on the outside protected from the sun by a system of screens. (b) A column structure based on a 10×10 m module supports the surrounding sun screen system and the exhibition building, the containers, sheds, balcony, staircase and walkways. (c) Sun-protecting fabric wings on front walls.

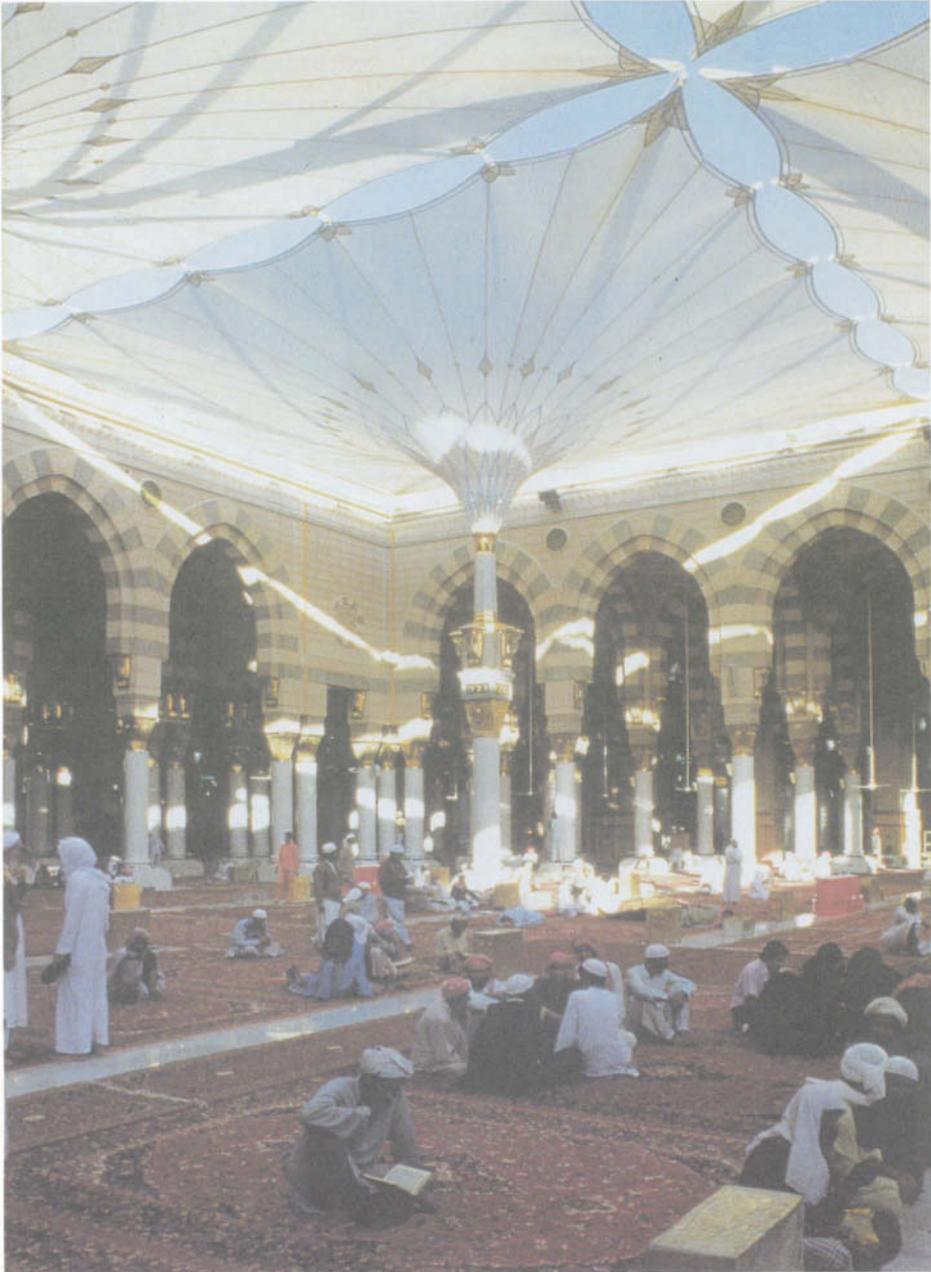


Fig. 9. Extension of the Sacred Mosque of the Prophet at Medina, Saudi Arabia (SL GMBH Rasch and Associates). (a) When the umbrellas are opened, they reveal their gathered membranes to create a light-weight vault.



Fig. 10. *British Council, Madrid, Spain* (Jestico and Whiles). (a) Exploded axonometry. To ameliorate poor internal air circulation and lack of daylighting an inverted cone deeply penetrates the building.



Fig. 11. *Hong Kong Shanghai Bank, Hong Kong* (Foster Associates). The suspension structure in asymmetrical trusses: the “short” part of the hanger holding up the service modules and escape stairs; the “long” part holding up the central floor spans. The vaste banking hall atrium where natural lighting is increased by a sophisticated array of movable mirrors powered by a computer-controlled electric motor.

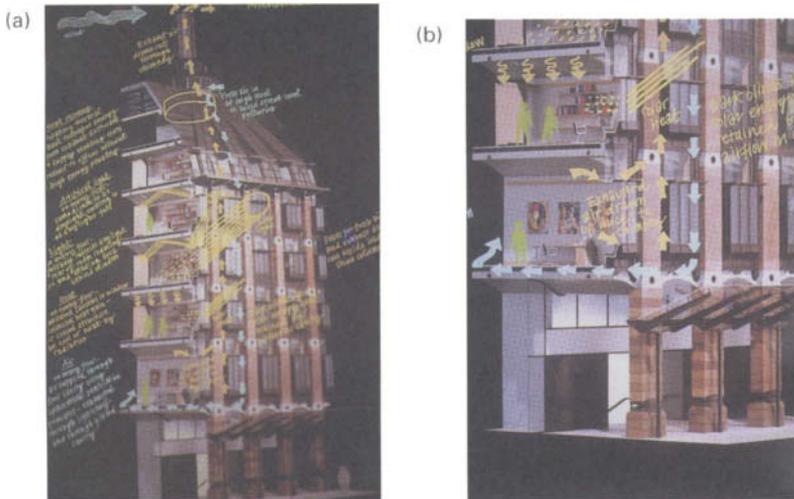


Fig. 12. *New Parliamentary Building at Westminster, U.K.* (Michael Hopkins and Partners). (a) Axonometric view. Particular daylighting and ventilation systems have been adopted in the project. Exhaust air is drawn up through chimneys on top of the building. (b) The vaulted ceiling, constituted by precast concrete elements, is used as a thermal mass. The daylighting contribution is increased by reflectants elements on ceiling, which utilisation is connected to the one of the external brises-soleil.

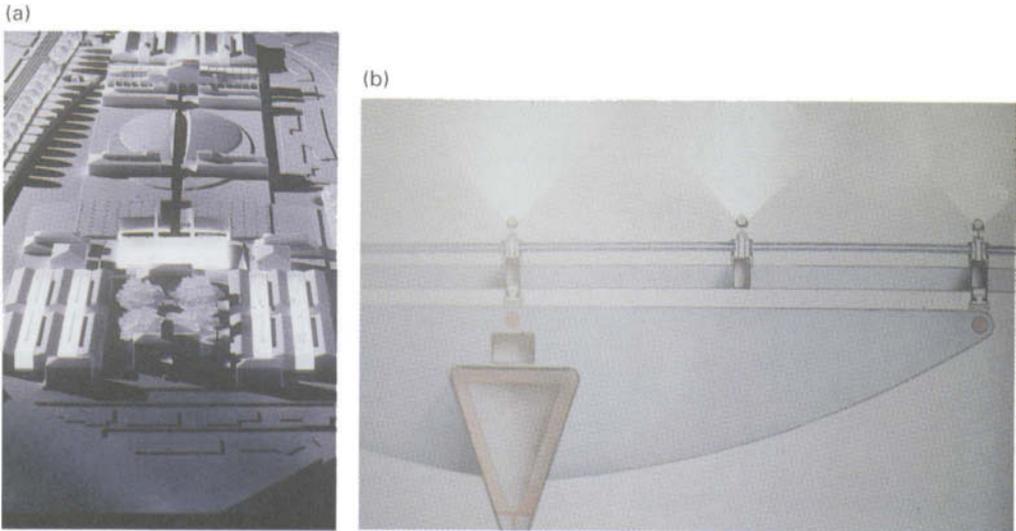


Fig. 14. *National Museum of Natural Sciences, Florence, Italy* (L. Macci, G. Maggiora, A. Breschi, A. Cortesi, M. Moretti, M. Sala). (left) View of the complex.



Fig. 15. *British Pavilion, Expo 92, Seville, Spain* (Nicholas Grimshaw). (a) The buildings within a building idea is more than just a way to preserve the impressive unity of the interior. It is also a clear architectural expression of the energy conservation strategy of the building.



Fig. 15. (b) On the roof of the building the cooling device takes the form of a series of elegant, double-curved, linear-fabric structures, risen up above the flat roof itself on V-shaped steel struts. (c) The most impressive of this device is the “water wall” of the East facade. A sheer glass curtain wall, with no projecting mullions or transoms, supports a continuous sheet of water falling into a pool, half inside and half outside the building. (d) Within the dominant, “cathedral-like” space apparently free-standing accommodational “poods” provide special spaces for audio-visual presentations and the like. Circulation between the poods and platforms is via a system of bridges and ramped travelators.

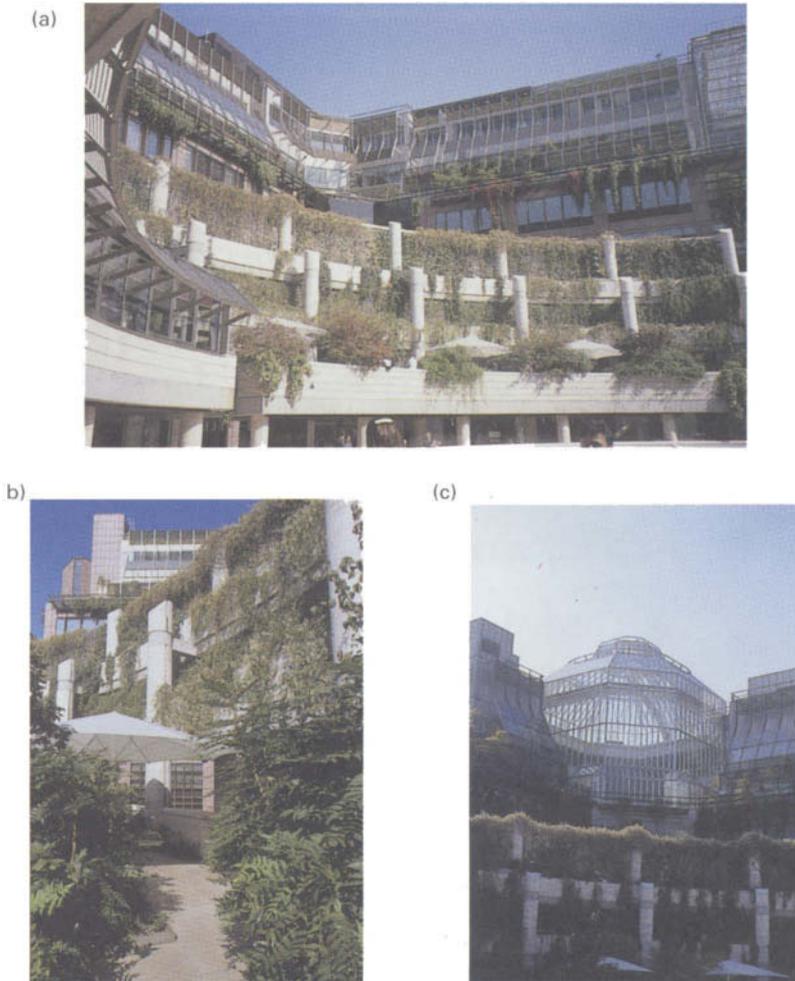


Fig. 16. *Shopping centre and offices in Finsbury Avenue, London, U.K. (Ove Arup Associates).* (top) Based around a closed internal courtyard, the offices also look on to the surrounding city streets. (left) The theatrical image of the pergola and other ramping levels contribute to the creation of small terraces on the structure of a green oasis. (right) Far above the floor is a fretwork of steel roofing that owes its origin to buildings such as the mid-Victorian iron and glass Temperate House at Kew Gardens.

(a)



(b)



Fig. 17. *El Palenque*, exhibition structure, Expo '92, Seville, Spain (J. M. De La Prada Poole). (a) The Palenque is an area of 8000 m² including a space for shows with capacity for 1500 spectators, together with other areas for restaurants and shops. (b) The white PVC covering (13% transmissivity) has a controlled irrigation system to avoid the overheating of the external side and the re-irradiation to the spaces below.

(c)



Fig. 17. (c) On top of each conical structure is a warm air exhaust opening combined with an evaporative cooling system to create an evaporative tower.

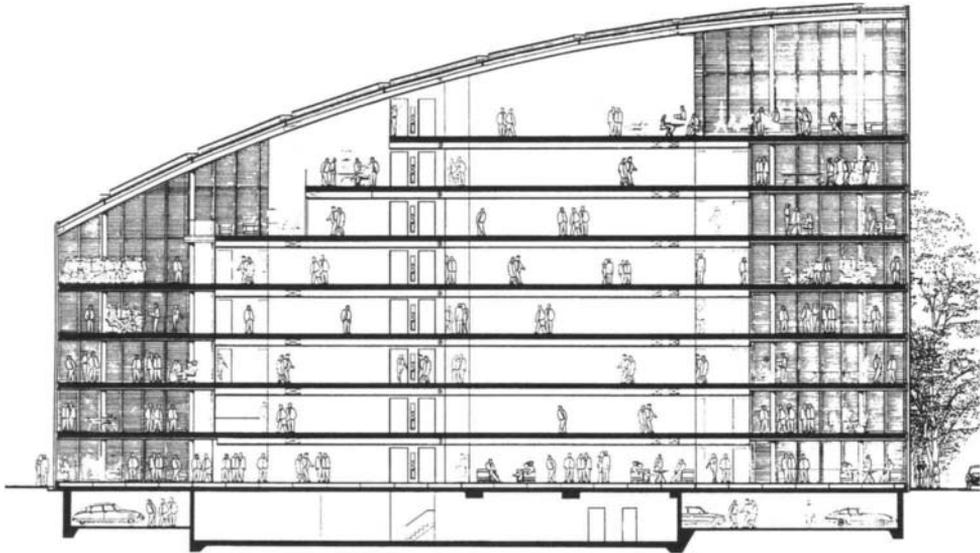


Fig. 3(b). Section. The building is clad with a triple skin comprising Pilkington Planar glazing, computer controlled blinds and a transparent inner layer to moderate extremes of outside temperatures.

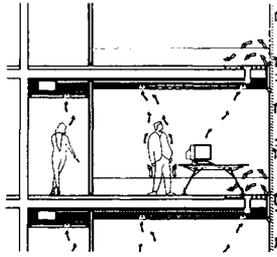
climate moderation and aesthetic representation and found its initial expression in the industrial architecture of the turn of the century.

The freedom given by the availability of new materials making it possible to replace opaque masonry with transparent glazed walls proved revolutionary, heralding a new light filled architecture. It was only after the indiscriminate glazing of the 50s and 60s with its detrimental effects on the internal built environment and the oil crisis of the early 1970s that pressure was exerted to improve the thermal performance of glazing systems.

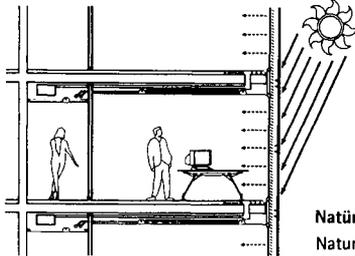
In order that curtain walling be considered as a practical alternative to traditional building techniques it ought to possess comparable characteristics. The basic requirements of any building facade as that of a climate modifier include the admission of light and its control, the provision of a reasonable layer of insulation, natural ventilation and cooling, resistance to external forces and the possibility of integrating different components. Modern curtain walling systems, often chosen for their aesthetic qualities or lower construction cost must also evolve to include these qualities, since, as experience has proven, it is far more expensive, and in many cases impossible, to upgrade existing curtain walling systems than it is traditional construction typologies.

By modifying the characteristics of window elements their thermal and lighting performances may be improved. Components operating under neural network control reduce heat losses by infra-red radiation and operate mechanical ventilation for cooling internal spaces.

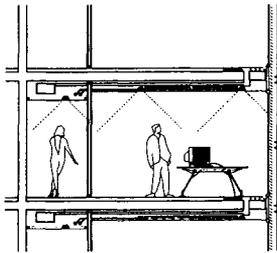
In addition to building facade aesthetic, the functional requirements of curtain walling may be described as solar gain control, daylight and ventilation control, cost



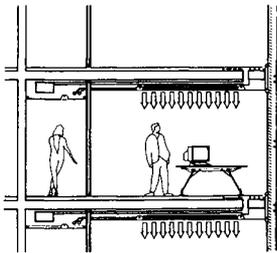
Gebäudetechnik: Luftbewegung
Services: Airflow



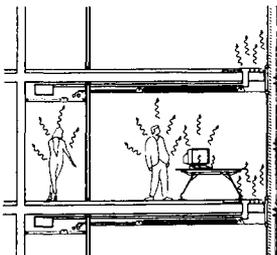
Natürliche Belichtung, Verschattung, Blendschutz
Natural Daylight, Shading and Glaze Control



Gebäudetechnik: Strom
Services: Electric



Gebäudetechnik: Kühlung
Services: Cooling



Gebäudetechnik: Heizung
Services: Heating

Fig. 3(d). Section. Integrated services.

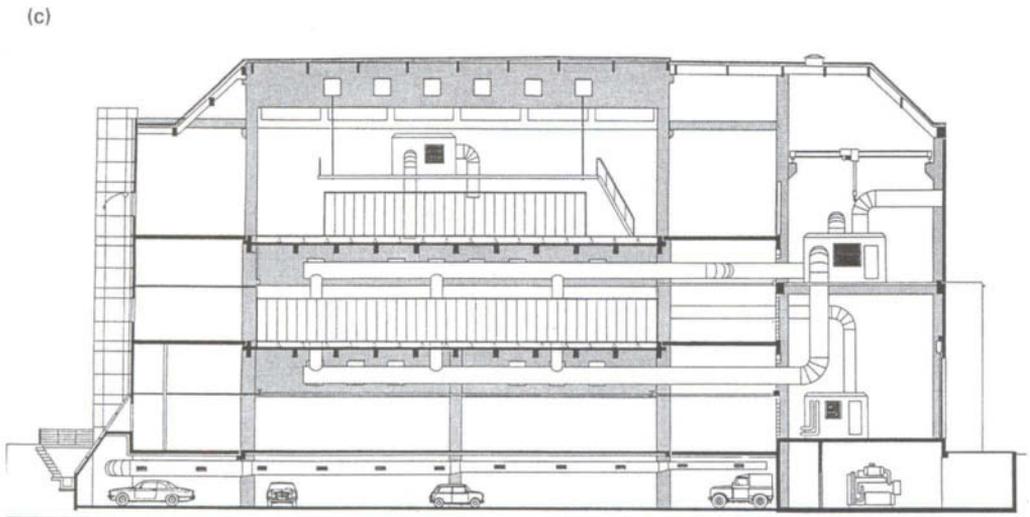
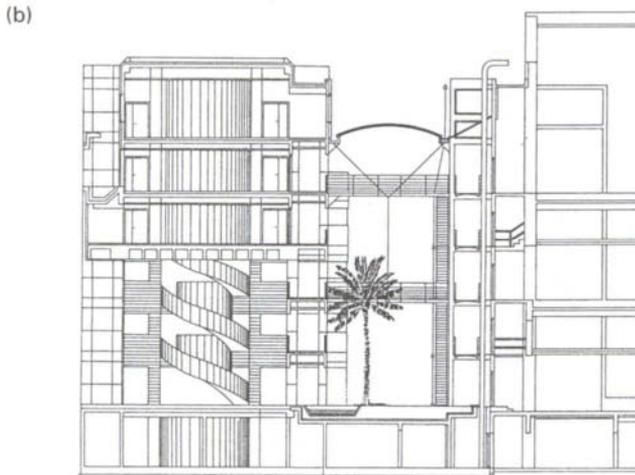


Fig. 5(b). Cross-section on the vast atrium with the articulated distribution of stairs and walkways. (c). Longitudinal section. The exposed technological structures become a characteristic element of the architectural composition of the building.

savings in heating or air-conditioning and automatic adjustment by neural network systems. Facade devices acting as an intelligent interface between indoors and outdoors installed on the ‘skin’ of the building provide the appropriate thermal insulation and air-exchanges necessary for improving internal conditions. Where coupled with transparent insulation materials with good optical performances and transmission switching, these devices may act as efficient solar air collectors, as controllable, nightly

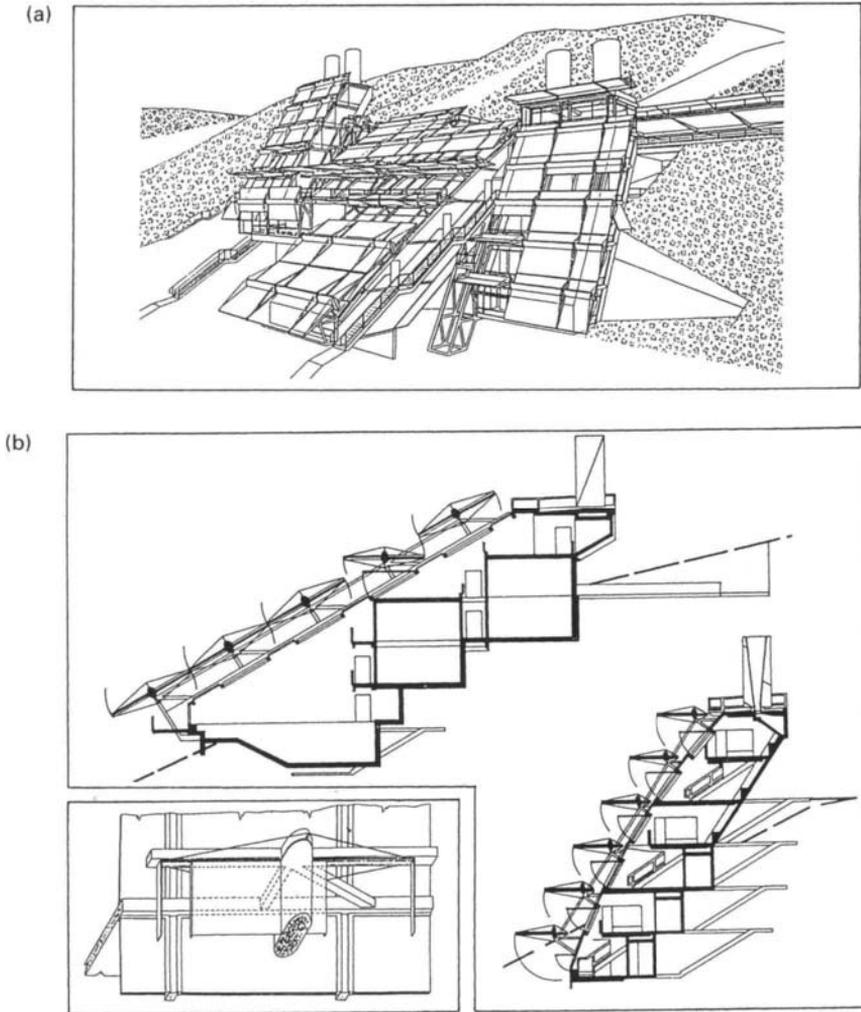


Fig. 7. Residential building, Malibu, California, U.S.A. (A.A.V. Architects). (a) Perspective view of the south facade. (b) Cross-section. The access of light into inner rooms is mechanically controlled with brises-soleil.

insulated direct-gain windows and as air exchangers, selecting automatically the appropriate function changing with the the external environmental conditions.

Neural network technology mimics the problem solving process of the brain, applying previously gained knowledge to new problems or situations, thereby developing an ability to read each different situation and consequently 'conducting' the system's various components to take the appropriate action.

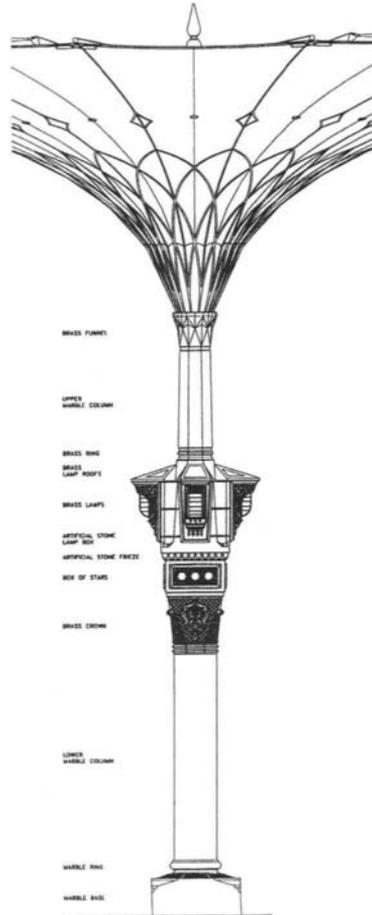


Fig. 9(b). Vertical elevation. The supporting columns are mainly in marble, with copper and artificial stone inserted into the capitals where the lamps and air outlets are installed.

2.1. *Business Promotion Centre, Duisburg, Germany (Sir Norman Foster and Partners)*

Positioned at the entrance of a long axial park connecting the city of Duisburg with the University, the elegantly curving form of the glazed Business Promotional Centre has become the most potent urban sign of the entire development. The seven-storey Business Centre is a collaboration with Kaiserbautechnik, environmental engineers also acting as private developer. It is a landmark building which hopes to regenerate business and promote growth in the Ruhr area. The ground floor contains a banking and exhibition hall in a double height space; office and conference spaces occupy the

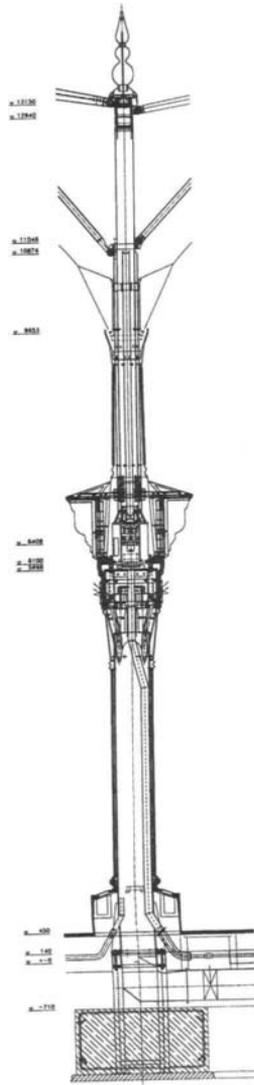


Fig. 9(c). Vertical section. Each umbrella has four lamps integrated into the claddings above the column capital which illuminate the courts at night, and two air outlets linked to the building's air conditioning system.

remaining area and terminate in a grand three storey terrace which can be rented for suitable commercial purposes.

High quality architecture, bordering on sculpture in glass, it is part of a new generation of electronically controlled buildings which provide a high level of environmental comfort in the work-place. The triple layered cladding system uses computer

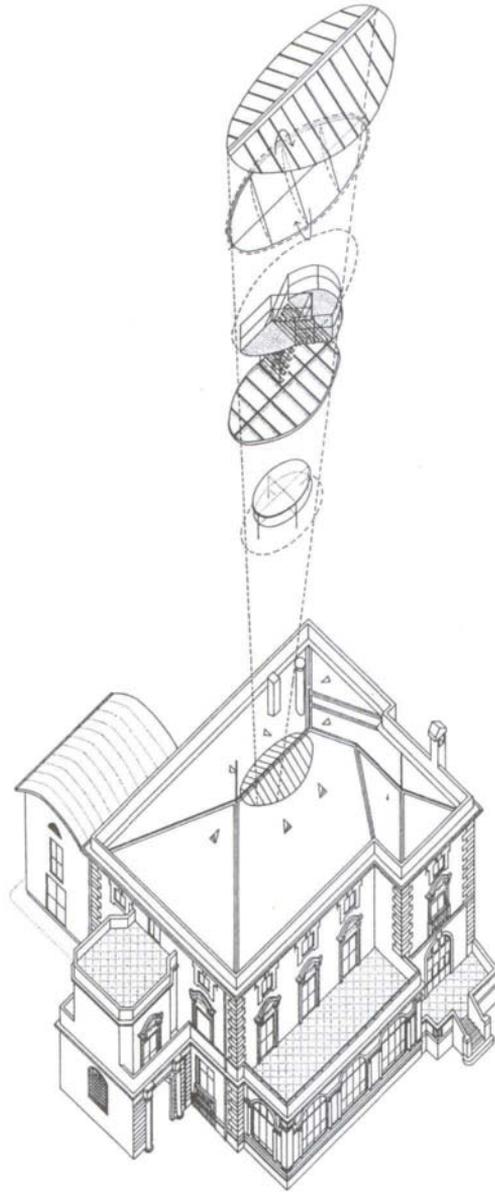
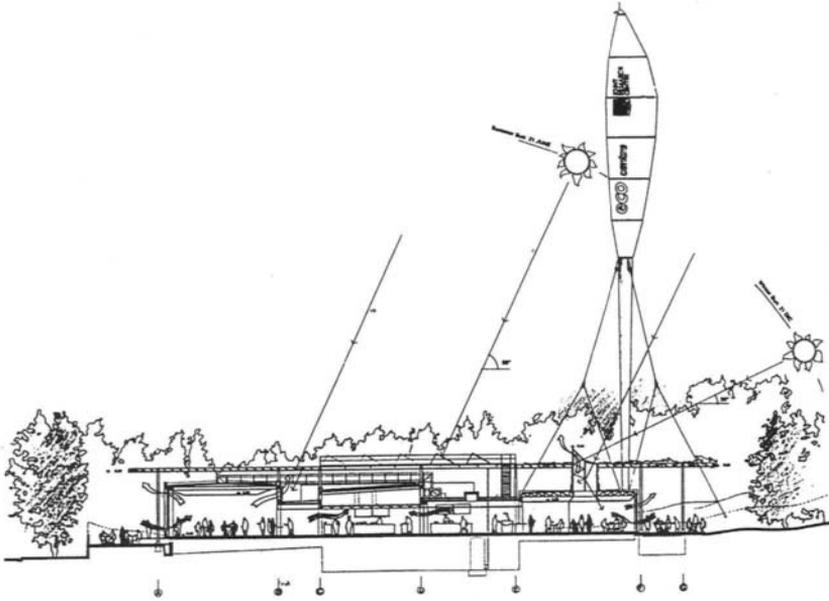


Fig. 10(b). Comprising new lightweight stair topped by a glazed rooflight, this area provides a focus for the users' activities. Excessive solar gain is prevented by a diaphragm blind.

controlled blinds by Kaiserbautechnik: an individual control panel modifies the thermal and visual comfort in each room allowing the user to control temperature and light by adjusting the light sensitive shading in the transparent cladding: this panel is part

(a)



(b)

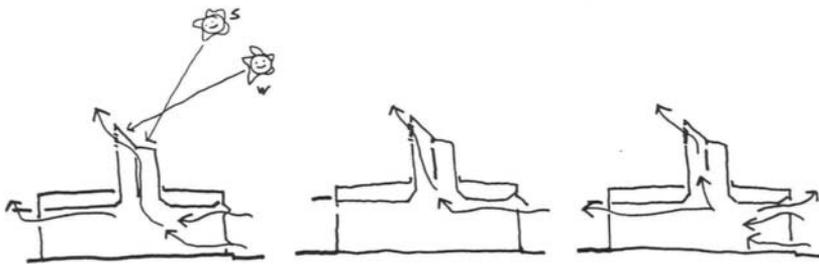


Fig. 13. *Eco Centre Project: proposal for a naturally ventilated canteen, Ispra, Italy (Mario Cucinella). (a) Longitudinal section. Outside air can enter the spaces through the low level openings and through natural convection rise to exhaust either via the Skylight openings or the high level opening windows. (b) Diagrams showing light reflection and air movement in the Skylights.*

of a network linked to a centralised intelligent building management system which controls the total energy use of the building.

3. Greenhouses

A greenhouse as a bioclimatic or architectonic element is generally a south-facing glass volume and may be either an extension or an element incorporated into the construction. The internal space, large or small, acts as a collector and is separated from the outside by a transparent material, glass or polycarbonate, and from the interior by solid or transparent partitions. This definition is valid for many types of

such as a veranda or loggia, to enclosed internal courts or patios, to roofing over public spaces between different buildings. Greenhouses generally accumulate heat in thermal masses capable to free it slowly, but they also may be used to heat the adjacent rooms directly. Greenhouses do not generally need to be equipped with auxiliary heating systems; this would be a waste of energy, due to the reduced glazed surfaces thermal insulation coefficient.

In common with multistorey buildings, the presence of vegetation in glasshouses of low-density buildings, even when fitted with simple flower-boxes and an automatic watering system is an enhancing feature and at the same time a natural method of controlling the internal microclimate, whilst in large office buildings the image of internal court transformed into a hanging garden, as in the famous Ford Foundation building in New York has become the solution adopted in certain meritable schemes. The provision of a garden space, with plants and vegetation, within a building located in a congested urban centre creates an environment that surpasses even the benefits of its energy characteristics. In this case the idea of a greenhouse, an extensive area treated as an internal garden, allows a dialogue between the different spaces which address it and also between the people who are working or living there.

In predominantly cold climatic areas, the greenhouse plays a dual role: on the one hand it provides a system of absorption in the periods of direct solar radiation, but essentially they are spaces which reduce heat losses from the building without diminishing the intensity of natural light and allow a more gradual passage from the internal to the external climate. When the covering surface becomes very large, particularly in nordic countries with predominantly cold climates these spaces become partially protected areas which connect different buildings and serve to moderate the extreme external climate, as is evident in many commercial arcades, civic spaces or small 'campus' arrangements comprising independent buildings. If the conservatory space has a purely seasonal utilisation, if occupied solely during the temperate period or is simply maintained at a temperature lower than that of the building interior then the structural masonry which divides it from the inhabited spaces must be thermally insulated.

In other cases the spaces are directly connected to the internal environment, or separated by simple glass panels, and are utilised as permanently habitable spaces and are essentially extensions of the principal building spaces. In this case the temperature of the greenhouse should be regulated using a system of fresh air ventilation, reducing the incident solar radiation, transferring the excess heat to the appropriate structure or thermal mass and adequately insulating the external glass walls during nocturnal hours.

In temperate or warm climates the greenhouse provides protection during the winter months for the relevant volumes of the building (internal courts, terraces, loggias, etc.) which for the rest of the year are, for all intents and purposes, open spaces. In order to achieve this, it is necessary that the closing systems allow a total or partial removal of the glass partitions according to seasonal needs, adopting a technological solution which utilises light materials and are easily manoeuvrable. Moreover, the characteristics of an internal garden have the practical aim of cooling to achieve the necessary environmental conditions using vegetation, which, with its natural process

of evaporation and humidification of the air produces a real effect on the immediate environment further to being a fundamental element for improving quality of life.

The systems for the control of radiation in greenhouses are not dissimilar to those for the general treatment of glazed surfaces or other elements which experience direct gain: movable shading devices may be applied internally or externally to the skin of the greenhouse with total or partial opening systems for the glazed space incorporating, when possible, natural ventilation systems allowing air circulation to moderate excessive overheating.

3.1. *S.A.S. Head Office, Frosundavik, Sweden (Niels A. Torp)*

The S.A.S. (the Swedish national airline) recreation centre is essentially composed of a series of independent, differently articulated buildings linked by a large fully-glazed atrium, glazed throughout its full height. Further to providing natural light to their interiors, this large scale glasshouse made possible the creation of an internal street, where bars, shops and meeting spaces promote an urban ambience. The plants and pools that are to be found along the 'street' each contribute to the provision of a comfortable microclimate combined with the openings in the top of the glasshouse that permit the exhaust of warm, stale air so aiding the cross ventilation of the space.

The buildings front onto the internal street and their visual communication is reinforced by the balconies, terraces and galleries that characterise each block. The external walls and the roof of each different facet is in glass formed by predefined models, assembled utilising a system of joints to minimise thermal bridging. The curtain walls are the patterned, screen-printed sheets of toughened glass which are mounted outside, and at a distance from, the prefabricated, infill wall units which are clad with naturally-anodized, corrugated aluminium sheeting.

3.2. *Domilens Laboratories, France (Del Sud Associates)*

One of the important designs concepts of this building was to develop an internal area of vegetation thereby generating a filter zone between the offices and laboratories. Consequently there is a concentration of circulation around and through this large winter garden with staircases and connecting galleries at various levels and piping and conditioning services expressed clearly within the space, achieving an overall dynamic effect. The roof comprises curved metal frames which support the glass and which rest on box-section ring beams which are in turn borne by the concrete structure and have an auxiliary function as eaves channels. The large garden is illuminated from above and from two glazed faces, favourably benefitting the internal environment and working conditions. The structure is a grid concrete structure, and the external facade comprises two large glazed surfaces, treated with selective coatings which have a characteristic intense blue colour avoiding possible glare factor.

4. **Movable shading devices**

One of the major reasons for the evolution and use of shading devices derives from the drive to control the energy consumption for the heating of buildings. In the sphere

of conceptual passive climatisation the physical and geometrical form of the building shell is exploited in order to augment the absorption of solar energy either by passive or active means that may then be modified in order to achieve the appropriate level and system of control. However, the increase of the glazed surface resulting in a large thermal gain during wintertime can create problems of summertime overheating.

The use of shading devices is not new to modern architecture, and no discussion of the same would be complete without a mention of Le Corbusier who from the laboratories at Saint Dier of 1946, the Unit d'habitation in Marseilles of 1949, the Palaces at Chandigarh to the monastery at La Tourette, established the function of bris-soleil as functional integrated building elements. Although the use of fixed shading devices may be swiftly and easily comprehended the acceptance of shading devices as mobile elements has been more difficult: heretofore such elements have been considered as super-imposed on the structure but without becoming visually predominant elements.

In reference to the thermal behaviour of the construction, the more effective choice is that which places the shading devices externally on the facade creating a ventilated cavity thereby reducing the heat accumulation of the structure. Generally considered less effective are shading systems located within the space having the sole function of light control; these permit the ingress of the sun's rays, thus heating the air and raising the room temperature through convective heat gain.

Depending on the specific design solution adopted, shading device typologies are so diverse that it is difficult to categorize the possible types other than the obvious distinction between fixed and movable shading devices. In particular the latter may be applied in a specific way to the various parts of the building, the roof, their own structural system or simply as an element applied to the fixed construction. Moreover, the shading may be articulated by devices of varying weights and dimensions, ranging from centimetres to metres, and situated in various positions, either parallel to the facade (generally on south facing elevations), perpendicular (east or west facing) or may be modulated slats parallel to, coplanar with or inclined to the facade.

Movable shading comprises autonomous facade components such as the classic sunbreakers in thin vertical or horizontal slats, as well as elements in various materials and forms which act as part of the external cladding system envisaged by the designer.

Frequently this function becomes incorporated into the structural frame system: from traditional timber shutters to metal awnings, to the slats inserted in the external cladding component as in the facade of the Institute of the Arab World by Jean Nouvel, and finally to the microcomponents inserted directly into the cavity between double glazing and acting with magnetic commands for a gradual reflection and control of the sun's rays.

Furthermore, the presence of vegetation; trees and climbing deciduous plants, particularly on the south-facing facade provide an effective form of shading from direct radiation as demonstrated by an endless series of applied examples, both in traditional and contemporary architecture.

Movable shading components obviously have a great advantage in that they may be used according to the climatic situation and the internal requirements, but this possibility has been limited by the necessity of the physical presence of an operator

or has been entrusted to rudimentary automation systems using various devices to exploit the principles of physics. Today the study of the application of shading devices concentrates on the management of shading elements in different climatic and seasonal conditions, through the ever more sophisticated control of the microclimate on one hand and, on the other, through the widespread operational applications (nonetheless being economically compatible with the cost of the building) of an electronic base and of the server mechanism for regulation and command purposes.

A network of sensors connected to an integrated circuit and with some of the server-mechanisms applied to the movable shading devices may independently manage its optimal regulation; they may be extended to ventilation and the insertion of other servicing systems as a function of the internal and external climatic parameters and the imposed requirements.

4.1. The Institute of Arabian Affairs, Paris, France (Jean Nouvel)

The building is articulated in volumes of reducing thickness, allowing in all of its parts a view of the outside through filters applied to the glazed walls. One of the most fascinating effects of the design is the play of transparency and reflection of materials, derived from the innovative solution utilising metallic implants in the glazing, whose introduction was generated by particular technological requirements. The south facade comprises panels automatically powered by photo-electric cells, in a way which regulates the opening and diaphragm of the sun-shading elements, as such filtering the light to the interior of the facade more exposed to the sun. The facade towards the Seine presents a density of lines produced by rails suspended level by level from stainless steel rods. The shimmering transparency of the building is continued in the patio which is made of translucent alabaster tiles suspended from fine metal clamps.

The more emblematic element is the south facade of 30 × 80 m, facing the Science Faculty, and composed of 240 panels in glass and aluminium, framed in a tartan grid of external profiles which continues also onto the adjoining sides but in transparent panels. The light regulating structure is comprised of an aluminium grill, profiled according to the typical decorative motifs of the arab tradition, and inserted between two sheets of glass, of which the innermost is openable for maintenance. The mobile parts are formed by specially shaped concentric metal slats which function like the diaphragm of a camera, progressively closing in order to regulate light with centralised commands and a total of 16,000 mobile elements. Furthermore many internal partitions are made with glazed frames and finished in stainless steel, while the vertical structural frame has been reclad with sheet aluminium.

4.2. Residential building, Malibu, California, USA (A.A.V. Architects)

The intervention anticipated the transformation of three housing units into a single villa. The designer, having considered the special location of the building whose south elevation is oriented towards the sea, has created a continuous glazed wall, shaded by large fabric fins. The access of light to the internal spaces is mechanically regulated

by the bris-soleil: these elements, by virtue of the position which they assume, regulate the illumination of the interior. The principle structure is formed by a series of trussed beams formed by 200×200 mm box section steel connected to the façade in a precast reinforced concrete structure; on these are positioned the various aluminium frames constituting the framework of the PVC fabric, which derive their details from the curtain wall.

4.3. *Belgian Pavillion, Seville, Spain (Driesen-Meersman-Thomaes)*

The rooms of the exhibition are located within a shaded volume of 50×50 m plan dimension with a height of 25 m, whose external structure has been constructed by cylindrical steel columns, 21–25 m tall, disposed according to a 10 m centre to centre grid. The screen of the sunshield, suspended between the slender white columns, create a piazza-patio. The circular steel columns are anchored at ground level to the plinths of the foundation, while at roof level they support the aluminium sunbreaker elements. The structure of the pavilion is made up of laminated timber beams supporting the external sunshading elements: these in turn are supported by steel cylindrical poles onto which are connected a skeleton clad with white impermeable canvas in polystyrene and PVC, tied back at its extremities. The mechanism at some points of the pavilion, is free to rotate, and allows the control of the ingress of light according to the different inclination of the sun's rays.

4.4. *Extension of the Sacred Mosque of the Prophet at Medina, Saudi Arabia (SL GMBH Rasch & Associates)*

The roof of the Holy Mosque of the Prophet at Medina, in Saudi Arabia, is made by positioning twelve tensile umbrella type structures in two internal courts. Each structure is formed by a supporting column at the summit of which there are hooked four principle poles and eight secondary which, together with a series of internal ties restrain the square shaped membrane. Each umbrella extends to 17×18 m and together with the structure create, in the open position, a light roof above the courts and cleverly resolves the climatic problem of this historic complex, without the burden of grave environmental impact.

The principle which has been adopted anticipates the extension of the membrane in the summer daytime hours for protection against strong solar radiation, while their nocturnal retraction allows the massive walls to expel the heat which has built up during the day. In winter the sequence is exactly the contrary in order to allow the heating of the marble ground and walls, the thermal inertia is preserved during the night by closing the membrane which does not allow the excessive loss of heat from the court. In the closed position the umbrellas assume the form of miniature minarets complete with spire atop. The opening and the closing of the membranes are regulated by a computerised opening system responding to climatic requirements of different seasons and different atmospheric conditions. In the slow and lingering movement of some tens of seconds, the minarets reveal their membranal nature through a spectacular manoeuvre, and they close as do flowers, to leave the internal court uncovered.

The retracted structures are also equipped with sensors which inhibits the opening of the devices in winds with a velocity greater than 36 km/h. The supporting columns of each umbrella have been built in marble with copper and artificial stone elements inserted into the capital of the column along with four lamps for nocturnal illumination and two small openings to provide fresh air whilst the umbrellas are in the open position. The sensitivity of this project both to the environment and its historic context displays the potential highs to which a regard for the environment and good design can reach.

5. Light ducts

In the field of illuminance a similar move took place to that in the field of building servicing: the desire for complete control of the internal climate by hermetically sealing the building envelope and the application of artificial means of heating and ventilation, isolating the building from external influences.

This attitude is, nevertheless, changing and is assisted by a rediscovery of the general comprehension of energy problems and the possibility of optimising and exploiting renewable resources in a way which is integrated with contemporary technology.

Furthermore, the development of the technology of artificial lighting that initially prevailed, brought about a general and indiscriminate use of these systems, negating the importance of natural lighting. The attitude which favours sources of artificial lighting is generated by the possible negative effects on the internal environment by natural lighting for instance the glare factor and overheating produced by uncontrolled sun rays. The almost exclusive use of artificial lighting in the working environment has nevertheless brought about difficulties from the point of view of visual comfort, producing psycho-physical fatigue and lack of motivation, not to mention the elevated cost of management. For these reasons there has been a return to the use of natural lighting, seeking to eliminate the negative characteristics, but above all to integrate natural with artificial lighting by considering the problems of intensity, distribution and colour of the light: natural and artificial lighting do not have to interfere among themselves, they have to coexist in a balanced way in the built environment.

The light which we are able to transfer by natural means to the interior of the construction is an important contribution for human wellbeing. The day-time natural illumination, with its variations in colour and intensity in the course of the day and the course of the year constitute the most basic perception of the passing of time, bringing attention to natural rhythms which may prevent stress or fatigue often provoked by activities carried out in artificially-lit conditions. The perception of the passing of time through the variations of light during the day is basic to our lives and is a fundamental part of the psycho-physical equilibrium of the individual.

More recent study of this type of problem has brought about the theorisation and elaboration of new techniques which seek to convey and radiate the excess of light rather than simply avoiding it. The employment of more advanced techniques of illumination with daylight allow, not only the proportioning of the quantity of light

and its orientation in a uniform way to eliminate some negative aspects such as glare or overheating, but also the receipt of consistent results in the reduction of climatisation costs and savings of electrical energy used for illumination with artificial sources. Challenging the conception that the more effective systems of daily illumination utilise the reflected light from the north sky rather than that directly from the sun, recent research considers the exploitation of the strongest sources of light and the manipulation thereof to obtain optimal results. Furthermore, in reference to artificial light the same criteria may be adopted, such as mirrors which direct rays in an indirect way, avoiding glare and uncomfortable reflections and trying to project light upwards, on the ceilings so as to obtain a uniform distribution.

A particular area, which is still in an experimental phase, is that which attempts to bring light to the interior of the building with materials and new technologies, such as fibre optics to guide the light or interceptors and concentrators of the light and heliostats. Roof mounted mobile receptor elements on which a series of Fresnel lenses can be applied are oriented to the south and connected to an optical duct comprising a sheath of optical fibres which transfer the daylight to the interior of the building. The solutions may be integrated with the architecture of the building without interfering with the construction technique and with a production and installation expenditure compatible with the economic level of the actual servicing system. A foreseeable reduction in the cost of fibre optics and other components of such systems may in a few years allow greater accessibility of such interventions and provide a solution to the illumination requirements for interiors, in particular of basements and semi-basement levels. The materials utilised are made up of high efficiency fibre optics of methacrylate polymers whilst the Fresnel lens is made of a thin plate of cast acetate in which are incised a series of concentric lines which concentrate the sun's rays to a central focus. A movable system commands a solar pointer to maintain the concentration of the rays on the entrance of the fibre optics, which convey the light through a duct with the appropriate adaptors throughout the building. Every optic fibre has a minimum thickness of 250 μm ; the bundle crosses the building protected by a flexible sheath.

The diffusion of the light to the internal environment is achieved simply from the extremity of the fibre sheath, where the light exits with an angle of diffusion of about 60° , or alternatively the fibre may be connected to an adaptor for the propagation of light from the ceiling of a room or may be located behind diffusers and lighting fixtures which give a sensation of a window to the outside.

The techniques of transferring natural light to the interior of a building are particularly interesting for the industrial and commercial typology, where the major dimensional extension of the roof in relation to the volume utilised allows the greater part of the interior to be supplied with direct illumination. At any rate, in many buildings it is necessary to relearn the value of daylight, in all of its variations in order to create a more humane environment in what may otherwise be a potentially oppressive workspace.

5.1. *British Council, Madrid, Spain (Jestico & Whiles)*

Calle General Martinez is a major avenue running east from Paseo de la Castellana just north of Madrid city centre. Amongst the more recent apartment blocks of the district a few large period villas from the turn of the century, known as 'palacetes', survive.

The building that houses the British Council was originally designed by Ferreras and constructed in 1870 for the Institucion Libre de Ensenanza. A large house of three floors, the building is of classical design with rendered and stucco external walls and slate roof. A series of extensions and modifications to the original elements, such as lean-tos, enlargement of windows and an external escape stairs had obscured the architectural intentions of the original building. The lack of natural lighting internally and an unfavourable internal distribution affected its potential use as a cultural or educational centre. The building was completely reinstated in the following manner: public facilities, library and information space for the arts and sciences were located on the ground floor, with key administrative offices on the first floor and secondary offices on the second. The various lean-tos and additions were demolished, leaving only one block intact, which after careful redesign has been transformed into an arts center, accessible both from an independent access and from the main building through a glazed passage, underlining at the same time its different function and its architectural shape.

The most significant intervention in the internal renovation, which serves to alleviate the dark and oppressive character of the attic storey, is expressed externally by a curved-glass opening placed over the ridge. Beneath this aperture an elliptical void in the form of an inverted cone, pierces the internal space from the roof down to the first floor.

With its axis slightly inclined to the north and east this skylight is oriented to increase the penetration of the morning sun to the interior of the building and a movable panel reduces the solar gain as the day progresses.

To connect the first and second floors a new lightweight stairs in perforated metal was inserted: whilst supplementing an existing stairs to the attic, it creates an alternative means of escape, replacing the stairs removed in the restoration. On the first floor, an oval panel in etched glass, inset into the ceiling, allows light to penetrate down to the ground floor. An excessive thermal gain and problems with glare are overcome by an oval diaphragm, composed of fabric stretched over a metal frame. In the closed position, the light is filtered and the heat which gathers at the top of the building is released in the form of hot air through the top of the inverted cone. In Madrid's cold winter the users can benefit from a certain gain by closing the diaphragm and directing the heated air, by means of ventilation ducts, to the public spaces on the ground floor. Elsewhere the building was reorganized with the insertion of some new partitions and furniture, consistent with the new interventions, with light steel structures, glass and material, in coherence with the new project.

5.2. *Hong Kong Shanghai Bank, Hong Kong (Foster Associates)*

The Hong Kong Shanghai Bank, as well as experimenting with an advanced construction system utilising a range of specially designed and produced components is a building years before its time in terms of its systems to convey daylight to the interior of the workspace, even when light cannot enter in a natural way through the external skin. The light collection system consists of an external mobile reflecting structure and a fixed internal mirror inside the building. The external suntracking collector formed from two lines of 24 mirrors, varies according to the inclination of the sun by means of active photosensitive cells. The light for reflection is concentrated onto a parabolic reflector situated at the top of the central atrium on the tenth floor from where it is diffused throughout the interior.

6. Integrated ventilation

The facade may be integrated with the servicing of the building in various ways which differ one from the other in the level of complexity of the functions developed by the servicing and by the solar facade. With an increase in the level of functional complexity there is also an increase in the level of 'intelligence' of the control system, and the integration with the servicing systems occurs in one of two ways:

- (1) A passive system with a low level of integration, where the facade contributes to the heating and protects against the overheating of both itself and the relative space. The facade generates a flow of warm air which is introduced to the room interior with a priority over traditional servicing providing that the temperature has previously been set to an interval which guarantees the wellbeing of the occupant. For cost control, a simple heating system is considered adequate (for example a radiator) whether natural, manually administered or forced ventilation action is utilised. In such a way the number of control shutters is reduced and the subsystem for automatic control becomes simplified.
- (2) Passive integrated systems with heating and ventilation services. The facade is integrated with a heating servicing system comprised of ventilating heaters, which compensate for the loss of energy in each room and from a communal mechanism for each room which compensates for the attendant loss of energy in the flow of external air which must be used for air-exchange. Consequently, the facade provides all the other functions described in the previous case as well as those of integrated ventilation with intake and extraction servicing for the renewal of the air; the number of shutter controls is increased and their management must be automated.

As a rule it is preferable to use insulated glass in geographic zones with a harsh climate, while in other zones it is possible to use single glazing.

The glazed panels are generally mounted in aluminium fixed frames on a profile obtained with laminated pressed steel which is in turn connected to the rear of the loadbearing concrete panel. The double structure allows the three dimensional

adjustment of the glazed walls. The profile in aluminium is composed of a structural frame and beading with the two elements separated by a continuous gasket which also acts as a thermal break.

6.1. *New Parliament Building at Westminster, UK (Michael Hopkins & Partners)*

The new Parliamentary Building at Westminster will contain 210 offices for the members of parliament and their staff. The building is articulated internally with a central covered court. The offices are located at the perimeter of the building and are characterised by a bay window facade without openings to the exterior due to noise and air pollution problems; the design for the facade is based on a mechanical system of ventilation. At times, the floor formed by elements in precast concrete becomes utilised for thermal accumulation. The contribution of internal lighting is increased by reflective ceiling elements whose utilisation is connected to the external sun shades. The facade is formed by triple glazed panels with a reflective coating; within the frames of the glazing system there are channels for ventilation and for the system of blinds. At roof level bronze anodised aluminium ducts connect to 14 solar chimneys. At the base of each chimney energy is recovered through the use of heat exchangers in connection with the outgoing air; this system preheats the external fresh air which is brought to the interior through small intake grills (it is not recirculated air) and is distributed through channels in the external walls and in the floors. The cooling of the building is obtained by means of heat pumps which utilise water from boreholes 90 m deep, eliminating the use of refrigerants and CFCs.

6.2. *Eco Centre Project: proposal for a naturally ventilated canteen, Ispra, Italy (Mario Cucinella)*

In the field of retrofitting, integrated ventilation is undoubtedly a key issue in the improvement of a building's energy performance.

The retrofitting program outlined by the Ispra Establishment of the Joint Research Centre of the Commission of the European Communities essentially comprises a detailed review and environmental assessment of its site and buildings with a view to reducing energy losses from the entire complex.

In this instance, Building No. 8, the Research Centre's canteen building, is the object of the retrofitting exercise. A single storey building from the 1960s, it has already been extended on a number of occasions and at present accommodates kitchens, serverys, dining areas and a small supermarket. The architectural proposals involved building a 5000 m² shading structure over the group of buildings, installing skylights in the canteen and landscaping the areas around the buildings. Prior to considering the ventilation process per se, it is worth noting that many of the architectural interventions initiate the modification of the internal environment, allowing the designer to work from a more moderate base condition: this strategy eases the incipient burden of the ventilation system and represents the holistic approach to retrofitting. The shading roof reduces solar heat gain to the building and, in the case of the canteen areas, this element not only improves thermal comfort conditions but

visual comfort as well, by substantially reducing glare through the existing large glazing surfaces. The newly inserted skylight shafts improve the air movement within the canteen area: ventilation grids will create a vertical flow of fresh air during the summer season.

Previously the two canteen spaces required mechanical ventilation throughout the year: supply air handling units heated or cooled the incoming air as necessary. In the new canteen the installation of the characteristic chimney-shaped skylights with louvred exhaust openings generate a natural process of air exhaustion; in the old canteen this process is permitted by the replacement of clerestory windows with opening lights. Single glazing has been removed from the facade of each canteen area and that which replaces it incorporates high and low level opening lights. Incoming air through low level openings rises by natural convection to exit through the skylight or the high level opening lights. Automatic high level windows and openings are thermostatically controlled but during extremely warm weather the users of the canteen spaces may moderate their own thermal comfort by opening low level windows or doors. The servery and the kitchen mechanical extract system will continue to draw air through the canteen.

7. Cooling technology

Historically, the importance of passive cooling techniques has been manifested in the evolution of different building forms, constructional methods and orientational alignments. From the earliest examples of construction a respect for the natural environment and the extremes of climate has been evident from the hillside Italian villas, taking full advantage of the fresh breezes, to buildings with massive walls and small openings found in various extremely hot climatic regions.

The subject of cooling technology addresses issues ranging from the making of buildings to post-construction applications of cooling techniques. Ideally the issues of cooling should be addressed in the design stage of a building in order to generate a holistic attitude to the reduction of heat gains by the building. Effective cooling not only addresses the removal of heat from the building but also the reduction of heat gains by the building: this may be applied whether in new-build or retrofitting situations.

Air conditioning, still considered a luxury during the 1950s has become a modern 'necessity'—whether or not a reflection of design competence in contemporary building or simply a result of higher expectations of thermal comfort by building occupants. In recent years the widespread use of air conditioning units has occurred parallel with an awareness of their negative climatological effects on the greater urban environment and the damaging effects of some of the process components. In more northern climates the use of air conditioning has become common in situations where their need is questionable, to say the least. The fragile relationship between the urban climate and summertime energy consumption of buildings for cooling needs is well-trodden territory and has been amply addressed by much research material which has commendably compiled economical and social statistical analyses, projected working and living conditions to identify progressive techniques and possible alternatives. By

utilising one, or a combination of the accepted means of natural ventilation, the building designer can both at the early design stage or in a retrofit situation significantly reduce the cooling load. In northern climates the use of natural ventilation is enough in some cases but with the presence of office equipment the occupant load increases and a further possibility is the use of a method of convective cooling which requires more careful planning to ensure good ventilation routes. Radiant cooling in combination with movable insulation is useful in hot climatic regions where ventilation succeeds only in heating the building and hot external air must be cooled before entry to the building; the building shell is heavily insulated and protected from solar gain and at night the insulation is removed; any heat that has built up during the day is released in the form of radiant energy to the black, night sky, the principle may also be used with a system of heat collectors to gather heat from inside the building and convey it to the exterior rather like a heating system operating in reverse.

Evaporative cooling is perhaps the most effective form of the natural cooling methods, useful in hot areas it takes advantage of the physical principle of latent energy; that is the large amount of energy required to change the physical state of a substance. This is evident in the cooling sensation experienced as ethyl alcohol evaporates from your skin: it is also the same principle on which the refrigerator is based. Apart from the chiller plant of air conditioning units evaporative cooling is not commonly used in buildings because of the obvious constructional difficulties but its effects have been well understood since ancient times as evident in the use of fountains in public spaces and the presence of a pool in the centre of the roman townhouse typology.

Earth cooling involves the construction of part or all of a building below ground taking advantage of the earth as a heat sink to stabilise its internal temperature. In the subterranean settlements to be found in North Africa built-up heat is transmitted by conduction to the earth which is at a lower temperature. A more indirect approach is to pre-cool the incoming air by means of underground ducts or through a subterranean basement storey.

7.1. *Passive cooling techniques*

- Cooling with ventilation: comfort ventilation; convective cooling.
- Radiant cooling: direct radiant cooling; indirect radiant cooling.
- Evaporative cooling: direct evaporation; indirect evaporation.
- Earth cooling: direct coupling; indirect coupling.
- Dehumidification

Cooling performances may be effected by both technological elements, such as passive solar components, and architectural elements thereby requiring the incorporation of these techniques into the general conception of building technology.

Investigating the possible integration of Solar Technology into industrial and commercial buildings promotes a more rational use of energy in buildings. Many office buildings, often by nature of what they contain, have a tendency to overheat during the summer; air-conditioning moderates the internal atmosphere but by so doing consumes vast amounts of peak load electricity whilst on an urban scale creates

unfavourable climatic effects. Energy consumption in summer is an increasing tendency in all European countries that can be reduced considerably by the rational use of buildings elements. Due to their extensive use of air-conditioning in the summer season, industrial and commercial buildings are prime subjects for considering the application of energy saving devices. Excessive heat is generated by industrial processes and office and catering equipment, which when combined with extreme summer temperatures results in a constant use of air-conditioning units.

Building devices may act as an intelligent interface between indoors and outdoors, which for the greater part are installed on the 'skin' of the building providing the appropriate thermal and air exchanges necessary for improving indoor conditions. Nowadays many important buildings throughout the world improve thermal conditions by creating this external skin surface with devices which are independent of the other internal parts. The exclusion of unwanted heat is effected by protecting the building from solar radiation, reducing heat gains from the ingress of warm air, by fitting insulation and by the appropriate sizing, positioning and shading of openings.

7.2. National Museum of Natural Sciences, Florence, Italy (L. Macce, G. Maggiora, A. Breschi, A. Cortesi, M. Moretti, M. Sala)

The decision to design an underground main hall, comprising the central core of the Museum, was assumed in consideration of the historical value of the existing buildings for the city of Florence, which represent an important document of 19th century expansion. The need for natural, top-lighting for the main hall and the desire for an architectural view from the lower level towards the other buildings, suggested the glazed roof solution. Possible strategies to minimise or avoid overheating during the summer season have been analysed, taking into account architectural constraints as well as the representative aspects of this part of the Museum. The solution utilises micronised water as a reflective layer to reduce solar penetration into the building: the white, soft cloud of mist will reflect a large part of the direct radiation, just as clouds and fog operate in nature. The cooling effect of evaporation will remove heat from the roof structure. It is envisaged that the realisation of this solution will be achieved through the use of a pipe network attached to the glazing frames, incorporating micronizers for the creation of the floating cloud and a pod into which drains the water for the cycle of filtration, pressurization and micronization. From the architectural point of view, the water cloud will appear as a virtual floating roof, creating a liquid sculpture for the Museum of Nature. The possibility of operating the system during the night will increase the night cooling of the entire structure.

7.3. British Pavilion, Expo 92, Seville, Spain (Nicholas Grimshaw)

Designed to represent the spirit of Britain, the British Pavilion bears many of the nautical hallmarks of Grimshaw's work: the single layer of the north wall and the internal layer of the south wall are constructed with constant reference to yachting technology using curved steel masts, spreaders and rigging with translucent PVC coated polyester fabric stretched between them. At another level, the building is further enhanced by its demonstration of the concept of cooling; in effect the entire

building could be described as a testament to cooling technology. Prior to the introduction of any mechanical cooling the building utilises various techniques and devices to moderate the extremes of temperature.

Essentially the building encloses a large volume in which there are floating terraces and exhibition pods. The envelope of the building is completely non-uniform with the different elements responding as necessary to the climatic conditions. On the east wall Grimshaw has introduced the water sculpture by William Pye to create a cooling water wall, 65 m long \times 18 m tall. The west wall shields the interior of the building from the full force of the afternoon sun and acts as a thermal store whilst the south wall appears like a line of sails providing the minimal shading required when the sun is at its highest but more importantly allows the air to circulate between the sails and the wall removing built up heat.

8. Outdoor spaces

The sensitivity of human perception to a changing climate, even when of a gentle magnitude is at the basis of study which attempts to determine and define physiological wellbeing in the presence of variable environmental parameters: the temperature and the humidity of the air, its velocity, the presence of thermal radiation from closely surrounding surfaces: these parameters, in the case of external spaces are not only influenced by the built environment but are also added to by the natural where they may either be reduced or reinforced.

The formation of large surfaces of water or dense areas of vegetation are amongst those more community-based interventions with which man has modified the microclimate of external spaces in warm climatic zones. Furthermore, the dimension of the street and its orientation, the ground materials, the form of the spaces, the height of the buildings all play a role in the definition of the external microclimate and within which the limits of other urbanistic and architectural parameters may be utilised in the design phase to achieve the desired results.

The principle of evaporative cooling as discussed previously in the section related to passive cooling plays a major role in the climate modification of outdoor spaces, historical references abound: the use of fountains and water surfaces in hot countries represent a constant architectural tradition; nevertheless it is only with study and recent application that these elements have been utilised in more scientific and precise ways, exploiting their maximum potential.

Evaporation occurs as a natural process, in the presence of water surfaces in environments with low relative humidity or through the transpiration of vegetation but may be promoted with increased air velocity, the emission of water particles using pumps and nebulisers or with the irrigation of surfaces at elevated temperatures, such as roofs, ground surfaces and covers in general.

In the historic context, the pedestrianisation of many historic centres and city districts opens for consideration the newly perceived importance of the street and the square as places of socialising and as a matrix of urban space. The possibilities of human gathering and interaction are facilitated by the characteristics of external space whose success is independent of meteorological characteristics and favour

environmental interventions with bioclimatic technologies and restrained costs; techniques which are compatible with functional and environmental aspects of urban design.

The consideration of external space in bioclimatic design does not signify that every court or open space may be considered a climatic control element: many are the parameters to be satisfied and the considerations which begin with the climate type determine the characteristics of a controllable space in its microclimate. These parameters may be the modifying conditions in the design of external space and represent the variables which define the surrounding climate in every situation, are the same as those which influence architectural design:

- Direct solar radiation
- Temperature of surrounding surfaces
- Air temperature
- Air velocity
- Relative humidity.

In the applications for external space, nevertheless, the specific characteristics of the place of intervention are still more conclusive in the conception of a design, and in spite of the fact that architectural tradition and culture have always considered the themes of external space, there are but few realised examples which demonstrate full competence with the support of study and sufficient scientific investigation. Amongst recent works, one of the more significant must surely be the Expo '92 in Seville, whether from the point of view of investment or the influx of the general public which from the methodological point of view has revealed that there are profound differences between the conventional conditioning systems applied to buildings and the treatment of external space and that in the latter case the servicing systems become a unique design problem which must be confronted from its basis at this time, with accurate investigative instruments. Furthermore, conceptually correct systems of intervention could be inadequate to the specific project application, since carrying out models should not be passively assumed, and every situation shows original parameters and features that should be solved through a collaboration among different specialistic contributions during the whole project development.

8.1. Shopping centre and offices in Finsbury Avenue, London, UK (Ove Arup Associates)

The glazing is shaded by vertically slatted bris-soleil, located externally, which also function as service communication trenches for maintenance, acting as diagonal wind-bracing ties at the upper floor levels. The sun shades, made of bronze anodised aluminium are mounted on a system of aluminium beams which extend along the east and west facades. Within the Finsbury building there is a large octagonal atrium, the structure of which is white synthepulvin-coated aluminium. This atrium constitutes the roof of a broad court against which run galleries assigned to offices and public walkways. In the centre and at four corners of the atrium there are sun-shades, the internal frames of which are made of grey aluminium, as are the glazing frames and the handrails. The cleaning and the maintenance of the atrium exterior is assured by a movable scaffold.

The broad covering structure, in which the various office spaces are to be found, contains a piazza internally, which has been conceived and designed not as a circumscribed entity, but in an interchanging relationship with the surrounding buildings and destined to constitute a focal point for recreational and cultural activities, in the sphere of a more broad design for the urban requalification of an area of the city of London. The realisation of this objective has been formalised in a prefabricated load-bearing structure of reinforced concrete which in the upper part houses flowers and timber pergolas and in the lower part contains routes and relaxation points. The theatrical image of the pergola and other ramping levels contribute to the creation of small terraces on the structure of a green oasis, evoking memories of an amphitheatre which descends with terraced seating at the lower levels of the piazza where the shops and services are concentrated to feed the metropolis.

8.2. *El Palenque, Exhibition Structure, Expo 1992, Seville, Spain (J. M. De La Prada Poole)*

El Palenque is a large space covered by a tensile sail structure, which has housed numerous performances/exhibitions and cultural entertainment during the course of the Expo at Seville. The lower part of the area was comprised of two connected piazzas, with clearly differentiated characteristics. The first elevated on its plinth of about one metre, bordering the second by three sides forming a belt of separation between it and the pedestrian avenues. It is treated as a shaded and fresh area protected from the surrounding context by four barriers; two of vegetation and two of water nebulisers and fountains. The second piazza, to the interior of the former, constitutes the performance space proper. Its general organisation and disposition of the vegetation areas at the front attempts to recreate the idea of a roman theatre. For complete shielding against the sun's rays large roofs and sails in PVC have been utilised, positioned with tensile structure systems above metal openwork. The form of the tense membrane itself suggested locating hot air extractors, similar to gigantic upturned funnels, on top of the structure together with water nebulizers so as to create evaporative towers that are able to lower the temperature of the air close to the ground. To control the external overheating of the membrane, an evaporative cooling method has been used with a continuous irrigation produced by microporated on the surface facing the sun.

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