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Preface

Purpose

The purpose of the *CRC Handbook of Engineering Tables* is to provide in a single volume a ready reference for the practicing engineer in industry, government, and academia. The tables and figures provided in this book include data and information from all fields of engineering in a comprehensive format. This information is organized into five sections: Electrical and Computer Engineering; Civil and Environmental Engineering; Chemical Engineering, Chemistry and Material Science; Mechanical Engineering; and General Engineering and Mathematics. The 450 tables and figures are compiled from 51 books and are inclusive of most ready available, important data widely used by the engineering practitioner.

Locating Your Topic

Two avenues of access to information are provided. A complete table of contents is provided at the front of the book. An index is provided at the end of the book. The *CRC Handbook of Engineering Tables* provides answers to most engineering data with reference to the original source. The reader may find it valuable to refer to the original source for a fuller discussion of the underlying theory. We hope that this handbook will be ready at hand to provide data on engineering methods, devices, materials, chemistry, and mathematics.

Acknowledgement

The handbook was compiled with the generous help of the editors and authors of the original sources and I am grateful for their assistance. I wish to acknowledge the diligent help of my editor, Nora Konopka, and my editorial project development supervisor, Helena Redshaw.

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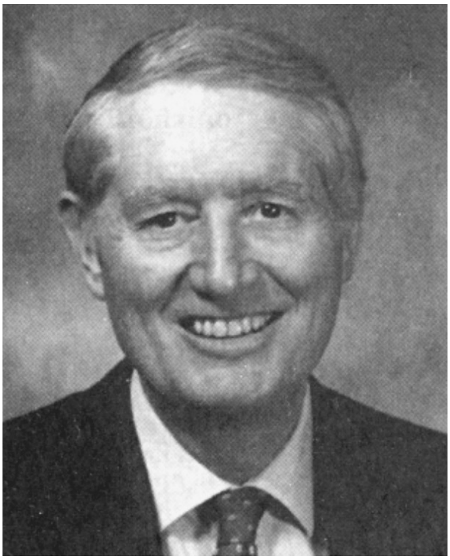
Dedication

I wish to dedicate this book to the memory of my mother and father, Marion Fraser Dorf and William Carl Dorf.

Editor-in-Chief



Richard C. Dorf, professor of electrical and computer engineering at the University of California, Davis, teaches graduate and undergraduate courses in electrical engineering in the fields of circuits and control systems. He earned a Ph.D. in electrical engineering from the U.S. Naval Postgraduate School, an M.S. from the University of Colorado, and a B.S. from Clarkson University. Highly concerned with the discipline of engineering and its wide value to social and economic needs, he has written and lectured internationally on the contributions and advances in engineering and their value to society.

Professor Dorf has extensive experience with education and industry and is professionally active in the fields of robotics, automation, electric circuits, and communications. He has served as a visiting professor at the University of Edinburgh, Scotland; the Massachusetts Institute of Technology; Stanford University; and the University of California, Berkeley.

A Fellow of The Institute of Electrical and Electronics Engineers, Dr. Dorf is widely known to the profession for his *Modern Control Systems*, 10th Edition (Prentice Hall 2004) and *Introduction to Electric Circuits,* 6th Edition (Wiley 2004). He is the Editor-in-Chief of the *Electrical Engineering Handbook,* 2nd Edition (CRC Press 1997), the *Technology Management Handbook* (CRC Press 1999), and the *Engineering Handbook,* 2nd Edition (CRC Press 2004).

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Parameters and Characteristics of Discrete Capacitors

Capacitor Type	Range	Rated Voltage, V_R	TTC ppm/°C	Tolerance ±%	Insulation Resistance, MΩµF	Dissipation Factor, %	Dielectric Absorption %	Temperature Range, °C	Comments, Applications	Cost
Polycarbonate	100 pF–30 µF	50–800	±50	10	5×10^5	0.2	0.1	–55/+125	High quality, small, low TC	High
Polyester/Mylar	1000 pF–50 µF	50–600	+400	10	10^5	0.75	0.3	–55/+125	Good, popular	Medium
Polypropylene	100 pF–50 µF	100–800	–200	10	10^5	0.2	0.1	–55/+105	High quality low absorption	High
Polystyrene	10 pF–2.7 µF	100–600	–100	10	10^6	0.05	0.04	–55/+85	High quality, large, low TC, signal filters	Medium
Polysulfone	1000 pF–1 µF		+80	5	10^5	0.3	0.2	–55/+150	High temperature	High
Parylene	5000 pF–1 µF		±100	10	10^5	0.1	0.1	–55/+125		High
Kapton	1000 pF–1 µF		+100	10	10^5	0.3	0.3	–55/+220	High temperature	High
Teflon	1000 pF–2 µF	50–200	–200	10	5×10^6	0.04	0.04	–70/+250	High temperature lowest absorption	High
Mica	5 pF–0.01 µF	100–600	–50	5	2.5×10^4	0.001	0.75	–55/+125	Good at RF, low TC	High
Glass	5 pF–1000 pF	100–600	+140	5	10^6	0.001		–55/+125	Excellent long-term stability	High
Porcelain	100 pF–0.1 µF	50–400	+120	5	5×10^5	0.10	4.2	–55/+125	Good long-term stability	High
Ceramic (NPO)	100 pF–1 µF	50–400	±30	10	5×10^3	0.02	0.75	–55/+125	Active filters, low TC	Medium
Ceramic	10 pF–1 µF	50–30,000						–55/+125	Small, very popular selectable TC	Low
Paper	0.01 µF–10 µF	200–1600	±800	10	5×10^3	1.0	2.5	–55/+125	Motor capacitors	Low
Aluminum	0.1 µF–1.6 F	3–600	+2500	–10/+100	100	10	8.0	–40/+85	Power supply filters short life	High
Tantalum (Foil)	0.1 µF–1000 µF	6–100	+800	–10/+100	20	4.0	8.5	–55/+85	High capacitance small size, low inductance	High
Thin-film	10 pF–200 pF	6–30	+100	10	10^6	0.01		–55/+125		High
Oil	0.1 µF–20 µF	200–10,000				0.5			High voltage filters, large, long life	
Vacuum	1 pF–1000 pF	2000–3600							Transmitters	

From Whitaker, J.C., The origins of AC line disturbances, in *AC Power Systems Handbook*, 2nd ed., CRC Press, Boca Raton, FL, 1999, p. 56. Originally published in Filanovsky, I.M., Capacitance and Capacitors, in *The Electronics Handbooks*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1996, p. 371. With permission.

Electrical Properties of Common Insulating Liquids

Liquid	Viscosity cST (37.8°C)	Dielectric Constant (at 60 Hz, 25°C)	Dissipation Factor (at 60 Hz, 100°C)	Breakdown Strength (kV cm^{-1})
Capacitor oil	21	2.2	0.001	>118
Pipe cable oil	170	2.15	0.001	>118
Self-contained cable oil	49.7	2.3	0.001	>118
Heavy cable oil	2365	2.23	0.001	>118
Transformer oil	9.75	2.25	0.001	>128
Alkyl benzene	6.0	2.1	0.0004	>138
Polybutene pipe cable oil	110 (SUS)	2.14 (at 1 MHz)	0.0003	>138
Polybutene capacitor oil	2200 (SUS at 100°C)	2.22 (at 1 MHz)	0.0005	>138
Silicone fluid	50	2.7	0.00015	>138
Castor oil	98 (100°C)	3.74	0.06	>138
$C_8F_{16}O$ fluorocarbon	0.64	1.86	<0.0005	>138

From Whitaker, J.C., The origins of AC line disturbances, in *AC Power Systems Handbook*, 2nd ed., CRC Press, Boca Raton, FL, 1999, p. 64. Originally published in Bartnikas, R., Dielectrics and Insulators, in *The Electrical Engineering Handbook*, Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1993, p. 1132. With permission.

Types of Systemwide Protection Equipment Available to Facility Managers and the AC Line Abnormalities That Each Approach Can Handle

System	Type 1	Type 2	Type 3
UPS system and standby generator	All source transients; no load transients	All	All
UPS system	All source transients; no load transients	All	All outages shorter than the battery supply discharge time
Secondary spot network[1]	None	None	Most, depending on the type of outage
Secondary selective network[2]	None	Most	Most, depending on the type of outage
Motor-generator set	All source transients; no load transients	Most	Only brown-out conditions
Shielded isolation transformer	Most source transients; no load transients	None	None
Suppressors, filters, lightning arrestors	Most transients	None	None
Solid-state line voltage regulator/filter	Most source transients; no load transients	Some, depending on the response time of the system	Only brown-out conditions

[1] Dual power feeder network.
[2] Dual power feeder network using a static (solid-state) transfer switch.

From Whitaker, J.C., Power system protection alternatives, in *AC Power Systems Handbook*, 2nd ed., CRC Press, Boca Raton, FL, 1999, p. 267. After Key, Lt. Thomas, "The Effects of Power Disturbances on Computer Operation," IEEE Industrial and Commercial Power Systems Conference, Cincinnati, June 7, 1978, and Federal Information Processing Standards Publication No. 94, *Guideline on Electrical Power for ADP Installations*, U.S. Department of Commerce, National Bureau of Standards, Washington, D.C., 1983.

Comparison of System Grounding Methods

Characteristic Assuming No Fault Escalation	System Grounding Method		
	Solidly Grounded	Ungrounded	High Resistance
Operation of overcurrent device on first ground fault	Yes	No	No
Control of internally generated transient overvoltages	Yes	No	Yes
Control of steady-state overvoltages	Yes	No	Yes
Flash hazard	Yes	No	No
Equipment damage from arcing ground-faults	Yes	No	No
Overvoltage (on unfaulted phases) from ground-fault[1]	L-N Voltage	>>L-L-Voltage	L-L Voltage
Can serve line-to-neutral loads	Yes	No	No

[1] L = line, N = neutral

From Whitaker, J.C., Facility grounding, in *AC Power Systems Handbook*, 2nd ed., CRC Press, Boca Raton, FL:, 1999, p. 373. After IEEE Standard 142, "Recommended Practice for Grounding Industrial and Commercial Power Systems," IEEE, New York, 1982.

Typical Resistivity of Common Soil Types

Type of Soil Resistivity in Ω/cm	Average	Minimum	Maximum
Filled land, ashes, salt marsh	2400	600	7000
Top soils, loam	4100	340	16,000
Hybrid soils	6000	1000	135,000
Sand and gravel	90,000	60,000	460,000

From Whitaker, J.C., Facility grounding, in *AC Power Systems Handbook*, 2nd ed., CRC Press, Boca Raton, FL, 1999, p. 379.

Specifications of Standard Copper Wire

Wire Size AWG	Dia. in Mils	Cir. Mil Area	Turns per Linear Inch[1] Enamel	S.C.E.	D.C.C.	Ohms per 100 ft[2]	Current Carry Capacity[3]	Dia. in mm
1	289.3	83810	—	—	—	0.1239	119.6	7.348
2	257.6	05370	—	—	—	0.1563	94.8	6.544
3	229.4	62640	—	—	—	0.1970	75.2	5.827
4	204.3	41740	—	—	—	0.2485	59.6	5.189
5	181.9	33100	—	—	—	0.3133	47.3	4.621
6	162.0	26250	—	—	—	0.3951	37.5	4.115
7	144.3	20820	—	—	—	0.4982	29.7	3.665
8	128.5	16510	7.6	—	7.1	0.6282	23.6	3.264
9	114.4	13090	8.6	—	7.8	0.7921	18.7	2.906
10	101.9	10380	9.6	9.1	8.9	0.9989	14.8	2.588
11	90.7	8234	10.7	—	9.8	1.26	11.8	2.305
12	80.8	6530	12.0	11.3	10.9	1.588	9.33	2.063
13	72.0	5178	13.5	—	12.8	2.003	7.40	1.828
14	64.1	4107	15.0	14.0	13.8	2.525	5.87	1.628
15	57.1	3257	16.8	—	14.7	3.184	4.65	1.450
16	50.8	2583	18.9	17.3	16.4	4.016	3.69	1.291
17	45.3	2048	21.2	—	18.1	5.064	2.93	1.150
18	40.3	1624	23.6	21.2	19.8	6.386	2.32	1.024
19	35.9	1288	26.4	—	21.8	8.051	1.84	0.912
20	32.0	1022	29.4	25.8	23.8	10.15	1.46	0.812
21	28.5	810	33.1	—	26.0	12.8	1.16	0.723
22	25.3	642	37.0	321.3	30.0	16.14	0.918	0.644
23	22.6	510	41.3	—	37.6	20.36	0.728	0.573
24	20.1	404	46.3	37.6	35.6	25.67	0.577	0.511
25	17.9	320	51.7	—	38.6	32.37	0.458	0.455
26	15.9	254	58.0	46.1	41.8	40.81	0.363	0.406
27	14.2	202	64.9	—	45.0	51.47	0.288	0.361
28	12.6	160	72.7	54.6	48.5	64.9	0.228	0.321
29	11.3	127	81.6	—	51.8	81.83	0.181	0.286
30	10.0	101	90.5	64.1	55.5	103.2	0.144	0.255
31	8.9	50	101	—	59.2	130.1	0.114	0.227
32	8.0	63	113	74.1	61.6	164.1	0.090	0.202
33	7.1	50	127	—	66.3	206.9	0.072	0.180
34	6.3	40	143	86.2	70.0	260.9	0.057	0.160
35	5.6	32	158	—	73.5	329.0	0.045	0.143
36	5.0	25	175	103.1	77.0	414.8	0.036	0.127
37	4.5	20	198	—	80.3	523.1	0.028	0.113
38	4.0	16	224	116.3	83.6	659.6	0.022	0.101
39	3.5	12	248	—	86.6	831.8	0.018	0.090

Notes:

[1] Based on 25.4 mm.

[2] Ohms per 1000 ft measured at 20°C.

[3] Current carrying capacity at 700 C.M./A.

From Whitaker, J.C., Conversion tables, in *AC Power Systems Handbook*, 2nd., CRC Press, Boca Raton, FL, 1999, pp. 528–529.

Parameters of Some First-Generation Cellular Standards

Parameters	AMPS	C450	NMT 450	NTT	TACS
Tx Frequency (MHz)					
Mobile	824–849	450–455.74	453–457.5	925–940	890–915
Base Station	869–894	460–465.74	463–467.5	870–885	935–960
Channel bandwidth (kHz)	30	20	25	25	25
Spacing between forward and reverse channels (MHz)	45	10	10	55	45
Speech signal FM deviation	±12	±5	±5	±5	±9.5
Control signal data rate (kbps)	10	5.28	1.2	0.3	8
Handoff decision is based on	Power received at base	Round-trip delay	Power received at base	Power received at base	Power received at base

From Godara, L.C., Cellular systems, in *Handbook of Antennas in Wireless Communications*, Godara, L.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-15.

Parameters of Some Second-Generation Cellular Standards

Parameters	IS-54	GSM	IS-95	PDC
TX frequencies (MHz)				
Mobile	824–849	890–915	824–849	940–956 and 1429–1453
Base station	869–894	935–960	869–894	810–826 and 1477–1501
Channel bandwidth (kHz)	30 kHz	200 kHz	1250 kHz	25 kHz
Spacing between forward and reverse channels (MHz)	45	45	45	30/48
Modulation	π/4 DQPSK	GMSK	BPSK/QPSK	π/4 DQPSK
Frame duration (ms)	40	4.615	20	20

From Godara, L.C., Cellular systems, in *Handbook of Antennas in Wireless Communications*, Godara, L.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-16.

Comparison of Satellite Systems as a Function of Orbit

Characteristic	LEO	MEO	GEO
Satellite height (km)	600–1,500	9,000–11,000	35,800
Orbital period (hr)	1–2	6–8	24
Number of satellites	40–80	8–20	2–4
Two-way propagation delay (ms)	10–15	150–250	480–540
Satellite life (years)	3–7	10–15	10–15
Elevation angle	Medium	Best	Good
Visibility of satellite	Short	Medium	Permanent
Handheld terminal	Possible	Possible	Restricted
Handover	Frequent	Infrequent	None
Cost of satellite	Maximum	Minimum	Medium
Gateway cost	Highest	Medium	Lowest
Network complexity	Complex	Medium	Simplest
Radio frequency output power	Low	Medium	High
Propagation loss	Low	Medium	High

From Ryan, M.J., Satellite-based mobile communications, in *Handbook of Antennas in Wireless Communications,* Godara, L.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **2**-8.

Summary of Transmission Media Characteristics

Cable Type	Twisted Shielded Pair
Capacitance	30.0 pF/ft max — wire to wire
Characteristic Impedance	70.0 to 85.0 ohms at 1 MHz
Cable Attenuation	1.5 dbm/100 ft at 1 MHz
Cable Twists	4 twists per foot maximum
Shield Coverage	90% minimum
Cable Termination	Cable impedance (±2%)
Direct Coupled Stub Length	Maximum of 1 ft
Transformer Coupled Stub Length	Maximum of 20 ft

From deLong, C., AS 15531/MIL-STD-1553B digital time division command/response multiplex data bus, in *The Avionics Handbook,* Spitzer, C.R., Ed., CRC Press, Boca Raton, FL, 2001, , p. **1**-5.

CSDB Physical Characteristics

Modulation Technique	Non-Return to Zero (NRZ)
Logic Sense for Logic "0"	Line B Positive with Respect to Line A
Logic Sense for Logic "1"	Line A Positive with Respect to Line B
Bus Receiver	High Impedance, Differential Input
Bus Transmitter	Differential Line Driver
Bus Signal Rates	Low Speed: 12,500 bps High Speed: 50,000 bps
Signal Rise-Time and Fall-Time	Low Speed: 8 μs High-Speed: 0.8–1.0 μs
Receiver Capacitance Loading	Typical: 600 pF Maximum: 1,200 pF
Transmitter Driver Capability	Maximum: 12,000 pF

From Harrison, L.H., Commercial standard digital bus, in *The Avionics Handbook,* Spitzer, C.R., Ed., CRC Press, Boca Raton, FL, 2001, p. **3**-4. Originally published in *Commercial Standard Digital Bus,* 8th ed., Collins General Aviation Division, Rockwell International Corporation, Cedar Rapids, IA, January 30, 1991.

Sensor Data Required for Full Flight Regime Operation

Input Data	Data Source
Attitude	Pitch and Roll Angles — 2 independent sources
Airspeed	Calibrated Airspeed
	Low Speed Awareness Speed(s) (e.g., Vstall)
	High Speed Awareness Speed(s) (e.g., Vmo)
Altitude	Barometric Altitude (pressure altitude corrected with altimeter setting)
	Radio Altitude
Vertical Speed	Vertical Speed (inertial if available, otherwise raw air data)
Slip/Skid	Lateral Acceleration
Heading	Magnetic Heading
	True Heading or other heading (if selectable)
	Heading Source Selection (if other than Magnetic selectable)
Navigation	Selected Course
	VOR Bearing/Deviation
	DME Distance
	Localizer Deviation
	Glideslope Deviation
	Marker Beacons
	Bearings/Deviations/Distances for any other desired nav signals (e.g., ADF, TACAN, RNAV/FMS)
Reference Information	Selected Airspeed
	Selected Altitude
	Selected Heading
	Other Reference Speed Information (e.g., V_1, V_R, Vapch)
	Other Reference Altitude Information (e.g., landing minimums [DH/MDA], altimeter setting)
Flight Path	Pitch Angle
	Roll Angle
	Heading (Magnetic or True, same as Track)
	Ground Speed (inertial or equivalent)
	Track Angle (Magnetic or True, same as Heading)
	Vertical Speed (inertial or equivalent)
	Pitch Rate, Yaw Rate
Flight Path Acceleration	Longitudinal Acceleration
	Lateral Acceleration
	Normal Acceleration
	Pitch Angle
	Roll Angle
	Heading (Magnetic or True, same as Track)
	Ground Speed (inertial or equivalent)
	Track Angle (Magnetic or True, same as Heading)
	Vertical Speed (inertial or equivalent)
Automatic Flight Control System	Flight Director Guidance Commands
	Autopilot/Flight Director Modes
	Autothrottle Modes
Miscellaneous	Wind Speed
	Wind Direction (and appropriate heading reference)
	Mach
	Windshear Warning(s)
	Ground Proximity Warning(s)
	TCAS Resolution Advisory Information

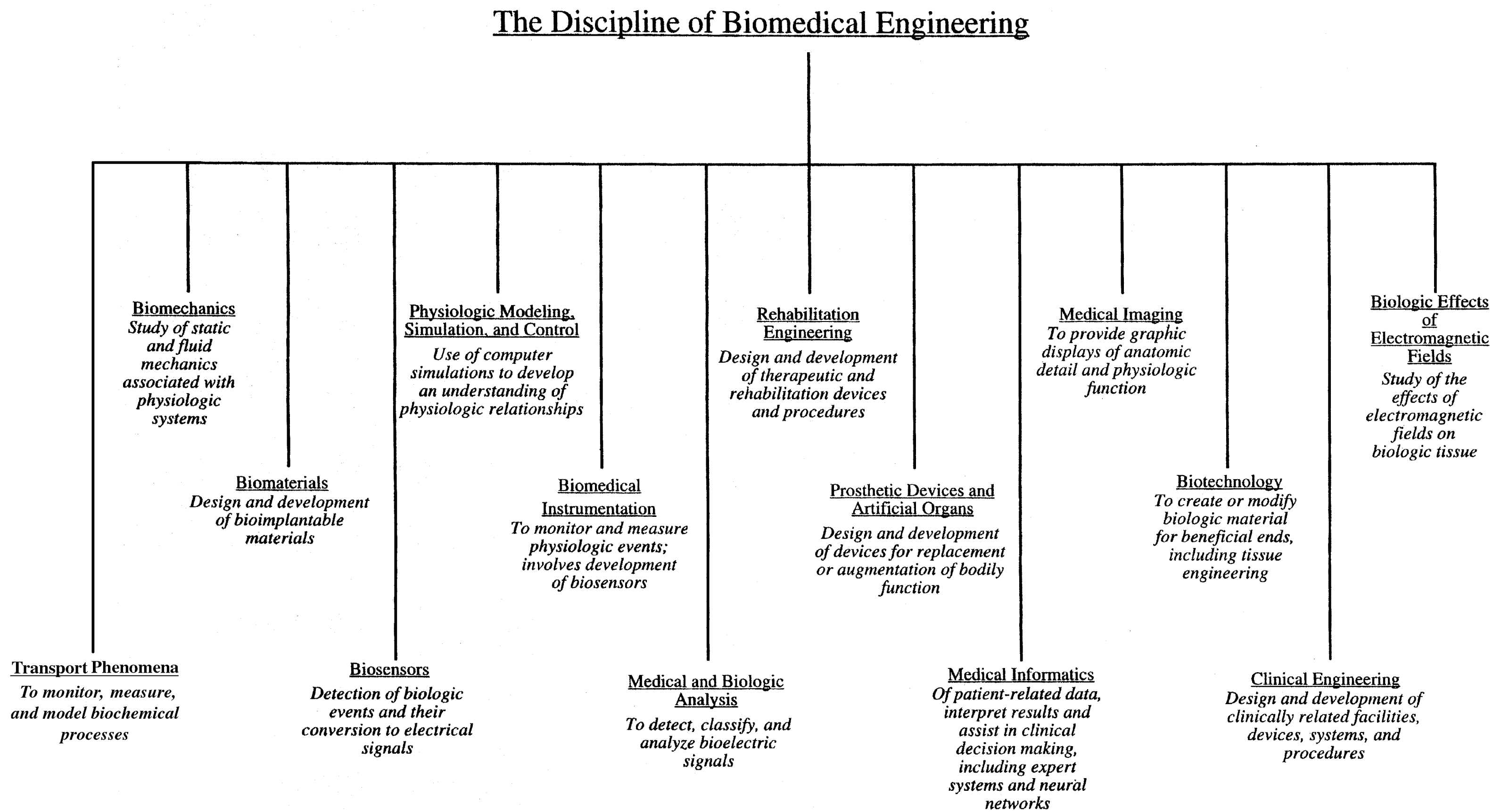
From Wood, R.B. and Howells, P.J., Head-up displays, in *The Avionics Handbook,* Spitzer, C.R., Ed., CRC Press, Boca Raton, FL, 2001, p. **4**-14.

Categorization of Fault-Tolerant Software Techniques

Multiversion Software
N-Version Program
Cranfield Algorithm for Fault-Tolerance (CRAFT) Food Taster
Distinct and Dissimilar Software
Recovery Blocks
Deadline Mechanism
Dissimilar Backup Software
Exception Handlers
Hardened Kernel
Robust Data Structures and Audit Routines
Run Time Assertions[a]
Hybrid Multiversion Software and Recovery Block Techniques
Tandem
Consensus Recovery Blocks

[a] Not a complete fault-tolerant software technique as it only detects errors.

From Hitt, E.F. and Mulcare, D., Fault-tolerant avionics, in *The Avionics Handbook,* Spitzer, C.R., Ed., CRC Press, Boca Raton, FL, 2001, p. **28**-20. Originally from Hitt, E. et al., *Study of Fault-Tolerant Software Technology,* NASA CR 172385.



From *The Biomedical Engineering Handbook,* 2nd ed., Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000. p. x.

Hematocytes

Cell Type	Number Cells per mm^3 Blood*	Corpuscular Diameter (μm)*	Corpuscular Surface Area (μm^2)*	Corpuscular Volume (μm^3)*	Mass Density (g/cm^3)*	Percent Water*	Percent Protein*	Percent Extractives*†
Erythrocytes	4.2–5.4	6–9 (7.5)	120–163	80–100	1.089–1.100	64–68	29–35	1.6–2.8
(red blood cells)	$\times 10^6$ ♀	Thickness	(140)	(90)	(1.098)	(66)	(32)	(2)
	4.6–6.2	1.84–2.84						
	$\times 10^6$ ♂	"Neck"						
	(5×10^6)	0.81–1.44						
Leukocytes	4000–11000	6–10	300–625	160–450	1.055–1.085	52–60	30–36	4–18
(white blood cells)	(7500)					(56)	(33)	(11)
Granulocytes								
Neutrophils:	$2–6 \times 10^3$	8–8.6	422–511	268–333	1.075–1.085	—	—	—
55–70% WBC (65%)	(4875)	(8.3)	(467)	(300)	(1.080)			
Eosinophils:	45–480	8–9	422–560	268–382	1.075–1.085	—	—	—
1–4% WBC (3%)	(225)	(8.5)	(491)	(321)	(1.080)			
Basophils:	0–113	7.7–8.5	391–500	239–321	1.075–1.085	—	—	—
0–1.5% WBC (1%)	(75)	(8.1)	(445)	(278)	(1.080)			
Agranulocytes								
Lymphocytes:	1000–4800	6.75–7.34	300–372	161–207	1.055–1.070	—	—	—
20–35% WBC (25%)	(1875)	(7.06)	(336)	(184)	(1.063)			
Monocytes:	100–800	9–9.5	534–624	382–449	1.055–1.070	—	—	—
3–8% WBC (6%)	(450)	(9.25)	(579)	(414)	(1.063)			
Thrombocytes	(1.4 ♂),	2–4 (3)	16–35	5–10	1.04–1.06	60–68	32–40	Neg.
(platelets)	2.14 (♀)–5	Thickness	(25)	(7.5)	(1.05)	(64)	(36)	
(2.675×10^5)	$\times 10^5$	0.9–1.3						

*Normal physiologic range, with "typical" value in parentheses.

†Extractives include mostly minerals (ash), carbohydrates, and fats (lipids).

From Schneck, D.J., An outline of cardiovascular structure and function, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1., Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-2.

Plasma

Constituent	Concentration Range (mg/dl plasma)	Typical Plasma Value (mg/dl)	Molecular Weight Range	Typical Value	Typical size (nm)
Total protein, 7% by weight	6400–8300	7245	21,000–1,200,000	—	—
Albumin (56% TP)	2800–5600	4057	66,500–69,000	69,000	15 × 4
α_1-*Globulin* (5.5% TP)	300–600	400	21,000–435,000	60,000	5–12
α_2-*Globulin* (7.5% TP)	400–900	542	100,000–725,000	200,000	50–500
β-*Globulin* (13% TP)	500–1230	942	90,000–1,200,000	100,000	18–50
γ-*Globulin* (12% TP)	500–1800	869	150,000–196,000	150,000	23 × 4
Fibrinogen (4% TP)	150–470	290	330,000–450,000	390,000	(50–60) × (3–8)
Other (2% TP)	70–210	145	70,000–1,000,000	200,000	(15–25) × (2–6)
Inorganic ash, 0.95% by weight	930–1140	983	20–100	—	— (Radius)
Sodium	300–340	325	—	22.98977	0.102 (Na^+)
Potassium	13–21	17	—	39.09800	0.138 (K^+)
Calcium	8.4–11.0	10	—	40.08000	0.099 (Ca^{2+})
Magnesium	1.5–3.0	2	—	24.30500	0.072 (Mg^{2+})
Chloride	336–390	369	—	35.45300	0.181 (Cl^-)
Bicarbonate	110–240	175	—	61.01710	0.163 (HCO_3^-)
Phosphate	2.7–4.5	3.6	—	95.97926	0.210 (HPO_4^{2-})
Sulfate	0.5–1.5	1.0	—	96.05760	0.230 (SO_4^{2-})
Other	0–100	80.4	20–100	—	0.1–0.3
Lipids (fats), 0.80% by weight	541–1000	828	44,000–3,200,000	= Lipoproteins	Up to 200 or more
Cholesterol (34% TL)	12–105 "free" 72–259 esterified, 84–364 "total"	59 224 283	386.67	Contained mostly in intermediate to LDL β-lipoproteins; higher in women	
Phospholipid (35% TL)	150–331	292	690–1010	Contained mainly in HDL to VHDL α_1-lipoproteins	
Triglyceride (26% TL)	65–240	215	400–1370	Contained mainly in VLDL α_2-lipoproteins and chylomicrons	
Other (5% TL)	0–80	38	280–1500	Fat-soluble vitamins, prostaglandins, fatty acids	
Extractives, 0.25% by weight	200–500	259	—	—	—
Glucose	60–120, fasting	90	—	180.1572	0.86 D
Urea	20–30	25	—	60.0554	0.36 D
Carbohydrate	60–105	83	180.16–342.3	—	0.74–0.108 D
Other	11–111	61	—	—	—

From Schneck, D.J., An outline of cardiovascular structure and function, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-3.

Arterial System*

Blood Vessel Type	(Systemic) Typical Number	Internal Diameter Range	Length Range†	Wall Thickness	Systemic Volume	(Pulmonary) Typical Number	Pulmonary Volume
Aorta	1	1.0–3.0 cm	30–65 cm	2–3 mm	156 ml	—	—
Pulmonary artery	—	2.5–3.1 cm	6–9 cm	2–3 cm	—	1	52 ml
Wall morphology: Complete tunica adventitia, external elastic lamina, tunica media, internal elastic lamina, tunica intima, subendothelium, endothelium, and vasa vasorum vascular supply							
Main branches	32	5 mm–2.25 cm	3.3–6 cm	≃2 mm	83.2 ml	6	41.6 ml
(Along with the aorta and pulmonary artery, the largest, most well-developed of all blood vessels)							
Large arteries	288	4.0–5.0 mm	1.4–2.8 cm	≃1 mm	104 ml	64	23.5 ml
(A well-developed tunica adventitia and vasa vasorum, although wall layers are gradually thinning)							
Medium arteries	1152	2.5–4.0 mm	1.0–2.2 cm	≃0.75 mm	117 ml	144	7.3 ml
Small arteries	3456	1.0–2.5 mm	0.6–1.7 cm	≃0.50 mm	104 ml	432	5.7 ml
Tributaries	20,736	0.5–1.0 mm	0.3–1.3 cm	≃0.25 mm	91 ml	5184	7.3 ml
(Well-developed tunica media and external elastic lamina, but tunica adventitia virtually nonexistent)							
Small rami	82,944	250–500 µm	0.2–0.8 cm	≃125 µm	57.2 ml	11,664	2.3 ml
Terminal branches	497,664	100–250 µm	1.0–6.0 mm	≃60 µm	52 ml	139,968	3.0 ml
(A well-developed endothelium, subendothelium, and internal elastic lamina, plus about two to three 15-µm-thick concentric layers forming just a very thin tunica media; no external elastic lamina)							
Arterioles	18,579,456	25–100 µm	0.2–3.8 mm	≃20–30 µm	52 ml	4,094,064	2.3 ml
Wall morphology: More than one smooth muscle layer (with nerve association in the outermost muscle layer), a well-developed internal elastic lamina; gradually thinning in 25- to 50-µm vessels to a single layer of smooth muscle tissue, connective tissue, and scant supporting tissue.							
Metarterioles	238,878,720	10–25 µm	0.1–1.8 mm	≃5–15 µm	41.6 ml	157,306,536	4.0 ml
(Well-developed subendothelium; discontinuous contractile muscle elements; one layer of connective tissue)							
Capillaries	16,124,431,360	3.5–10 µm	0.5–1.1 mm	≃0.5–1 µm	260 ml	3,218,406,696	104 ml
(Simple endothelial tubes devoid of smooth muscle tissue; one-cell-layer-thick walls)							

*Vales are approximate for a 68.7-kg individual having a total blood volume of 5200 ml.

†Average uninterrupted distance between branch origins (except aorta and pulmonary artery, which are total length).

From Schneck, D.J., An outline of cardiovascular structure and functions, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-8.

Venous System

Blood Vessel Type	(Systemic) Typical Number	Internal Diameter Range	Length Range	Wall Thickness	Systemic Volume	(Pulmonary) Typical Number	Pulmonary Volume
Postcapillary venules	4,408,161,734	8–30 μm	0.1–0.6 mm	1.0–5.0 μm	166.7 ml	306,110,016	10.4 ml
(Wall consists of thin endothelium exhibiting occasional pericytes (pericapillary connective tissue cells) which increase in number as the vessel lumen gradually increases)							
Collecting venules	160,444,500	30–50 μm	0.1–0.8 mm	5.0–10 μm	161.3 ml	8,503,056	1.2 ml
(One complete layer of pericytes, one complete layer of veil cells (veil-like cells forming a thin membrane), occasional primitive smooth muscle tissue fibers that increase in number with vessel size)							
Muscular venules	32,088,900	50–100 μm	0.2–1.0 mm	10–25 μm	141.8 ml	3,779,136	3.7 ml
(Relatively thick wall of smooth muscle tissue)							
Small collecting veins	10,241,508	100–200 μm	0.5–3.2 mm	≃30 μm	329.6 ml	419,904	6.7 ml
(Prominent tunica media of continuous layers of smooth muscle cells)							
Terminal branches	496,900	200–600 μm	1.0–6.0 mm	30–150 μm	206.6 ml	34,992	5.2 ml
(A well-developed endothelium, subendothelium, and internal elastic lamina; well-developed tunica media but fewer elastic fibers than corresponding arteries and much thinner walls)							
Small veins	19,968	600 μm–1.1 mm	2.0–9.0 mm	≃0.25 mm	63.5 ml	17,280	44.9 ml
Medium veins	512	1–5 mm	1–2 cm	≃0.50 mm	67.0 ml	144	22.0 ml
Large veins	256	5–9 mm	1.4–3.7 cm	≃0.75 mm	476.1 ml	48	29.5 ml
(Well-developed wall layers comparable to large arteries but about 25% thinner)							
Main branches	224	9.0 mm–2.0 cm	2.0–10 cm	≃1.00 mm	1538.1 ml	16	39.4 ml
(Along with the vena cava and pulmonary veins, the largest, most well-developed of all blood vessels)							
Vena cava	1	2.0–3.5 cm	20–50 cm	≃1.50 mm	125.3 ml	—	—
Pulmonary veins	—	1.7–2.5 cm	5–8 cm	≃1.50 mm	—	4	52 ml
Wall morphology: Essentially the same as comparable major arteries but a much thinner tunica intima, a much thinner tunica media, and a somewhat thicker tunica adventitia; contains a vasa vasorum							

Total systemic blood volume: 4394 ml—84.5% of total blood volume; 19.5% in arteries (~3:2 large:small), 5.9% in capillaries, 74.6% in veins (~3:1 large:small); 63% of volume is in vessels greater than 1 mm internal diameter

Total pulmonary blood volume: 468 ml—9.0% of total blood volume; 31.8% in arteries, 22.2% in capillaries, 46% in veins; 58.3% of volume is in vessels greater than 1 mm internal diameter; remainder of blood in heart, about 338 ml (6.5% of total blood volume)

From Schneck, D.J., An outline of cardiovascular structure and functions, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-8.

Main Endocrine Glands and the Hormones They Produce and Release

Gland	Hormone	Chemical Characteristics
Hypothalamus/median eminence	Thyrotropin-releasing hormone (TRH)	Peptides
	Somatostatin	
	Gonadotropin-releasing hormone	Amine
	Growth hormone-releasing hormone	
	Corticotropin-releasing hormone	
	Prolactin inhibitor factor	
Anterior pituitary	Thyrotropin (TSH)	Glycoproteins
	Luteinizing hormone	
	Follicle-stimulating hormone (FSH)	Proteins
	Growth hormone	
	Prolactin	
	Adrenocorticotropin (ACTH)	
Posterior pituitary	Vasopressin (antidiuretic hormone, ADH)	
	Oxytocin	Peptides
Thyroid	Triidothyronine (T3)	Tyrosine derivatives
	Thyroxine (T4)	
Parathyroid	Parathyroid hormone (PTH)	Peptide
Adrenal cortex	Cortisol	Steroids
	Aldosterone	
Adrenal medulla	Epinephrine	Catecolamines
	Norepinephrine	
Pancreas	Insulin	Proteins
	Glucagon	
	Somatostatin	
Gonads: Testes	Testosterone	Steroids
Ovaries	Oestrogen	
	Progesterone	

From Cramp, D.G. and Carson, E.R., Endocrine system, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **2**-3.

Typical Lung Volumes for Normal, Healthy Males

Lung Volume	Normal Values	
Total lung capacity (TLC)	6.0×10^{-3} m^3	(6,000 cm^3)
Residual volume (RV)	1.2×10^{-3} m^3	(1,200 cm^3)
Vital capacity (VC)	4.8×10^{-3} m^3	(4,800 cm^3)
Inspiratory reserve volume (IRV)	3.6×10^{-3} m^3	(3,600 cm^3)
Expiratory reserve volume (ERV)	1.2×10^{-3} m^3	(1,200 cm^3)
Functional residual capacity (FRC)	2.4×10^{-3} m^3	(2,400 cm^3)
Anatomic dead volume (V_D)	1.5×10^{-4} m^3	(150 cm^3)
Upper airways volume	8.0×10^{-5} m^3	(80 cm^3)
Lower airways volume	7.0×10^{-5} m^3	(70 cm^3)
Physiologic dead volume (V_D)	1.8×10^{-4} m^3	(180 cm^3)
Minute volume ($\dot{V}_e$) at rest	1.0×10^{-4} m^3/s	(6,000 cm^3/min)
Respiratory period (T) at rest	4s	
Tidal volume (V_T) at rest	4.0×10^{-4} m^3	(400 cm^3)
Alveolar ventilation volume (V_A) at rest	2.5×10^{-4} m^3	(250 cm^3)
Minute volume during heavy exercise	1.7×10^{-3} m^3/s	(10,000 cm^3/min)
Respiratory period during heavy exercise	1.2 s	
Tidal volume during heavy exercise	2.0×10^{-3} m^3	(2,000 cm^3)
Alveolar ventilation volume during exercise	1.8×10^{-3} m^3	(1,820 cm^3)

From Johnson, A.T., Lausted, C.G., and Bronzino, J.D., Respiratory system, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **7**-7.

Molecular Masses, Gas Constants, and Volume Fractions for Air and Constituents

Constituent	Molecular Mass kg/mol	Gas Constant, N·m/(mol·K)	Volume Fraction in Air, m^3/m^3
Air	29.0	286.7	1.0000
Ammonia	17.0	489.1	0.0000
Argon	39.9	208.4	0.0093
Carbon dioxide	44.0	189.0	0.0003
Carbon monoxide	28.0	296.9	0.0000
Helium	4.0	2078.6	0.0000
Hydrogen	2.0	4157.2	0.0000
Nitrogen	28.0	296.9	0.7808
Oxygen	32.0	259.8	0.2095

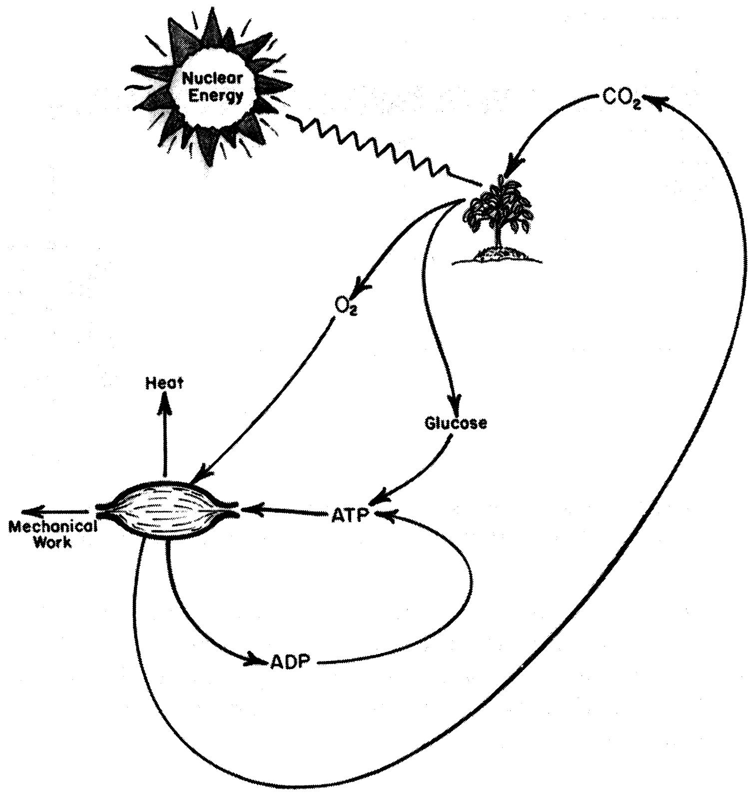
Note: Universal gas constant is 8314.43 N·m/kg·mol·K.

From Johnson, A.T., Lausted, C.G., and Bronzino, J.D., Respiratory system, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **7**-9.

Conductivity Values for Cardiac Bidomain

S/mm	Clerc [1976]	Roberts [1982]
g_{ix}	1.74×10^{-4}	3.44×10^{-4}
g_{iy}	1.93×10^{-5}	5.96×10^{-5}
g_{ax}	6.25×10^{-4}	1.17×10^{-4}
g_{ay}	2.36×10^{-4}	8.02×10^{-5}

From Plonsey, R., Volume conductor theory, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **9**-5.



Schematic of energy transformations leading to muscular mechanical work. (From Johnson, A.T. and Hurley, B.F., Factors affecting mechanical work in humans, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **27**-2.)

Typical Values and Estimates for Young's Modulus *E*

Compact bone	20	GPa
Keratin	3	GPa
Basilar membrane fibers	1.9	GPa
Microtubules	1.2	GPa
Collagen	1	GPa
Reissner's membrane	60	MPa
Actin	50	MPa
Red blood cell, extended (assuming thickness = 10 nm)	45	MPa
Rubber, elastin	4	MPa
Basilar membrane ground substance	200	kPa
Tectorial membrane	30	kPa
Jell-O	3	kPa
Henson's cells	1	kPa

From Steele, C.R., Baker, G.J., Tolomeo, J.A., and Zetes-Tolomeo, D.E., Cochlear mechanics, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **35**-4.

Properties of Bone, Teeth, and Biomaterials

Material	Young's modulus E[GPa]	Density ρ (g/cm³)	Strength (MPa)
Hard Tissue	17	1.8	130 (tension)
Tooth, bone, human compact bone, longitudinal direction			
Tooth dentin	18	2.1	138 (compression)
Tooth enamel	50	2.9	
Polymers			
Polyethylene (UHMW)	1	0.94	30 (tension)
Polymethyl methacrylate, PMMA	3	1.1	65 (tension)
PMMA bone cement	2	1.18	30 (tension)
Metals			
316L Stainless steel (wrought)	200	7.9	1000 (tension)
Co-Cr-Mo (cast)	230	8.3	660 (tension)
Co Ni Cr Mo (wrought)	230	9.2	1800 (tension)
Ti6A14V	110	4.5	900 (tension)
Composites			
Graphite-epoxy (unidirectional fibrous, high modulus)	215	1.63	1240 (tension)
Graphite-epoxy (quasi-isotropic fibrous)	46	1.55	579 (tension)
Dental composite resins (particulate)	10-16		170-260 (compression)
Foams			
Polymer foams	10^{-4}–1	0.002–0.8	0.01–1 (tension)

From Lakes, R., Composite biomaterials, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **40**-6.

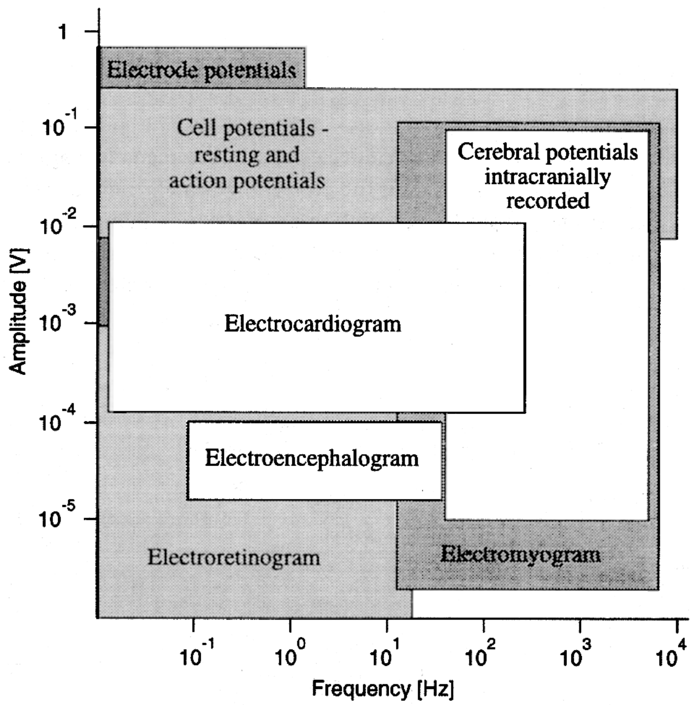
Biomedical Signals

Classification	Acquisition	Frequency Range	Dynamic Range	Comments
Bioelectric				
Action potential	Microelectrodes	100 Hz–2 kHz	10 μV–100 mV	Invasive measurement of cell membrane potential
Electroneurogram (ENG)	Needle electrode	100 Hz–1 kHz	5 μV–10 mV	Potential of a nerve bundle
Electroretinogram (ERG)	Microelectrode	0.2–200 Hz	0.5 μV–1 mV	Evoked flash potential
Electro-oculogram (EOG)	Surface electrodes	dc–100 Hz	10 μV–5 mV	Steady-corneal-retinal potential
Electroencephalogram (EEG)				
Surface	Surface electrodes	0.5–100 Hz	2–100 μV	Multichannel (6–32) scalp potential
Delta range		0.5–4 Hz		Young children, deep sleep and pathologies
Theta range		4–8 Hz		Temporal and central areas during alert states
Alpha range		8–13 Hz		Awake, relaxed, closed eyes
Beta range		13–22 Hz		
Sleep spindles		6–15 Hz	50–100 μV	Bursts of about 0.2 to 0.6 s
K-complexes		12–14 Hz	100–200 μV	Bursts during moderate and deep sleep
Evoked potentials (EP)	Surface electrodes		0.1–20 μV	Response of brain potential to stimulus
Visual (VEP)		1–300 Hz	1–20 μV	Occipital lobe recordings, 200-ms duration
Somatosensory (SEP)		2 Hz–3 kHz		Sensory cortex
Auditory (AEP)		100 Hz–3 kHz	0.5–10 μV	Vertex recordings

Biomedical Signals (continued)

Classification	Acquisition	Frequency Range	Dynamic Range	Comments
Electrocorticogram	Needle electrodes	100 Hz–5 kHz		Recordings from exposed surface of brain
Electromyography (EMG)				
Single-fiber (SFEMG)	Needle electrode	500 Hz–10 kHz	1–10 μV	Action potentials from single muscle fiber
Motor unit action potential (MUAP)	Needle electrode	5 Hz–10 kHz	100 μV–2 mV	
Surface EMG (SEMG)	Surface electrodes			
Skeletal muscle		2–500 Hz	50 μV–5 mV	
Smooth muscle		0.01–1 Hz		
Electrocardiogram (ECG)	Surface electrodes	0.05–100 Hz	1–10 mV	
High-Frequency ECG	Surface electrodes	100 Hz–1 kHz	100 μV–2 mV	Notchs and slus waveforms superimposed on the ECG.

From Cohen, A., Biomedical signals: Origin and dynamic characteristics; frequency-domain analysis, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **52**-4.



Amplitudes and spectral range of some important biosignals. The various biopotentials completely cover the area 10^{-6} V to almost 1 V and from dc to 10 kHz. (From Nagel, J.H., Biopotential amplifiers, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **70**-5.)

Representative Thermal Property Values

Tissue	Thermal Conductivity (W/m-K)	Thermal Diffusivity (m^2/s)	Perfusion (m^3/m^3-sec)
Aorta	0.461 [16]	1.25×10^{-7} [16]	
Fat of spleen	0.3337 [44]	1.314×10^{-7} [44]	
Spleen	0.5394 [44]	1.444×10^{-7} [44]	0.023 [45]
Pancreas	0.5417 [44]	1.702×10^{-7} [44]	0.0091 [45]
Cerebral cortex	0.5153 [44]	1.468×10^{-7} [44]	0.0067 [46]
Renal cortex	0.5466 [44]	1.470×10^{-7} [44]	0.077 [47]
Myocardium	0.5367 [44]	1.474×10^{-7} [44]	0.0188 [48]
Liver	0.5122 [44]	1.412×10^{-7} [44]	0.0233 [49]
Lung	0.4506 [44]	1.307×10^{-7} [44]	
Adenocarcinoma of breast	0.5641 [44]	1.436×10^{-7} [44]	
Resting muscle bone	0.478 [50]	1.59×10^{-7} [50]	0.0007 [48]
Whole blood (21°C)	0.492 [50]	1.19×10^{-7} [50]	
Plasma (21°C)	0.570 [50]	1.21×10^{-7} [50]	
Water	0.628 [6]	1.5136×10^{-7} [6]	

All conductivities and diffusivities are from humans at 37°C except the value for skeletal muscle which is from sheep at 21°C. Perfusion values are from various mammals as noted in the references. Significant digits do not imply accuracy. The temperature coefficient for thermal conductivity ranges from –0.000254 to 0.0039 W/m-K-°C with 0.001265 W/m-K-°C typical of most tissues as compared to 0.001575 W/m-K-°C for water [44]. The temperature coefficient for thermal diffusivity ranges from -4.9×10^{-10} m^2/s-°C to 8.4×10^{-10} m^2/s-°C with 5.19×10^{-10} m^2/s-°C typical of most tissues as compared to 4.73×10^{-10} m^2/s-°C for water [44]. The values provided in this table are representative values presented for tutorial purposes. The reader is referred to the primary literature for values appropriate for specific design applications.

From Baish, J.W., Microvascular heat transfer, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 2, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **98**-6.

Summary of Several Types of Wavelet Bases for $L^2(R)$

Type of Wavelet	Decay of $\psi(t)$ in Time	Regularity of $\psi(t)$ in Time	Type of Wavelet Basis
Stromberg, 1982	Exponential	$\psi(t) \in C^k$; k can be chosen arbitrarily large	Orthonormal
Meyer, 1985	Faster than any chosen inverse polynomial	$\psi(t) \in C^\infty$ (band limited)	Orthonormal
Battle–Lemarié, 1987, 1988 (splines)	Exponential	$\psi(t) \in C^k$; k can be chosen arbitarily large	Orthonormal
Daubechies, 1988	Compactly supported	$\psi(t) \in C^\alpha$; α can be chosen as large as we please	Orthonormal

From Vaidyanathan, P.P. and Djokovic, I., Wavelet transforms, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 212.

Debye Temperature and Resistivity of Nonmagnetic Metals

Metal	ρ_{20} at $T = 293$ K [$10^{-8}\,\Omega * \text{m}$]	Θ [K]	0.15 Θ [K]	ρ at Θ [$10^{-8}\,\Omega * \text{m}$]
Ag	1.62	214	32	1.16
Cu	1.68	320	48	1.94
Au	2.22	160	24	1.17
Al	2.73	374	56	3.79
Zn	6.12	180	27	3.65
Pt	10.6	220	33	7.91
Pb	20.8	84.5	12.7	5.5
W	5.39	346	52	6.76

From Nowak, S., Resistor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 284.

Comparison of Capacitor Dielectric Constants

Dielectric	ε_r (Dielectric Constant)
Air or vacuum	1.0
Paper	2.0–6.0
Plastic	2.1–6.0
Mineral oil	2.2–2.3
Silicone oil	2.7–2.8
Quartz	3.8–4.4
Glass	4.8–8.0
Porcelain	5.1–5.9
Mica	5.4–8.7
Aluminium oxide	8.4
Tantalum pentoxide	26
Ceramic	12–400,000

From Nowak, S., Capacitor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 295. Originally from *The Electrical Engineering Handbook,* Dorf, R., Ed., CRC Press, Boca Raton, FL, 1993.

υ′ Index of Various Capacitors

Capacitor Definition	Main Parameters	υ′ [cm³/μF]
Variable air	500 pF/250 V	200,000
Mica	10 nF/500 V	250
Ceramic (rutile)	1000 pF/500 V	600
Ferroelectronic	40 nF /250 V	50
Ferroelectric multilayer	0.68 μF/50 V	1.5
Polystyrene	2 μF/160 V	300
Polyester (mylar)	0.1 μF/160 V	12.4
Polycarbonate — metalized	0.15 μF/160 V	5.6
Electrolytic Al(HV)[a]	40 μF/350 V	1.3
Electrolytic Al(LV)[a]	120 μF/7 V	0.008
"Golden" capacitor	1 F/5.5 V	0.00001
Electrolytic Ta (wet)	10 μF/100 V	0.038
Electrolytic Ta (dry)	5.6 μF/10 V	0.0026

[a] HV: High voltage, LV: low voltage.

From Nowak, S., Capacitor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 296. Originally from Badian, L., *Handbuch der Electronik.,* Franzis-Verlag, Munich, Vol. 3, 1979.

Capacitors

Capacitor Name	υ' cm³/μF	Class	$delta_{max}$ after 1000 h [%]	Smallest $t\,\delta_p$ [%]	Power Factor × 10^{-4}	TCC ppm/K	Maximum Work Temperature [°C]	Remarks	
Polystyrene	300	1	0.5	±0.5	2–5	–100	70	For telecommunications filter	Neutral polymer
Teflon	300	1	0.5	±0.5	6	–150	280	Special applications	
Polyethylene	200	1	1	±1	5	–500	100		
Polypropylene	50	2	5	±5	6–8	–200	110		
Metalized polypropylene	10	2	5	±0.5	6–8	–200	85		
Metalized Polyester	5.6	2	10	±10	50 (200 at 1 MHz)	—	—	For ac pulse	Polar polymer
Polyester (polyethylene tereftalate)	12	2	5	±10	50 (200 at 1 MHz)	Large	150		
Polycarbonate	12	2	10	±10	20	Large	100		
Metalized polycarbonate	5.6	2	10	±10	20	Large	100		

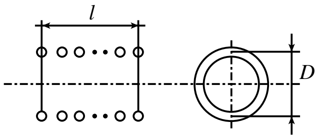
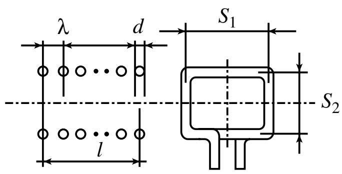
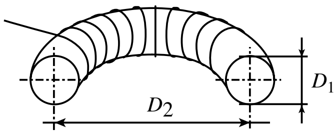
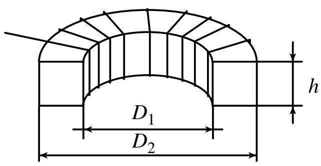
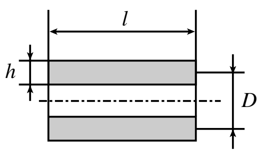
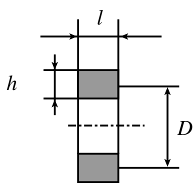
From Nowak, S., Capacitor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 306.

Inductor Qualifiers and Attributes

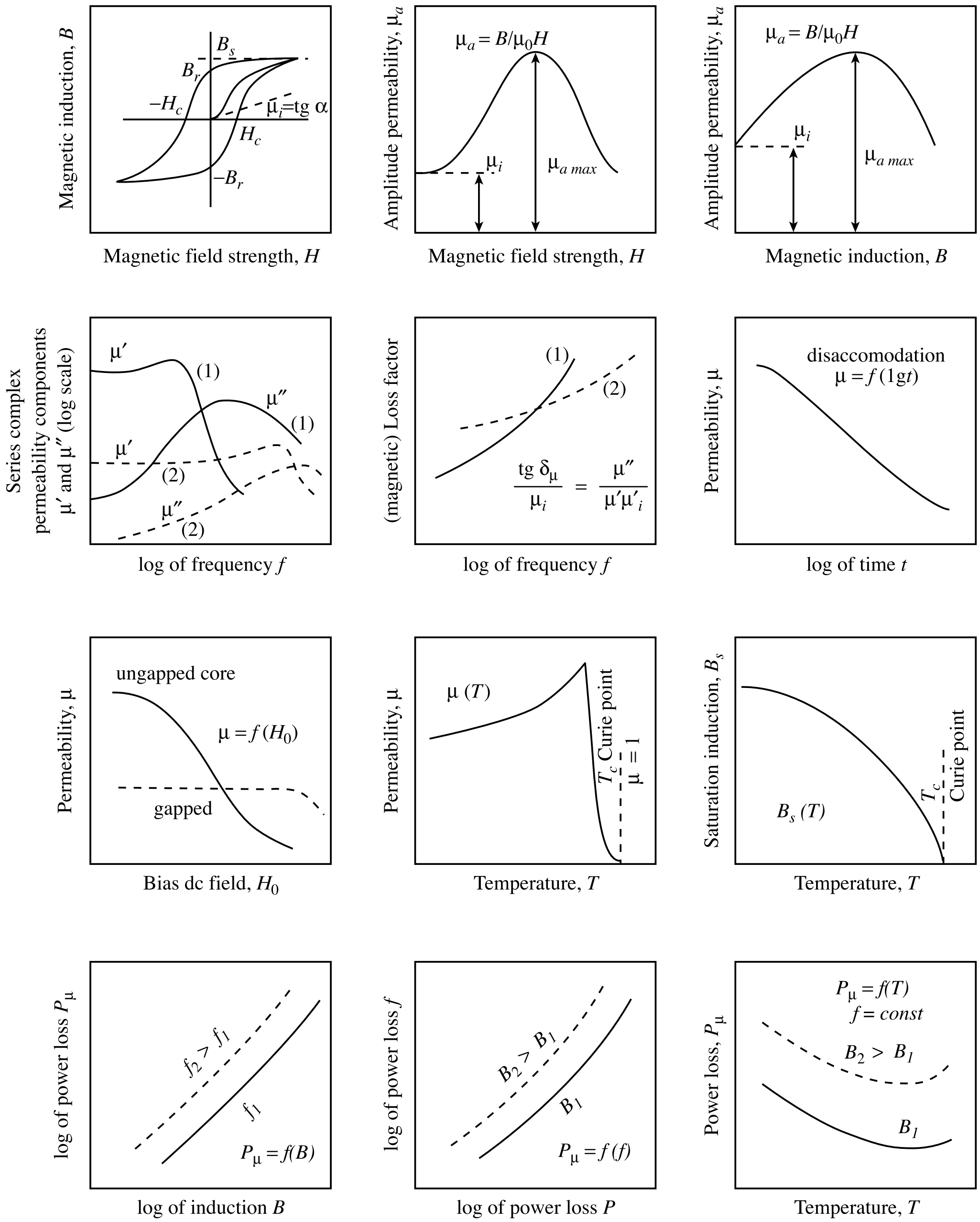
Inductor Qualifier	Inductor: Attribute or Quality
Ideal, perfect	Linear inductor having only a "pure" inductance, i.e., no power loss is related to the flow of time-varying current through the inductor winding. In the ideal inductor, the current of sine wave lags the induced voltage by angle $\varphi = 90°$ ($\pi/2$ rad). The concept of the ideal inductor is used only in idealized or simplified circuit analysis.
Nonideal	Usually, a linear inductor in which the power loss in the winding and core is taken into account. The current of sine wave lags the induced voltage by angle $0° \leq \varphi < 90°$ (90° for ideal, power lossfree inductor; 0° for pure resistor). The concept of nonideal inductor is used as a first order approximation of a real inductor.
Linear	Inductor, ideal or nonideal, for which the induced voltage drop across it is proportional to the flowing time-varying current in its steady state. Linear inductor can be described or be used to describe the circuit in terms of transfer function. An air inductor is an example of linear inductor.
Nonlinear	Inductor for which the induced voltage drop is not proportional to the time-varying current flowing by it. As a rule, cored inductors (specifically if a core forms a closed magnetic circuit) are nonlinear. This is a consequence of the strong nonlinear dependence of magnetic induction B, proportional to voltage $u = dL/dt$, on magnetic field strength H, proportional to current i.
Real	Inductor with electrically behavioral aspects and characteristics that are all taken into account, e.g., magnetic power loss, magnetic flux leakage, self-winding and interwinding capacitances and related dielectric power loss, radiation power loss, parasitic couplings, and so on, and dependences of these factors on frequency, induction, temperature, time, etc.
Air	Inductor not containing magnetic materials as constituents or in its magnetically perceptible vicinity
Cored	Inductor in which a magnetic material in the form of a core serves intentionally as a path, complete or partial, for guidance of magnetic flux generated by current flowing through inductor winding
Lumped or discrete	Inductor assumed to be concentrated at a single point
Distributed	Inductor with inductance and other properties that are distributed over a physical distance(s) which is(are) comparable to a wavelength

From Nowak, S., Capacitor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 314.

Inductance L_0 of Various Air Inductors Dimensionally Similar but Having the Same Number of Turns

	Winding (Coil) Dimensions	When Coil Dimensions Are:	Inductance L_0 for n=100 Turns Is:
(a)		$D_1 = 2$ cm $l = 10$ cm	19 µH
(b)		$S_1 = 1.5$ cm $S_2 = 2.5$ cm $\lambda = 0.05$ cm $l = 10$ cm $d = 0.05$ cm $G\,(0.6;4) = 0.4$ $H\,(1;100) = 0$	32 µH
(c)		$D_1 = 1$ cm $D_2 = 3$ cm	10.3 µH
		$D_1 = 2$ cm $D_2 = 3$ cm	41 µH
(d)		$D_1 = 2$ cm $D_2 = 4$ cm $h = 1$ cm	13.9 µH
		$D_1 = 1$ cm $D_2 = 5$ cm $h = 2$ cm	64.4 µH
(e)		$D = 2$ cm $h = 0.5$ cm $l = 4$ cm	74 µH
(f)		$D = 2$ cm $h = 0.5$ cm $l = 0.2$ cm	245 µH

From Postupolski, T.W., Inductor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 316.

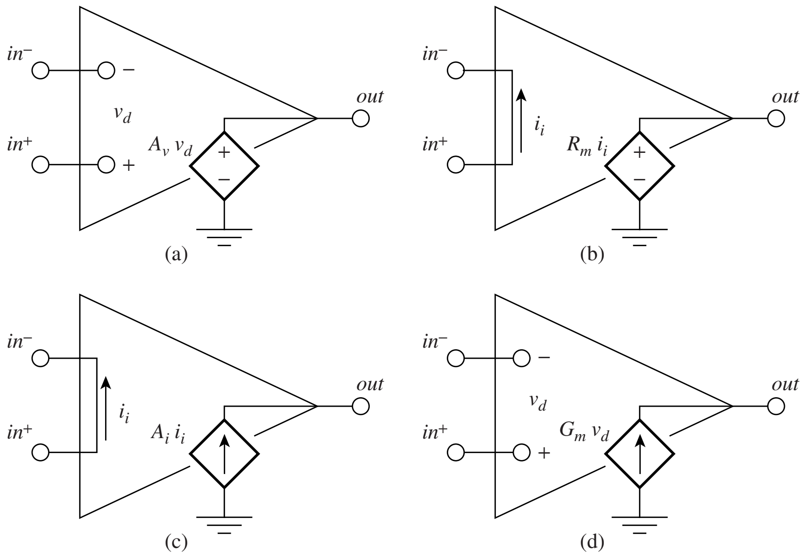


Basic characteristics of magnetic materials essential for inductor applications. (From Postupolski, T.W., Inductor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 331.)

Ideal Op Amp Types

Input	Output	Gain	Type
V	V	A_v	Voltage
I	V	R_m	Transimpedance
I	I	A_i	Current
V	I	G_m	Transconductance

From Nairn, D.G., The ideal operational amplifier, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 428.



The four possible op amp configurations: (a) the voltage op amp, (b) the transimpedance op amp, (c) the current op amp, and (d) the transconductance op amp. (From Nairn, D.G., The ideal operational amplifier, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 428.)

ITRS Microprocessor Roadmap

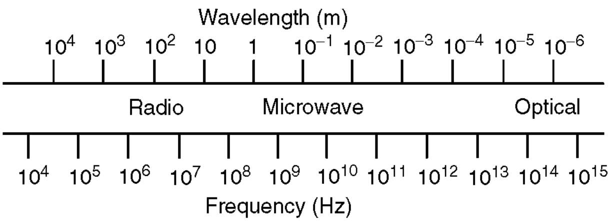
Characteristic	2001	2004	2007	2010	2013	2016
Transistor gate length (nm)	90	53	35	25	18	13
Feature size scale factor ($S_{feature}$)	1	0.59	0.39	0.28	0.20	0.14
Chip size (mm^2)	310	310	310	310	310	310
Million transistors/mm^2	0.89	1.78	3.1	7.14	14.27	28.54
Million transistors/chip	275.9	551.8	961	2213.4	4423.7	8847.4
Clock frequency (GHz)	1.684	3.99	6.739	11.511	19.348	28.751
Supply voltage (V)	1.1	1	0.7	0.6	0.5	0.4
Maximum power (W)	130	160	190	218	251	288

From Cottrell, D., Design automation technology roadmap, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 2161.

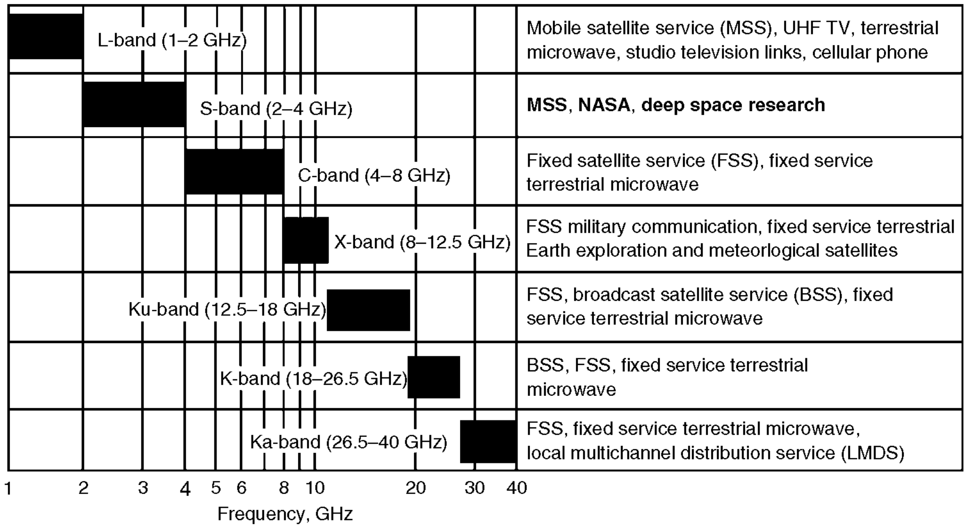
Properties of the Relative Sensitivity

Property Number	Relation	Property Number	Relation
1	$S_x^{ky} = S_{kx}^y = S_x^y$	10	$S_x^{y_1/y_2} = S_x^{y_1} - S_x^{y_2}$
2	$S_x^x = S_x^{kx} = S_{kx}^x = 1$	11	$S_{x_1}^y = S_{x_2}^y S_{x_1}^{x_2}$
3	$S_{1/x}^y = S_x^{1/y} = -S_x^y$	12[a]	$S_x^y = S_x^{\lvert y\rvert} + j\arg y S_x^{\arg y}$
4	$S_x^{y_1 y_2} = S_x^{y_1} + S_x^{y_2}$	13[a]	$S_x^{\arg y} = \frac{1}{\arg y}\operatorname{Im} S_x^y$
5	$S_x^{\Pi_{i=1}^n y_i} = \sum_{i=1}^{n} S_x^{y_i}$	14[a]	$S_x^{\lvert y\rvert} = \operatorname{Re} S_x^y$
6	$S_x^{y^n} = n\, S_x^y$	15	$S_x^{y+z} = \frac{1}{y+z}\left(y\, S_x^y + z\, S_x^z\right)$
7	$S_x^{x^n} = n\, S_x^{kx^n} = n$	16	$S_x^{\Sigma_{i=1}^n y_i} = \frac{\sum_{i=1}^{n} y_i\, S_x^{y_i}}{\sum_{i=1}^{n} y_i}$
8	$S_{x^n}^y = \frac{1}{n} S_x^y$	17	$S_x^{\ln y} = \frac{1}{\ln y} S_x^y$
9	$S_{x^n}^x = S_{kx^n}^x = \frac{1}{n}$		

[a] In this relation, y is a complex quantity and x is a real quantity.
From Filanovsky, I., Sensitivity and selectivity, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 2294.



Portion of the electromagnetic spectrum. (From Palais, J., Fiber optic communications systems, in *The Communications Handbook,* 2nd ed., Gibson, J.D., Ed., CRC Press, Boca Raton, FL, 2002, p. **44**-2.)



The general arrangement of the frequency spectrum that is applied to satellite communications and other radiocommunications services. Indicated are the short-hand letter designations along with an explanation of the typical applications. Note that the frequency ranges indicated are the general ranges and do not correspond exactly to the ITU frequency allocations and allotments. (From Elbert, B.R., Geostationary communications satellites and applications, in *The Communications Handbook,* 2nd ed., Gibson, J.D., Ed., CRC Press, Boca Raton, FL, 2002, p. **56**-5.)

The Primary Strengths of Satellite Communications

Feature of Satellite Service	Application
Wide-area coverage	Domestic, regional, global
Wide bandwidth	Up to 1 GHz per coverage
Independent of land-based networks	Does not require connection to terrestrial infrastructure
Rapid installation	Individual sites can be installed and activated in one day for VSAT or two months of major hub
Low cost per added site	Depends on type of service; can be as low as $600 for DTH
Uniform service characteristics	Determined by coverage and type of transmission system
Total service from a single provider	By the satellite operator or a separate organization that leases transponder capacity
Mobile Communication	Requires line-of-sight path over the coverage area

From Elbert, B.R., Geostationary communications satellites and applications, in *The Communications Handbook,* 2nd ed., Gibson, J.D., Ed., CRC Press, Boca Raton, FL, 2002, p. **56**-7.

Access time The total time needed to retrieve data from memory. For a disk drive this is the sum of the time to position the read/write head over the desired track and the time until the desired data rotates under the head.

Active filter A form of power electronic converter designed to effectively cancel harmonic currents by injecting currents that are equal and opposite to, or 180° out of phase with, the target harmonics. Active filters allow the output current to be controlled and provide stable operation against AC source impedance variations without interfering with the system impedance.

The main type of active filter is the series type in which a voltage is added in series with an existing bus voltage. The other type is the parallel type in which a current is injected into the bus and cancels the line current harmonics.

Algorithm A systematic and precise, step-by-step procedure (such as a recipe, a program, or set of programs) for solving a certain kind of problem or accomplishing a task, for instance converting a particular kind of input data to a particular kind of output data, or controlling a machine tool. An algorithm can be executed by a machine.

Address A unique identifier for the place where information is stored (as opposed to the contents actually stored there). Most storage devices may be regarded by the user as a linear array, such as bytes or words in RAM or sectors on a disk. The address is then just an ordinal number of the physical or logical position. In some disks, the address may be compound, consisting of the cylinder or track and the sector within that cylinder.

In more complex systems, the address may be a "name" that is more relevant to the user but must be translated by the underlying software or hardware.

Antenna A device used to couple energy from a guiding structure (transmission line, waveguide, etc.) into a propagation medium, such as free space, and vice versa. It provides directivity and gain for the transmission and reception of electromagnetic waves.

Appropriate technology The technology that will accomplish a task adequately given the resources available. Adequacy can be verified by determining that increasing the technological content of the solution results in diminishing gains or increasing costs.

Attenuation The exponential decrease, with distance, in the amplitude of an electric signal traveling along a very long transmission line due to losses in the supporting medium. In electromagnetic systems attenuation is due to conductor and dielectric losses. In fiber optic systems attenuation arises from intrinsic material properties (absorption and Rayleigh scattering) and from waveguide properties such as bending, microbending, splices, and connectors.

Automation Refers to the bringing together of machine tools, materials handling process, and controls with little worker intervention, including

1. a continuous flow production process that integrates various mechanisms to produce an item with relatively few or no worker operations, usually through electronic control;
2. self-regulating machines (feedback) that can perform highly precise operations in sequence; and
3. electronic computing machines.

In common use, however, the term is often used in reference to any type of advanced mechanization or as a synonym for technological progress; more specifically, it is usually associated with cybernetics.

Base (1) The number of digits in a number system (10 for decimal, 2 for binary).

(2) One of the three terminals of a bipolar transistor.

(3) A register's value that is added to an immediate value or to the value in an index register in order to form the effective address for an instruction such as LOAD or STORE.

Bayesian theory Theory based on Bayes' rule, which allows one to relate the *a priori* and *a posteriori* probabilities. If $P(c_i)$ is the *a priori* probability that a pattern belongs to class c_i, $P(\mathbf{x_k})$ is the probability of pattern $\mathbf{x_k}$, $P(\mathbf{x_k}|c_i)$ is the class conditional probability that the pattern is $\mathbf{x_k}$ provided that it belongs to class c_i, $P(c_i|\mathbf{x_k})$ is the *a posteriori* conditional probability that the given pattern class membership is c_i, given pattern $\mathbf{x_k}$, then

$$P(c_i|\mathbf{x_k}) = \frac{P(\mathbf{x_k}|c_i)P(c_i)}{P(\mathbf{x_k})}$$

The membership of the given pattern is determined by

$$\max_{c_i} P(c_i|\mathbf{x_k}) = \max_{c_i} P(\mathbf{x_k}|c_i)P(c_i)$$

Hence, the *a posteriori* probability can be determined as a function of the *a priori* probability.

Binary-coded decimal (BCD) A weighted code using patterns of four bits to represent each decimal position of a number.

Bit (1) The fundamental unit of information representation in a computer, short for "binary digit" and with two values usually represented by "0" and "1." Bits are usually aggregated into "bytes" (7 or 8 bits) or "words" (12–60 bits).

A single bit within a word may represent the coefficient of a power of 2 (in numbers), a logical TRUE/FALSE quantity (masks and Boolean quantities), or part of a character or other compound quantity. In practice, these uses are often confused and interchanged.

(2) In Information Theory, the unit of information. If an event E occurs with a probability $P(E)$, it conveys information of $\log_2(1/P(E))$ binary units or bits. When a bit (binary digit) has equiprobable 0 and 1 values, it conveys exactly 1.0 bit (binary unit) of information; the average information is usually less than this.

Boundary condition (1) The conditions satisfied by a function at the boundary of its interval of definition. They are generally distinguished in hard or soft also called Neumann (the normal derivative of the function is equal to zero) or Dirichlet (the function itself is equal to zero).

(2) The conditions satisfied from the electromagnetic field at the boundary between two different media.

(3) Rules that govern the behavior of electromagnetic fields as they move from one medium into another medium.

Broadcasting Sending a message to multiple receivers.

Bus (1) A data path connecting the different subsystems or modules within a computer system. A computer system will usually have more than one bus; each bus will be customized to fit the data transfer needs between the modules that it connects.

(2) A conducting system or supply point, usually of large capacity. May be composed of one or more conductors, which may be wires, cables, or metal bars (busbars).

(3) A node in a power system problem.

(4) A heavy conductor, typically used with generating and substation equipment.

Byte In most computers, the unit of memory addressing and the smallest quantity directly manipulated by instructions. The term *byte* is of doubtful origin, but was used in some early computers to denote any field within a word (e.g., DEC PDP-10). Since its use on the IBM "Stretch" computer (IBM 7030) and especially the IBM System/360 in the early 1960s, a byte is now generally understood to be 8 bits, although 7 bits is also a possibility.

Cache An intermediate memory store having storage capacity and access times somewhere in between the general register set and main memory. The cache is usually invisible to the programmer, and its effectiveness comes from being able to exploit program locality to anticipate memory-access patterns and to hold closer to the CPU: most accesses to main memory can be satisfied by the cache, thus making main memory appear to be faster than it actually is.

A hit occurs when a reference can be satisfied by the cache; otherwise a miss occurs. The proportion of hits (relative to the total number of memory accesses) is the hit ratio of the cache.

Capacitance The measure of the electrical size of a capacitor, in units of farads. Thus a capacitor with a large capacitance stores more electrons (coulombs of charge) at a given voltage than one with a smaller capacitance.

In a multiconductor system separated by nonconductive mediums, capacitance (C) is the proportionality constant between the charge (q) on each conductor and the voltage (V) between each conductor. The total equilibrium system charge is zero. Capacitance is dependent on conductor geometry, conductor spatial relationships, and the material properties surrounding the conductors.

Capacitors are constructed as two metal surfaces separated by a nonconducting electrolytic material. When a voltage is applied to the capacitor, the electrical charge accumulates in the metals on either side of the nonconducting material, negative charge on one side and positive on the other. If this material is a fluid then the capacitor is electrolytic; otherwise, it is nonelectrolytic.

Causal system A system whose output does not depend on future input; the output at time t may depend only on the input signal $\{f(\tau) : \tau \leq t\}$. For example, the voltage measured across a particular element in a passive electric circuit does not depend upon future inputs applied to the circuit and hence is a causal system.

If a system is not causal, then it is noncausal. An ideal filter which will filter in real time all frequencies present in a signal $f(t)$ requires knowledge of $\{f(\tau) : \tau > t\}$ and is an example of a noncausal system.

Central processing unit (CPU) A part of a computer that performs the actual data processing operations and controls the whole computing system. It is subdivided into two major parts:

1. The arithmetic and logic unit (ALU), which performs all arithmetic, logic, and other processing operations.

2. The control unit (CU), which sequences the order of execution of instructions, fetches the instructions from memory, decodes the instructions, and issues control signals to all other parts of the computing system. These control signals activate the operations performed by the system.

Channel (1) The medium along which data travel between the transmitter and receiver in a communication system. This could be a wire, coaxial cable, free space, etc.

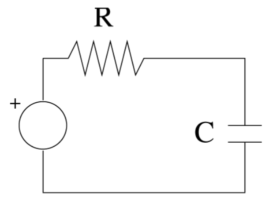
(2) The conductivity path between the source and the drain of a field effect transistor.

(3) A single path for transmitting electrical signals. Example 1: The band of frequencies from 50 Hz to 15 KHz (Channel A) and 15 KHz to 75 KHz (Channel B) which frequency modulates the main carrier of an FM stereo transmitter. Example 2: A portion of the electromagnetic spectrum assigned for operation of a specific carrier from the FM broadcast band (88 to 108 MHz) of frequencies 200 KHz wide designated by the center frequency beginning at 88.1 MHz and continuing in successive steps to 107.9 MHz.

Chaos (1) Erratic and unpredictable dynamic behavior of a deterministic system that never repeats itself. Necessary conditions for a system to exhibit such behavior are that it be nonlinear and have at least three independent dynamic variables.

(2) In microelectronics, deterministic motion, in which the statistics are essentially those of a Gaussian random process.

Circuit A physical device consisting of an interconnection of elements, or a topological model of such a device. For example, an electric circuit may be constructed by interconnecting a resistor and a capacitor to a voltage source. A representation of this circuit is shown by the diagram in the figure.



Circuit example.

Code (1) A technique for representing information in a form suitable for storage or transmission.

(2) A mapping from a set of messages into binary strings.

Computer (1) An electronic, electromechanical, or purely mechanical device that accepts input, performs some computational operations on the input, and produces some output.

(2) Functional unit that can perform substantial computations, including numerous arithmetic operations, or logic operations, without human intervention during a run.

(3) General or special-purpose programmable system that is able to execute programs automatically. It has one or more associated processing units, memory, and peripheral equipment for input and output. Uses internal memory for storing programs and/or data.

Conductivity (1) The reciprocal of resistivity.

(2) A measure of a material's ability to conduct electrical current. Conductivity σ is the ratio of the conduction current to the electric field in Ohm's Law:

$$J_c = \sigma E$$

Dielectric (1) A medium that exhibits negligible or no electrical conductivity and thus acts as a good electrical insulator.

(2) A medium characterized by zero conductivity, unity relative permeability, and a relative permittivity greater than one. Also known as an insulator.

Dielectries are usually used to separate two conducting bodies such as to form a capacitor.

Electric field In a region of space, if a test charge q experiences a force F, then the region is said to be characterized by an electric field of intensity E given by

$$E = \frac{F}{q}$$

Electromagnetic energy Energy contained in electromagnetic fields and associated polarizable and magnetizable media.

Ethernet A standard for interconnecting devices on a local area network (LAN).

Gate (1) A logical or physical entity that performs one logical operation, such as AND, NOT, or OR.

(2) The terminal of a FET which controls the flow of electrons from source to drain. It is usually considered to be the metal contact at the surface of the die. The gate is usually so thin and narrow that if any appreciable current is allowed to flow, it will rapidly heat up and self-destruct due to I-R loss. This same resistance is a continuing problem in low noise devices and has resulted in the creation of numerous methods to alter the gate structure and reduce this effect.

Ground (1) An earth-connected electrical conducting connection that may be designed or nonintentionally created.

(2) The electrical "zero" state, used as the reference voltage in computer systems.

Hologram Medium that when illuminated optically, provides a three-dimensional image of stored information, sometimes called holograph.

Laser Acronym that stands for light amplification by stimulated emission of radiation. Usually refers to an oscillator rather than an amplifier; commonly also refers to similar systems that operate at non-optical frequencies or with nonelectromagnetic wave fields.

Node A symbol representing a physical connection between two electrical components in a circuit.

Noise (1) Any undesired disturbance, whether originating from the transmission medium or the electronics of the receiver itself, that gets superimposed onto the original transmitted signal by the time it reaches the receiver. These disturbances tend to interfere with the information content of the original signal and will usually define the minimum detectable signal level of the receiver.

(2) Any undesired disturbance superimposed onto the original input signal of an electronic device; noise is generally categorized as being either external (disturbances superimposed onto the signal before it reaches the device) or internal (disturbances added to the signal by the receiving device itself). Some common examples of external noise are crosstalk and impulse noise as a result of atmospheric disturbances or manmade electrical devices. Some examples of internal noise include thermal noise, shot noise, l/f noise, and intermodulation distortion.

Permeability Tensor relationship between the magnetic field vector and the magnetic flux density vector in a medium with no hysteresis; flux density divided by the magnetic field in scalar media. Permeability indicates the ease with which a magnetic material can be magnetized. An electromagnet with a higher permeable core material will produce a stronger magnetic field than one with a lower permeable core material. Permeability is analogous to conductance when describing electron flow through a material.

Port (1) A terminal pair.

(2) A place of connection between one electronic device and another.

(3) A point in a computer system where external devices can be connected.

Random signal A signal $X(t)$ that is either noise $N(t)$, an interfering signal $s(t)$, or a sum of these:

$$X(t) = s_1(t) + \cdots + s_m(t) + N_1(t) + \cdots + N_n(t)$$

Resolution (1) The act of deriving from a sound, scene, or other form of intelligence, a series of discrete elements from which the original may subsequently be reconstructed. The degree to which nearly equal values of a quantity can be discriminated.

(2) The fineness of detail in a measurement. For continuous systems, the minimum increment that can be discerned.

(3) The ability to distinguish between two units of measurement.

(4) The number of pixels per linear unit (or per dimension) in a digital image.

(5) The smallest feature of a given type that can be printed with acceptable quality and control.

Sensor A transducer or other device whose input is a physical phenomenon and whose output is a quantitative measurement of that physical phenomenon. Physical phenomena that are typically measured by a sensor include temperature or pressure to an internal, measurable value such as voltage or current.

Traveling wave An electromagnetic signal that propagates energy through space or a dielectric material.

Waveguide A system of conductive or dielectric materials in which boundaries and related dimensions are defined such that electromagnetic waves propagate within the bounded region of the structure. Although most waveguides utilize a hollow or dielectric filled conductive metal tube, a solid dielectric rod in which the dielectric constant of the rod is very much different from the dielectric constant of the surrounding medium can also be used to guide a wave. Waveguides rapidly attenuate energy at frequencies below the waveguide lower cut-off frequency, and are limited in bandwidth at the upper end of the frequency spectrum due to wave attenuation as well as undesired mode propagation.

From *Comprehensive Dictionary of Electrical Engineering*, Laplante, P.A., Ed., CRC Press, Boca Raton, FL, 1999.

Cost of Selected Memory Devices

Year	Device	Size (bits)	Cost ($)	Cost ($/MB)	Speed (ns)
1943	Relay	1	—	—	100,000,000
1958	Magnetic drum (IBM650)	80,000	157,400	1.7E+07	4,800,000
1959	Vacuum tube flip-flop	1	8.10	6.8E+07	10,000
1960	Core	8	5.00	5.2E+06	11,500
1964	Transistor flip-flop	1	59.00	4.9E+08	200
1966	I.C. flip-flop	1	6.80	5.7E+07	200
1970	Core	8	0.70	7.3E+05	770
1972	I.C. flip-flop	1	3.30	2.8E+07	170
1975	256 bit static RAM	256	—	—	1,000
1977	1 Kbit static RAM	1,024	1.62	1.3E+04	500
1977	4 Kbit DRAM	4,096	16.40	3.4E+04	270
1979	16 Kbit DRAM	16,384	9.95	5.1E+03	350
1982	64 Kbit DRAM	65,536	6.85	8.8E+02	200
1985	256 Kbit DRAM	262,144	6.00	1.9E+02	200
1989	1 Mbit DRAM	1,048,576	20.00	1.6E+02	120
1991	4 M x 9 DRAM SIMM	37,748,736	165.00	3.7E+01	80
1995	16 MB ECC DRAM DIMM	150,994,944	489.00	2.7E+01	70
1999	64 MB PC-100 DIMM	536,870,912	55.00	8.6E–01	60/10
2001	256 MB PC-133 DIMM	2,147,483,648	88.00	3.4E–01	45/7
2002	1 Gbit chip	1,073,741,824	—	—	—
2005	4 Gbit chip	4,294,967,296	—	—	—

From McCallum, J.C., Price-performance of computer technology, in *The Computer Engineering Handbook,* Oklobdzija, V.G., Ed., CRC Press, Boca Raton, FL, 2002, p. **4**-10.

4-Bit Fractional Two's Complement Numbers

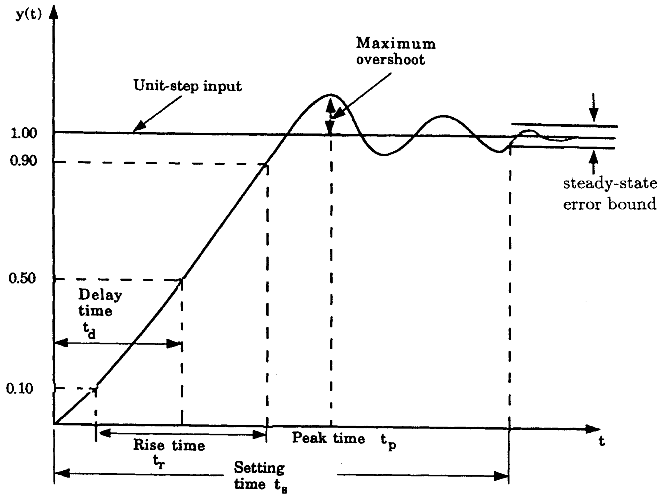
Decimal Fraction	Binary Representation
+7/8	0111
+3/4	0110
+5/8	0101
+1/2	0100
+3/8	0011
+1/4	0010
+1/8	0001
+0	0000
−1/8	1111
−1/4	1110
−3/8	1101
−1/2	1100
−5/8	1011
−3/4	1010
−7/8	1001
−1	1000

From Swartzlander, E.E. Jr., High-speed computer arithmetic, in *The Computer Engineering Handbook,* Oklobdzija, V.G., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-2.

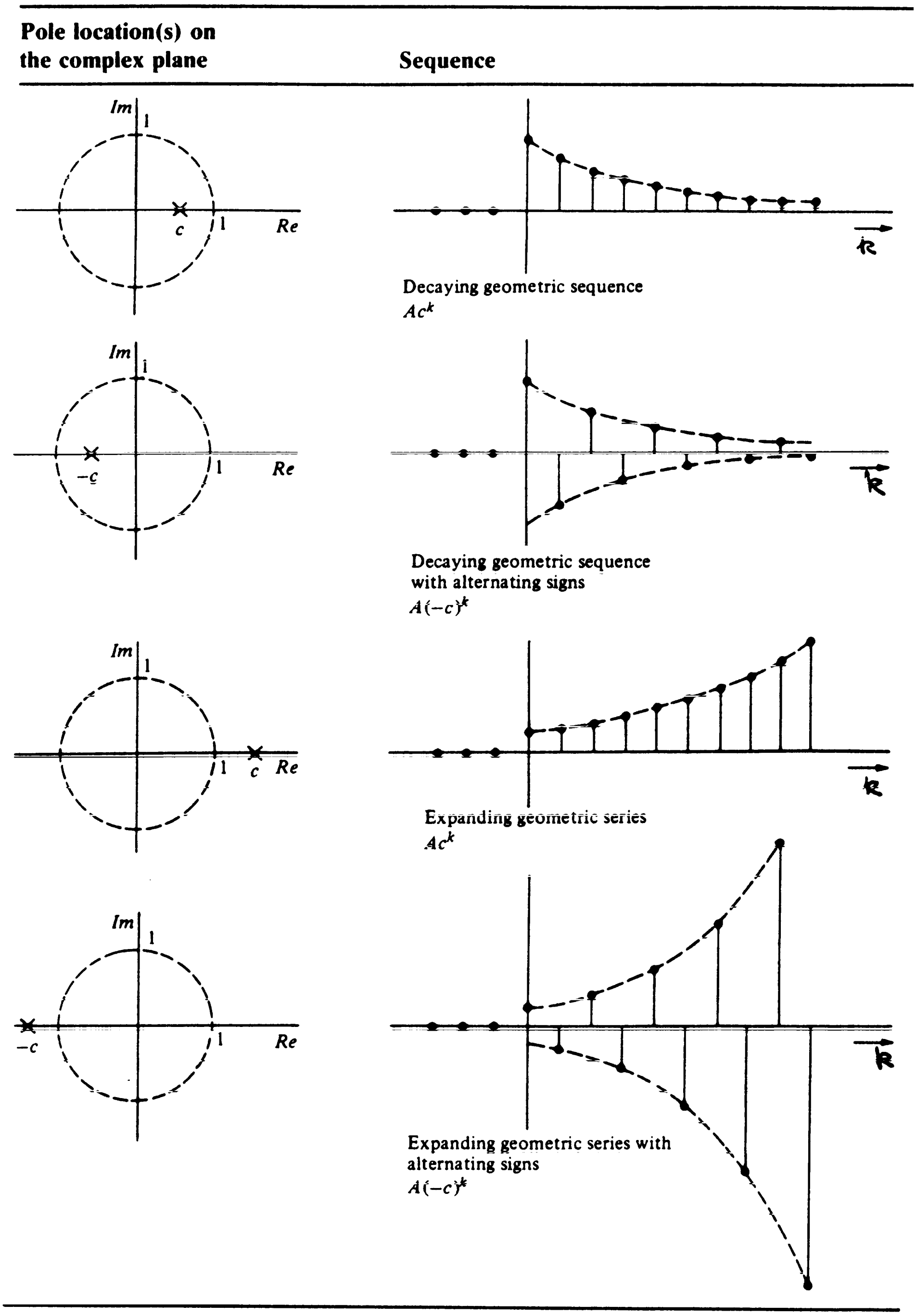
DFT Parameters

DFT Parameter	Notation or Units
Sample size	N samples
Sample period	T_s seconds
Record length	$T = NT_s$ seconds
Number of harmonics	N harmonics
Number of positive (negative) harmonics	$N/2$ harmonics
Frequency spacing between harmonics	$\Delta f = 1/T = 1/NT_s = f_s/N$ Hz
DFT frequency (one-sided baseband range)	$f \in [0, f_s/2)$ Hz
DFT frequency (two-sided baseband range)	$f \in [-f_s/2, f_s/2)$ Hz
Frequency of the *k*th harmonic	$f_k = kf_s/N$ Hz

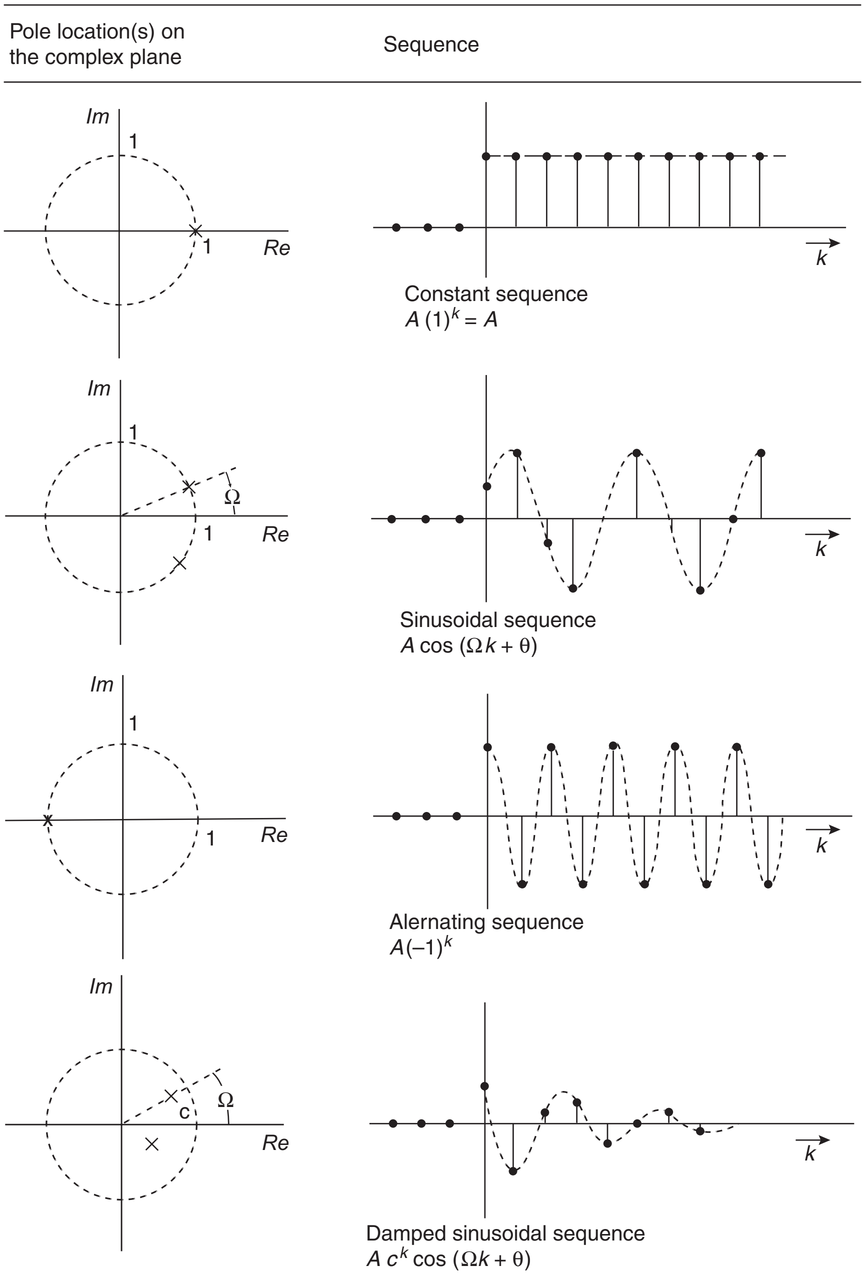
From Taylor, F.J., Digital signal processing, in *The Computer Engineering Handbook,* Oklobdzija, V.G., Ed., CRC Press, Boca Raton, FL, 2002, p. **24**-9.



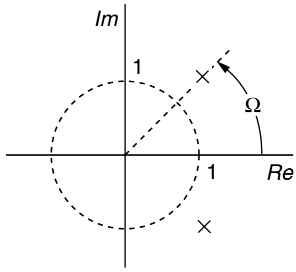
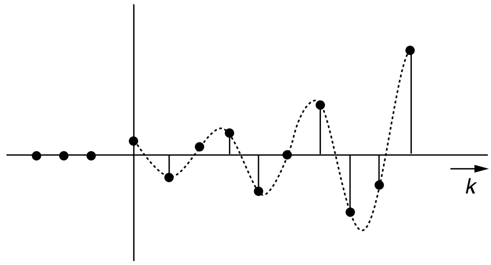
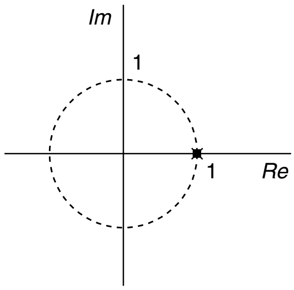
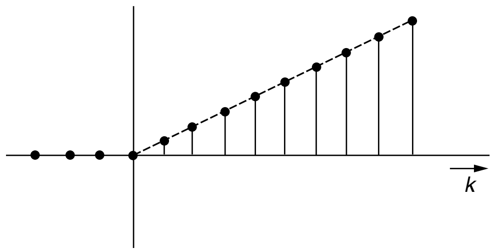
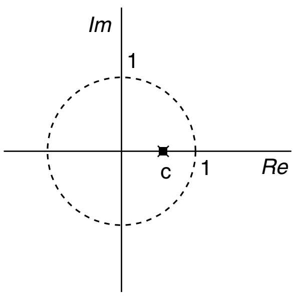
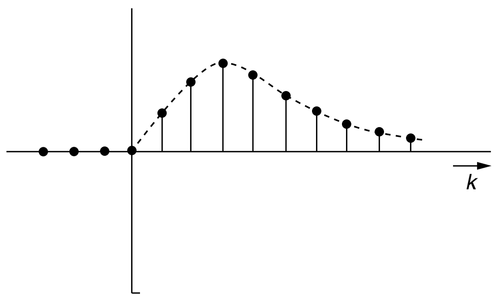
Typical underdamped unit-step response of a control system. An overdamped unit-step response would not have a peak. (From Yang, J.-S. and Levine, W.S., Specification of control systems, in *The Control Handbook,* Levine, W.S., Ed., CRC Press, Boca Raton, FL, 1996, p. 158.)



Sequences corresponding to various z-transform pole locations. (From Santina, M.S., Stubberud, A.R., and Hostetter, G.H., Discrete-time systems, in *The Control Handbook,* Levine, W.S., Ed., CRC Press, Boca Raton, FL, 1996, pp. 243-245.)



(Continued) Sequences corresponding to various z-transform pole locations.

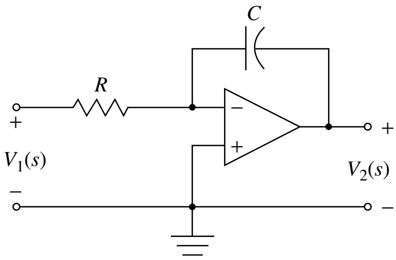
Pole location(s) on the complex plane	Sequence
	 Exponentially expanding sinusoidal sequence $A^k \cos(\Omega k + \theta)$
	 Ramp sequence $Ak(1)^k = Ak$
	 Ramp-weighted geometric sequence Akc^k

(Continued) Sequences corresponding to various z-transform pole locations.

Transfer Functions of Dynamic Elements and Networks

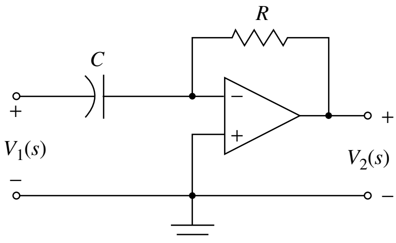
Element or System	G(s)

1. Integrating circuit, filter



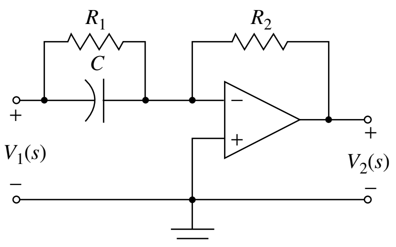
$$\frac{V_2(s)}{V_1(s)} = \frac{1}{RCs}$$

2. Differentiating circuit



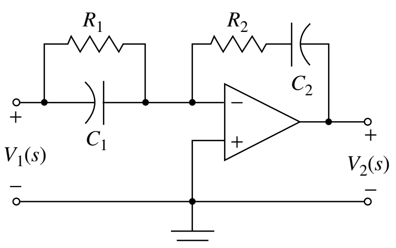
$$\frac{V_2(s)}{V_1(s)} = RCs$$

3. Differentiating circuit



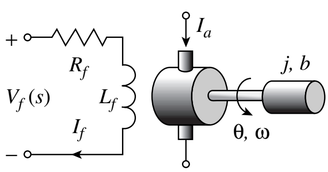
$$\frac{V_2(s)}{V_1(s)} = -\frac{R_2(R_1Cs+1)}{R_1}$$

4. Integrating filter



$$\frac{V_2(s)}{V_1(s)} = -\frac{(R_1C_1s+1)(R_2C_2s+1)}{R_1C_2s}$$

5. dc motor, field-controlled, rotational actuator

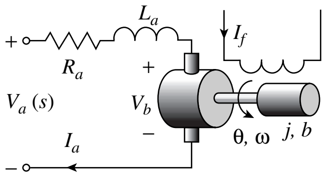


$$\frac{\theta(s)}{V_f(s)} = \frac{K_m}{s(Js+b)(L_fs+R_f)}$$

Transfer Functions of Dynamic Elements and Networks (continued)

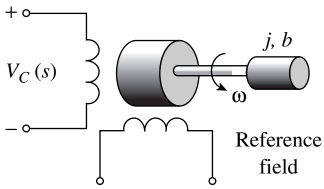
Element or System	G(s)

6. dc motor, armature-controlled, rotational actuator



$$\frac{\theta(s)}{V_a(s)} = \frac{K_m}{s\left[(R_a + L_a s)(Js + b) + K_b K_m\right]}$$

7. ac motor, two-phase control field, rotational actuator

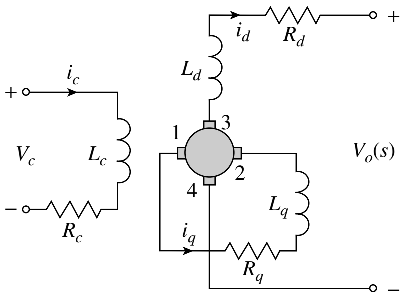


$$\frac{\theta(s)}{V_c(s)} = \frac{K_m}{s(\tau s + 1)}$$

$$\tau = J/(b - m)$$

m = slope of linearized torque-speed curve (normally negative)

8. Amplidyne, voltage and power amplifier

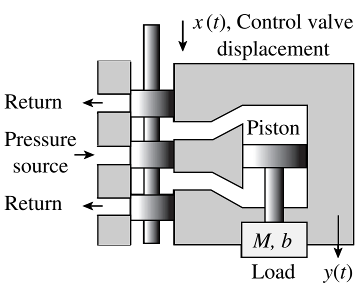


$$\frac{V_o(s)}{V_c(s)} = \frac{(K/R_c R_q)}{(s\tau_c + 1)(s\tau_q + 1)}$$

$$\tau_c = L_c/R_c,\ \tau_q = L_q/R_q$$

For the unloaded case, $i_d \simeq 0$, $\tau_c \simeq \tau_q$,
$0.05\ \text{s} < \tau_c < 0.5\text{s}$
$V_{12} = V_q$, $V_{34} = V_d$

9. Hydraulic actuator



$$\frac{Y(s)}{X(s)} = \frac{K}{s(Ms + B)}$$

$$K = \frac{Ak_x}{k_p},\quad B = \left(b + \frac{A^2}{k_p}\right)$$

$$k_x = \left.\frac{\partial g}{\partial x}\right|_{x_0},\quad k_p = \left.\frac{\partial g}{\partial P}\right|_{P_0},$$

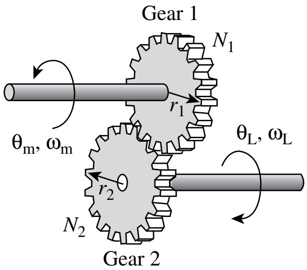
$$g = g(x, P) = \text{flow}$$

$$A = \text{area of piston}$$

Transfer Functions of Dynamic Elements and Networks (continued)

Element or System	G(s)

10. Gear train, rotational transformer

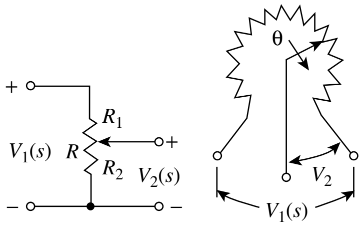


$$\text{Gear ratio} = n = \frac{N_1}{N_2}$$

$$N_2\theta_L = N_1\theta_m,\ \theta_L = n\theta_m$$

$$\omega_L = n\omega_m$$

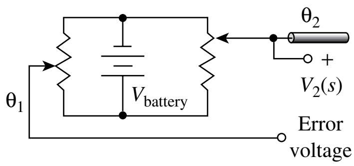
11. Potentiometer, voltage control



$$\frac{V_2(s)}{V_1(s)} = \frac{R_2}{R} = \frac{R_2}{R_1 + R_2}$$

$$\frac{R_2}{R} = \frac{\theta}{\theta_{max}}$$

12. Potentiometer error detector bridge

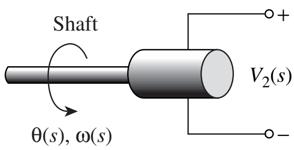


$$V_2(s) = k_s\left(\theta_1(s) - \theta_2(s)\right)$$

$$V_2(s) = k_s\theta_{error}(s)$$

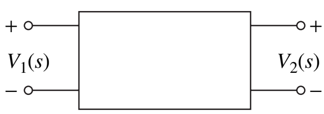
$$k_s = \frac{V_{battery}}{\theta_{max}}$$

13. Tachometer, velocity sensor



$V_2(s) = K_t\omega(s) = K_t s\theta(s)$;
K_t = constant

14. dc amplifier



$$\frac{V_2(s)}{V_1(s)} = \frac{k_a}{s\tau + 1}$$

R_o = output resistance

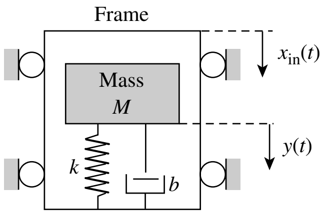
C_o = output capacitance

$\tau = R_oC_o$, $\tau \ll 1s$
and is often negligible for
controller amplifier

Transfer Functions of Dynamic Elements and Networks (continued)

Element or System	G(s)

15. Accelerometer, acceleration sensor



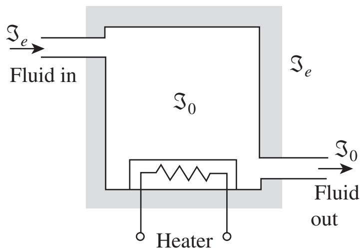
$$x_o(t) = y(t) - x_m(t);$$

$$\frac{X_o(s)}{X_{in}(s)} = \frac{-s^2}{s^2 + (b/M)s + k/M}$$

For low-frequency oscillations, where $\omega < \omega_n$,

$$\frac{X_o(j\omega)}{X_{in}(j\omega)} \simeq \frac{\omega^2}{k/M}$$

16. Thermal heating system



$$\frac{\mathcal{T}(s)}{q(s)} = \frac{1}{C_1 s + (QS + 1/R)}$$, where

$\mathcal{T} = \mathcal{T}_o - \mathcal{T}_e$ = temperature difference due to thermal process

C_t = thermal capacitance

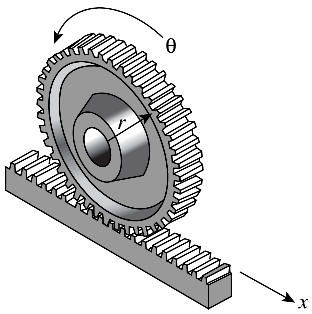
Q = fluid flow rate = constant

S = specific heat of water

R_t = thermal resistance of insulation

$q(s)$ = rate of heat flow of heating element

17. Rack and pinion



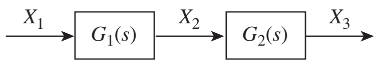
$x = r\theta$
converts radial motion to linear motion

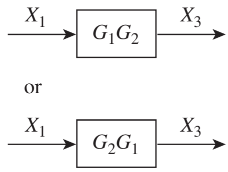
From Dorf, R.C. and Bishop, R.H., Mathematical models of systems, in *Modern Control Systems*, 9th ed., Prentice-Hall, Englewood Cliffs, NJ.

Block Diagram Transformations

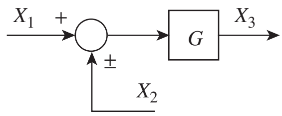
Transformation — Original Diagram — Equivalent Diagram

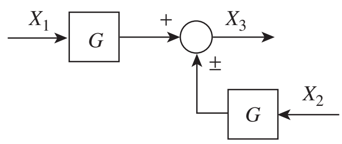
1. Combining blocks in cascade



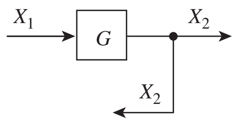


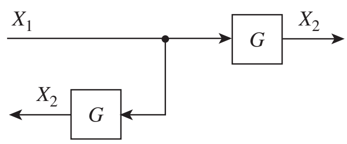
2. Moving a summing point behind a block



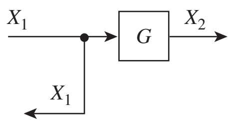


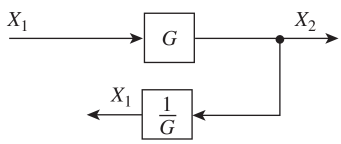
3. Moving a pickoff point ahead of a block



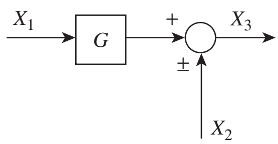


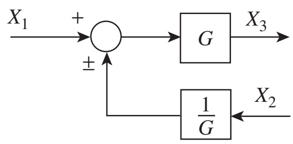
4. Moving a pickoff point behind a block



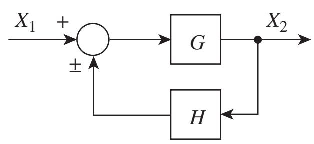


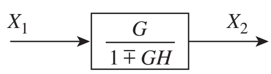
5. Moving a summing point ahead of a block





6. Eliminating a feedback loop



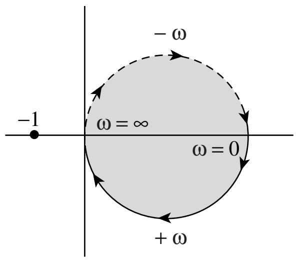


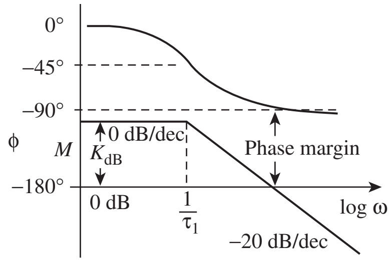
From Dorf, R.C. and Bishop, R.H., Mathematical Models of Systems, in *Modern Control Systems*, 9th ed., Prentice-Hall, Englewood Cliffs, NJ.

Transfer Function Plots for Typical Transfer Functions

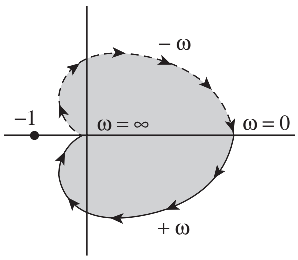
G(s)	Polar Plot	Bode Diagram

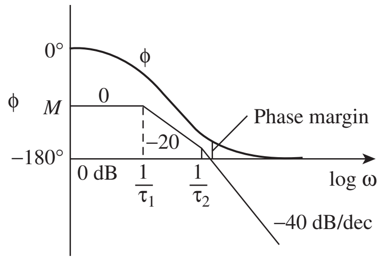
1. $\frac{K}{s\tau_1 + 1}$



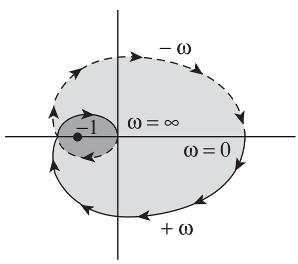


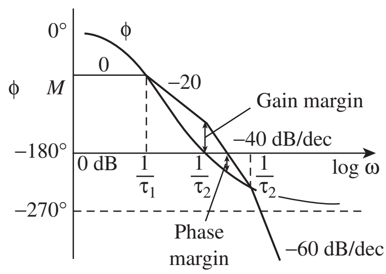
2. $\frac{K}{(s\tau_1 + 1)(s\tau_2 + 1)}$



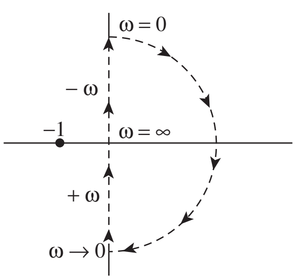


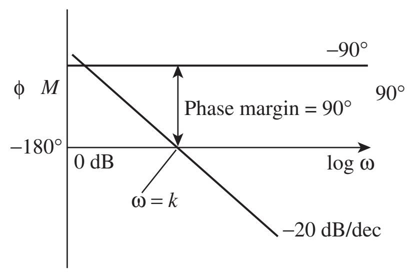
3. $\frac{K}{(s\tau_1 + 1)(s\tau_2 + 1)(s\tau_3 + 1)}$

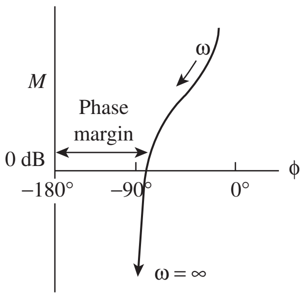
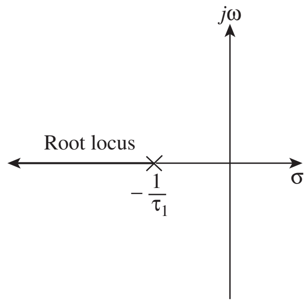
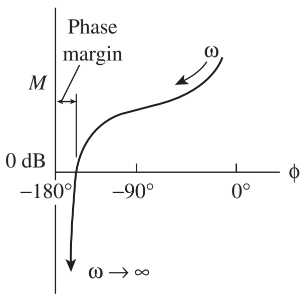
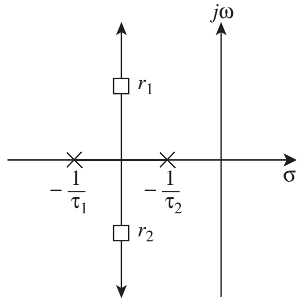
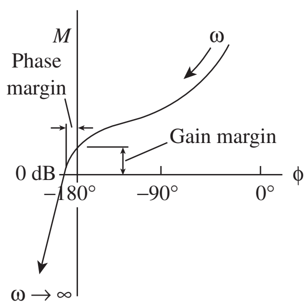
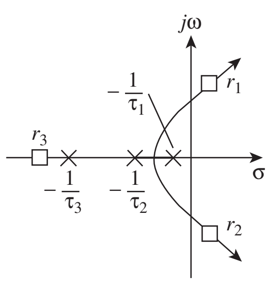
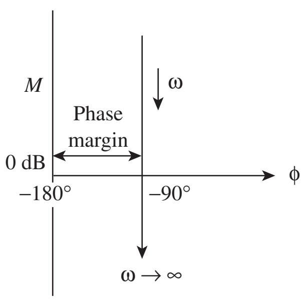
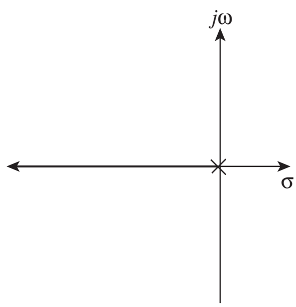




4. $\frac{K}{s}$



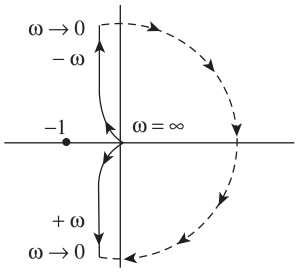


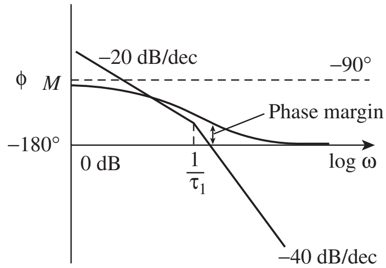
Nichols Diagram	Root Locus	Comments
		Stable; gain margin = ∞
		Elementary regulator; stable; gain margin = ∞
		Regulator with additional energy-storage component; unstable, but can be made stable by reducing gain
		Ideal integrator; stable

Transfer Function Plots for Typical Transfer Functions (continued)

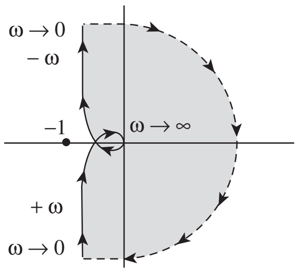
G(s)	Polar Plot	Bode Diagram

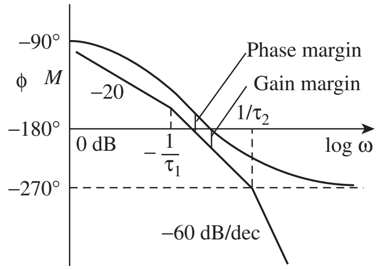
5. $\frac{K}{s(s\tau_1+1)}$



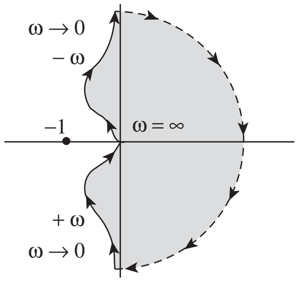


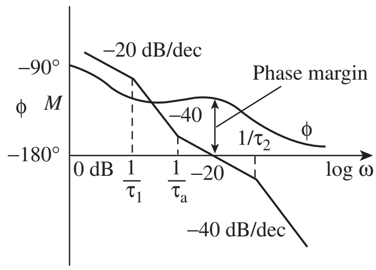
6. $\frac{K}{s(s\tau_1+1)(s\tau_2+1)}$



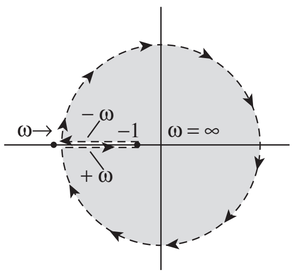


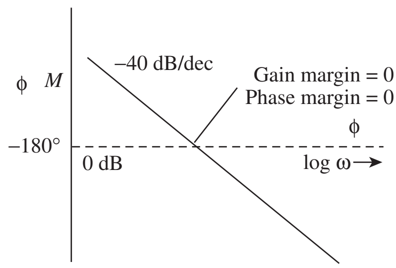
7. $\frac{K(s\tau_a+1)}{(s\tau_1+1)(s\tau_2+1)}$

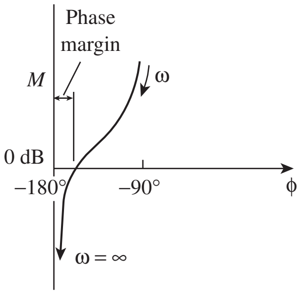
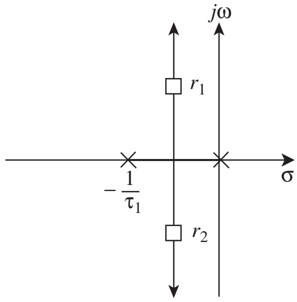
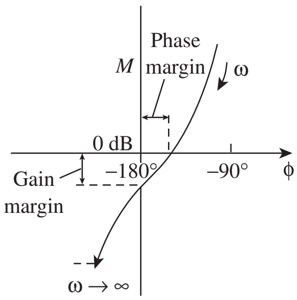
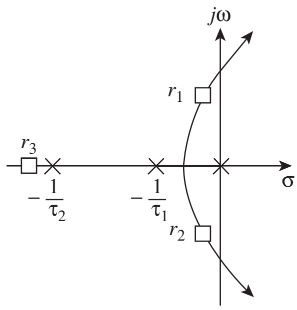
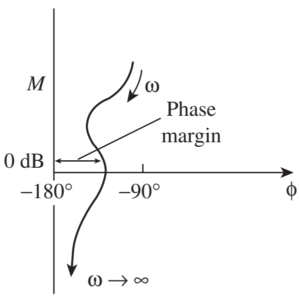
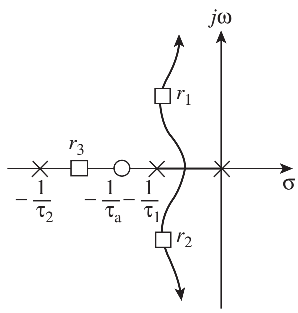
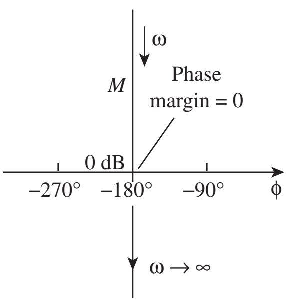
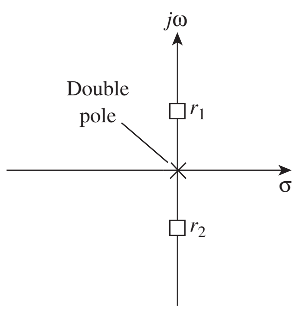




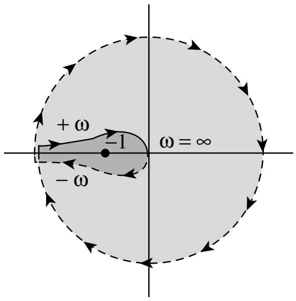
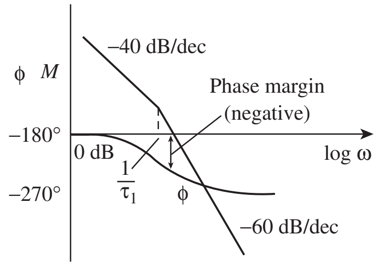
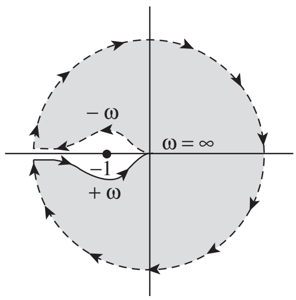
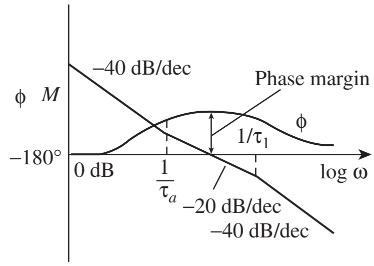
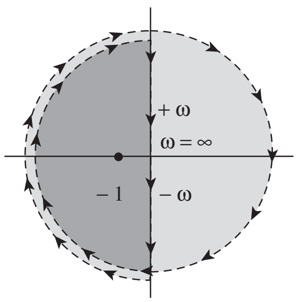
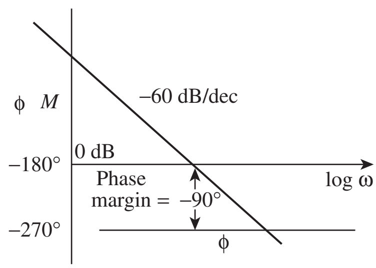
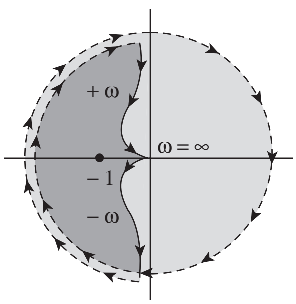
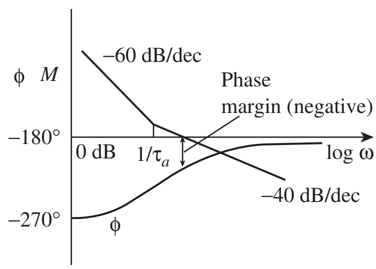
8. $\frac{K}{s^2}$

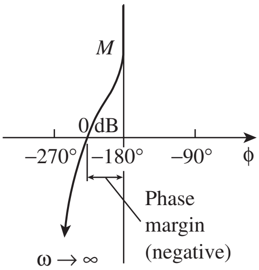
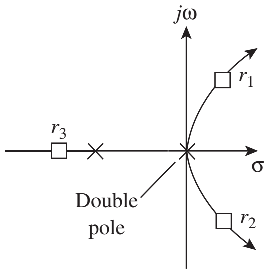
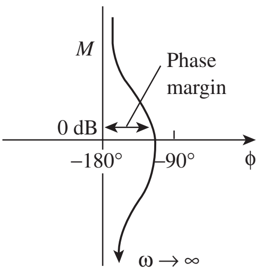
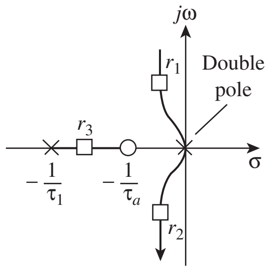
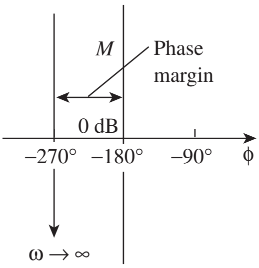
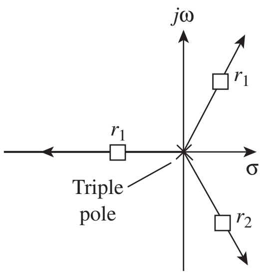
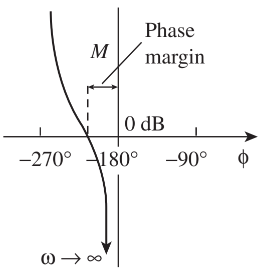
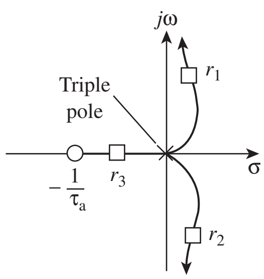




<table>
<tr><th>Nichols Diagram</th><th>Root Locus</th><th>Comments</th></tr>
<tr><td>
</td><td>
</td><td>Elementary instrument servo; inherently stable; gain margin = ∞</td></tr>
<tr><td>
</td><td>
</td><td>Instrument servo with field control motor or power servo with elementary Wark-Leonard drive; stable as shown, but may become unstable with increased gain</td></tr>
<tr><td>
</td><td>
</td><td>Elementary instrument servo with phase-lead (derivative) compensator; stable</td></tr>
<tr><td>
</td><td>
</td><td>Inherently marginally stable; must be compensated</td></tr>
</table>

Transfer Function Plots for Typical Transfer Functions (continued)

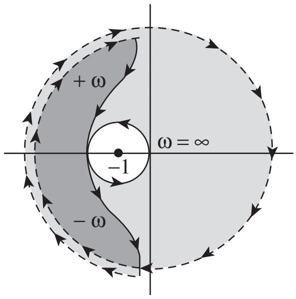
<table>
<tr><th>G(s)</th><th>Polar Plot</th><th>Bode Diagram</th></tr>
<tr><td>9. $\frac{K}{s^2(s\tau_1+1)}$</td><td>
</td><td>
</td></tr>
<tr><td>10. $\frac{K(s\tau_a+1)}{s^2(s\tau_1+1)}$
$\tau_a > \tau_1$</td><td>
</td><td>
</td></tr>
<tr><td>11. $\frac{K}{s^3}$</td><td>
</td><td>
</td></tr>
<tr><td>12. $\frac{K(s\tau_a+1)}{s^3}$</td><td>
</td><td>
</td></tr>
</table>

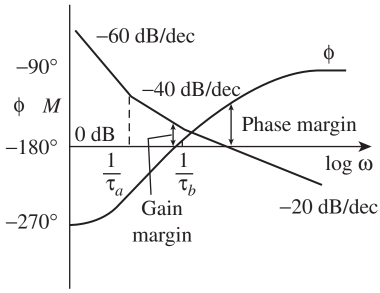
Nichols Diagram	Root Locus	Comments
		Inherently unstable; must be compensated
		Stable for all gains
		Inherently unstable
		Inherently unstable

Transfer Function Plots for Typical Transfer Functions (continued)

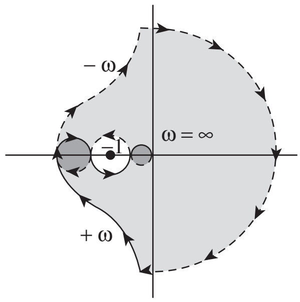
G(s)	Polar Plot	Bode Diagram

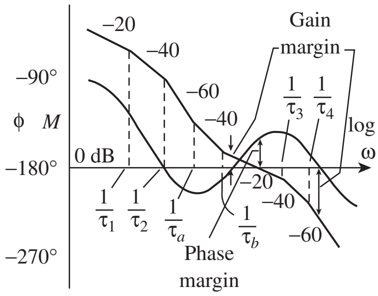
13. $\dfrac{K(s\tau_a+1)(s\tau_b+1)}{s^3}$



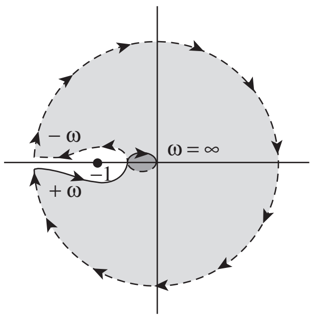


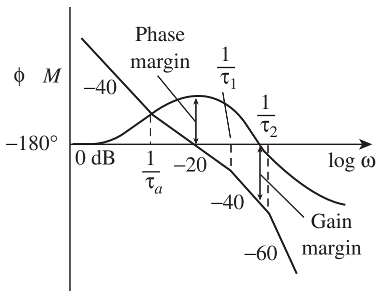
14. $\dfrac{K(s\tau_a+1)(s\tau_b+1)}{s(s\tau_1+1)(s\tau_2+1)(s\tau_3+1)(s\tau_4+1)}$

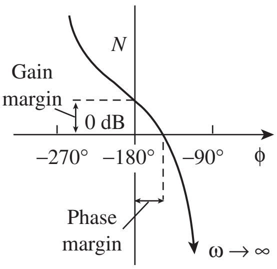
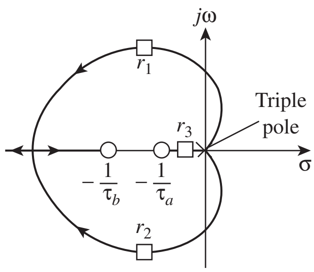
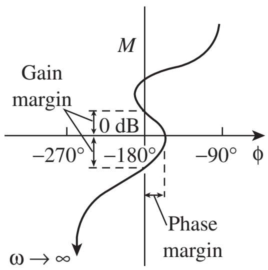
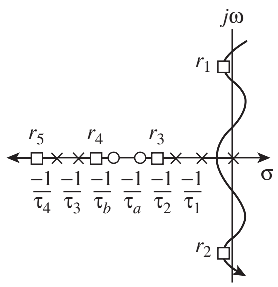
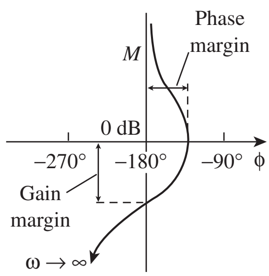
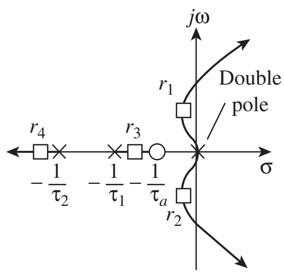




15. $\dfrac{K(s\tau_a+1)}{s^2(s\tau_1+1)(s\tau_2+1)}$





Nichols Diagram	Root Locus	Comments
		Conditionally stable; becomes unstable if gain is too low
		Conditionally stable; stable at low gain, becomes unstable as gain is raised, again becomes stable as gain is further increased, and becomes unstable for very high gains
		Conditionally stable; becomes unstable at high gain

From Dorf, R.C. and Bishop, R.H., Stability in the frequency domain, in *Modern Control Systems*, 9th ed., Prentice-Hall, Englewood Cliffs, NJ.

Fraction of Area Occupied by the Eight Primaries of the Neugebauer Model

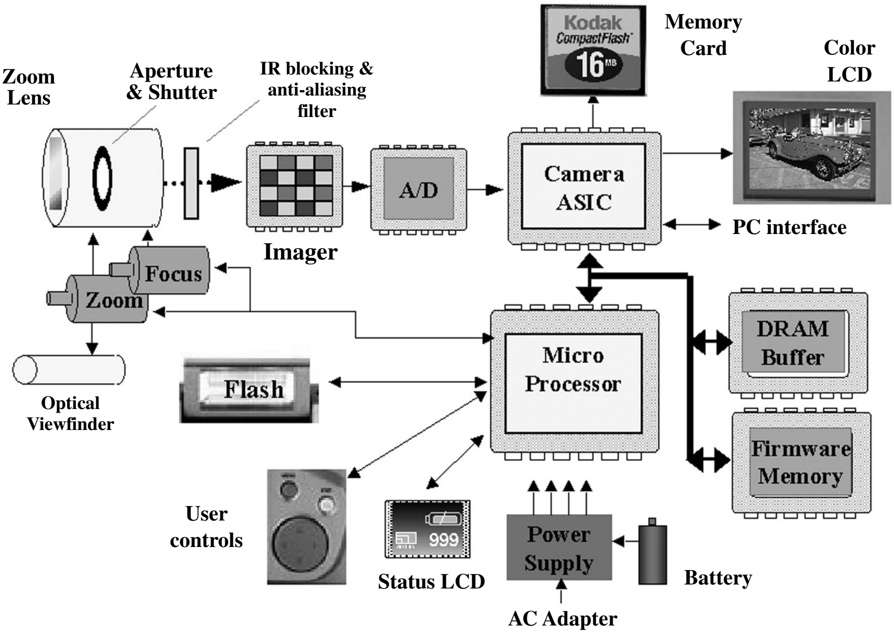
Primary	Ink Combination	Reflectance	Fraction of Area
White	—	$R_1(\lambda)$	$a_1 = (1-c)(1-m)(1-y)$
Cyan	Cyan	$R_2(\lambda)$	$a_2 = c(1-m)(1-y)$
Magenta	Magenta	$R_3(\lambda)$	$a_3 = (1-c)m(1-y)$
Yellow	Yellow	$R_4(\lambda)$	$a_4 = (1-c)(1-m)y$
Red	Magenta, yellow	$R_5(\lambda)$	$a_5 = (1-c)my$
Green	Cyan, yellow	$R_6(\lambda)$	$a_6 = c(1-m)y$
Blue	Cyan, magenta	$R_7(\lambda)$	$a_7 = cm(1-y)$
Black	Cyan, magenta, yellow	$R_8(\lambda)$	$a_8 = cmy$

From Emmel, P., Physical models for color prediction, in *Digital Color Imaging Handbook,* Sharma, G., Ed., CRC Press, Boca Raton, FL, 2003, p. 222.

Characterization vs. Calibration

	Characterization	Calibration
Stability	Stable with time (assumption)	Short-term drifts and environmental sensitivity
Process	Time consuming	Real-time, repeatable
Sensors	Expensive colorimetry	Inexpensive densitometry
Complexity	Three-dimensional or four-dimensional problem [3×3 matrix, 3-D lookup table (LUT) with interpolation, includes black]	One-dimensional problem (four LUTs)
Required by	Colorant characteristics, halftone orientation strategy	Dot gain, electrical and mechanical drift, d_{max}
Detail	Smooth functions	Detailed functions (can contain kinks and flat spots)
Method	Statistical averaging process	Measurement process

From Hains, C., Wang, S.-G., and Knox, K., Digital color halftones, in *Digital Color Imaging Handbook,* Sharma, G., Ed., CRC Press, Boca Raton, FL, 2003, p. 431.



Block diagram of the hardware components used in a typical digital camera. (From Parulski, K. and Spaulding, K., Color image processing for digital cameras, in *Digital Color Imaging Handbook,* Sharma, G., Ed., CRC Press, Boca Raton, FL, 2003, p. 729.)

Some Basic DTFT Pairs

	Sequence	Fourier Transform
1.	$\delta[n]$	1
2.	$\delta[n - n_0]$	$e^{-j\omega n_0}$
3.	$1\ (-\infty < n < \infty)$	$\sum_{k=-\infty}^{\infty} 2\pi\delta(\omega + 2k)$
4.	$a^n u[n]\ (\lvert a\rvert < 1)$	$\frac{1}{1 - ae^{-j\omega}}$
5.	$u[n]$	$\frac{1}{1 - e^{-j\omega}} + \sum_{k=-\infty}^{\infty} \pi\delta(\omega + 2\pi k)$
6.	$(n + 1)a^n u[n]\ (\lvert a\rvert < 1)$	$\frac{1}{\left(1 - ae^{-j\omega}\right)^2}$
7.	$\frac{r^2 \sin\omega_p(n+1)}{\sin\omega_p} u[n]\ (\lvert r\rvert < 1)$	$\frac{1}{1 - 2r\cos\omega_p e^{-j\omega} + r^2 e^{j2\omega}}$
8.	$\frac{\sin\omega_c n}{\pi n}$	$Xe^{j\omega} = \begin{cases} 1, & \lvert\omega\rvert < \omega_c \\ 0, & \omega_c < \lvert\omega\rvert \le \pi \end{cases}$

Some Basic DTFT Pairs (continued)

	Sequence	Fourier Transform
9.	$x[n] - \begin{cases} 1, & 0 \le n \le M \\ 0, & \text{otherwise} \end{cases}$	$\frac{\sin[\omega(M+1)/2]}{\sin(\omega/2)} = e^{-j\omega M/2}$
10.	$e^{j\omega n_0}$	$\sum_{k=-\infty}^{\infty} 2\pi\delta(\omega - \omega_0 + 2\pi k)$
11.	$\cos(\omega_0 n + \phi)$	$\pi \sum_{k=-\infty}^{\infty} \left[e^{j\phi}\delta(\omega - \omega_0 + 2\pi k) + e^{-j\phi}\delta(\omega + \omega_0 + 2\pi k)\right]$

From Jenkins, W.K., Fourier series, Fourier transforms, and the DFT, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **1**-12. Originally from A.V. Oppenheim and R.W. Schafer, *Discrete-Time Signal Processing*, © 1989. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ.

Properties of the DTFT

	Sequence $x[n]$ $y[n]$	Fourier Transform $X(e^{j\omega})$ $Y(e^{j\omega})$
1.	$ax[n] + by[n]$	$aX(e^{j\omega}) + bY(e^{j\omega})$
2.	$x[n - n_d]$ (n_d an integer)	$e^{-j\omega n}\ d\ X(e^{j\omega})$
3.	$e^{j\omega_0 n}x[n]$	$X\left(e^{j(\omega-\omega_0)}\right)$
4.	$x[-n]$	$X(e^{-j\omega})$ if $x[n]$ is real $X^*(e^{j\omega})$
5.	$nx[n]$	$j\frac{dX(e^{j\omega})}{d\omega}$
6.	$x[n] * y[n]$	$X(e^{j\omega})\ Y(e^{j\omega})$
7.	$x[n]\ y[n]$	$\frac{1}{2\pi}\int_{-x}^{x} X(e^{j\theta})Y(e^{j(\omega-\theta)})d\theta$
	Parseval's Theorem	
8.	$\sum_{n=-\infty}^{\infty} \lvert x[n]\rvert^2 = \frac{1}{2\pi}\int_{-\pi}^{\pi} \lvert X(e^{j\omega})\rvert^2 d\omega$	
9.	$\sum_{n=-\infty}^{\infty} x[n]y^*[n] = \frac{1}{2\pi}\inf_{-\pi}^{\pi} X(e^{j\omega})Y^*(e^{j\omega})d\omega$	

From Jenkins, W.K., Fourier series, Fourier transforms, and the DFT, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **1**-13. Originally from A.V. Oppenheim and R.W. Schafer, *Discrete-Time Signal Processing*, © 1989. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ.

Properties of the DFT

	Finite-Length Sequence (Length N)	N-Point DFT (Length N)
1.	$x[n]$	$X[k]$
2.	$x_1[n], x_2[n]$	$X_1[k], X_2[k]$
3.	$ax_1[n] + bx_2[n]$	$aX_1[k] + bX_2[k]$
4.	$X[n]$	$Nx[((-k))_N]$
5.	$x[((n_m))_N]$	$W_N^{km}X[k]$
6.	$W_N^{-\ln}x[n]$	$X[((k-l))_N]$
7.	$\sum_{m=0}^{N-1} x_1(m)x_2\left[\left(\left(n_m\right)\right)_N\right]$	$X_1[k]X_2[k]$
8.	$x_1[n]x_2[n]$	$\frac{1}{N}\sum_{l=0}^{N-1} X_1(l)X_2\left[\left(\left(k-l\right)\right)_N\right]$
9.	$x^*[n]$	$X^*[((-k))_N]$
10.	$x^*[((-n))_N]$	$X^*[k]$
11.	$\text{Re}\{x[n]\}$	$x_{ep}[k] = \frac{1}{2}\left\{X\left[\left(\left(k\right)\right)_N\right] + K^*\left[\left(\left(-k\right)\right)_N\right]\right\}$
12.	$j\text{Im}\{x[n]\}$	$x_{op}[k] = \frac{1}{2}\left\{X\left[\left(\left(k\right)\right)_N\right] - X^*\left[\left(\left(-k\right)\right)_N\right]\right\}$
13.	$x_{ep}[n] = \frac{1}{2}\left\{x[n] + x^*\left[\left(\left(-n\right)\right)_N\right]\right\}$	$\text{Re}\{X[k]\}$
14.	$x_{op}[n] = \frac{1}{2}\left\{x[n] - x^*\left[\left(\left(-n\right)\right)_N\right]\right\}$	$j\text{Im}\{X[k]\}$
Properties 15–17 apply only when $x[n]$ is real		
15.	Symmetry properties	$\begin{cases} X[k] = X^*\left[\left(\left(-k\right)\right)_N\right] \\ \text{Re}\{X[k]\} = \text{Re}\left\{X\left[\left(\left(-k\right)\right)_N\right]\right\} \\ \text{Im}\{X[k]\} = -\text{Im}\left\{X\left[\left(\left(-k\right)\right)_N\right]\right\} \\ \lvert X[k]\rvert = \left\lvert X\left[\left(\left(-k\right)\right)_N\right]\right\rvert \\ \sphericalangle\{X[k]\} = -\sphericalangle\left\{X\left[\left(\left(-k\right)\right)_N\right]\right\} \end{cases}$
16.	$x_{ep}[n] = \frac{1}{2}\left\{x[n] + x\left[\left(\left(-n\right)\right)_N\right]\right\}$	$\text{Re}\{X[k]\}$
17.	$x_{op}[n] = \frac{1}{2}\left\{x[n] - x\left[\left(\left(-n\right)\right)_N\right]\right\}$	$j\text{Im}\{X[k]\}$

From Jenkins, W.K., Fourier series, Fourier transforms, and the DFT, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **1**-16. Originally from A.V. Oppenheim and R.W. Schafer, *Discrete-Time Signal Processing*, © 1989. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ.

Summary of the Four Types of Linear-Phase FIR Filters

	Odd Length (N)	Even Length (N)
Even symmetry	Type I	Type II
$h(\alpha + n) = h(\alpha - n)$	$\sum_{k=0}^{\frac{1}{2}[N-1]} a(k)\cos(\omega k)$	$\sum_{k=1}^{\frac{1}{2}N} b(k)\cos\left(\omega\left[k-\frac{1}{2}\right]\right)$
$\alpha = \frac{N-1}{2}$	$a(0) = h\left(\frac{N-1}{2}\right)$	zero at $\omega = \pi$
$\beta = 0$	$a(k) = 2h\left(\frac{N-1}{2} - k\right)$	$b(k) = 2h\left(\frac{N}{2} - k\right)$
		$\cos\left(\frac{1}{2}\omega\right)\sum_{k=0}^{\frac{1}{2}N-1} \hat{b}(k)\cos(\omega k)$
Odd symmetry	Type III	Type IV
$h(\alpha + n) = -h(\alpha - n)$	$\sum_{k=1}^{\frac{1}{2}[N-1]} c(k)\sin(\omega k)$	$\sum_{k=1}^{\frac{1}{2}N} d(k)\sin\left(\omega\left[k-\frac{1}{2}\right]\right)$
$\alpha = \frac{N-1}{2}$	zeros at $\omega = 0, \pi$	zero at $\omega = 0$
$\beta = \frac{\pi}{2}$	$c(k) = 2h\left(\frac{N-1}{2} - k\right)$	$d(k) = 2h\left(\frac{N}{2} - k\right)$
	$h\left(\frac{N-1}{2}\right) = 0$	
	$\sin(\omega)\sum_{k=0}^{\alpha-1} \hat{c}(k)\cos(\omega k)$	$\sin\left(\frac{1}{2}\omega\right)\sum_{k=0}^{\frac{1}{2}N-1} \hat{d}(k)\cos(\omega k)$

From Karam, L.J., McClellan, J.H., and Selesnick, I.W., Digital filtering, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **11**-12.

Basic Parameters for Three Classes of Acoustic Signals

	Frequency Range in Hz	Sampling Rate in kHz	PCM Bis per Sample	PCM Bit Rate in kb/s
Telephone speech	300–3,400[a]	8	8	64
Wideband speech	50–7,000	16	8	128
Wideband audio (stereo)	10–20,000	48[b]	2 × 16	2 × 768

[a] Bandwidth in Europe; 200 to 3200 Hz in the U.S.
[b] Other sampling rates: 44.1 kHz, 32 kHz.

From Noll, P., MPEG digital audio coding standards, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **40**-2.

CD and DAT Bit Rates

Storage Device	Audio Rate (Mb/s)	Overhead (Mb/s)	Total Bit Rate (Mb/s)
Compact disc (CD)	1.41	2.91	4.32
Digital audio tape (DAT)	1.41	1.05	2.46

Note: Stereophonic signals, sampled at 44.1 kHz; DAT supports also sampling rates of 32 kHz and 48 kHz.

From Noll, P., MPEG digital audio coding standards, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **40**-2.

Summary of the Functionalities and Characteristics of the Existing Standards

	ITU		ISO		
Attribute	H.261	H.263	MPEG-1	MPEG-2	MPEG-4
Applications	Video-conferencing	Video-phone	CD storage	Broadcast	Wide range (multimedia)
Bit rate	64K–1M	<64 K	1.0–1.5M	2–10M	5K–4M
Material	Progressive	Progressive	Progressive, interlaced	Progressive, interlaced	Progressive, interlaced
Object shape	Rectangular	Arbitrary (simple)	Rectangular	Rectangular	Arbitrary
			Residual Coding		
Transform	8 × 8 DCT	8 × 8 DCT	8 × 8 DCT	8 × 8 DCT	8 × 8 DCT
Quantizer	Uniform	Uniform	Weighted uniform	Weighted uniform	Weighted uniform
			Motion Compensation		
Type	Block	Block	Block	Block	Block, sprites
Block size	16 × 16	16 × 16, 8 × 8	16 × 16	16 × 16	16 × 16, 8 × 8
Prediction type	Forward	Forward, backward	Forward backward	Forward, backward	Forward, backward
Accuracy	One pixel	Half pixel	Half pixel	Half pixel	Half pixel
Loop filter	Yes	No	No	No	No
			Scalability		
Temporal	No	Yes	Yes	Yes	Yes
Spatial	No	Yes	No	Yes	Yes
Bit rate	No	Yes	No	Yes	Yes
Object	No	No	No	No	Yes

From Al-Shaykh, O., Neff, R., Taubman, D., and Zakhor, A., Video sequence compression, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **55**-16.

EV and ICEV Efficiencies from Crude Oil to Traction Effort

ICEV	Efficiency (%) Max.	Efficiency (%) Min.	EV	Efficiency (%) Max.	Efficiency (%) Min.
Crude oil			Crude oil		
Refinery (petroleum)	90	85	Refinery (fuel oil)	97	95
Distribution to fuel tank	99	95	Electricity generation	40	33
Engine	22	20	Transmission to wall outlet	92	90
Transmission/axle	98	95	Battery charger	90	85
Wheels			Battery (lead/acid)	75	75
			Motor/controller	85	80
			Transmission/axle	98	95
			Wheels		
Overall efficiency (crude oil to wheels)	19	15	Overall efficiency (crude oil to wheels)	20	14

From Husain, I., Inroduction to electric vehicles, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 12.

Nominal Energy Density of Sources

Energy Source	Nominal Specific Energy (Wh/kg)
Gasoline	12,500
Natural gas	9350
Methanol	6050
Hydrogen	33,000
Coal (bituminous)	8200
Lead-acid battery	35
Lithium-polymer battery	200
Flywheel (carbon-fiber)	200

From Husain, I., Energy Source: Battery, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 44.

Specific Energy of Batteries

Battery	Specific Energy (Wh/kg) Theoretical	Specific Energy (Wh/kg) Practical
Lead-acid	108	50
Nickel-cadmium		20–30
Nickel-zinc		90
Nickel-iron		60
Zinc-chlorine		90
Silver-zinc	500	100
Sodium-sulfur	770	150–300
Aluminum-air		300

From Husain, I., Energy source: Battery, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 47.

USABC Objectives for EV Battery Packs

Parameter	Mid-Term	Commercialization	Long-Term
Specific energy (Wh/kg) (C/3 discharge rate)	80–100	150	200
Energy density (Wh/liter) (C/3 discharge rate)	135	230	300
Specific power (W/kg)(80% *DoD* per 30 s)	150–200	300	400
Specific power (W/kg), Regen. (20% *DoD* per 10 s)	75	150	200
Power density (W/liter)	250	460	600
Recharge time, h (20% → 100% *SoC*)	<6	4–6	3–6
Fast recharge time, min	<15	<30	<15
Calendar life, years	5	10	10
Life, cycles	600 @ 80% *DoD*	1000 @ 80% *DoD* 1600 @ 50% *DoD* 2670 @ 30% *DoD*	1000 @ 80% *DoD*
Lifetime urban range, miles	100,000	100,000	100,000
Operating environment, °C	–30 to +65	–40 to +50	–40 to +85
Cost, US$/kWh	<150	<150	<100
Efficiency, %	75	80	80

From Husain, I., Energy Source: Battery, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 68.

Properties of EV and HEV Batteries

Battery Type	Specific Energy, Wh/kg	Specific Power, W/kg	Energy Efficiency, %	Cycle Life	Estimated Cost, US$/*kWh*
Lead-acid	35–50	150–400	80	500–1000	100–150
Nickel-cadmium	30–50	100–150	75	1000–2000	250–350
Nickel-metal-hydride	60–80	200–300	70	1000–2000	200–350
Aluminum-air	200–300	100	<50	Not available	Not available
Zinc-air	100–220	30–80	60	500	90–120
Sodium-sulfur	150–240	230	85	1000	200–350
Sodium-nickel-chloride	90–120	130–160	80	1000	250–350
Lithium-polymer	150–200	350	Not available	1000	150
Lithium-ion	80–130	200–300	>95	1000	200

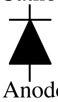
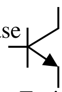
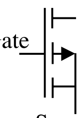
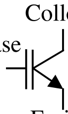
From Husain, I., Energy Source: Battery, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 68.

Fuel Cell Types

Fuel Cell Variety	Fuel	Electrolyte	Operating Temperature	Efficiency	Applications
Phosphoric acid	H_2, reformate (LNG, methanol)	Phosphoric acid	~200°C	40–50%	Stationary (>250 kW)
Alkaline	H_2	Potassium hydroxide solution	~80°C	40–50%	Mobile
Proton exchange membrane	H_2, reformate (LNG, methanol)	Polymer ion exchange film	~80°C	40–50%	EV and HEV, industrial up to ~80 kW
Direct methanol	Methanol, ethanol	Solid polymer	90–100°C	~30%	EV and HEVs, small portable devices (1 W to 70 kW)
Molten carbonate	H_2, CO (coal gas, LNG, methanol)	Carbonate	600–700°C	50–60%	Stationary (>250 kW)
Solid oxide	H_2, CO (coal gas, LNG, methanol)	Yttria-stabilized zirconia	~1000°C	50–65%	Stationary

From Husain, I., Alternative energy sources, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 86.

Summary of Power Devices

Name	Symbol	Turn On	Turn Off	Comments
Diode	Cathode  Anode	• Positive anode to cathode voltage	• Reverse anode current • Recovery time before turning off	• Turn off and on depend on circuit conditions • High power capabilities
SCR	Cathode Gate  Anode	• Small gate pulse (current) • Slow to medium turn-on time (~5 μs)	• Anode current goes below holding • Delay time before forward voltage can be applied (10–200 μs)	• Very high power • Needs additional circuit to turn off • On voltage ≈2.5 V
GTO	Cathode Gate  Anode	• Small gate pulse (current) • Slow to medium turn-on time (~10 μs)	• Remove charge from gate (medium current) • Medium speed (~0.5 μs)	• High power • Easier to turn off than SCR • On voltage ≈2.5 V
BJT	Collector Base  Emitter	• Medium current to base to turn on • Medium speed (0.5 μs)	• Remove current from base • Medium speed (0.2 μs)	• Medium power • Easy to control • Medium drive requirements • On voltage ≈1.5 V
MOSFET	Drain Gate  Source	• Voltage to gate (v_{GS}) • Very high speed (0.2 μs)	• Remove voltage from gate • High speed (0.5 μs)	• Low power • Very easy to control • Simple gate drive requirement • High on losses ≈0.1 Ω on resistance
IGBT	Collector Base  Emitter	• Voltage to gate (v_{GS}) • High speed (0.4 μs)	• Remove voltage from gate • High speed (~0.7 μs)	• Medium power • Very easy to control • On voltage ≈3.0 V • Combines MOS and BJT technologies

From Husain, I., Power electronics and motor drives, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 165.

Wind Power Installed Capacity

Canada	83
China	224
Denmark	1450
India	968
Ireland	63
Italy	180
Germany	2874
Netherlands	363
Portugal	60
Spain	834
Sweden	150
U.K.	334
U.S.	1952
Other	304
Total	9839

From Johnson, G.L., Wind power, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **1**-2.

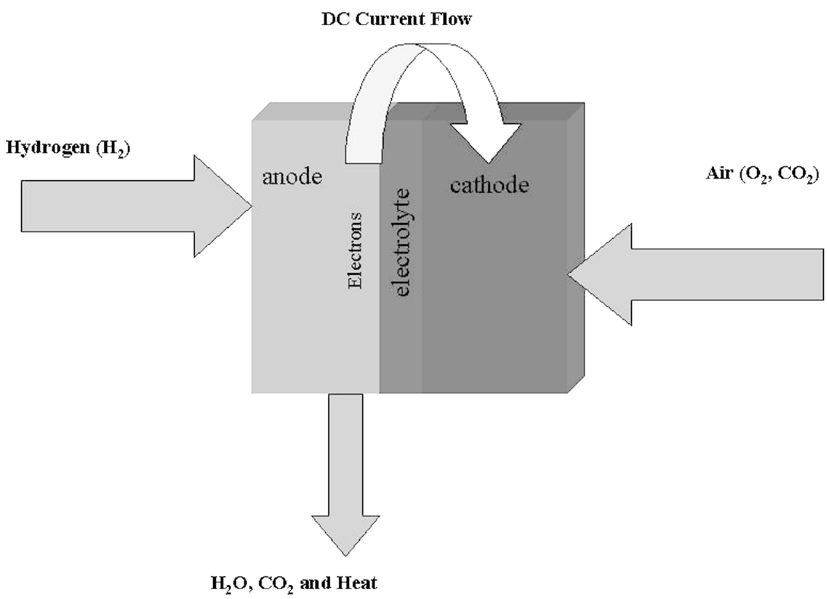
Comparison of Five Fuel Cell Technologies

Type	Electrolyte	Operating Temperature (°C)	Applications	Advantages
Polymer Electrolyte Membrane (PEM)	Solid organic polymer poly-perflouro-sulfonic acid	60–100	Electric utility, transportation, portable power	Solid electrolyte reduces corrosion, low temperature, quick start-up
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90–100	Military, space	Cathode reaction faster in alkaline electrolyte; therefore high performance
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	175–200	Electric utility, transportation, and heat	Up to 85% efficiency in co-generation of electricity
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates soaked in a matrix	600–1000	Electric utility	Higher efficiency, fuel flexibility, inexpensive catalysts
Solid Oxide (SOFC)	Solid zirconium oxide to which a small amount of yttria is added	600–1000	Electric utility	Higher efficiency, fuel flexibility, inexpensive catalysts. Solid electrolyte advantages like PEM

From Rahman, S., Advanced energy technologies, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **1**-12.

Technology	Size	Fuel Sources	AC interface Type	Applications
Fuel Cells	.5Kw – Larger units With Stacking	Natural Gas Hydrogen Petroleum Products	Inverter type	Continuous
Microturbines	10Kw–100Kw Larger sizes	Natural Gas Petroleum Products	Inverter type	Continuous Standby
Batteries	.1Kw–2Mw+	Storage	Inverter type	PQ, Peaking
Flywheel	>.1Kw–.5Kw	Storage	Inverter type	PQ, Peaking
PV	>.1Kw–1Kw	Sunlight	Inverter type	Peaking
Gas Turbine	10Kw–5Mw+	Natural Gas Petroleum Products	Rotary type	Continuous, Peaking Standby

Distributed generation technology chart. (From Kennedy, J.R., Distributed utilities, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **2**-28.)



Basic fuel cell operation. (From Kennedy, J.R., Distributed utilities, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **2**-29.)

Usual Operating Conditions for Transformers (ANSI/IEEE, C57.12.01-1989 (R1998))

Temperature of cooling air	≤40°C
24hr average temperature of cooling air	≤30°C
Minimum ambient temperature	≥–30°C
Load current[a]	Harmonic factor ≤0.05 per unit
Altitude[b]	≤3300 ft (1000 m)
Voltage[c] (without exceeding limiting temperature rise)	• Rated output KVA at 105% rated secondary voltage, power factor ≥0.80 • 110% rated secondary voltage at no load

[a] Any unusual load duty should be specified to the manufacturer.

[b] At higher altitudes, the reduced air density decreases dielectric strength; it also increases temperature rise reducing capability to dissipate heat losses (ANSI/IEEE, C57.12.01-1989 (R1998)).

[c] Operating voltage in excess of rating may cause core saturation and excessive stray losses, which could result in overheating and excessive noise levels (ANSI/IEEE, C57.94-1982 (R1987), C57.12.01-1989 (R1998)).

From Payne, P.A., Dry type transformers, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **3**-65.

Resistivity and Temperature Coefficient of Some Materials

Material	Resistivity at 20°C (Ω-m)	Temperature Coefficient (°C)
Silver	1.59×10^{-8}	243.0
Annealed copper	1.72×10^{-8}	234.5
Hard-drawn copper	1.77×10^{-8}	241.5
Aluminum	2.83×10^{-8}	228.1

From Reta-Hernandez, M., Transmission line parameters, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **4**-65.

Most Commonly Found Relays for Generator Protection

Identification Number	Function Description	Relay Type
87G	Generator phase phase windings protection	Differential protection
87T	Step-up transformer differential protection	Differential protection
87U	Combined differential transformer and generator protection	Differential protection
40	Protection against the loss of field voltage or current supply	Offset mho relay
46	Protection against current imbalance. Measurement of phase negative sequence current	Time-overcurrent relay
32	Anti-motoring protection	Reverse-power relay
24	Overexcitation protection	Volt/Hertz relay
59	Phase overvoltage protection	Overvoltage relay
60	Detection of blown voltage transformer fuses	Voltage balance relay
81	Under- and overfrequency protection	Frequency relays
51V	Backup protection against system faults	Voltage controlled or voltage-restrained time overcurrent relay
21	Backup protection against system faults	Distance relay
78	Protection against loss of synchronization	Combination of offset mho and blinders

From Benmouyal, G., The protection of synchronous generators, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **9**-12.

Appliances and Sectors under Direct Utility Control, U.S. — 1983

Appliance or Sector	Number Controlled	Percent of Total Controlled
Electric water heaters	648,437	43%
Air conditioners	515,252	34%
Irrigation pumps	14,261	1%
Space heating	50,238	3%
Swimming pool pumps	258,993	17%
Other	13,710	1%
Total	**1,500,891**	**100%**
Residential	1,456,212	97%
Commercial	29,830	2%
Industrial	588	—
Agricultural	14,261	1%

From Merrill, H.M., Power system planning, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **13**-43. Originally from *New Electric Power Technologies: Problems and Prospects for the 1990s,* Washington, D.C.: U.S. Congress, Office of Technology Assessment, OTA-E-246, July 1985.

Typical Characteristics of Integrated Circuit Resistors

Resistor Type	Sheet Resistivity (per square)	Temperature Coefficient (ppm/°C)
Semiconductor		
Diffused	0.8 to 260 Ω	1100 to 2000
Bulk	0.003 to 10 kΩ	2900 to 5000
Pinched	0.001 to 10 kΩ	3000 to 6000
Ion-implanted	0.5 to 20 kΩ	100 to 1300
Deposited resistors		
Thin-film		
Tantalum	0.01 to 1 kΩ	∓100
SnO_2	0.08 to 4 kΩ	–1500 to 0
Ni-Cr	40 to 450 Ω	∓100
Cermet (Cr-SiO)	0.03 to 2.5 kΩ	∓150
Thick-film		
Ruthenium-silver	10 Ω to 10 MΩ	∓200
Palladium-silver	0.01 to 100 kΩ	–500 to 150

From Pecht, M. and Lall, P., Resistors, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 13.

Speech Coder Performance Comparisons

Algorithm (acronym)	Standardization Body	Standardization Identifier	Rate kbits/s	Subjective MOS	Subjective DRT	Subjective DAM
μ-law PCM	ITU-T	G.711	64	4.3	95	73
ADPCM	ITU-T	G.721	32	4.1	94	68
LD-CELP	ITU-T	G.728	16	4.0	94[a]	70[a]
RPE-LTP	GSM	GSM	13	3.5	—	—
VSELP	CTIA	IS-54	8	3.5	—	—
CELP	U.S. DoD	FS-1016	4.8	3.13[b]	90.7[b]	65.4[b]
IMBE	Inmarsat	IMBE	4.1	3.4	—	—
LPC-10e	U.S. DoD	FS-1015	2.4	2.24[b]	86.2[b]	50.3[b]

[a] Estimated.
[b] From results of 1996 U.S. DoD 2400 bits/s vocoder competition.

From McClellan, S. and Gibson, J.D., Coding, transmission, and storage, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 345.

Surface Mount Substrate Material

Substrate Material (Units)	T_g – Glass Transition Temperature (°C)	TCE – Thermal Coefficient of X–Y Expansion (PPM/°C)	Thermal Conductivity (W/M°C)	Moisture Absorption (%)
FR-4 Epoxy glass	125	13–18	0.16	0.10
Polymide glass	250	12–16	0.35	0.35
Copper-clad invar	Depends on resin	5–7	160XY — 15–20Z	NA
Poly Aramid fiber	250	3–8	0.15	1.65
Alumina/ceramic	NA	5–7	20–45	NA

From Blackwell, G.R., Surfact mount technology, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 692.

Emissivities of Some Common Materials

Material	Temperature (°C)	Emissivity
Tungsten	2000	0.28
Nickel-chromium (80-20)	600	0.87
Lampblack	20–400	0.96
Polished silver	200	0.02
Glass	1000	0.72
Platinum	600	0.1
Graphite	3600	0.8
Aluminum (oxidized)	600	0.16
Carbon filament	1400	0.53

From Watkins, L.S., Sources and detectors, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 818.

Thermal Conductivities of Typical Packaging Materials at Room Temperature

Materials	Thermal Conductivity (W/m K)
Air	0.024
Mylar	0.19
Silicone rubber	0.19
Solder mask	0.21
Epoxy (dielectric)	0.23
Ablefilm 550 dielectric	0.24
Nylon	0.24
Polytetrafluorethylene	0.24
RTV	0.31
Polyimide	0.33
Epoxy (conductive)	0.35
Water	0.59
Mica	0.71
Ablefilm 550 K	0.78
Thermal greases/pastes	1.10
Borosilicate glass	1.67
Glass epoxy	1.70
Stainless steel	15
Kovar	16.60
Solder (Pb-In)	22
Alumina	25
Solder 80-20 Au-Sn	52
Silicon	118
Molybdenum	138
Aluminum	156
Beryllia	242
Gold	298
Copper	395
Silver	419
Diamond	2000

From Bar-Cohen, A., Thermal management of electronics, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 855. Originally from C.A. Harper, *Electronic Packaging and Interconnection Handbook,* New York: McGraw-Hill, 1991, p. 27. R.R. Tummala and E.J. Rymaszewski, *Microelectronics Packaging Handbook,* New York: Van Nostrand Reinhold, 1989, p. 174.

Relative Permeability, μ_r, of Some Diamagnetic, Paramagnetic, and Ferromagnetic Materials

Material	μr	M_s, A/m²
Diamagnetics		
Bismuth	0.999833	
Mercury	0.999968	
Silver	0.9999736	
Lead	0.9999831	
Copper	0.9999906	
Water	0.9999912	
Paraffin wax	0.99999942	
Paramagnetics		
Oxygen (s.t.p.)	1.000002	
Air	1.00000037	
Aluminum	1.000021	
Tungsten	1.00008	
Platinum	1.0003	
Manganese	1.001	
Ferromagnetics		
Purified iron: 99.96% Fe	280,000	2.158
Motor-grade iron: 99.6% Fe	5,000	2.12
Permalloy: 78.5% Ni, 21.5% Fe	70,000	2.00
Supermalloy: 79% Ni, 15% Fe, 5% Mo, 0.5% Mn	1,000,000	0.79
Permendur: 49% Fe, 49% Ca, 2% V	5,000	2.36
Ferrimagnetics		
Manganese–zinc ferrite	750	0.34
	1,200	0.36
Nickel–zinc ferrite	650	0.29

From Bate, G., Magnetism, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 902. Originally from F. Brailsford, *Physical Principles of Magnetism*, London: Van Nostrand, 1966. With permission.

"Hard" and "Soft" Magnetic Materials

	High M_s	Low H_c	Low M_r	High μ
Soft				
Fe	1700 emu/cc	1 Oe	<500	20,000
80 Ni 20 Fe	660	0.1	<300	50,000
Mn Zn ferrite	400	0.02	<200	5,000
$Co_{70}Fe_5Si_{15}B_{10}$	530	0.1	<250	10,000
	High M_s	High H_c	High M_r	T_c
Hard				
Particles				
γ-Fe_2O_3	400	250–450	200–300	115–126
CrO_2	400	450–600	300	120
Fe	870–1100	1100–1500	435–550	768
$BaO.6Fe_2O_3$	238–370	800–3000	143–260	320
Alloys				
$SmCo_5$	875	40,000	690	720
Sm_2Co_{17}	1000	17,000	875	920
$Fe_{14}BNd_2$	1020	12,000	980	310

From Bate, G., Magnetism, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 908.

Standard Rectangular Waveguides

EIA[a] Designation WR[b]( )	Physical Dimensions Inside, cm (in.) Width	Inside Height	Outside, cm (in.) Width	Outside Height	Cut-off Frequency for Air-filled Waveguide, GHz	Recommended Frequency Range for TE_{10} Mode, GHZ
2300	58.420 (23.000)	29.210 (11.500)	59.055 (23.250)	29.845 (11.750)	0.257	0.32–0.49
2100	53.340 (21.000)	26.670 (10.500)	53.973 (21.250)	27.305 (10.750)	0.281	0.35–0.53
1800	45.720 (18.000)	22.860 (9.000)	46.350 (18.250)	23.495 (9.250)	0.328	0.41–0.62
1500	38.100 (15.000)	19.050 (7.500)	38.735 (15.250)	19.685 (7.750)	0.394	0.49–0.75
1150	29.210 (11.500)	14.605 (5.750)	29.845 (11.750)	15.240 (6.000)	0.514	0.64–0.98
975	24.765 (9.750)	12.383 (4.875)	25.400 (10.000)	13.018 (5.125)	0.606	0.76–1.15
770	19.550 (7.700)	9.779 (3.850)	20.244 (7.970)	10.414 (4.100)	0.767	0.96–1.46
650	16.510 (6.500)	8.255 (3.250)	16.916 (6.660)	8.661 (3.410)	0.909	1.14–1.73
510	12.954 (5.100)	6.477 (2.500)	13.360 (5.260)	6.883 (2.710)	1.158	1.45–2.20
430	10.922 (4.300)	5.461 (2.150)	11.328 (4.460)	5.867 (2.310)	1.373	1.72–2.61
340	8.636 (3.400)	4.318 (1.700)	9.042 (3.560)	4.724 (1.860)	1.737	2.17–3.30
284	7.214 (2.840)	3.404 (1.340)	7.620 (3.000)	3.810 (1.500)	2.079	2.60–3.95
229	5.817 (2.290)	2.908 (1.145)	6.142 (2.418)	3.233 (1.273)	2.579	3.22–4.90
187	4.755 (1.872)	2.215 (0.872)	5.080 (2.000)	2.540 (1.000)	3.155	3.94–5.99
159	4.039 (1.590)	2.019 (0.795)	4.364 (1.718)	2.344 (0.923)	3.714	4.64–7.05
137	3.485 (1.372)	1.580 (0.622)	3.810 (1.500)	1.905 (0.750)	4.304	5.38–8.17
112	2.850 (1.122)	1.262 (0.497)	3.175 (1.250)	1.588 (0.625)	5.263	6.57–9.99
90	2.286 (0.900)	1.016 (0.400)	2.540 (1.000)	1.270 (0.500)	6.562	8.20–12.50
75	1.905 (0.750)	0.953 (0.375)	2.159 (0.850)	1.207 (0.475)	7.874	9.84–15.00
62	1.580 (0.622)	0.790 (0.311)	1.783 (0.702)	0.993 (0.391)	9.494	11.90–18.00
51	1.295 (0.510)	0.648 (0.255)	1.499 (0.590)	0.851 (0.335)	11.583	14.50–22.00
42	1.067 (0.420)	0.432 (0.170)	1.270 (0.500)	0.635 (0.250)	14.058	17.60–26.70
34	0.864 (0.340)	0.432 (0.170)	1.067 (0.420)	0.635 (0.250)	17.361	21.70–33.00
28	0.711 (0.280)	0.356 (0.140)	0.914 (0.360)	0.559 (0.220)	21.097	26.40–40.00
22	0.569 (0.224)	0.284 (0.112)	0.772 (0.304)	0.488 (0.192)	26.362	32.90–50.10
19	0.478 (0.188)	0.239 (0.094)	0.681 (0.268)	0.442 (0.174)	31.381	39.20–59.60

Standard Rectangular Waveguides (continued)

EIA[a] Designation WR[b]( )	Physical Dimensions Inside, cm (in.) Width	Inside, cm (in.) Height	Outside, cm (in.) Width	Outside, cm (in.) Height	Cut-off Frequency for Air-filled Waveguide, GHz	Recommended Frequency Range for TE_{10} Mode, GHZ
15	0.376 (0.148)	0.188 (0.074)	0.579 (0.228)	0.391 (0.154)	39.894	49.80–75.80
12	0.310 (0.122)	0.155 (0.061)	0.513 (0.202)	0.358 (0.141)	48.387	60.50–91.90
10	0.254 (0.100)	0.127 (0.050)	0.457 (0.180)	0.330 (0.130)	59.055	73.80–112.00
8	0.203 (0.080)	0.102 (0.040)	0.406 (0.160)	0.305 (0.120)	73.892	92.20–140.00
7	0.165 (0.065)	0.084 (0.033)	0.343 (0.135)	0.262 (0.103)	90.909	114.00–173.00
5	0.130 (0.051)	0.066 (0.026)	0.257 (0.101)	0.193 (0.076)	115.385	145.00–220.00
4	0.109 (0.043)	0.056 (0.022)	0.211 (0.083)	0.157 (0.062)	137.615	172.00–261.00
3	0.086 (0.034)	0.043 (0.017)	0.163 (0.064)	0.119 (0.047)	174.419	217.00–333.00

[a] Electronic Industry Association.
[b] Rectangular waveguide.

From Demarest, K., Waveguides, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 947. Originally from S.Y. Liao, *Microwave Devices and Circuits,* 3rd ed., Englewood Cliffs, NJ: Prentice-Hall, 1990, p. 118. With permission.

Material Parameters for Several Semiconductors

Semiconductor	E_g (eV)	ε_r	κ (W/cm-K) @300 K	E_c (V/cm)	$\tau_{minority}$ (s)
Si	1.12	11.9	1.5	3×10^5	2.5×10^{-3}
GaAs	1.42	12.5	0.54	4×10^5	$\sim 10^{-8}$
InP	1.34	12.4	0.67	4.5×10^5	$\sim 10^{-8}$
α-SiC	2.86	10.0	4	$(1–5) \times 10^6$	$\sim (1–10) \times 10^{-9}$
β-SiC	2.2	9.7	4	$(1–5) \times 10^6$	$\sim (1–10) \times 10^{-9}$

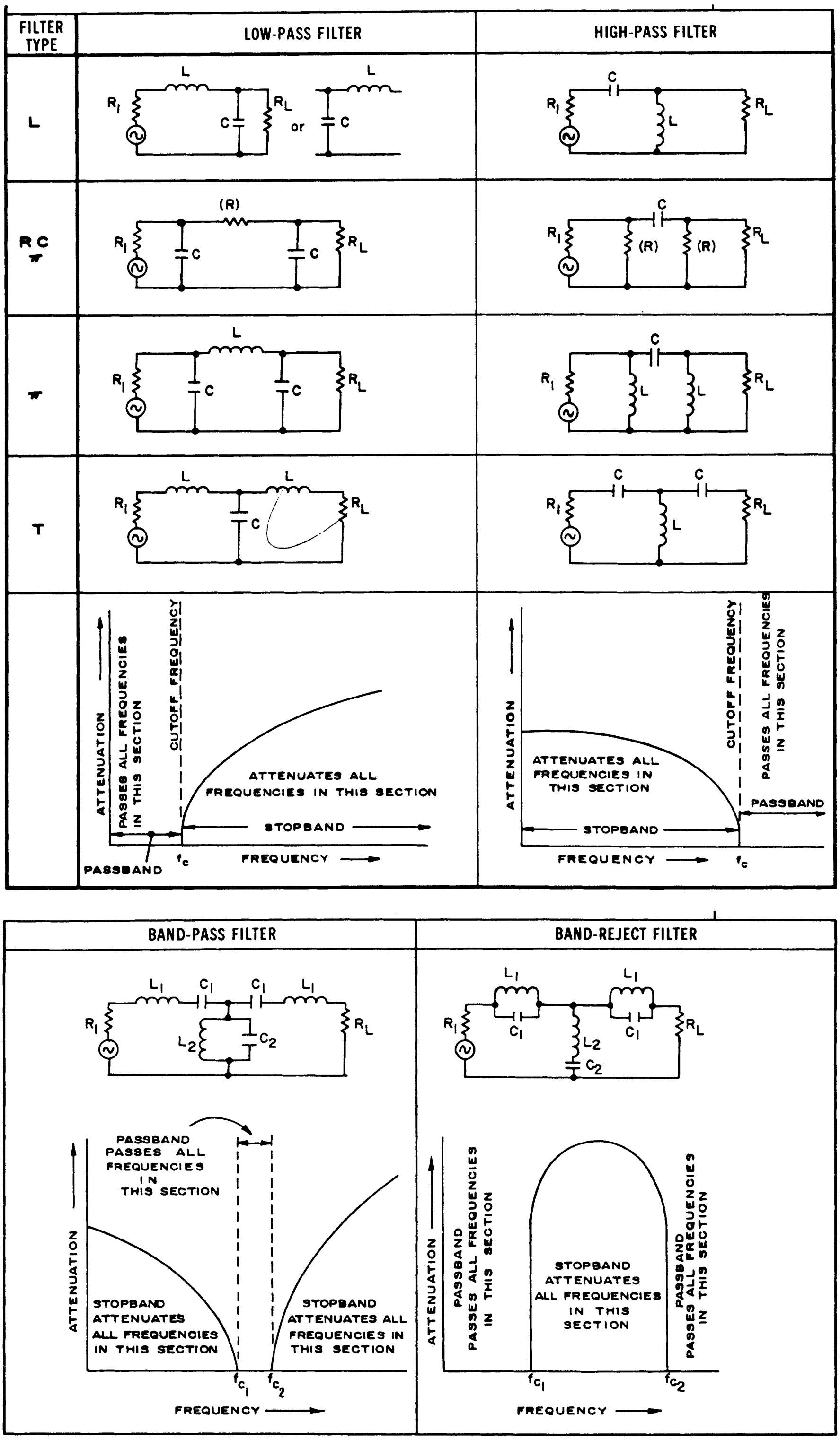
From Trew, R.J., Active microwave devices, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 991.

Absorption Loss Is a Function of Type of Material and Frequency (Loss Shown Is at 150 kHz)

Metal	Relative Conductivity	Relative Permeability	Absorption Loss *A*, dB/mm
Silver	1.05	1	52
Copper—annealed	1.00	1	51
Copper—hard drawn	0.97	1	50
Gold	0.70	1	42
Aluminum	0.61	1	40
Magnesium	0.38	1	31
Zinc	0.29	1	28
Brass	0.26	1	26
Cadmium	0.23	1	24
Nickel	0.20	1	23
Phosphor–bronze	0.18	1	22
Iron	0.17	1000	650
Tin	0.15	1	20
Steel, SAE1045	0.10	1000	500
Beryllium	0.10	1	16
Lead	0.08	1	14
Hypernik	0.06	80000	3500[a]
Monel	0.04	1	10
Mu-metal	0.03	80000	2500[a]
Permalloy	0.03	80000	2500[a]
Steel, stainless	0.02	1000	220[a]

[a] Assuming that material is not saturated.

From Hemmings, L.H., Grounding, shielding, and filtering, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1007.



Filters provide a variety of frequency characteristics. (From Hemmings, L.H., Grounding, shielding, and filtering, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1012.)

Radar Bands

Band	Frequency Range	Principal Applications
HF	3–30 MHz	Over-the-horizon radar
VHF	30–300 MHz	Long-range search
UHF	300–1000 MHz	Long-range surveillance
L	1000–2000 MHz	Long-range surveillance
S	2000–4000 MHz	Surveillance
		Long-range weather characterization
		Terminal air traffic control
C	4000–8000 MHz	Fire control
		Instrumentation tracking
X	8–12 GHz	Fire control
		Air-to-air missile seeker
		Marine radar
		Airborne weather characterization
Ku	12–18 GHz	Short-range fire control
		Remote sensing
Ka	27–40 GHz	Remote sensing
		Weapon guidance
V	40–75 GHz	Remote sensing
		Weapon guidance
W	75–110 GHz	Remote sensing
		Weapon guidance

From Belcher, Jr., M.L. and Nessmith, J.T., Pulse radar, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1044.

Typical Acoustic Properties

Material	Velocity (km/s) Longitudinal	Velocity (km/s) Shear	Impedance ($kg/m^2 s \times 10^6$) Longitudinal	Impedance ($kg/m^2 s \times 10^6$) Shear	Density ($kg/m^3 \times 10^3$)	Comments
Alcohol, methanol	1.103		0.872		0.791	Liq. 25°C
Aluminum, rolled	6.42	3.04	17.33	8.21	2.70	Isot.
Brass, 70% Cu, 30% Zn	4.70	2.10	40.6	18.14	8.64	Isot.
Cadmium sulphide	4.46	1.76	21.5	8.5	4.82	Piez crys *Z*-dir
Castor oil	1.507		1.42		0.942	Liq. 20°C
Chromium	6.65	4.03	46.6	28.21	7.0	Isot.
Copper, rolled	5.01	2.27	44.6	20.2	8.93	Isot.
Ethylene glycol	1.658		1.845		1.113	Liq. 25°C
Fused quartz	5.96	3.76	13.1	8.26	2.20	Isot.
Glass, crown	5.1	2.8	11.4	6.26	2.24	Isot.
Gold, hard drawn	3.24	1.20	63.8	23.6	19.7	Isot.
Iron, cast	5.9	3.2	46.4	24.6	7.69	Isot.
Lead	2.2	0.7	24.6	7.83	11.2	Isot.
Lithium niobate, $LiNbO_3$	6.57	4.08	30.9	19.17	4.70	Piez crys *X*-dir
		4.79		22.53		
Nickel	5.6	3.0	49.5	26.5	8.84	Isot.
Polystyrene, styron	2.40	1.15	2.52	1.21	1.05	Isot.
PZT-5H	4.60	1.75	34.5	13.1	7.50	Piez ceram *Z*
Quartz	5.74	3.3	15.2	8.7	2.65	Piez crys *X*-dir
		5.1		13.5		
Sapphire Al_2O_3	11.1	6.04	44.3	25.2	3.99	Cryst. *Z*-axis
Silver	3.6	1.6	38.0	16.9	10.6	Isot.
Steel, mild	5.9	3.2	46.0	24.9	7.80	Isot.
Tin	3.3	1.7	24.2	12.5	7.3	Isot.
Titanium	6.1	3.1	27.3	13.9	4.48	Isot.
Water	1.48		1.48		1.00	Liq. 20°C
YAG $Y_3Al_{15}O_{12}$	8.57	5.03	39.0	22.9	4.55	Cryst. *Z*-axis
Zinc	4.2	2.4	29.6	16.9	7.0	Isot.
Zinc oxide	6.37	2.73	36.1	15.47	5.67	Piez crys *Z*-dir

From Farnell, G.W., Ultrasound, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1171.

Ferroelectric, Piezoelectric, and Electrostrictive Materials

Type	Material Class	Example	Applications
Electret	Organic	Waxes	No recent
Electret	Organic	Fluorine based	Microphones
Ferroelectric	Organic	PVF2	No known
Ferroelectric	Organic	Liquid crystals	Displays
Ferroelectric	Ceramic	PZT thin film	NV-memory
Piezoelectric	Organic	PVF2	Transducer
Piezoelectric	Ceramic	PZT	Transducer
Piezoelectric	Ceramic	PLZT	Optical
Piezoelectric	Single crystal	Quartz	Freq. control
Piezoelectric	Single crystal	$LiNbO_3$	SAW devices
Electrostrictive	Ceramic	PMN	Actuators

From Etzold, K.F., Ferroelectric and piezoelectric materials, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1180.

Material Parameters for Type I Superconductors*

Material	T_c (K)	λ_o (nm)	ξ_o (nm)	Δ_o (meV)	$\mu_0 H_{co}$ (mT)
Al	1.18	50	1600	0.18	110.5
In	3.41	65	360	0.54	123.0
Sn	3.72	50	230	0.59	130.5
Pb	7.20	40	90	1.35	180.0
Nb	9.25	85	40	1.50	198.0

* The penetration depth λ_o is given at zero temperature, as are the coherence length ξ_o, the thermodynamic critical field H_{co}, and the energy gap Δ_o.

From Delin, K.A. and Orlando, T.P., Superconductivity, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1224. Originally from R.J. Donnelly, "Cryogenics," in *Physics Vade Mecum,* H.L. Anderson, Ed., New York: American Institute of Physics, 1981. With permission.

Material Parameters for Conventional Type II Superconductors*

Material	T_c (K)	$\lambda_{GL}(0)$ (nm)	$\xi_{GL}(0)$ (nm)	Δ_o (meV)	$\mu_0 H_{c2,o}$ (T)
Pb-In	7.0	150	30	1.2	0.2
Pb-Bi	8.3	200	20	1.7	0.5
Nb-Ti	9.5	300	4	1.5	13.0
Nb-N	16.0	200	5	2.4	15.0
$PbMo_6S_8$	15.0	200	2	2.4	60.0
V_3Ga	15.0	90	2–3	2.3	23.0
V_3Si	16.0	60	3	2.3	20.0
Nb_3Sn	18.0	65	3	3.4	23.0
Nb_3Ge	23.0	90	3	3.7	38.0

* The values are only representative because the parameters for alloys and compounds depend on how the material is fabricated. The penetration depth $\lambda_{GL}(0)$ is given as the coefficient of the Ginzburg–Landau temperature dependence as $\lambda_{GL}(T) = \lambda_{GL}(0)(1 - T/T_c)^{-1/2}$; likewise for the coherence length where $\xi_{GL}(T) = \xi_{GL}(0)(1 - T/T_c)^{-1/2}$. The upper critical field $H_{c2,o}$ is given at zero temperature as well as the energy gap Δ_o.

From Delin, K.A. and Orlando, T.P., Superconductivity, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1225. Originally from R.J. Donnelly, "Cryogenics," in *Physics Vade Mecum,* H.L. Anderson, Ed., New York: American Institute of Physics, 1981. With permission.

Spontaneous Polarizations and Curie Temperatures for a Range of Ferroelectrics

Material	T_c(k)	P_s(cm-2)	T(k)
KH_2PO_4 (KDP)	123	0.053	96
Triglycine sulphate	322	0.028	293
Polyvinylidene fluoride (PVDF)	>453	0.060	293
DOBAMBC (liquid crystal)	359	$\sim 3 \times 10^{-5}$	354
$PbTiO_3$	763	0.760	293
$BaTiO_3$	393	0.260	296

From Whatmore, R.W., Pyroelectric materials and devices, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1230.

Pyroelectric Properties of Selected Materials

Material (Temperature)	Pyroelectric Coefficient P 10^{-4} cm^{-2} K^{-1}	Dielectric Properties (1 kHz) ϵ	tanδ	Volume-Specific Heat c' 10^6 Jm^{-3} K^{-1}	Thermal Conductivity K 10^{-7} m^2 s^{-1}	F_v m^2 C^{-1}	F_D 10^{-5} Pa$^{-1/2}$	F_{vid} 10^6 sC^{-1}
TGS (35°C)	5.5	55	0.025	2.6	3.3	0.43	6.1	1.3
DTGS (40°C)	5.5	43	0.020	2.4	3.3	0.60	8.3	1.8
PVDF polymer	0.27	12	0.015	2.43	0.62	0.10	0.88	1.6
$LiTaO_3$ crystal	2.3	47	0.005	3.2	13.0	0.17	4.9	0.13
Modified PZ ceramic	3.8	290	0.003	2.5		0.06	5.8	
Modified PT ceramic	3.8	220	0.011	2.5		0.08	3.3	

PZ = $PbZrO_3$, PT = $PbTiO_3$.

From Whatmore, R.W., Pyroelectric materials and devices, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1233.

Electrical Properties of a Number of Representative Insulating Liquids

Liquid	Viscosity cSt (37.8°C)	Dielectric Constant (at 60 Hz, 25°C)	Dissipation Factor (at 60 Hz, 100°C)	Breakdown Strength, (kV cm^{-1})
Capacitor oil	21	2.2	0.001	>118
Pipe cable oil	170	2.15	0.001	>118
Self-contained cable oil	49.7	2.3	0.001	>118
Heavy cable oil	2365	2.23	0.001	>118
Transformer oil	9.75	2.25	0.001	>128
Alkyl benzene	6.0	2.1	0.0004	>138
Polybutene pipe cable oil	110 (SUS)	2.14 (at 1 MHz)	0.0003	>138
Polybutene capacitor oil	2200 (SUS at 100°C)	2.22 (at 1 MHz)	0.0005	>138
Silicone fluid	50	2.7	0.00015	>138
Castor oil	98 (100°C)	3.74	0.06	>138
$C_8F_{16}O$ fluorocarbon	0.64	1.86	<0.0005	>138

From Bartnikas, R., Dielectrics and insulators, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1247. Originally from Bartnikas, R., Ed., *Engineering Dielectrics,* Vol. III, *Electrical Insulating Liquids,* Monograph 2, ASTM, Philadelphia, PA, 1994; Encyclopedia Issue, *Insul. Circuits,* June/July 1972.

Electrical and Physical Properties of Some Common Solid Insulating Materials

Material	Specific Gravity	Maximum Operating Temperature (°C)	Dielectric Constant 20°C 60 Hz	Dielectric Constant 20°C 1 kHz	Dielectric Constant 20°C 1 MHz	Dissipation Factor 20°C 60 Hz	Dissipation Factor 20°C 1 kHz	Dissipation Factor 20°C 1 MHz	AC Dielectric Strength (kV cm–1)
Alumina (Al_2O_3)	3.1–3.9	1950	8.5	8.5	8.5	1×10^{-3}	1×10^{-3}	1×10^{-3}	98–157
Porcelain (mullite)	2.3–2.5	1000	8.2	8.2	8.2	1.4×10^{-3}	5.7×10^{-4}	2×10^{-4}	94–157
Steatite $3MgO \cdot 4SiO_2 \cdot H_2O$	2.7–2.9	1000–1100	5.5	5.0	5.0	1.3×10^{-3}	4.5×10^{-4}	3.7×10^{-4}	200
Magnesium oxide (MgO)	3.57	<2800	9.65	9.65	9.69	$<3 \times 10^{-4}$	$<3 \times 10^{-4}$	$<3 \times 10^{-4}$	>2000
Glass (soda lime)	2.47	110–460	6.25	6.16	6.00	5.0×10^{-3}	4.2×10^{-3}	2.7×10^{-3}	4500
Mica ($KAl_2(OH)_2Si_3AlO_{10}$)	2.7–3.1	550	6.9	6.9	5.4	1.5×10^{-3}	2.0×10^{-4}	3.5×10^{-4}	3000–8200
SiO_2 film		<900		3.9			7×10^{-4}		1000–10,000
Si_3 N_4		<1000		12.7			$<1 \times 10^{-4}$		1000–10,000
Ta_2O_5	8.2	<1800		28			1×10^{-2}		
HfO_2		4700°F		35			1×10^{-2}		
Low-density PE	(density: 0.910–0.925 g cm^{-3})	70	2.3	2.3	2.3	2×10^{-4}	2×10^{-4}	2×10^{-4}	181–276
Medium-density PE	(density: 0.926–0.940 g cm^{-3})	70	2.3	2.3	2.3	2×10^{-4}	2×10^{-4}	2×10^{-4}	197–295
High-density PE	(density: 0.941–0.965 g cm^{-3})	70	2.35	2.35	2.35	2×10^{-4}	2×10^{-4}	2×10^{-4}	177–197

XLPE	(density: 0.92 g cm^{-3})	90	2.3		2.28	3×10^{-4}		4×10^{-4}	217
EPR	0.86	300–350°F		3.0–3.5		4×10^{-3}			354–413
Polypropylene	0.90	128–186	2.22–2.28	2.22–2.28	2.22–2.28	$2–3 \times 10^{-4}$	$2.5–3.0 \times 10^{-4}$	4.6×10^{-4}	295–314
PTFE	2.13–2.20	<327	2.0	2.0	2.0	$<2 \times 10^{-4}$	$<2 \times 10^{-4}$	$<2 \times 10^{-4}$	189
Glass-reinforced polyester premix	1.8–2.3	265	5.3–7.3		5.0−6.4	$1–4 \times 10^{-2}$		$0.8–2.2 \times 10^{-2}$	90.6–158
Thermoplastic polyester	1.31–1.58	250	3.3–3.8 (100 Hz)			$1.5–2.0 \times 10^{-3}$			232–295
Polyimide polyester	1.43–1.49	480°F		3.4 (100 kHz)			$1–5 \times 10^{-3}$ (100 kHz)		220
Polycarbonate	1.20	215	3.17		2.96	9×10^{-4}		1×10^{-2}	157
Epoxy (with mineral filler)	1.6–1.9	200 (decomposition temperature)	4.4–5.6	4.2–4.9	4.1–4.6	$1.1–8.3 \times 10^{-2}$	$0.19–1.4 \times 10^{-1}$	$0.13–1.4 \times 10^{-1}$	98.4–158
Epoxy (with silica filler)	1.6–2.0	200 (decomposition temperature)	3.2–4.5	3.2–4.0	3.0–3.8	$0.8–3.0 \times 10^{-2}$	$0.8–3.0 \times 10^{-2}$	$2–4 \times 10^{-2}$	158–217
Silicone rubber	1.1–1.5	700°F	3.3–4.0		3.1–3.7	$1.5–3.0 \times 10^{-2}$		$3.0–5.0 \times 10^{-3}$	158–197

From Bartnikas, R., Dielectrics and insulators, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, pp. 1249–1250. Originally from Bartnikas, R. and Eichhorn, R.M., Eds., *Engineering Dielectrics,* Vol. IIA, *Electrical Properties of Solid Insulating Materials: Molecular Structure and Electrical Behavior,* STP 783, ASTM, Philadelphia, PA, 1983; Encyclopedia Issue, *Insul. Circuits,* June/July 1972.

Physical and Chemical Transduction Principles

	Secondary Signal					
Primary Signal	Mechanical	Thermal	Electrical	Magnetic	Radiant	Chemical
Mechanical	(Fluid) mechanical and acoustic effects (e.g., diaphragm, gravity balance, echo sounder)	Friction effects (e.g., friction calorimeter) Cooling effects (e.g., thermal flow meters)	Piezoelectricity Piezoresistivity Resistive, capacitive, and inductive effects	Magneto-mechanical effects (e.g., piezo-magnetic effect)	Photoelastic systems (stress-induced birefringence) Interferometers Sagnac effect Doppler effect	
Thermal	Thermal expansion (bimetal strip, liquid-in-glass and gas thermometers, resonant frequency) Radiometer effect (light mill)		Seebeck effect Thermoresistance Pyroelectricity Thermal (Johnson) noise		Thermooptical effects (e.g., in liquid crystals) Radiant emission	Reaction activation (e.g., thermal dissociation)
Electrical	Electrokinetic and electro-mechanical effects (e.g., piezoelectricity, electro-meter, Ampere's law)	Joule (resistive) heating Peltier effect	Charge collectors Langmuir probe	Biot-Savart's law	Electrooptical effects (e.g., Kerr effect) Pockel's effect Electroluminescence	Electrolysis Electromigration
Magnetic	Magnetomechanical effects (e.g., magnetorestriction, magnetometer)	Thermomagnetic effects (e.g., Righi-Leduc effect) Galvanomagnetic effects (e.g., Ettingshausen effect)	Thermomagnetic effects (e.g., Ettingshausen-Nernst effect) Galvanomagnetic effects (e.g., Hall effect, magnetoresistance)		Magnetooptical effects (e.g., Faraday effect) Cotton-Mouton effect	
Radiant	Radiation pressure	Bolometer thermopile	Photoelectric effects (e.g., photovoltaic effect, photoconductive effect)		Photorefractive effects Optical bistability	Photosynthesis, -dissociation
Chemical	Hygrometer Electrodeposition cell Photoacoustic effect	Calorimeter Thermal conductivity cell	Potentiometry Conductimetry Amperometry Flame ionization Volta effect Gas-sensitive field effect	Nuclear magnetic resonance	(Emission and absorption) spectroscopy Chemiluminiscence	

From Smith, R.L., Sensors, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1256. Originally from T. Grandke and J. Hesse, Introduction, Vol. 1: *Fundamentals and General Aspects, Sensors: A Comprehensive Survey,* W. Gopel, J. Hesse, and J. H. Zemel, Eds., Weinheim, Germany: VCH, 1989. With permission.

Electrical Properties of Metals Used in Transmission Lines

Metal	Relative Conductivity (Copper = 100)	Electrical Resistivity at 20°C, $\Omega \cdot m$ (10^{-8})	Temperature Coefficient of Resistance (per °C)
Copper (HC, annealed)	100	1.724	0.0039
Copper (HC, hard-drawn)	97	1.777	0.0039
Aluminum (EC grade, 1/2 H-H)	61	2.826	0.0040
Mild steel	12	13.80	0.0045
Lead	8	21.4	0.0040

From Chen, M.-S., Alternating current overhead: Line parameters, models, standard voltages, insulators, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1323.

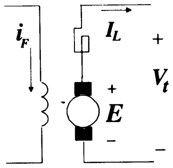
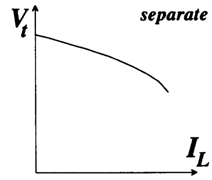
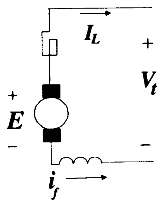
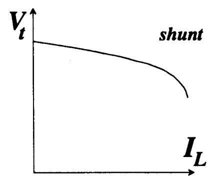
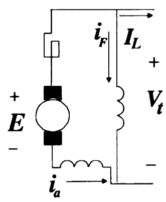
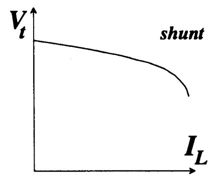
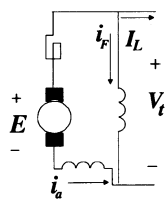
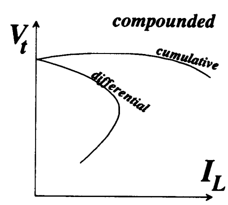
Typical Synchronous Generator Parameters[a]

Parameter	Symbol	Round Rotor	Salient-Pole Rotor with Damper Windings
Synchronous reactance			
d-axis	X_d	1.0–2.5	1.0–2.0
q-axis	X_q	1.0–2.5	0.6–1.2
Transient reactance			
d-axis	X'_d	0.2–0.35	0.2–0.45
q-axis	X'_q	0.5–1.0	0.25–0.8
Subtransient reactance			
d-axis	X''_d	0.1–0.25	0.15–0.25
q-axis	X''_q	0.1–0.25	0.2–0.8
Time constants			
Transient			
Stator winding open-circuited	T'_{do}	4.5–13	3.0–8.0
Stator winding short-circuited	T'_d	1.0–1.5	1.5–2.0
Subtransient			
Stator winding short-circuited	T''_d	0.03–0.1	0.03–0.1

[a] Reactances are per unit, i.e., normalized quantities. Time constants are in seconds.

From Liu, C.-C., Vu, K.T., and Yu, Y., Generators, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1451. Originally from M.A. Laughton and M.G. Say, eds., *Electrical Engineer's Reference Book,* Stoneham, Mass.: Butterworth, 1985.

Excitation Methods and Voltage Current Characteristics for DC Generators

Excitation Methods		Characteristics
Separate		 For low currents, the curve is nearly a straight line. As load current increases, the armature reaction becomes more severe and contributes to the nonlinear drop.
Series		 At no load, there is no field current, and voltage is due to the residual flux of the stator core. The voltage rises rapidly over the range of low currents, but the resistive drop soon becomes dominant.
Shunt		 Voltage buildup depends on the residual flux. The shunt field resistance must be less than a critical value.
Compounded		
There are two field windings. Depending on how they are set up, one may have *cumulative* if the two fields are additive, *differential* if the two fields are subtractive.		*Cumulative:* An increase in load current increases the resistive drop, yet creates more flux. At high currents, however, resistive drop becomes dominant. *Differential:* An increase in load current not only increases the resistive drop, but also reduces the net flux. Voltage drops drastically.

From Liu, C.-C., Vu, K.T., and Yu, Y., Generators, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1455. Originally from S.J. Chapman, *Electric Machinery Fundamentals,* New York: McGraw-Hill, 1991.

Complex Envelope Functions for Various Types of Modulation

Type of Modulation	Mapping Functions $g[m]$	Corresponding Quadrature Modulation $x(t)$	$y(t)$	Corresponding Amplitude and Phase Modulation $R(t)$	$\theta(t)$	Linearity	Remarks
AM	$1 + m(t)$	$1 + m(t)$	0	$\lvert 1 + m(t) \rvert$	$\begin{cases} 0, & m(t) > -1 \\ 180°, & m(t) < -1 \end{cases}$	L[b]	$m(t) > -1$ required for envelope detection.
DSB-SC	$m(t)$	$m(t)$	0	$\lvert m(t) \rvert$	$\begin{cases} 0, & m(t) > 0 \\ 180°, & m(t) < 0 \end{cases}$	L	Coherent detection required.
PM	$e^{jD_p m(t)}$	$\cos[D_p m(t)]$	$\sin[D_p m(t)]$	1	$D_p m(t)$	NL	D_p is the phase deviation constant (radian/volts).
FM	$e^{jD_f \int_{-\infty}^{t} m(\sigma)d\sigma}$	$\cos\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	$\sin\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	1	$D_f \int_{-\infty}^{t} m(\sigma)d\sigma$	NL	D_f is the frequency deviation constant (radian/volt-sec).
SSB-AM-SC[a]	$m(t) \pm j\hat{m}(t)$	$m(t)$	$\pm \hat{m}(t)$	$\sqrt{[m(t)]^2 + [\hat{m}(t)]^2}$	$\tan^{-1}[\pm \hat{m}(t)/m(t)]$	L	Coherent detection required.
SSB-PM[a]	$e^{jD_p[m(t) \pm j\hat{m}(t)]}$	$e^{\mp D_p \hat{m}(t)}\cos[D_p m(t)]$	$e^{\mp D_p \hat{m}(t)}\sin[D_p m(t)]$	$e^{\mp D_p \hat{m}(t)}$	$D_p m(t)$	NL	
SSB-FM[a]	$e^{jD_f \int_{-\infty}^{t} [m(\sigma) \pm j\hat{m}(\sigma)]d\sigma}$	$e^{\mp D_f \int_{-\infty}^{t} \hat{m}(\sigma)d\sigma}\cos\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	$e^{\mp D_f \int_{-\infty}^{t} \hat{m}(\sigma)d\sigma}\sin\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	$e^{\mp D_f \int_{-\infty}^{t} \hat{m}(\sigma)d\sigma}$	$D_f \int_{-\infty}^{t} m(\sigma)d\sigma$	NL	
SSB-EV[a]	$e^{\{\ln[1 + m(t)] \pm j\hat{\ln}[1 + m(t)]\}}$	$[1 + m(t)] \cos \{\hat{\ln}[1 + m(t)]\}$	$\pm[1 + m(t)]\sin\{\hat{\ln}[1 + m(t)]\}$	$1 + m(t)$	$\pm\hat{\ln}[1 + m(t)]$	NL	$m(t) > -1$ is required so that the ln will have a real value.
SSB-SQ[a]	$e^{(1/2)\{\ln[1 + m(t)] \pm j\hat{\ln}[1 + m(t)]\}}$	$\sqrt{1 + m(t)} \cos\left\{\frac{1}{2} \hat{\ln}[1 = m(t)]\right\}$	$\pm\sqrt{1 + m(t)} \sin\left\{\frac{1}{2} \hat{\ln}[1 + m(t)]\right\}$	$\sqrt{1 + m(t)}$	$\pm \frac{1}{2} \hat{\ln}[1 + m(t)]$	NL	$m(t) > -1$ is required so that the ln will have a real value.
QM	$m_1(t) + jm_2(t)$	$m_1(t)$	$m_2(t)$	$\sqrt{m_1^2(t) + m_2^2(t)}$	$\tan^{-1}[m_2(t)/m_1(t)]$	L	Used in NTSC color television: requires coherent detection.

L = linear, NL = nonlinear, [ˆ.] is the Hilbert transform (i.e., –90° phase-shifted version) of [·]. The Hilbert transform is $\hat{x}(t) \triangleq x(t) * \frac{1}{\pi t} = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{x(\lambda)}{t-\lambda} d\lambda$

[a] Use upper signs for upper sideband signals and lower signs for lower sideband signals.

[b] In the strict sense, AM signals are not linear because the carrier term does not satisfy the linearity (superposition) condition.

From Dorf, R.C. and Wan, Z., Modulation and demodulation, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1505. Orignally from L. W. Couch, *Digital and Analog Communication Systems*, New York: Macmillan, 1990. With permission.

Protected Service Signal Intensities for Standard Broadcasting (AM)

Class of Station	Power (kW)	Class of Channel Used	Signal Strength Contour of Area Protected from Objectionable Interference* (μV/m)		Permissible Interfering Signal	
			Day†	Night	Day†	Night‡
A	10–50	Clear	SC 100 AC 500	SC 500 50% SW AC 500 GW	SC 5 AC 250	SC 25 AC 250
B	0.25–50	Clear Regional	500	2000†	25 AC 250	25 250
C	0.25–1	Local	500	Not precise§	SC 25	Not precise
D	0.25–50	Clear Regional	500	Not precise	SC 25 AC 250	Not precise

* When a station is already limited by interference from other stations to a contour of higher value than that normally protected for its class, this higher-value contour shall be the established protection standard for such station. Changes proposed by Class A and B stations shall be required to comply with the following restrictions. Those interferers that contribute to another station's RSS using the 50% exclusion method are required to reduce their contribution to that RSS by 10%. Those lesser interferers that contribute to a station's RSS using the 25% exclusion method but do not contribute to that station's RSS using the 50% exclusion method may make changes not to exceed their present contribution. Interferers not included in a station's RSS using the 25% exclusion method are permitted to increase radiation as long as the 25% exclusion threshold is not equaled or exceeded. In no case will a reduction be required that would result in a contributing value that is below the pertinent value specified in the table.

† Groundwave.

‡ Skywave field strength for 10% or more of the time. For Alaska, Class SC is limited to 5 μV/m.

§ During nighttime hours, Class C stations in the contiguous 48 states may treat all Class B stations assigned to 1230, 1240, 1340, 1400, 1450, and 1490 kHz in Alaska, Hawaii, Puerto Rico and the U.S. Virgin Islands as if they were Class C stations.

Note: SC = same channel; AC = adjacent channel; SW = skywave; GW = groundwave; RSS = root of sum squares.

From Lindsey III, J.F. and Doelizsch, D.F., Radio broadcasting, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1515. Originally from FCC Rules and Regulations, Revised 1991; vol. III, pt. 73.182(a).

Coding Gains with BPSK or QPSK

Coding Technique Used	Coding Gain (dB) at 10^{-5} BER	Coding Gain (dB) at 10^{-8} BER	Data Rate Capability
Ideal coding	11.2	13.6	
Concatenated Reed–Solomon and convolution (Viterbi decoding)	6.5–7.5	8.5–9.5	Moderate
Convolutional with sequential decoding (soft decisions)	6.0–7.0	8.0–9.0	Moderate
Block codes (soft decisions)	5.0–6.0	6.5–7.5	Moderate
Concatenated Reed–Solomon and short block	4.5–5.5	6.5–7.5	Very high
Convolutional with Viterbi decoding	4.0–5.5	5.0–6.5	High
Convolutional with sequential decoding (hard decisions)	4.0–5.0	6.0–7.0	High
Block codes (hard decisions)	3.0–4.0	4.5–5.5	High
Block codes with threshold decoding	2.0–4.0	3.5–5.5	High
Convolutional with threshold decoding	1.5–3.0	2.5–4.0	Very high

BPSK: modulation technique—binary phase-shift keying; QPSK: modulation technique—quadrature phase-shift keying; BER: bit error rate.

From Dorf, R.C. and Wan, Z., Error control coding, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1554. Originally from V.K. Bhargava, "Forward error correction schemes for digital communications," *IEEE Communication Magazine,* 21, 11–19, © 1983 IEEE. With permission.

Comparison of Orbit and Link Parameters for LEO, MEO, and GEO for the Particular Case of Circular Orbits (eccentricity, e, = 0) and for Elevation Angle (el = 10°)

Orbit	LEO	MEO/ICO	GEO
Example system	Iridium®	ICO-P	INTELSAT
Inclination, i (deg.)	86.4	±45	0
Altitude, h (km)	780	10,400	35,786
Semi-major axis radius, a (km)	7159	16,778	42,164
Orbit period (minutes)	100.5	360.5	1436.1
$(r_e + h)/r_e$	1.1222	2.6305	6.6107
Earth central angle, γ (deg.)	18.658	58.015	71.433
Nadir angle, θ (deg.)	61.3	22	8.6
Nadir spread factor 10 log($4\pi h^2$ (dB m²))	128.8	151.3	162.1
Slant range, r_s (km)	2325	14,450	40,586
One-way time delay (ms)	2.6	51.8	139.1
Maximum spread factor			
10 log($4\pi r_s^2$ (dB m²))	138.3	154.2	163.2
20 log(r_s/h (dB))	9.5	2.9	1.1
Ground coverage area (km²)	13.433 × 106	120.2 × 106	174.2 × 106
Fraction of earth area	0.026	0.235	0.34

Note: earth radius, r_e, (km) = 6378.14; earth surface area, a_e, (km²) = 511.2 × 10^6; elevation angle, el (degrees) = 10.

From DiFonzo, D.F., Satellites and aerospace, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1701.

Partial List of Satellite Frequency Allocations

Band	Uplink	Downlink	Satellite Service
VHF		0.137–0.138	Mobile
VHF	0.3120–0.315	0.387–0.390	Mobile
L-Band		1.492–1.525	Mobile
	1.610–1.6138		Mobile, radio astronomy
	1.613.8–1.6265	1.6138–1.6265	Mobile LEO
	1.6265–1.6605	1.525–1.545	Mobile
		1.575	Global positioning system
		1.227	GPS
S-Band	1.980–2.010	2.170–2.200	MSS (available Jan. 1, 2000)
	1.980–1.990	2.165–2.200	(proposed for U.S. in 2000)
	2.110–2.120	2.290–2.300	Deep-space research
		2.4835–2.500	Mobile
C-Band	5.85–7.075	3.4–4.2	Fixed (FSS)
	7.250–7.300	4.5–4.8	FSS
X-Band	7.9–8.4	7.25–7.75	FSS
Ku-Band	12.75–13.25	10.7–12.2	FSS
	14.0–14.8	12.2–12.7	Direct Broadcast (BSS) (U.S.)
Ka-Band		17.3–17.7	FSS (BSS in U.S.)
			22.55–23.55 Intersatellite
			24.45–24.75 Intersatellite
			25.25–27.5 Intersatellite
	27–31	17–21	FSS
Q	42.5–43.5, 47.2–50.2	37.5–40.5	FSS, MSS
	50.4–51.4		Fixed
		40.5–42.5	Broadcast Satellite
V	54.24–58.2–		Intersatellite
	59–64		Intersatellite

Note: Frequencies in GHz. Allocations are not always global and may differ from region to region in all or subsets of the allocated bands.

From DiFonzo, D.F., Satellites and aerospace, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1703. Originally from Final Acts of the World Administrative Radio Conference (WARC-92), Malaga-Torremolinos, 1992; 1995 World Radiocommunication Conference (WRC-95).

Specifications of TDMA and CDMA Systems

TDMA		CDMA	
Bandwidth per channel	30 kHz	Bandwidth per channel	1.23 MHz
Time slots	3	Speech coder	8 kbps(max.)—a variable rate vocoder
Modulation	π/4-DQPSK	Forward radio channels	Pilot (1) sync (1), paging (7), traffic channels (55), total 64 channels
Speech coder	8 kbps—VSELP code (vector sum excited LPC*)		
Channel coding	Rate 1/2 convolutional (13 kbps)	Reverse radio channels	Access (9), traffic channels (55)
Total transmit rate	48 kbps per channel	Power control	Forward, reverse
Equalizer	Up to 40 μs	Diversity	Rake receiver

* LPC = linear predictive code.

From Lee, W.C.Y., Mobile radio and cellular communications, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1710.

Switching Algebra Summary

(P1) $XY = YX$	(S1) $X + Y = Y + X$	Commutativity
(P2) $X(YZ) = (XY)Z$	(S2) $X + (Y + Z) = (X + Y) + Z$	Associativity
(P3) $XX = X$	(S3) $X + X = X$	Idempotency
(P4) $X(X + Y) = X$	(S4) $X + XY = X$	Absorption
(P5) $X(Y + Z) = XY + XZ$	(S5) $X + YZ = (X + Y)(X + Z)$	Distributivity
(P6) $X\overline{X} = 0$	(S6) $X + \overline{X} = 1$	Complementarity
(C1) $\overline{\overline{X}} = X$		Involution
(P7) $\overline{XY} = \overline{X} + \overline{Y}$	(S7) $\overline{X + Y} = \overline{X}\,\overline{Y}$	De Morgan's
(P8) $X(\overline{X} + Y) = XY$	(S8) $X + \overline{X}Y = X + Y$	
(B1) $\overline{1} = 0$		
(P10) $X \cdot 0 = 0$	(S10) $X + 1 = 1$	
(P11) $X \cdot 1 = X$	(S11) $X + 0 = X$	
(P13) $(X + Y)(Y + Z)(\overline{X} + Z) = (X + Y)(\overline{X} + Z)$	(S13) $XY + YZ + \overline{X}Z = XY + \overline{X}Z$	Consensus

From Preparata, F.P., Combinational networks and switching algebra, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1858.

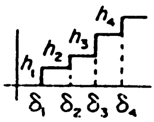
Binary-to-Decimal Conversion

Two-Bit Binary	Decimal Value	Three-Bit Binary	Decimal Value	Four-Bit Binary	Decimal Value	Five-Bit Binary	Decimal Value	Six-Bit Binary	Decimal Value
00	0	000	0	0000	0	10000	16	100000	32
01	1	001	1	0001	1	10001	17	100001	33
10	2	010	2	0010	2	10010	18	100010	34
11	3	011	3	0011	3	10011	19	100011	35
		100	4	0100	4	10100	20	100100	36
		101	5	0101	5	10101	21	100101	37
		110	6	0110	6	10110	22	100110	38
		111	7	0111	7	10111	23	100111	39
				1000	8	11000	24	101000	40
				1001	9	11001	25	101001	41
				1010	10	11010	26	101010	42
				1011	11	11011	27	101011	43
				1100	12	11100	28	101100	44
				1101	13	11101	29	101101	45
				1110	14	11110	30	101110	46
				1111	15	11111	31	101111	47

From Tinder, R.F., Number systems, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1993.

DFs of Single-Valued Nonlinearities

General quantizer

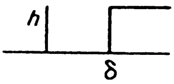


- $a < \delta_1$: $N_p = 0$
- $\delta_{M+1} > a > \delta_M$: $N_p = \left(4/\alpha^2\pi\right)\sum_{m=1}^{M} h_m\left(a^2 - \delta_m^2\right)^{1/2}$

Uniform quantizer
$h_1 = h_2 = \cdots h$
$\delta_m = (2m - 1)\delta/2$

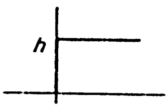
- $a < \delta$: $N_p = 0$
- $(2M + 1)\delta > a > (2M - 1)\delta$: $N_p = \left(4h/a^2\pi\right)\sum_{n=1}^{M}\left(a^2 - n^2\delta^2\right)^{1/2}$
- $n = (2m - 1)/2$

Relay with dead zone



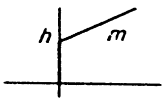
- $a < \delta$: $N_p = 0$
- $a > \delta$: $N_p = 4h(a^2 - \delta^2)^{1/2}/a^2\pi$

Ideal relay



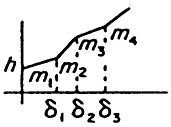
$N_p = 4h/a\pi$

Preload



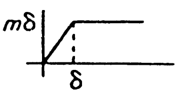
$N_p = (4h/a\pi) + m$

General piecewise linear



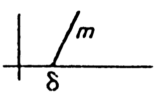
- $a < \delta_1$: $N_p = (4h/a\pi) + m_1$
- $\delta_{M+1} > \alpha > \delta_M$: $N_p = (4h/a\pi) + m_{M+1} + \sum_{i=1}^{M}\left(m_j - m_{j+1}\right)N_i\left(\delta_j/a\right)$

Ideal saturation



$N_p = mN_s(\delta/a)$

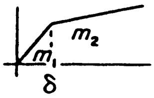
Dead zone



$N_p = m[1 - N_s(\delta/a)$

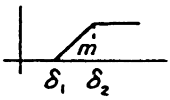
DFs of Single-Valued Nonlinearities (continued)

Gain changing nonlinearity

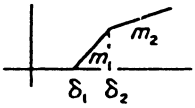


$N_p = (m_1 - m_2)N_s(\delta/a) + m_2$

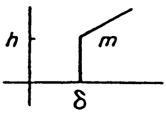
Saturation with dead zone



$N_p = m[N_s(\delta_2/a) - N_s(\delta_1/a)]$

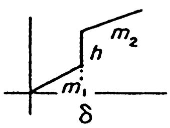


$N_p = -m_1N_s(\delta_1/a) + (m_1 - m_2)N_s(\delta_2/a) + m_2$



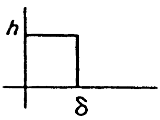
$a < \delta$ $N_p = 0$

$a > \delta$ $N_p = 4h(a^2 - \delta^2)^{1/2}/a_2\pi + m - mN_s(\delta/a)$



$a < \delta$ $N_p = m_1$

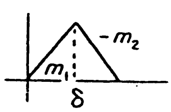
$a > \delta$ $N_p = (m_1 - m_2)N_s(\delta/a) + m_2 + 4h(a^2 - \delta^2)^{1/2}/a^2\pi$



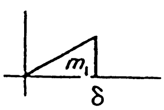
$a < \delta$ $N_p = 4h/a\pi$

$a > \delta$ $N_p = 4h/[a - (a^2 - \delta^2)^{1/2}]/a^2\pi$

Limited field of view



$N_p = (m_1 + m_2)N_s(\delta/a) - m_2N_s[(m_1 + m_2)\delta/m_2a]$



$a < \delta$ $N_p = m_1$

$a > \delta$ $N_p = m_1N_s(\delta/a) - 4m_1\delta(a^2 - \delta^2)^{1/2}/a^2\pi$

$y = x^m$ $m > -2$ Γ is the gamma function

$$N_p = \frac{\Gamma(m+1)a^{m-1}}{2^{m-1}\Gamma[(3+m)/2]\Gamma[(1+m)/2]}$$

$$= \frac{2}{\sqrt{\pi}}\frac{\Gamma[(m+2)/2]a^{m-1}}{\Gamma[(m+3)/2]}$$

From Atherton, D.P., Nonlinear control systems, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, pp. 2318–2319.

Illuminance Categories and Illuminance Values for Generic Types of Activities in Interiors

Type of Activity	Illuminance Category	Ranges of Illuminances		Reference Work-Plane
		Lux	Footcandles	
Public spaces with dark surroundings	A	20–30–50	2–3–5	General lighting throughout spaces
Simple orientation for short temporary visits	B	50–75–100	5–7.5–10	
Working spaces where visual tasks are only occasionally performed	C	100–150–200	10–15–20	
Performance of visual tasks of high contrast or large size	D	200–300–500	20–30–50	Illuminance on task
Performance of visual tasks of medium contrast or small size	E	500–750–1,000	50–75–100	
Performance of visual tasks of low contrast or very small size	F	1,000–1,500–2,000	100–150–200	
Performance of visual tasks of low contrast and very small size over a prolonged period	G	2,000–3,000–5,000	200–300–500	Illuminance on task, obtained by a combi- nation of general and local (supplementary lighting)
Performance of very prolonged and exacting visual tasks	H	5,000–7,500–10,000	500–750–1,000	
Performance of very special visual tasks of extremely low contrast and small size	I	10,000–15,000–20,000	1,000–1,500–2,000	

From Chen, K., Industrial illuminating systems, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 2449. Originally from *IES Lighting Handbook, Application Volume*.

Representative Transducers

Measurand	Transducer	Operating Principles
Displacement (Length)	Resistive Capacitive Inductive	Change in resistance, capacitance, or inductance caused by linear or angular displacement of transducer element
Force	Strain gage	Resistance, piezoresistivity
Temperature	Thermistor	Resistance
	Thermocouple	Peltier, seebeck effect
Pressure	Diaphragm	Diaphragm motion sensed by a displacement technique.
Flow	Differential pressure	Pressure drop across restriction
	Turbine	Angular velocity proportional to flow rate

From Schmalzel, J.L., Instruments, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 2470.

Worldwide Radio Navigation Aids

System	Frequency		Number of Stations	Number of Users in 1996			
	Hz	Band		Air	Marine	Space	Land
Omega	10–13 kHz	VLF	8	15,000	10,000	0	0
Loran-C/Chaika	100 kHz	LF	50	120,000	550,000	0	25,000
Decca	70–130 kHz	LF	150	2,000	20,000	0	0
Beacons*	200–1600 kHz	MF	4000	130,000	500,000	0	0
Instrument Landing System (ILS)*	108–112 MHz 329–335 MHz	VHF UHF	1500	150,000	0	0	0
VOR*	108–118 MHz	VHF	1500	180,000	0	0	0
SARSAT/COSPAS	121.5 MHz 243,406 MHz	VHF UHF	5 satellites	200,000	200,000	0	100,000
Transit	150, 400 MHz	VHF	7 satellites	0	0	0	0
PLRS	420–450 MHz	UHF	None	0	0	0	2,000
JTIDS	960–1213 MHz	L	None	500	0	0	0
DME*	962–1213 MHz	L	1500	90,000	0	4	0
Tacan*	962–1213 MHz	L	850	15,000	0	4	0
Secondary Surveillance Radar (SSR)*	1030, 1090 MHz	L	800	250,000	0	0	0
Identification Friend or Foe (IFF)							
GPS-GLONASS	1227, 1575 MHz	L	24 + 24 satellites	120,000	275,000	4	125,000
Satellite Control Network (SCN)	1760–1850 MHz 2200–2300 MHz	S S	10	0	0	200	0
Spaceflight Tracking and Data Network (STDN)	2025–2150 MHz 2200–2300 MHz	S	3 satellites 10 ground	0	0	50	0
Radar Altimeter	4200 MHz	C	None	20,000	0	0	0
MLS*	5031–5091 MHz	C	30	100	0	0	0
FPQ-6, FPQ-16 radar	5.4–5.9 GHz	C	10	0	0	0	0
Weather/map radar	10 GHz	X	None	10,000	0	0	0
Shuttle rendezvous radar	13.9 GHz	Ku	None	0	0	4	0
Airborne Doppler radar	13–16 GHz	Ku	None	20,000	0	0	0
SPN-41 carrier-landing monitor	15 GHz	Ku	25	1600	0	0	0
SPN-42/46 carrier-landing radar	33 GHz	Ka	25	1600	0	0	0

* Standardized by International Civil Aviation Organization.

From Kayton, M., Navigation systems, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 2482.

Classifications of Chemical Biomedical Sensors

1. Electrochemical
   a. Amperometric
   b. Potentiometric
   c. Coulometric
2. Optical
   a. Colorimetric
   b. Emission and absorption spectroscopy
   c. Fluorescence
   d. Chemiluminescence
3. Thermal methods
   a. Calorimetry
   b. Thermoconductivity
4. Nuclear magnetic resonance

From Neuman, M., Biomedical sensors, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 2587.

Approximate Ultrasonic Attenuation Coefficient, Speed, and Characteristic Impedance for Water and Selected Tissues at 3.5 MHz

Tissue	Attenuation Coefficient (m^{-1})	Speed (m/s)	Characteristic Impedance (10^6 Pa s/m)
Water	0.2	1520	1.50
Amniotic fluid	0.7	1510	1.51
Blood	7	1550	1.60
Liver	35	1580	1.74
Muscle	50	1560	1.72
Bone	800	3360	5.70
Lung	1000	340	0.25

From Frizzell, L.A., Ultrasound, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 2623.

Parasitics in Various Electronic Packages

Package Type	Parasitic Capacitance, pF	Parasitic Inductance, nH
Flip chip	0.1	0.01
Chip on board/wire bond	0.5	1–2
Pin grid array	1	2
Quad flat pack	1	1–6
Through-hole DIP	3	8–20

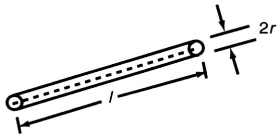
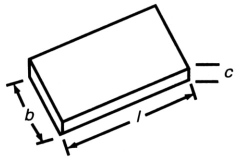
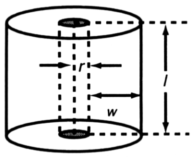
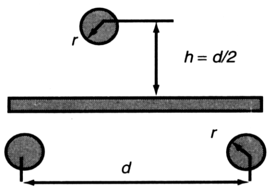
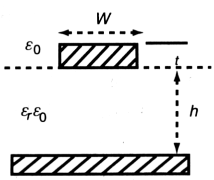
From Blackwell, G.R., Direct chip attach, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **4**-5.

Wiring Board Material Properties

Material	ε_r'	$\varepsilon_r''/\varepsilon_r'$	CTE (× 10^{-6}/°C)		T_g, °C
			x, y	z	
FR-4 epoxy-glass	4.0–5.0	0.02–0.03	16–20	60–90	125–135
Polyimide-glass	3.9–4.5	0.005–0.02	12–14	60	>260
Teflon®	2.1	0.0004–0.0005	70–120		—
Benzocyclobutene	2.6	0.0004	35–60		>350
High-temperature one-component epoxy-glass	4.45–4.45	0.02–0.022			170–180
Cyanate ester-glass	3.5–3.9	0.003–0.007			240–250
Ceramic	~10.0	0.0005	6–7		—
Copper	—	—	17		—
Copper/invar/copper	—	—	3–6		—

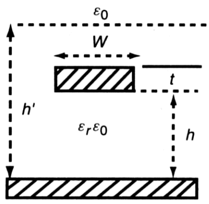
From Blackwell, G.R., Circuit boards, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **5**-3.

Interconnect Models

Interconnect type	Model
 Round wire	$L \cong 0.002l\left[\ln\left(\frac{2l}{r}-0.75\right)\right], \mu H; l > r$ l, r in cm.
 Straight rectangular bar or ribbon	$L \cong 0.002l\left[\ln\frac{2l}{b+c}+0.5+0.2235\frac{b+c}{l}\right], \mu H$ b, c, l in cm.
 Via	$L = 0.002l\left[\ln\frac{2l}{r+W}-1+\xi\right], \mu H$ where $\xi = 0.25\left[\cos\left(\frac{r}{r+W}\frac{\pi}{2}\right)-0.07\sin\left(\frac{r}{r+W}\pi\right)\right]$ l, r, W in cm.
 Round wire over a ground plane and parallel round wires	$Z_0 = \frac{120}{\sqrt{\varepsilon_r}}\cosh^{-1}\frac{d}{2r}$, ohm $= \frac{120}{\sqrt{\varepsilon_r}}\ln\frac{d}{r}$, ohm; $d \gg r$
 Microstrip	$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left[1+\frac{10h}{W_e}\right]^{-a.b}$ where $\frac{W_e}{h} = \frac{W}{h}+\frac{1.25}{\pi}\frac{t}{h}\left[1+\ln\frac{2[h^4+(2\pi W)^4]^{0.25}}{t}\right]$ $a = 1+\frac{1}{49}\ln\left\{\frac{\left[\left(\frac{W_e}{h}\right)^4+\left(\frac{W_e}{52h}\right)^2\right]}{\left[\left(\frac{W_e}{h}\right)^4+0.432\right]}\right\}$ $+\frac{1}{18.7}\ln\left[1+\left(\frac{W_e}{18.1h}\right)^3\right]$ $b = 0.564\left[\frac{\varepsilon_r-0.9}{\varepsilon_r+3}\right]^{0.053}$ $Z_0 = \frac{60}{\sqrt{\varepsilon_{reff}}}\ln\left[\frac{F_1 h}{W_e}+\sqrt{1+\left(\frac{2h}{W_e}\right)^2}\right]$ with $F_1 = 6+(2\pi-6)e^{-\left(30.666\frac{h}{W_e}\right)^{0.7528}}$

Interconnect Models (continued)

Interconnect type — **Model**



Buried microstrip

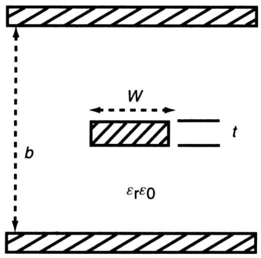
Z_0 same expression as microstrip with

$$\varepsilon_{r\text{eff}} = \varepsilon_r\left[1 - e^{K\frac{h'}{h}}\right]$$

where

$$K = \ln\left\{\frac{1}{\left[1 - \dfrac{\varepsilon_{r\text{eff}}(h'=h)}{\varepsilon_r}\right]}\right\}$$

$[\varepsilon_{r\text{eff}}(h'=h)]$ is given by the microstrip formula



Stripline

$$\varepsilon_{r\text{eff}} = \varepsilon_r$$

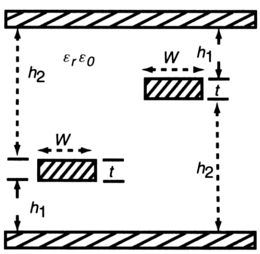
$$Z_0 = \frac{30}{\sqrt{\varepsilon_{r\text{eff}}}}\ln\left[1 + \frac{4}{\pi W_n}\left(\frac{8}{\pi W_n} + \sqrt{\frac{8}{\pi W_n} + 6.27}\right)\right]$$

where

$$W_n = \frac{W}{b-t} + \frac{t_n}{\pi(1-t_n)}$$

$$\times\left\{1 - \frac{1}{2}\ln\left[\left(\frac{t_n}{2-t_n}\right)^2 + \left(\frac{0.0796t_n}{1.1t_n + \dfrac{W}{b}}\right)^m\right]\right\}$$

$$t_n = \frac{t}{b} \quad \text{and} \quad m = b\left(\frac{1-t_n}{3-t_n}\right)$$



Asymmetric and dual striplines

$$Z_0 = \frac{80Y}{0.918\sqrt{\varepsilon_r}}\ln\left[\frac{3.8h_1 + 1.9t}{0.8W + t}\right]$$

$$Y = \left[1.0636 + 0.33136\frac{h_1}{h_2} - 1.9007\left(\frac{h_1}{h_2}\right)^3\right]$$

From Blackwell, G.R., Circuit boards, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **5**-13 to **5**-14.

Dielectric Constants and Wave Velocities within Various PCB Materials

Material	ε_r (at 30 MHz)	Velocity (in/ns)	Velocity (ps/in)
Air	1.0	11.76	85.0
PTFE/glass (Teflon™)	2.2	7.95	125.8
RO 2800	2.9	6.95	143.9
CE/custom ply (Canide ester)	3.0	6.86	145.8
BT/custom ply (Beta-triazine)	3.3	6.50	153.8
CE/glass	3.7	6.12	163.4
Silicon dioxide	3.9	5.97	167.5
BT/glass	4.0	5.88	170.1
Polyimide/glass	4.1	5.82	171.8
FR–4 glass	4.5	5.87	170.4
Glass cloth	6.0	4.70	212.8
Alumina	9.0	3.90	256.4

Note: Values measured at TDR frequencies using velocity techniques.

Values were not measured at 1 MHz, which provides faster velocity values. Units for velocity differ due to scaling and are presented in this format for ease of presentation.

From Montrose, M.I., EMC and printed circuit board design, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **6**-40. Originally from IPC–2141, *Controlled Impedance Circuit Boards and High Speed Logic Design,* Institute for Interconnecting and Packaging Electronics Circuits. © 1996. Reprinted with permission.

Wire Ampacity and Size

AWG wire size	Resistance, Ω per 1000 ft	Ampacity for low-temperature insulation	Ampacity for high-temperature insulation	Bare wire diameter mm (in)
30	100	2	4	0.254 (0.0100)
28	60	3	6	0.320 (0.0126)
26	40	4	7	0.404 (0.0159)
24	25	6	10	0.511 (0.0201)
22	14	8	13	0.643 (0.0253)
20	10	10	17	0.810 (0.0319)
18	6	15	24	1.024 (0.0403)

Note: **Ω**/1000 ft is approximate. Exact value depends on whether the conductor is solid or stranded, and if stranded, the type of stranding. Consult the manufacturers' data sheets for exact values.

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-4.

Parameters for Multimode and Single-Mode Fiber

Parameter	Multimode (62.5/125 μm)	Dispersion-Unshifted Single-Mode
Core size	62.5 ± 3.0 μm	8.3 μm (typical)
Mode field diameter	—	8.8–9.3 μm (typical)
Numerical aperture	0.275 ± 0.015	0.13 (typical)
Cladding diameter	125.0 ± 2.0 μm	125.0 ± 1.0 μm
Attenuation	≤3.5 dB/km at 850 nm	≤0.5 dB/km at 1310 nm
	≤1.5 dB/km at 1300 nm	≤0.4 dB/km at 1550 nm
Bandwidth	≥160 MHz·km at 850 nm	—
	≥500 MHz·km at 1300 nm	
Dispersion	—	≤3.5 ps/nm·km for 1285–1330 nm

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-24.

Standard Optical Cable Color Coding

Unit or Fiber	Color	Unit or Fiber	Color
1	Blue	7	Red
2	Orange	8	Black
3	Green	9	Yellow
4	Brown	10	Violet
5	Slate	11	Rose
6	White	12	Aqua

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-30.

Common Tests for Optical Fiber

Test	FOTP	Purpose
Core diameter	FOTP–43 and –58	Determine the size of the core in a multimode fiber to ensure compatibility with other fibers of the same core size as well as with end equipment.
Mode field diameter	FOTP–167	Measure of the spot size of light propagating in a single-mode fiber to ensure compatibility with other fibers of similar core size as well as with end equipment. Differences in mode field diameters of two fibers being spliced together can affect splice loss.
Cladding diameter	FOTP–176	Determine the size of the cladding. The consistency of cladding diameter can affect connector and mechanical splice performance.
Core–clad concentricity	FOTP–176	Distance between the center of the core and the center of the cladding. High values can affect splice and connector losses.
Core noncircularity	FOTP–176	Measures the roundness of multimode cores. High values can have a slight effect on splice and connector losses.
Cladding noncircularity	FOTP–176	Measures the roundness of the cladding. High values can have a slight effect on splice and connector losses.
Fiber cutoff wavelength	FOTP–80	Measures the minimum wavelength at which a single-mode fiber will support the propagation of only one mode. If the system wavelength is below the cutoff wavelength, multimode operation may occur introducing modal dispersion and higher attenuation. The difference in fiber and cable cutoff wavelength is due to the deployment of fiber during the test. Cabling can shift the cutoff wavelength to a lower value.
Cable cutoff wavelength	FOTP–170	
Curl	FOTP–111 (underdevelopment)	Measures the curvature of a short length of fiber in an unsupported condition. Excessive curl can affect splice loss in passive alignment fusion splicers such as mass fusion splicers.
Coating diameter	FOTP–173	Measures the outside diameter of a coated fiber. Out of spec values can affect cable manufacturing and potentially cable performance.
Numerical aperture	FOTP–47 and –177	Measures the numerical aperture of a fiber. Ensures compatibility with other fibers as well as end equipment.
Proof test	FOTP–31	Ensures the minimum strength of a fiber. Every fiber is normally subjected to the proof test.
Attenuation coefficient	FOTP–61 and –78	Measured by the fiber and cable manufacturers and reported to the customer in units of dB/km.
Bandwidth	FOTP–30 and –5	Measured by the fiber manufacturer and reported to the customer by the cable manufacturer in units of MHz·km.

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-47.

Common Tests for Optical Cable Design

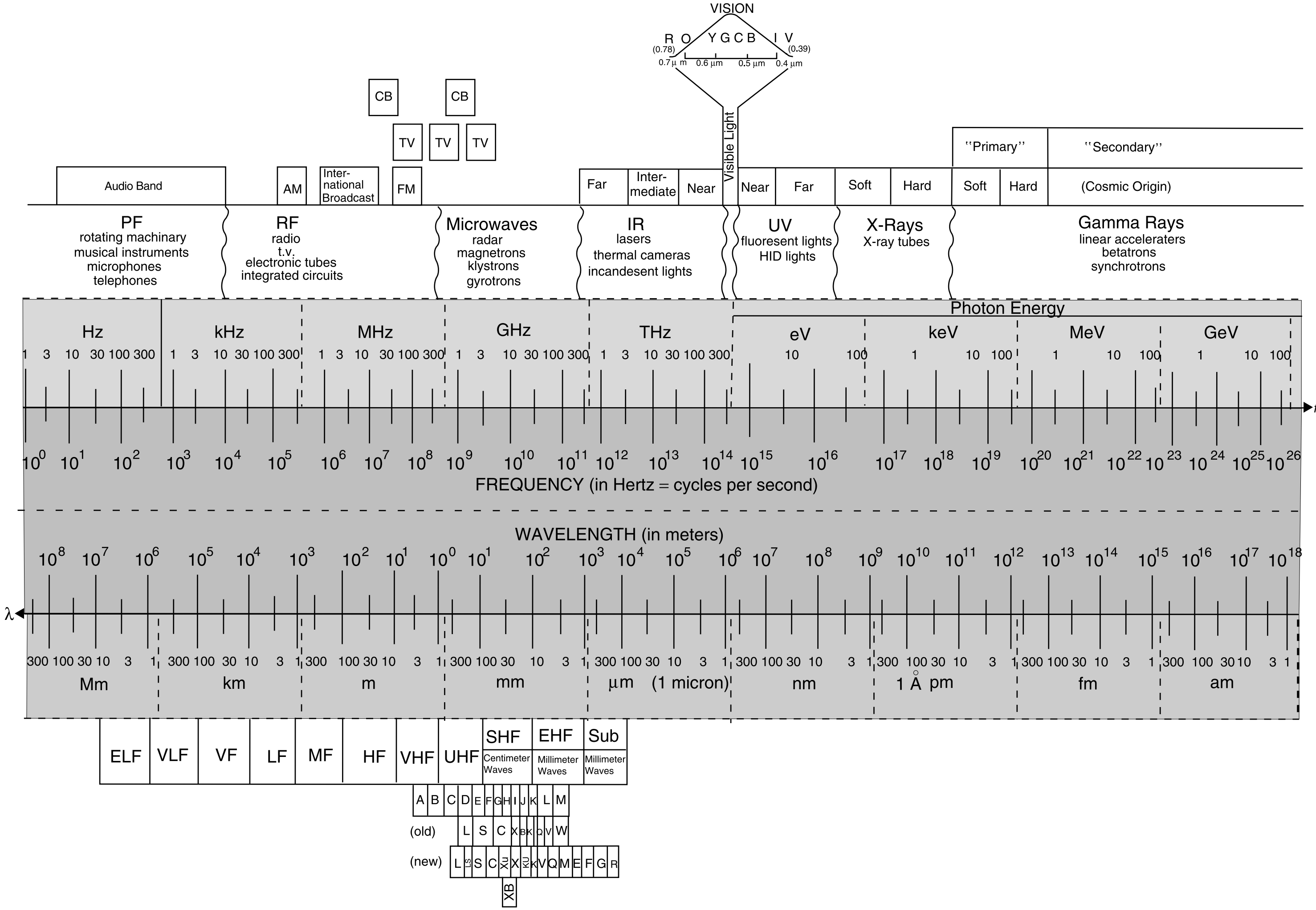
Test	FOTP	Purpose
Temperature cycling	FOTP–3	Simulates environmental conditions once the cable is deployed.
Impact	FOTP–25	Simulates an object being dropped on the cable for a sudden and brief impact.
Tensile	FOTP–33	Measures the performance of the cable at its rated tensile load simulating installation by pulling.
Compressive load	FOTP–41	Measures cable performance while under a compressive or crushing force.
Cable twist	FOTP–85	Measures the ability of the cable to perform when under a twist condition.
Cycle flex or bend	FOTP–104	Measures the ability of the cable to perform even when subjected to a bend, and withstand repeated bending during installation.
Water penetration	FOTP–82	Measures the ability of an outdoor cable to prevent the ingress of water along the length of the cable.
Filling and flooding compound flow	FOTP–81	Measures the resistance to flow of compound flow filling and flooding compounds at elevated temperatures.

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-47.

Cable Interconnects

Cable Designation	Nominal Z_0	V_p	Diameter, in	Nominal Atten. at 50 MHz, dB/100 ft	Nominal Atten. at 200 MHz, dB/100 ft	Nominal Atten. at 700 MHz, dB/100 ft	Max. Op. Voltage, RMS
RG-8A/U	52	0.66	0.405	1.6	3.2	6.5	4000
RG-8/X	50	0.78	0.242	2.5	5.4	11.1	600
RG-213/U	50	0.66	0.405	1.6	3.2	6.5	5000
RG-58/U	53.5	0.66	0.195	3.1	6.8	14.0	1900
RG-58A/U	50	0.66	0.195	3.3	7.3	17.0	1900
RG-58C/U	50	0.66	0.195	3.3	7.3	17.0	1900
RG-11A/U	75	0.66	0.405	1.3	2.9	5.8	5000
RG-59B/U	75	0.66	0.242	2.4	4.9	9.3	2300
RG-62B/U	93	0.84	0.242	2.0	4.2	8.6	750
RG-71/U	93	0.84	0.245	1.9	3.8	7.3	750
RG-141A/U	50	0.695	0.190	2.7	5.6	11.0	1400
RG-178B/U	50	0.695	0.70	10.5	19.0	37.0	1000
RG6A/U	75	0.66	0.332	1.9	4.1	8.1	2700

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-53.



(From Norgard, J., Electromagnetic spectrum, in *The Electronics Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 4.)

Properties of Magnetic Materials and Magnetic Alloys

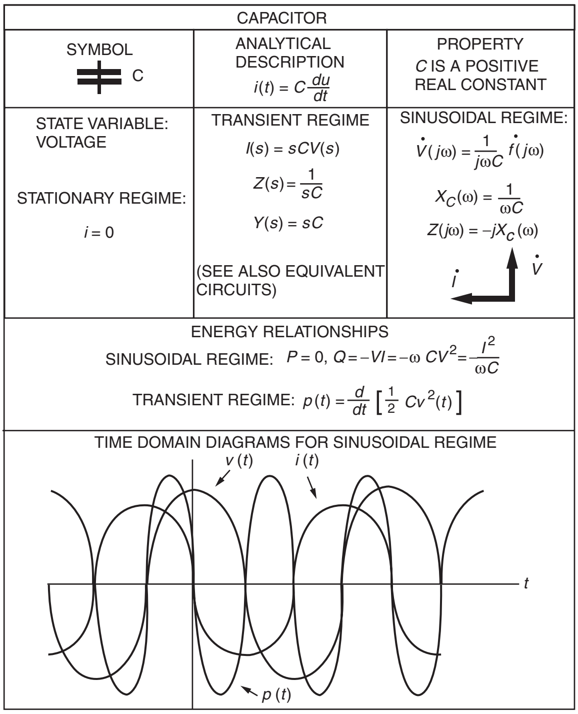
Material (Composition)	Initial Relative Permeability, μ_i/μ_0	Maximum Relative Permeability, μ_{max}/μ_0	Coercive Force *He*, A/m (Oe)	Residual Field B_r, Wb/m^2(G)	Saturation Field B_s, Wb/m^2(G)	Electrical Resistivity $\rho \times 10^{-8}\ \Omega \cdot m$	Uses
			Soft				
Commercial iron (0.2 imp.)	250	9000	≈80 (1)	0.77 (7700)	2.15 (21,500)	10	Relays
Purified iron (0.05 imp.)	10,000	200,000	4 (0.05)	—	2.15 (21,500)	10	
Silicon-iron (4 Si)	1500	7000	20 (0.25)	0.5 (5000)	1.95 (19,500)	60	Transformers
Silicon-iron (3 Si)	7500	55,000	8 (0.1)	0.95 (9500)	2 (20,000)	50	Transformers
Silicon-iron (3 Si)	—	116,000	4.8 (0.06)	1.22 (12,200)	2 (20,100)	50	Transformers
Mu metal (5 Cu, 2 Cr, 77 Ni)	20,000	100,000	4 (0.05)	0.23 (2300)	0.65 (6500)	62	Transformers
78 Permalloy (78.5 Ni)	8000	100,000	4 (0.05)	0.6 (6000)	1.08 (10,800)	16	Sensitive relays
Supermalloy (79 Ni, 5 Mo)	100,000	1,000,000	0.16 (0.002)	0.5 (5000)	0.79 (7900)	60	Transformers
Permendur (50 Cs)	800	5000	160 (2)	1.4 (14,000)	2.45 (24,500)	7	Electromagnets
Mn-Zn ferrite	1500	2500	16 (0.2)	—	0.34 (3400)	20×10^6	Core material for coils
Ni-Zn ferrite	2500	5000	8 (0.1)	—	0.32 (3200)	10^{11}	

From Parker, M.R. and Webb, W.E., Magnetic materials for inductive processes, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 151. Originally after Plonus, M.A., 1978, *Applied Electromagnetics*, McGraw-Hill, New York.

Units

Quantity	Symbol	Unit (S.I.)
Magnetic flux density	B	T (or Wb/m^2)
Magnetic field intensity	H	A/m
Magnetic flux	ϕ'	Wb
Magnetic flux linkage	Λ	Wb-turns
Self, mutual inductance	L, M	H
Magnetic permeability	μ	H/m

From Parker, M.R. and Webb, W.E., Magnetic materials for inductive processes, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 154.



Summary of capacitor properties. (From Filanovsky, I.M., Capacitance and capacitors, in *The Electronics Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 168.)

Frequency Response Magnitude Functions for Butterworth LP Prototype Filters

Order n	$\left\lvert \frac{V_2(\omega)}{V_1(\omega)} \right\rvert$
2	$\frac{1}{\sqrt{1+\omega^4}}$
3	$\frac{1}{\sqrt{1+\omega^6}}$
4	$\frac{1}{\sqrt{1+\omega^8}}$

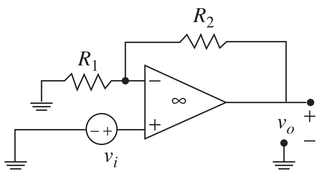
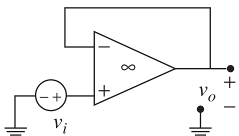
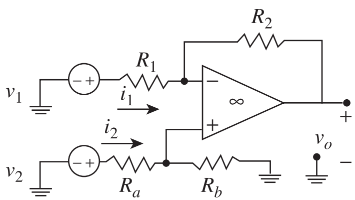
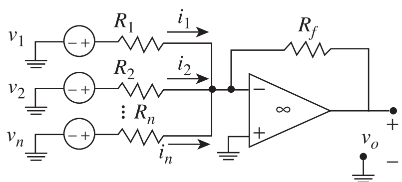
From Harrison, C., Passive filters, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 282.

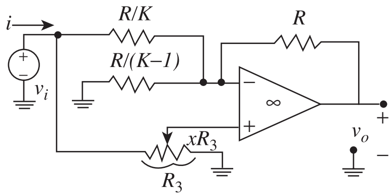
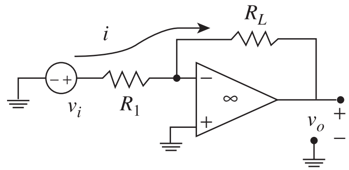
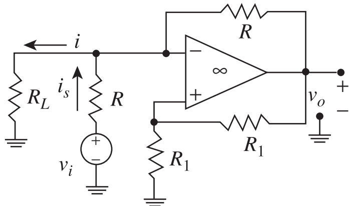
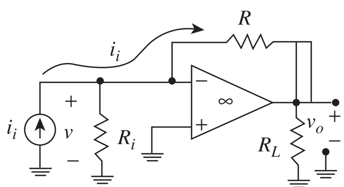
Frequency Response Magnitude Functions for Chebyshev LP Prototype Filters

Order n	Chebyshev Polynomial $T_n(\omega)$	$\left\lvert \frac{V_2(\omega)}{V_1(\omega)} \right\rvert$
2	$2\omega^2 - 1$	$\frac{1}{\sqrt{4\varepsilon^2\omega^4 - 4\varepsilon^2\omega^2 + (\varepsilon^2 + 1)}}$
3	$4\omega^3 - 3\omega$	$\frac{1}{\sqrt{16\varepsilon^2\omega^6 - 24\varepsilon^2\omega^4 + 9\varepsilon^2\omega^2 + 1}}$
4	$8\omega^4 - 8\omega^2 + 1$	$\frac{1}{\sqrt{64\varepsilon^2\omega^8 - 128\varepsilon^2\omega^6 + 80\varepsilon^2\omega^4 - 16\varepsilon^2\omega^2 + (\varepsilon^2 + 1)}}$

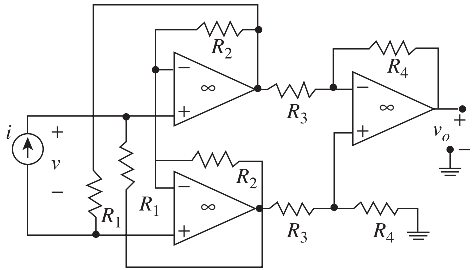
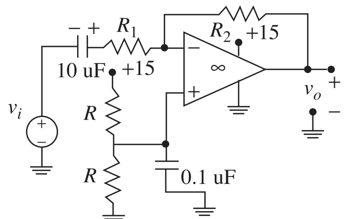
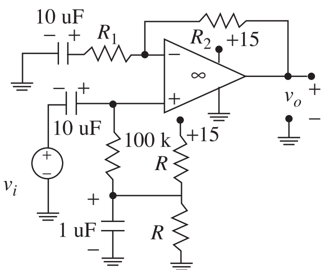
From Harrison, C., Passive filters, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 283.

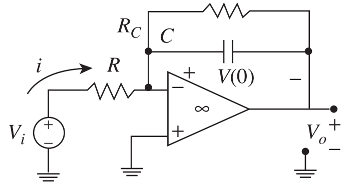
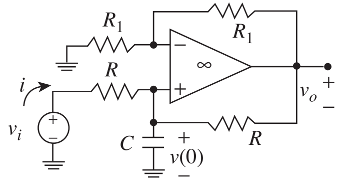
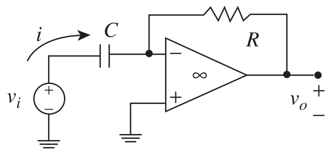
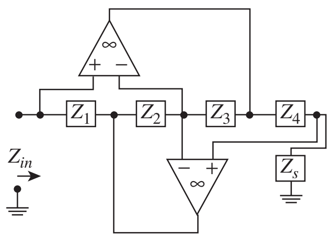
Op–amp Circuits

No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
1.	Noninverting amplifier		$\frac{\upsilon_O}{\upsilon_i} = 1 + \frac{R_2}{R_1}$	$R_{in} = \infty$ (ideally)	
2.	Buffer		$\frac{\upsilon_O}{\upsilon_i} = 1$	$R_{in} = \infty$ (ideally)	Special case of circuit 1
3.	Difference amplifier		$\upsilon_O = \frac{R_2}{R_1}(\upsilon_2 - \upsilon_1)$	$i_1 = \frac{\upsilon_1 - \upsilon_2 \frac{R_b}{(R_a + R_b)}}{R_1}$ $i_2 = \frac{\upsilon_2}{R_a + R_b}$	$\frac{R_1}{R_2} = \frac{R_a}{R_b}$
4.	Adder		$\upsilon_O = -\left\{\upsilon_1 \frac{R_f}{R_1} + \upsilon_2 \frac{R_f}{R_2} + \cdots + \upsilon_n \frac{R_f}{R_n}\right\}$	$i_1 = \frac{\upsilon_1}{R_1}$ $i_2 = \frac{\upsilon_2}{R_2}$ $\vdots$ $i_n = \frac{\upsilon_n}{R_n}$	

5.	Variable gain circuit		$\frac{v_O}{v_i} = (2Kx - K)$ $0 \le x \le 1, \quad K > 1$	$i = \frac{v_i}{R_3} + \frac{K v_i (1 - x)}{R}$	Potentionmeter R_3 adjusts the gain over the range $-K$ to $+K$
6.	Voltage-to-current converter		$i = \frac{v_i}{R_1}$		The current through R_L is independent of R_L
7.	Voltage-to-current converter with grounded load		$i = \frac{v_i}{R}$	$i_s = \frac{v_i}{R}\left(1 - \frac{R_L}{R}\right)$	$v_0 = v_i(2R_L/R)$ The current i is independent of R_L Circuit has wide band-width for $R_L \ll R$
8.	Current-to-voltage converter		$v_0 = -Ri_i$	$v = 0$	The voltage v_0 is independent of R_L and R_i

Op–amp Circuits (continued)

No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
9.	Current-to-voltage converter		$v_O = -2iR_1 \frac{R_4}{R_3}$	$v = 0$	
10.	Inverting amplifier with single supply		$v_O = 7.5 - v_i \frac{R_2}{R_1}$		$R = 3.9\ \text{k}\Omega$
11.	Noninverting amplifier with single supply		$v_O = 7.5 + v_i\left(1 + \frac{R_2}{R_1}\right)$		$R = 3.9\ \text{k}\Omega$

12.	Integrator		$\upsilon_O = -V(0) - \frac{1}{RC}\int_0^t \upsilon_i(t)dt$ $V(0)$ is the initial voltage across the capacitor, RC is very large.	$i = \frac{\upsilon_i}{R}$	Negative feedback is required at DC. A large value of R_C can be used or a feedback path can be established through an external circuit.
13.	De Boo integrator		$\upsilon_O = 2V(0) + \frac{2}{RC}\int_0^t \upsilon_i(t)dt$	$i = \frac{\upsilon_i}{R} - \frac{\upsilon_O}{2R}$	One end of capacitor is physically grounded.
14.	Differentiator		$\upsilon_O = RC\frac{d\upsilon_i}{dt}$	$i = C\frac{d\upsilon_i}{dt}$	Differentiators are usually avoided in the design of circuits because they accentuate noise.
15.	Generalized impedance converter (GIC)		$Z_{in} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}$		

From Aronhime, P., Operational amplifiers, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, pp. 554–556.

Operating Characteristics of Common Battery Types

	NiCd	NiMH	SLA	Li-ion	Li-polymer	Reusable Alkaline
Energy density, Wh/kg	50	75	30	100	175	80 (initial)
Cycle life[a] (typical)	1500	500	200–300	300–500	150	10 (to 65%)
Fast-charge time,[b] h	1 1/2	2–3	8–15	3–6	8–15	3–4
Self-discharge[c]	Moderate[d]	High	Low	Low	Very low	Very low
Cell voltage,[e] (nominal) V	1.25	1.25	2	3.6	2.7	1.5
Load current,[f]	Very high	Moderate	Low	High	Low	Very low
Exercise requirement[g]	/30 days	/90 days	/180 days	N/A	N/A	N/A
Battery cost[h]	Low	Moderate	Very low	Very high	High	Very low
(estimated, ref. only)	(50,000)	(80.00)	(25.00)	(100.00)	(90.00)	(5.00)
Cost per cycle[i] ($)	0.04	0.16	0.10	0.25	0.60	0.50
In commercial use since	1950	1970	1970	1990	(1997)	1990

[a] Cycle life indicates the typical number of charge–discharge cycles before the capacity decreases from the nominal 100% to 80% (65% for the reusable alkaline).

[b] Fast-charge time is the time required to fully charge an empty battery.

[c] Self-discharge indicates the self-discharge rate when the battery is not in use.

[d] Moderate refers to 1–2% capacity-loss per day.

[e] Cell voltage multiplied by the number of cells provides the battery terminal voltage.

[f] Load current is the maximum recommended current the battery can provide. High refers to a discharge rate of 1C; very high is a current higher than 1 *C*. C rate is a unit by which charge and discharge times are scaled. If discharged at 1, a 1000 mAh battery provides a current of 1000 mA; if discharged at 0.5C, the current is 500 mA.

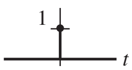
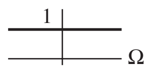
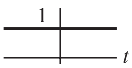
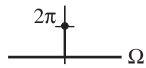
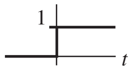
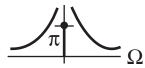
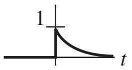
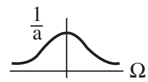
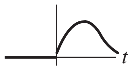
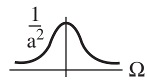
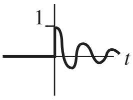
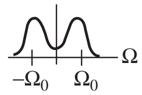
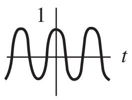
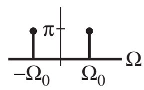
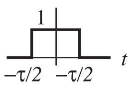
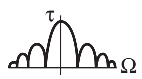
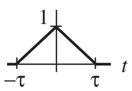
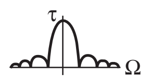
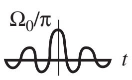
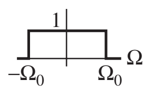
[g] Exercise requirement indicates the frequency the battery needs exercising to achieve maximum service life.

[h] Battery cost is the estimated commercial price of a commonly available battery.

[i] Cost-per-cycle indicates the operating cost derived by taking the average price of a commercial battery and dividing it by the cycle count.

From Buchmann, I., Batteries, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, pp. 1056.

Example Fourier Transform Pairs

$x(t)$	$x(t)$	$X(\Omega)$	$\lvert X(\Omega)\rvert$
	$\delta(t)$	1	
	1	$2\pi\delta(\Omega)$	
	$u(t)$	$\pi\delta(\Omega)+\dfrac{1}{j\Omega}$	
	$e^{-at}u(t),\ a>0$	$\dfrac{1}{a+j\Omega}$	
	$te^{-at}u(t),\ a>0$	$\dfrac{1}{(a+j\Omega)^2}$	
	$e^{-at}\cos(\Omega_0 t)u(t),\ a>0$	$\dfrac{a+j\Omega}{(a+j\Omega)^2+\Omega_0^2}$	
	$\cos(\Omega_0 t)$	$\pi[\delta(\Omega-\Omega_0)+\delta(\Omega+\Omega_0)]$	
	$1, \lvert t\rvert<\tau/2$ $0, \lvert t\rvert>\tau/2$	$\dfrac{\sin(\Omega\tau/2)}{\Omega/2}$	
	$1-\lvert t\rvert/\tau,\ \lvert t\rvert<\tau$ $0, \lvert t\rvert>\tau$	$\dfrac{1}{\tau}\dfrac{\sin^2(\Omega\tau/2)}{(\Omega/2)^2}$	
	$\dfrac{\sin(\Omega_0 t/2)}{\pi t}$	$1, \lvert\Omega\rvert<\Omega_0$ $0, \lvert\Omega\rvert>\Omega_0$	

From Hamann, J.C. and Pierre, J.W., Fourier waveform analysis, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, pp. 2119.

Advantages and Disadvantages of Satellites

Advantages	Disadvantages
Wide-area coverage	Propagation delay
Easy access to remote sites	Dependency on a remote facility
Costs independent of distance	Less control over transmission
Low error rates	Attenuation due to atmospheric particles (e.g., rain) severe at high frequencies
Adaptable to changing network patterns	Continual time-of-use charges
No right-of-way necessary; earth stations located at premises	Reduced transmission during solar equinox

From Sadiku, M.N.O., Satellite communications, in *The Handbook of Ad Hoc Wireless Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. **8**-2. Originally from D.J. Marihart, *IEEE Transactions on Power Delivery,* 16, 181–188, 2001.

Satellite Frequency Allocations

Frequency Band	Range (GHz)
L	1–2
S	2–4
C	4–8
X	8–12
Ku	12–18
K	18–27
Ka	27–40

From Sadiku, M.N.O., Satellite communications, in *The Handbook of Ad Hoc Wireless Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. **8**-5.

Typical Uplink and Downlink Satellite Frequencies (GHz)

Uplink Frequencies	Downlink Frequencies
5.925–6.425	3.700–4.200
7.900–8.400	7.250–7.750
14.00–14.50	11.70–12.20
27.50–30.00	17.70–20.20

From Sadiku, M.N.O., Satellite communications, in *The Handbook of Ad Hoc Wireless Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. **8**-5.

Frequency Allocations for FSS (Below ~30 GHz)

Downlinks (in GHz)	Uplinks (in GHz)
3.4–4.2 and 4.5–4.8	5.725–7.075
7.25–7.75	7.9–8.4
10.7–11.7	
11.7–12.2 (Region 2 only)	12.75 13.25 and 14.0–14.5
12.5–12.75 (Region 1 only)	
17.7–21.2	27.5–31.0

From Sadiku, M.N.O., Satellite communications, in *The Handbook of Ad Hoc Wireless Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. **8**-13.

Characteristics of Satellite PCS Systems

Parameter	Iridium	Globalstar	ICO
Company	Motorola	Loral/Qualcomm	ICO-Global
No. of satellites	66	48	10
No. of orbit planes	6	8	2
Altitude (km)	780	1414	10,355
Weight (lb)	1100	704	6050
Bandwidth (MHz)	5.15	11.35	30
Frequency up/down (GHz)	30/20	5.1/6.9	14/12
Spot beams/satellite	48	16	163
Carrier bit rate (k/sec)	50	2.4	36
Multiple access	TDMA/FDMA	CDMA/FDMA	TDMA/FDMA
Cost to build ($billion)	4.7	2.5	4.6
Service start date	1998	1999	2003

From Sadiku, M.N.O., Satellite communications, in *The Handbook of Ad Hoc Wireless Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. **8**-20.

Table of Laplace Operations

	$F(s)$	$fs(t)$
1.	$\int_0^\infty e^{-st} f(t)dt$	$f(t)$
2.	$AF(s) + BG(s)$	$Af(t) + Bg(t)$
3.	$sF(s) - f(+0)$	$f'(t)$
4.	$s^nF(s) - s^{n-1} f(+0) - s^{n-2} f^{(1t)} (+0) - \cdots - f^{(n-l)} (+0)$	$f^{(n)}(t)$
5.	$\frac{1}{s}F(s)$	$\int_0^t f(\tau)d\tau$
6.	$\frac{1}{s^2}F(s)$	$\int_0^t \int_0^\tau f(\lambda)d\lambda\, d\tau$
7.	$F_1(s)F_2(s)$	$\int_0^t f_1(t-\tau)f_2(\tau)d\tau = f_1 * f_2$
8.	$-F'(s)$	$tf(t)$
9.	$(-1)^nF^{(n)}(s)$	$t^n f(t)$
10.	$\int_s^\infty F(x)dx$	$\frac{1}{t}f(t)$
11.	$F(s-a)$	$e^{at}f(t)$
12.	$e^{-bs} F(s)$	$f(t-b)$, where $f(t) = 0;\ t < 0$
13.	$F(cs)$	$\frac{1}{c}f\left(\frac{t}{c}\right)$
14.	$F(cs-b)$	$\frac{1}{c}e^{(bt)/c}f\left(\frac{t}{c}\right)$
15.	$\frac{\int_0^a e^{-st} f(t)dt}{1-e^{-as}}$	$f(t+a) = f(t)$ periodic signal
16.	$\frac{\int_0^a e^{-st} f(t)dt}{1+e^{-as}}$	$f(t+a) = -f(t)$
17.	$\frac{F(s)}{1-e^{-as}}$	$f_1(t)$, the half-wave rectification of $f(t)$ in No. 16.

Table of Laplace Operations (continued)

	$F(s)$	$fs(t)$
18.	$F(s)\coth\frac{as}{2}$	$f_2(f)$, the full-wave rectification of $f(t)$ in No. 16.
19.	$\frac{p(s)}{q(s)}, q(s)=(s-a_1)(s-a_2)\cdots(s-a_m)$	$\sum_1^m \frac{p(a_n)}{q'(a_n)}e^{a_n t}$
20.	$\frac{p(s)}{q(s)}=\frac{\phi(s)}{(s-a)^r}$	$e^{at}\sum_{n=1}^{r}\frac{\phi^{(r-n)}(a)}{(r-n)!}\frac{t^{n-1}}{(n-1)!}+\cdots$

From Poularikas, A., Laplace transforms, in *The Handbook of Formulas and Tables for Signal Processing*, CRC Press, Boca Raton, FL, 1999, p. **2**-6.

Table of Laplace Transforms

	$F(s)$	$f(t)$
1.	s^n	$\delta^{(n)}(t)$ n^{th} derivative of the delta function
2.	s	$\frac{d\delta(t)}{dt}$
3.	1	$\delta(t)$
4.	$\frac{1}{s}$	1
5.	$\frac{1}{s^2}$	t
6.	$\frac{1}{s^n}(n=1,2,\cdots)$	$\frac{t^{n-1}}{(n-1)!}$
7.	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{\pi t}}$
8.	$s^{-3/2}$	$2\sqrt{\frac{t}{\pi}}$
9.	$s^{-[n+(1/2)]}$ $(n = 1,2,\cdots)$	$\frac{2^n t^{n-(1/2)}}{1\cdot 3\cdot 5\cdots(2n-1)\sqrt{\pi}}$
10.	$\frac{\Gamma(k)}{s^k}(k\geq 0)$	t^{k-1}
11.	$\frac{1}{s-a}$	e^{at}
12.	$\frac{1}{(s-a)^2}$	te^{at}
13.	$\frac{1}{(s-a)^n}(n=1,2,\cdots)$	$\frac{1}{(n-1)!}t^{n-1}e^{at}$
14.	$\frac{\Gamma(k)}{(s-a)^k}(k\geq 0)$	t^{k-1} e^{at}
15.	$\frac{1}{(s-a)(s-b)}$	$\frac{1}{(a-b)}(e^{at}-e^{bt})$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
16.	$\frac{s}{(s-a)(s-b)}$	$\frac{1}{(a-b)}\left(ae^{at}-be^{bt}\right)$
17.	$\frac{1}{(s-a)(s-b)(s-c)}$	$-\frac{(b-c)e^{at}+(c-a)e^{bt}+(a-b)e^{ct}}{(a-b)(b-c)(c-a)}$
18.	$\frac{1}{(s+a)}$	e^{-at} valid for complex a
19.	$\frac{1}{s(s+a)}$	$\frac{1}{a}\left(1-e^{-at}\right)$
20.	$\frac{1}{s^2(s+a)}$	$\frac{1}{a^2}\left(e^{-at}+at-1\right)$
21.	$\frac{1}{s^3(s+a)}$	$\frac{1}{a^2}\left[\frac{1}{a}-t+\frac{at^2}{2}-\frac{1}{a}e^{-at}\right]$
22.	$\frac{1}{(s+a)(s+b)}$	$\frac{1}{(b-a)}\left(e^{-at}-e^{-bt}\right)$
23.	$\frac{1}{s(s+a)(s+b)}$	$\frac{1}{ab}\left[1+\frac{1}{(a-b)}\left(be^{-at}-ae^{-bt}\right)\right]$
24.	$\frac{1}{s^2(s+a)(s+b)}$	$\frac{1}{(ab)^2}\left[\frac{1}{(a-b)}\left(a^2e^{-bt}-b^2e^{-at}\right)+abt-a-b\right]$
25.	$\frac{1}{s^3(s+a)(s+b)}$	$\frac{1}{(ab)}\left[\frac{a^3-b^3}{(ab)^2(a-b)}+\frac{1}{2}t^2-\frac{(a+b)}{ab}t+\frac{1}{(a-b)}\left(\frac{b}{a^2}e^{-at}-\frac{a}{b^2}e^{-bt}\right)\right]$
26.	$\frac{1}{(s+a)(s+b)(s+c)}$	$\frac{1}{(b-a)(c-a)}e^{-at}+\frac{1}{(a-b)(c-b)}e^{-bt}+\frac{1}{(a-c)(b-c)}e^{-ct}$
27.	$\frac{1}{s(s+a)(s+b)(s+c)}$	$\frac{1}{abc}-\frac{1}{a(b-a)(c-a)}e^{-at}-\frac{1}{b(a-b)(c-b)}e^{-bt}-\frac{1}{c(a-c)(b-c)}e^{-ct}$
28.	$\frac{1}{s^2(s+a)(s+b)(s+c)}$	$\begin{cases}\frac{ab(ct-1)-ac-bc}{(abc)^2}+\frac{1}{a^2(b-a)(c-a)}e^{-at}\\ +\frac{1}{b^2(a-b)(c-b)}e^{-bt}+\frac{1}{c^2(a-c)(b-c)}e^{-ct}\end{cases}$
29.	$\frac{1}{s^3(s+a)(s+b)(s+c)}$	$\begin{cases}\frac{1}{(abc)^3}\left[(ab+ac+bc)^2-abc(a+b+c)\right]-\frac{ab+ac+bc}{(abc)^2}t+\frac{1}{2abc}t^2\\ -\frac{1}{a^3(c-a)(c-a)}e^{-at}-\frac{1}{b^3(a-b)(c-b)}e^{-bt}-\frac{1}{c^3(a-c)(b-c)}\varepsilon^{-ct}\end{cases}$
30.	$\frac{1}{s^2+a^2}$	$\frac{1}{a}\sin at$
31.	$\frac{s}{s^2+a^2}$	$\cos at$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
32.	$\frac{1}{s^2-a^2}$	$\frac{1}{a}\sinh at$
33.	$\frac{s}{s^2-a^2}$	$\cosh at$
34.	$\frac{1}{s(s^2+a^2)}$	$\frac{1}{a^2}(1-\cos at)$
35.	$\frac{1}{s^2(s^2+a^2)}$	$\frac{1}{a^3}(at-\sin at)$
36.	$\frac{1}{(s^2+a^2)^2}$	$\frac{1}{2a^3}(\sin at - at\cos at)$
37.	$\frac{1}{(s^2+a^2)^2}$	$\frac{1}{2a}\sin at$
38.	$\frac{s^2}{(s^2+a^2)^2}$	$\frac{1}{2a}(\sin at + at\cos at)$
39.	$\frac{s^2-a^2}{(s^2+a^2)^2}$	$t\cos at$
40.	$\frac{s}{(s^2+a^2)(s^2+b^2)}(a^2 \neq b^2)$	$\frac{\cos at - \cos bt}{b^2-a^2}$
41.	$\frac{1}{(s-a)^2+b^2}$	$\frac{1}{b}e^{at}\sin bt$
42.	$\frac{s-a}{(s-a)^2+b^2}$	$e^{at}\cos bt$
43.	$\frac{1}{[(s+s)^2+b^2]^n}$	$\frac{-e^{-at}}{4^{n-1}b^{2n}}\sum_{r=1}^{n}\binom{2n-r-1}{n-1}(-2t)^{r-1}\frac{d^r}{dt^r}[\cos(bt)]$
44.	$\frac{s}{[(s+a)^2b^2]^n}$	$\left\{\frac{e^{-at}}{4^{n-1}b^{2n}}\sum_{r=1}^{n}\binom{2n-r-1}{n-1}(-2t)^{r-1}\frac{d^r}{dt^r}[a\cos(bt)+b\sin(bt)] - 2b\sum_{r=1}^{n-1}r\binom{2n-r-2}{n-1}(-2t)^{r-1}\frac{d^r}{dt^r}[\sin(bt)]\right\}$
45.	$\frac{3a^2}{s^3+a^3}$	$e^{-at}-e^{(at)/2}\left(\cos\frac{at\sqrt{3}}{2}-\sqrt{3}\sin\frac{at\sqrt{3}}{2}\right)$
46.	$\frac{4a^3}{s^4+4a^4}$	$\sin at\cosh at - \cos at\sinh at$
47.	$\frac{s}{s^4+4a^4}$	$\frac{1}{2a^2}(\sin at \cdot \sinh at)$
48.	$\frac{1}{s^4-a^4}$	$\frac{1}{2a^3}(\sinh at - \sin at)$
49.	$\frac{s}{s^4-a^4}$	$\frac{1}{2a^2}(\cosh at - \cos at)$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
50.	$\frac{8a^3s^2}{(s^2+a^2)^3}$	$(1+a^2t^2)\sin at - \cos at$
51.	$\frac{1}{s}\left(\frac{s-1}{s}\right)^n$	$L_n(t)=\frac{e^t}{n!}\frac{d^n}{dt^n}\left(t^ne^{-t}\right)$ [$L_n(t)$ is the Laguerre polynomial of degree n]
52.	$\frac{1}{(s+a)^n}$	$\frac{t^{(n-1)}e^{-at}}{(n-1)!}$ where n is a positive integer
53.	$\frac{1}{s(s+a)^2}$	$\frac{1}{a^2}\left[1-e^{-at}-ate^{-at}\right]$
54.	$\frac{1}{s^2(s+a)^2}$	$\frac{1}{a^3}\left[at-2+ate^{-at}+2e^{-at}\right]$
55.	$\frac{1}{s(s+a)^3}$	$\frac{1}{a^3}\left[1-\left(\frac{1}{2}a^2t^2+at+1\right)e^{-at}\right]$
56.	$\frac{1}{(s+a)(s+b)^2}$	$\frac{1}{(a-b)^2}\left\{e^{-at}+\left[(a-b)t-1\right]e^{-bt}\right\}$
57.	$\frac{1}{s(s+a)(s+b)^2}$	$\frac{1}{ab^2}-\frac{1}{a(a-b)^2}e^{-at}-\left[\frac{1}{b(a-b)}t+\frac{a-2b}{b^2(a-b)^2}\right]e^{-bt}$
58.	$\frac{1}{s^2(s+a)(s+b)^2}$	$\frac{1}{a^2(a-b)^2}e^{-at}+\frac{1}{ab^2}\left(t-\frac{1}{a}-\frac{2}{b}\right)+\left[\frac{1}{b^2(a-b)}t+\frac{2(a-b)-b}{b^3(a-b)^2}\right]e^{-bt}$
59.	$\frac{1}{(s+a)(s+b)(s+c)^2}$	$\left\{\begin{array}{l}\left[\frac{1}{(c-b)(c-a)}i+\frac{2c-a-b}{(c-a)^2(c-b)^2}\right]e^{-ct}\\ +\frac{1}{(b-a)(c-a)^2}e^{-at}+\frac{1}{(a-b)(c-b)^2}e^{-bt}\end{array}\right.$
60.	$\frac{1}{(s+a)(s^2+\omega^2)}$	$\frac{1}{a^2+\omega^2}e^{-at}+\frac{1}{\omega\sqrt{a^2+\omega^2}}\sin(\omega t-\phi);\ \phi=\tan^{-1}\left(\frac{\omega}{a}\right)$
61.	$\frac{1}{s(s+a)(s^2+\omega^2)}$	$\frac{1}{a\omega^2}-\frac{1}{a^2+\omega^2}\left(\frac{1}{\omega}\sin\omega t+\frac{a}{\omega^2}\cos\omega t+\frac{1}{a}e^{-at}\right)$
62.	$\frac{1}{s^2(s+a)(s^2+\omega^2)}$	$\left\{\begin{array}{l}\frac{1}{a\omega^2}t-\frac{1}{a^2\omega^2}+\frac{1}{a^2(a^2+\omega^2)}e^{-at}\\ +\frac{1}{\omega^3\sqrt{a^2+\omega^2}}\cos(\omega t+\phi);\ \phi=\tan^{-1}\left(\frac{a}{\omega}\right)\end{array}\right.$
63.	$\frac{1}{\left[(s+a)^2+\omega^2\right]^2}$	$\frac{1}{2\omega^3}e^{-at}\left[\sin\omega t-\omega t\cos\omega t\right]$
64.	$\frac{1}{s^2-a^2}$	$\frac{1}{a}\sinh at$
65.	$\frac{1}{s^2(s^2-a^2)}$	$\frac{1}{a^3}\sinh at-\frac{1}{a^2}t$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
66.	$\frac{1}{s^3(s^2-a^2)}$	$\frac{1}{a^4}(\cosh at-1)-\frac{1}{2a^2}t^2$
67.	$\frac{1}{s^3+a^3}$	$\frac{1}{3a^2}\left[e^{-at}-e^{\frac{a}{2}t}\left(\cos\frac{\sqrt{3}}{2}at-\sqrt{3}\sin\frac{\sqrt{3}}{2}at\right)\right]$
68.	$\frac{1}{s^4+4a^4}$	$\frac{1}{4a^3}(\sin at\cosh at-\cos at\sinh at)$
69.	$\frac{1}{s^4-a^4}$	$\frac{1}{2a^3}(\sinh at-\sin at)$
70.	$\frac{1}{\left[(s+a)^2-\omega^2\right]}$	$\frac{1}{\omega}e^{-at}\sinh\omega t$
71.	$\frac{s+a}{s\left[(s+b)^2+\omega^2\right]}$	$\begin{cases}\frac{a}{b^2+\omega^2}-\frac{1}{\omega}+\sqrt{\frac{(a-b)^2+\omega^2}{b^2+\omega^2}}e^{-bt}\sin(\omega t+\phi); \\ \phi=\tan^{-1}\left(\frac{\omega}{b}\right)+\tan^{-1}\left(\frac{\omega}{a-b}\right)\end{cases}$
72.	$\frac{s+a}{s^2\left[(s+b)^2+\omega^2\right]}$	$\begin{cases}\frac{1}{b^2+\omega^2}[1+at]-\frac{2ab}{(b^2+\omega^2)^2}+\frac{\sqrt{(a-b)^2+\omega^2}}{\omega(b^2+\omega^2)}e^{-bt}\sin(\omega t+\phi) \\ \phi=\tan^{-1}\left(\frac{\omega}{a-b}\right)+2\tan^{-1}\left(\frac{\omega}{b}\right)\end{cases}$
73.	$\frac{s+a}{(s+c)\left[(s+b)^2+\omega^2\right]}$	$\begin{cases}\frac{a-c}{(c-b)^2+\omega^2}e^{-ct}+\frac{1}{\omega}\sqrt{\frac{(a-b)^2+\omega^2}{(c-b)^2+\omega^2}}e^{-bt}\sin(\omega t+\phi) \\ \phi=\tan^{-1}\left(\frac{\omega}{a-b}\right)-\tan^{-1}\left(\frac{\omega}{c-b}\right)\end{cases}$
74.	$\frac{s+a}{s(s+c)\left[(s+b)^2+\omega^2\right]}$	$\begin{cases}\frac{a}{c(b^2+\omega^2)}+\frac{(c-a)}{c\left[(b-c)^2+\omega^2\right]}e^{-ct} \\ -\frac{1}{\omega\sqrt{b^2+\omega^2}}\sqrt{\frac{(a-b)^2+\omega^2}{(b-c)^2+\omega^2}}e^{-bt}\sin(\omega t+\phi) \\ \phi=\tan^{-1}\left(\frac{\omega}{b}\right)+\tan^{-1}\left(\frac{\omega}{a-b}\right)-\tan^{-1}\left(\frac{\omega}{c-b}\right)\end{cases}$
75.	$\frac{s+a}{s^2(s+b)^3}$	$\frac{a}{b^3}+\frac{b-3a}{b^4}+\left[\frac{3a-b}{b^4}+\frac{a-b}{2b^2}t^2+\frac{2a-b}{b^3}t\right]e^{-bt}$
76.	$\frac{s+a}{(s+c)(s+b)^3}$	$\frac{a-c}{(b-c)^3}e^{-ct}+\left[\frac{a-b}{2(c-b)}t^2+\frac{c-a}{(c-b)^2}t+\frac{a-c}{(c-b)^3}\right]e^{-bt}$
77.	$\frac{s^2}{(s+a)(s+b)(s+c)}$	$\frac{a^2}{(b-a)(c-a)}e^{-at}+\frac{b^2}{(a-b)(c-b)}e^{-bt}+\frac{c^2}{(a-c)(b-c)}e^{-ct}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
78.	$\dfrac{s^2}{(s+a)(s+b)^2}$	$\dfrac{a^2}{(b-a)^2}e^{-at}+\left[\dfrac{b^2}{(a-b)}t+\dfrac{b^2-2ab}{(a-b)^2}\right]e^{-bt}$
79.	$\dfrac{s^2}{(s+a)^3}$	$\left[2-2at+\dfrac{a^2}{2}t^2\right]e^{-at}$
80.	$\dfrac{s^2}{(s+a)(s^2+\omega^2)}$	$\dfrac{a^2}{(a^2+\omega^2)}e^{-at}-\dfrac{\omega}{\sqrt{a^2+\omega^2}}\sin(\omega t+\phi);\ \phi\tan^{-1}\left(\dfrac{\omega}{a}\right)$
81.	$\dfrac{s^2}{(s+a)^2(s^2+\omega^2)}$	$\begin{cases}\left[\dfrac{a^2}{(a^2+\omega^2)}t-\dfrac{2a\omega^2}{(a^2+\omega^2)^2}\right]e^{-at}-\dfrac{\omega}{(a^2+\omega^2)}\sin(\omega t+\phi); \\ \phi=-2\tan^{-1}\left(\dfrac{\omega}{a}\right)\end{cases}$
82.	$\dfrac{s^2}{(s+a)(s+b)(s^2+\omega^2)}$	$\begin{cases}\dfrac{a^2}{(b-a)(a^2+\omega^2)}e^{-at}+\dfrac{b^2}{(a-b)(b^2+\omega^2)}e^{-bt} \\ -\dfrac{\omega}{\sqrt{(a^2+\omega^2)(b^2+\omega^2)}}\sin(\omega t+\phi);\ \phi=-\left[\tan^{-1}\left(\dfrac{\omega}{a}\right)+\tan^{-1}\left(\dfrac{\omega}{b}\right)\right]\end{cases}$
83.	$\dfrac{s^2}{(s^2+a^2)(s^3+\omega^2)}$	$-\dfrac{a}{(\omega^2-a^2)}\sin(at)-\dfrac{\omega}{(a^2-\omega^2)}\sin(\omega t)$
84.	$\dfrac{s^2}{(s^2+\omega^2)^2}$	$\dfrac{1}{2\omega}(\sin\omega t+\omega t\cos\omega t)$
85.	$\dfrac{s^2}{(s+a)\left[(s+b)^2+\omega^2\right]}$	$\begin{cases}\dfrac{a^2}{(a-b)^2+\omega^2}e^{-at}+\dfrac{1}{\omega}\sqrt{\dfrac{(b^2-\omega^2)^2+4b^2\omega^2}{(a-b)^2+\omega^2}}e^{-bt}\sin(\omega t+\phi) \\ \phi=\tan^{-1}\left(\dfrac{-sb\omega}{b^2-\omega^2}\right)-\tan^{-1}\left(\dfrac{\omega}{a-b}\right)\end{cases}$
86.	$\dfrac{s^2}{(s+a)^2\left[(s+b)^2+\omega^2\right]}$	$\begin{cases}\dfrac{a^2}{(a-b)^2+\omega^2}te^{-at}-2\left[\dfrac{a\left[(b-a)^2+\omega^2\right]+a^2(b-a)}{\left[(b-a)^2+\omega^2\right]^2}\right]e^{-at} \\ +\dfrac{\sqrt{(b^2-\omega^2)^2+4b^2\omega^2}}{\omega\left[(a-b)^2+\omega^2\right]}e^{-bt}\sin(\omega t+\phi) \\ \phi=\tan^{-1}\left(\dfrac{-2b\omega}{b^2-\omega^2}\right)-2\tan^{-1}\left(\dfrac{\omega}{a-b}\right)\end{cases}$
87.	$\dfrac{s^2+a}{s^2(s+b)}$	$\dfrac{b^2+a}{b^2}e^{-bt}+\dfrac{a}{b}t-\dfrac{a}{b^2}$
88.	$\dfrac{s^2+a}{s^3(s+b)}$	$\dfrac{a}{2b}t^2-\dfrac{a}{b^2}t+\dfrac{1}{b^3}\left[b^2+a-(a+b^2)e^{-bt}\right]$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
89.	$\dfrac{s^2+a}{s(s+b)(s+c)}$	$\dfrac{a}{bc}+\dfrac{(b^2+a)}{b(b-c)}e^{-bt}-\dfrac{(c^2+a)}{c(b-c)}e^{-ct}$
90.	$\dfrac{s^2+a}{s^2(s+b)(s+c)}$	$\dfrac{b^2-a}{b^2(c-b)}e^{-bt}+\dfrac{c^2+a}{c^2(b-c)}e^{-ct}+\dfrac{a}{bc}t-\dfrac{a(b+c)}{b^2c^2}$
91.	$\dfrac{s^2+a}{(s+b)(s+c)(s+d)}$	$\dfrac{b^2+a}{(c-b)(d-b)}e^{-bt}+\dfrac{c^2+a}{(b-c)(d-c)}e^{-ct}+\dfrac{d^2+a}{(b-d)(c-d)}e^{-dt}$
92.	$\dfrac{s^2+a}{s(s+b)(s+c)(s+d)}$	$\dfrac{a}{bcd}+\dfrac{b^2+a}{b(b-c)(d-b)}e^{-bt}+\dfrac{c^2a}{c(b-c)(c-d)}e^{-ct}\ \dfrac{d^2+a}{d(b-d)(d-c)}e^{-dt}$
93.	$\dfrac{s^2+a}{s^2(s+b)(s+c)(s+d)}$	$\left\{\begin{aligned}&\dfrac{a}{bcd}t-\dfrac{a}{b^2c^2d^2}(bc+cd+db)+\dfrac{b^2+a}{b^2(b-c)(b-d)}e^{-bt}\\&+\dfrac{c^2+a}{c^2(c-b)(c-d)}e^{-ct}+\dfrac{d^2+a}{d^2(d-b)(d-c)}e^{-dt}\end{aligned}\right.$
94.	$\dfrac{s^2+a}{(s^2+\omega^2)^2}$	$\dfrac{1}{2\omega^3}(a+\omega^2)\sin\omega t-\dfrac{1}{2\omega^2}(a-\omega^2)t\cos\omega t$
95.	$\dfrac{s^2-\omega^2}{(s^2+\omega^2)^2}$	$t\cos\omega t$
96.	$\dfrac{s^2+a}{s(s^2+\omega^2)^2}$	$\dfrac{a}{\omega^4}-\dfrac{(a-\omega^2)}{2\omega^3}t\sin\omega t-\dfrac{a}{\omega^4}\cos\omega t$
97.	$\dfrac{s(s+a)}{(s+b)(s+c)^2}$	$\dfrac{b^2-ab}{(c-b)^2}e^{-bt}+\left[\dfrac{c^2-ac}{b-c}t+\dfrac{c^2-2bc+ab}{(b-c)^2}\right]e^{-ct}$
98.	$\dfrac{s(s+a)}{(s+b)(s+c)(s+d)^2}$	$\left\{\begin{aligned}&\dfrac{b^2-ab}{(c-b)(d-b)^2}e^{-bt}+\dfrac{c^2-ac}{(b-c)(d-c)^2}e^{-ct}+\dfrac{d^2-ad}{(b-d)(c-d)}te^{-dt}\\&+\dfrac{a(bc-d^2)+d(db+dc-2bc)}{(b-d)^2(c-d)^2}e^{-dt}\end{aligned}\right.$
99.	$\dfrac{s^2+a_1s+a_o}{s^2(s+b)}$	$\dfrac{b^2-a_1b+a_o}{b^2}e^{-bt}+\dfrac{a_o}{b}t+\dfrac{a_1b-a_o}{b^2}$
100.	$\dfrac{s^2+a_1s+a_o}{s^3(s+b)}$	$\dfrac{a_1b-b^2-a_o}{b^3}e^{-bt}+\dfrac{a_o}{2b}t^2+\dfrac{a_1b-a_o}{b^2}t+\dfrac{b^2-a_1b+a_o}{b^3}$
101.	$\dfrac{s^2+a_1s+a_o}{s(s+b)(s+c)}$	$\dfrac{a_o}{bc}+\dfrac{b^2-a_1b+a_o}{b(b-c)}e^{-bt}+\dfrac{c^2-a_1c+a_o}{c(c-b)}e^{-ct}$
102.	$\dfrac{s^2+a_1s+a_o}{s^2(s+b)(s+c)}$	$\dfrac{a_o}{bc}t+\dfrac{a_1bc-a_o(b+c)}{b^2c^2}+\dfrac{b^2-a_1b+a_o}{b^2(c-b)}e^{-bt}+\dfrac{c^2-a_1c+a_o}{c^2(b-c)}e^{-ct}$
103.	$\dfrac{s^2+a_1s+a_o}{(s+b)(s+c)(s+d)}$	$\dfrac{b^2-a_1b+a_o}{(c-b)(d-b)}e^{-bt}+\dfrac{c^2-a_1c+a_o}{(b-c)(d-c)}e^{-ct}+\dfrac{d^2-a_1d+a_o}{(b-d)(c-d)}e^{-dt}$
104.	$\dfrac{s^2+a_1s+a_o}{s(s+b)(s+c)(s+d)}$	$\dfrac{a_o}{bcd}-\dfrac{b^2-a_1b+a_o}{b(c-b)(d-b)}e^{-bt}-\dfrac{c^2-a_1c+a_o}{c(b-c)(d-c)}e^{-ct}-\dfrac{d^2-a_1d+a_o}{d(b-d)(c-d)}e^{-dt}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
105.	$\frac{s^2 + a_1 s + a_o}{s(s+b)^2}$	$\frac{a_o}{b^2} - \frac{b^2 - a_1 b + a_o}{b} te^{-bt} + \frac{b^1 - a_o}{b^2} e^{-bt}$
106.	$\frac{s^2 + a_1 s + a_o}{s^2(s+b)^2}$	$\frac{a_o}{b^2} t + \frac{a_1 b - 2a_o}{b^3} + \frac{b^2 - a_1 b + a_o}{b^2} t\varepsilon^{-bt} + \frac{2a_o - a_1 b}{b^3} e^{-bt}$
107.	$\frac{s^2 + a_1 s + a_o}{(s+b)(s+c)^2}$	$\frac{b^2 - a_1 b + a_o}{(c-b)^2} e^{-bt} + \frac{c^2 - a_1 c + a_o}{(b-c)} te^{-ct} + \frac{c^2 - 2bc + a_1 b - a_o}{(b-c)^2} e^{-ct}$
108.	$\frac{s^2}{(s+b)(s+c)(s+d)^2}$	$\begin{cases} \frac{b^3}{(b-c)(d-b)^2} e^{-bt} + \frac{c^3}{(c-b)(d-c)^2} e^{-ct} + \frac{d^3}{(d-b)(c-d)} te^{-dt} \\ \quad + \frac{d^2\left[d^2 - 2d(b+c) + 3bc\right]}{(b-d)^2(c-d)^2} e^{-dt} \end{cases}$
109.	$\frac{s^3}{(s+b)(s+c)(s+d)(s+f)^2}$	$\begin{cases} \frac{b^3}{(b-c)(d-b)(f-b)^2} e^{-bt} + \frac{c^3}{(c-b)(d-c)(f-c)^2} e^{-ct} \\ \quad + \frac{d^2}{(d-b)(c-d)(f-d)^2} e^{-dt} + \frac{f^3}{(f-b)(c-f)(d-f)} te^{-ft} \\ \quad + \left[\frac{3f^2}{(b-f)(c-f)(d-f)} \right. \\ \quad \left. + \frac{f^3\left[(b-f)(c-f) + (b-f)(d-f) + (c-f)(d-f)\right]}{(b-f)^2(c-f)^2(d-f)^2}\right] \varepsilon^{-dt} \end{cases}$
110.	$\frac{s^3}{(s+b)^2(s+c)^2}$	$-\frac{b^3}{(c-b)^2} te^{-bt} + \frac{b^2(3c-b)}{(c-b)^3} e^{-bt} - \frac{c^3}{(b-c)^2} te^{-ct} + \frac{c^2(3b-c)}{(b-c)^3} e^{-ct}$
111.	$\frac{s^3}{(s+d)(s+b)^2(s+c)^2}$	$\begin{cases} -\frac{d^3}{(b-d)^2(c-d)^2} e^{-dt} + \frac{b^3}{(c-b)^3(b-d)} te^{-bt} \\ \quad + \left[\frac{3b^2}{(c-b)^2(d-b)} + \frac{b^3(c+2d-3b)}{(c-b)^3(d-b)^2}\right] e^{-bt} + \frac{c^3}{(b-c)^2(c-d)} te^{-ct} \\ \quad + \left[\frac{3c^2}{(b-c)^2(d-c)} + \frac{c^3(b+2d-3c)}{(b-c)^3(d-c)^2}\right] e^{-ct} \end{cases}$
112.	$\frac{s^3}{(s+b)(s+c)(s^2+\omega^2)}$	$\begin{cases} \frac{b^3}{(b-c)(b^2+\omega^2)} e^{-bt} + \frac{c^3}{(c-b)(c^2+\omega^2)} e^{-ct} \\ \quad - \frac{\omega^2}{\sqrt{(b^2+\omega^2)(c^2+\omega^2)}} \sin(\omega t + \phi) \\ \quad \phi = \tan^{-1}\left(\frac{c}{\omega}\right) - \tan^{-1}\left(\frac{\omega}{b}\right) \end{cases}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
113.	$\dfrac{s^3}{(s+b)(s+c)(s+d)(s^2+\omega^2)}$	$\begin{cases} \dfrac{b^3}{(b-c)(d-b)(b^2+\omega^2)}e^{-bt}+\dfrac{c^3}{(c-d)(d-c)(c^2+\omega^2)}e^{-ct} \\ +\dfrac{d^3}{(d-b)(c-d)(d^2+\omega^2)}e^{-dt} \\ -\dfrac{\omega^2}{\sqrt{(b^2+\omega^2)(c^2+\omega^2)(d^2+\omega^2)}}\cos(\omega t-\phi) \\ \phi=\tan^{-1}\left(\dfrac{\omega}{b}\right)+\tan^{-1}\left(\dfrac{\omega}{c}\right)+\tan^{-1}\left(\dfrac{\omega}{d}\right) \end{cases}$
114.	$\dfrac{s^3}{(s+b)^2(s^2+\omega^2)}$	$\begin{cases} -\dfrac{b^3}{b^2+\omega^2}te^{-bt}+\dfrac{b^2(b^2+3\omega^2)}{(b^2+\omega^2)^2}e^{-bt}-\dfrac{\omega^2}{(b^2+\omega^2)}\sin(\omega t+\phi) \\ \phi=\tan^{-1}\left(\dfrac{b}{\omega}\right)-\tan^{-1}\left(\dfrac{\omega}{b}\right) \end{cases}$
115.	$\dfrac{s^2}{s^4+4\omega^4}$	$\cos(\omega t)\cosh(\omega t)$
116.	$\dfrac{s^3}{s^4-\omega^4}$	$\dfrac{1}{2}[\cosh(\omega t)+\cos(\omega t)]$
117.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{s^2(s+b)(s+c)}$	$\begin{cases} \dfrac{a_o}{bc}t-\dfrac{a_o(b+c)-a_1bc}{b^2c^2}+\dfrac{-b^3+a_2b^2-a_1b+a_o}{b^2(c-b)}e^{-bt} \\ +\dfrac{-c^3+a_2c^2-a_1c+a_o}{c^2(b-c)}e^{-ct} \end{cases}$
118.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{s(s+b)(s+c)(s+d)}$	$\begin{cases} \dfrac{a_o}{bcd}-\dfrac{-b^3+a_2b^2-a_1b+a_o}{b(c-b)(d-b)}e^{-bt}-\dfrac{-c^3+a_2c^2-a_1c+a_o}{c(b-c)(d-c)}e^{-ct} \\ -\dfrac{-d^3+a_2d^2-a_1d+a_o}{d(b-d)(c-d)}e^{-dt} \end{cases}$
119.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{s^2(s+b)(s+c)(s+d)}$	$\begin{cases} \dfrac{a_o}{bcd}t+\left[\dfrac{a_1}{bcd}-\dfrac{a_o(bc+bd+cd)}{b^2c^2d^2}\right]+\dfrac{-b^3+a_2b^2-a_1b+a_o}{b^2(c-b)(d-b)}\varepsilon^{-bt} \\ +\dfrac{-c^3+a_2c^2-a_1c+a_o}{c^2(b-c)(d-c)}e^{-ct}+\dfrac{-d^3+a_2d^2-a_1d+a_o}{d^2(b-d)(c-d)}e^{-dt} \end{cases}$
120.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{(s+b)(s+c)(s+d)(s+f)}$	$\begin{cases} \dfrac{-b^3+a_2b^2-a_1b+a_o}{(c-b)(d-b)(f-b)}e^{-bt}+\dfrac{-c^3+a_2c^2-a_1c+a_o}{(b-c)(d-c)(f-c)}e^{-ct} \\ +\dfrac{-d^3+a_2d^2-a_1d+a_o}{(b-d)(c-d)(f-d)}e^{-dt}+\dfrac{-f^3+a_2f^2-a_1f+a_o}{(b-f)(c-f)(d-f)}e^{-ft} \end{cases}$
121.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{s(s+b)(s+c)(s+d)(s+f)}$	$\begin{cases} \dfrac{a_o}{bcdf}-\dfrac{-b^3+a_2b^2-a_1b+a_o}{b(c-b)(d-b)(f-b)}e^{-bt}-\dfrac{-c^3+a_2c^2-a_1c+a_o}{c(b-c)(d-c)(f-c)}e^{-ct} \\ -\dfrac{d^3+a_2d^2-a_1d+a_o}{d(b-d)(c-d)(f-d)}e^{-dt}-\dfrac{-f^3+a_2f^2-a_1f+a_o}{f(b-f)(c-f)(d-f)}e^{-ft} \end{cases}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
122.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{(s+b)(s+c)(s+d)(s+f)(s+g)}$	$\left\{\begin{aligned} &\frac{-b^3+a_2b^2-a_1b+a_o}{(c-b)(d-b)(f-b)(g-b)}e^{-bt}+\frac{-c^3+a_2c^2-a_1c+a_o}{(b-c)(d-c)(f-c)(g-c)}e^{-ct} \\ &+\frac{-d^3+a_2d^2-a_1d+a_o}{(b-d)(c-d)(f-d)(g-d)}e^{-dt}+\frac{-f^3+a_2f^2-a_1f+a_o}{(b-f)(c-f)(d-f)(g-f)}e^{-ft} \\ &+\frac{-g^3+a_2g^2-a_1g+a_o}{(b-c)(c-g)(d-g)(f-g)}e^{-gt} \end{aligned}\right.$
123.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{(s+b)(s+c)(s+d)^2}$	$\left\{\begin{aligned} &\frac{-b^3+a_2b^2-a_1b+a_o}{(c-b)(d-b)^2}e^{-bt}+\frac{-c^3+a_2c^2-a_1c+a_o}{(b-c)(d-c)^2}e^{-ct} \\ &+\frac{-d^3+a_2d^2-a_1d+a_o}{(b-d)(c-d)}te^{-dt} \\ &+\frac{a_o(2d-b-c)+a_1(bc-d)^2+a_2d(db+dc-2bc)+d^2(d^2-2db-2dc+3bc)}{(b-d)^2(c-d)^2}e^{-dt} \end{aligned}\right.$
124.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{s(s+b)(s+c)(s+d)^2}$	$\left\{\begin{aligned} &\frac{a_o}{bcd^2}-\frac{-b^3+a_2b^2-a_1b+a_o}{b(c-b)(d-b)^2}e^{-bt}-\frac{-c^3+a_2c^2-a_1c+a_o}{c(b-c)(d-c)^2}e^{-ct} \\ &-\frac{-d^3+a_2d^2-a_1d+a_o}{d(b-d)(c-d)}te^{-dt}-\frac{3d^2-2a_2d+a_1}{d(b-d)(c-d)}e^{-dt} \quad z \\ &-\frac{(d^3+a_2d^2-a_1d+a_o)[(b-d)(c-d)-d(b-d)-d(c-d)]}{d^2(b-d)^2(c-d)^2}e^{-dt} \end{aligned}\right.$
125.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{(s+b)(s+c)(s+d)(s+f)^2}$	$\left\{\begin{aligned} &\frac{-b^3+a_2b^2-a_1b+a_o}{(c-b)(d-b)(f-b)^2}e^{-bt}+\frac{-c^3+a_2c^2-a_1c+a_o}{(b-c)(d-c)(f-c)^2}e^{-ct} \\ &+\frac{-d^3+a_2d^2-a_1d+a_o}{(b-d)(c-d)(f-d)^2}e^{-dt}+\frac{-f^3+a_2f^2-a_1f+a_o}{(b-f)(c-f)(d-f)}te^{-ft} \\ &+\frac{3f^2-2a_2f+a_1}{(b-f)(c-f)(d-f)}e^{-ft} \\ &-\frac{(-f^3+a_2f^2-a_1f+a_o)[(b-f)(c-f)+(b-f)(d-f)+(c-f)(d-f)]}{(b-f)^2(c-f)^2(d-f)^2}e^{-ft} \end{aligned}\right.$
126.	$\dfrac{s}{(s-a)^{3/2}}$	$\dfrac{1}{\sqrt{\pi t}}e^{at}(1+2at)$
127.	$\sqrt{s-a}-\sqrt{s-b}$	$\dfrac{1}{2\sqrt{\pi t^3}}\left(e^{bt}-e^{at}\right)$
128.	$\dfrac{1}{\sqrt{s}+a}$	$\dfrac{1}{\sqrt{\pi t}}-ae^{a^2t}erfc\left(a\sqrt{t}\right)$
129.	$\dfrac{\sqrt{s}}{s-a^2}$	$\dfrac{1}{\sqrt{\pi t}}+ae^{a^2t}erf\left(a\sqrt{t}\right)$
130.	$\dfrac{\sqrt{s}}{s+a^2}$	$\dfrac{1}{\sqrt{\pi t}}-\dfrac{2a}{\sqrt{\pi}}e^{-a^2t}\int_0^{a\sqrt{t}}e^{\lambda^2}d\lambda$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
131.	$\frac{1}{\sqrt{s}\left(s-a^2\right)}$	$\frac{1}{a}e^{a^2t}erf\left(a\sqrt{t}\right)$
132.	$\frac{1}{\sqrt{s}\left(s+a^2\right)}$	$\frac{2}{a\sqrt{\pi}}e^{-a^2t}\int_0^{a\sqrt{t}}e^{\lambda^2}d\pi$
133.	$\frac{b^2-a^2}{\left(s-a^2\right)\left(b+\sqrt{s}\right)}$	$e^{a^2t}\left[b-a\,erf\left(a\sqrt{t}\right)\right]-be^{b^2t}erfc\left(b\sqrt{t}\right)$
134.	$\frac{1}{\sqrt{s}\left(\sqrt{s}+a\right)}$	$e^{a^2t}erfc\left(a\sqrt{t}\right)$
135.	$\frac{1}{(s+a)\sqrt{s+b}}$	$\frac{1}{\sqrt{b-a}}e^{-at}erf\left(\sqrt{b-a}\sqrt{t}\right)$
136.	$\frac{b^2-a^2}{\sqrt{s}\left(s-a^2\right)\left(\sqrt{s}+b\right)}$	$e^{a^2t}\left[\frac{b}{a}erf\left(a\sqrt{t}\right)-1\right]+e^{b^2t}erfc\left(b\sqrt{t}\right)$
137.	$\frac{(1-s)^n}{s^{n+(1/2)}}$	$\begin{cases}\frac{n!}{(2n)!\sqrt{nt}}H_{2n}\left(\sqrt{t}\right)\\ \left[H_n(t)=\text{Hermite polynomial}=e^{x^2}\frac{d^n}{dx^n}\left(e^{-x^2}\right)\right]\end{cases}$
138.	$\frac{(1-s)^n}{s^{n+(3/2)}}$	$-\frac{n!}{\sqrt{\pi}(2n+1)!}H_{2n+1}\left(\sqrt{t}\right)$
139.	$\frac{\sqrt{s+2a}}{\sqrt{s}}-1$	$\begin{cases}ae^{-at}\left[I_1(at)+I_o(at)\right]\\ \left[I_n(t)=j^{-n}J_n(jt)\text{ where }J_n\text{ is Bessel's function of the first kind}\right]\end{cases}$
140.	$\frac{1}{\sqrt{s+a}\sqrt{s+b}}$	$e^{-(1/2)(a+b)t}I_o\left(\frac{a-b}{2}t\right)$
141.	$\frac{\Gamma(k)}{(s+a)^k(s+b)^k}\quad(k\geq 0)$	$\sqrt{\pi}\left(\frac{t}{a-b}\right)^{k-(1/2)}e^{-(1/2)(a+b)t}I_{k-(1/2)}\left(\frac{a-b}{2}t\right)$
142.	$\frac{1}{(s+a)^{1/2}(s+b)^{3/2}}$	$te^{-(1/2)(a+b)t}\left[I_o\left(\frac{a=b}{2}t\right)+I_1\left(\frac{a-b}{2}t\right)\right]$
143.	$\frac{\sqrt{s+2a}-\sqrt{s}}{\sqrt{s+2a}+\sqrt{s}}$	$\frac{1}{t}e^{-at}I_1(at)$
144.	$\frac{(a-b)^k}{\left(\sqrt{s+a}+\sqrt{s+b}\right)^{2k}}\quad(k>0)$	$\frac{k}{t}e^{-(1/2)(a+b)t}I_k\left(\frac{a-b}{2}t\right)$
145.	$\frac{\left(\sqrt{s+a}+\sqrt{s}\right)^{-2v}}{\sqrt{s}\sqrt{s+a}}$	$\frac{1}{a^v}e^{-(1/2)(at)}I_v\left(\frac{1}{2}at\right)$
146.	$\frac{1}{\sqrt{s^2+a^2}}$	$J_o(at)$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
147.	$\dfrac{\left(\sqrt{s^2+a^2}-s\right)^{\nu}}{\sqrt{s^2+a^2}} \quad (\nu>-1)$	$a^{\nu}J_{\nu}(at)$
148.	$\dfrac{1}{\left(s^2+a^2\right)^k} \quad (k>0)$	$\dfrac{\sqrt{\pi}}{\Gamma(k)}\left(\dfrac{t}{2a}\right)^{k-(1/2)} J_{k-(1/2)}(at)$
149.	$\left(\sqrt{s^2+a^3}-s\right)^{\mathbf{k}} \quad (k>0)$	$\dfrac{ka^k}{t}J_k(at)$
150.	$\dfrac{\left(s-\sqrt{s^2-a^2}\right)^{\nu}}{\sqrt{s^2-a^2}} \quad (\nu>-1)$	$a^{\nu}I_{\nu}(at)$
151.	$\dfrac{1}{\left(s^2-a^2\right)^k} \quad (k>0)$	$\dfrac{\sqrt{\pi}}{\Gamma(k)}\left(\dfrac{t}{2a}\right)^{k-(1/2)} I_{k-(1/2)}(at)$
152.	$\dfrac{1}{s\sqrt{s+1}}$	$erf\left(\sqrt{t}\right); erf(y) \overset{\Delta}{=}$ the error function $= \dfrac{2}{\sqrt{\pi}}\int_o^y e^{-u^2}du$
153.	$\dfrac{1}{\sqrt{s^2+a^2}}$	$J_a(at)$; Bessel function of 1st kind, zero order
154.	$\dfrac{1}{\sqrt{s^2+a^2}+s}$	$\dfrac{J_1(at)}{at}$; J_1 is the Bessel function of 1st kind, 1st order
155.	$\dfrac{1}{\left[\sqrt{s^2+a^2}+s\right]^N}$	$\dfrac{N}{a^N}\dfrac{J_N(at)}{t}$; $N = 1,2,3,\cdots$, J_N is the Bessel function of 1st kind, Nth order
156.	$\dfrac{1}{s\left[\sqrt{s^2+a^2}+s\right]^N}$	$\dfrac{N}{a^N}\int_o^t \dfrac{J_N(au)}{u}du$; $N = 1,2,3,\cdots$, J_N is the Bessel function of 1st kind, Nth order
157.	$\dfrac{1}{\sqrt{s^2+a^2}\left(\sqrt{s^2+a^2}+s\right)}$	$\dfrac{1}{a}J_1(at)$; J_1 is the Bessel function of lst kind, lst order
158.	$\dfrac{1}{\sqrt{s^2+a^2}\left[\sqrt{s^2+a^2}+s\right]^N}$	$\dfrac{1}{a^N}J_N(at)$; $N = 1,2,3,\cdots$, J_N is the Bessel function of lst kind, Nth order
159.	$\dfrac{1}{\sqrt{s^2-a^2}}$	$I_o(at)$; I_o is the modified Bessel function of 1st kind, zero order
160.	$\dfrac{e^{-ks}}{s}$	$S_k(t) = \begin{cases} 0 & when\ 0<t<k \\ 1 & when\ t>k \end{cases}$
161.	$\dfrac{e^{-ks}}{s^2}$	$\begin{cases} 0 & when\ 0<t<k \\ t-k & when\ t>k \end{cases}$
162.	$\dfrac{e^{-ks}}{s^{\mu}} \quad (\mu>0)$	$\begin{cases} 0 & when\ 0<t<k \\ \dfrac{(t-k)^{\mu-1}}{\Gamma(\mu)} & when\ t>k \end{cases}$
163.	$\dfrac{1-e^{-ks}}{s}$	$\begin{cases} 1 & when\ 0<t<k \\ 0 & when\ t>k \end{cases}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
164.	$\frac{1}{s(1-e^{-ks})} = \frac{1+\coth\frac{1}{2}ks}{2s}$	$S(k,t) = \begin{cases} n & \text{when} \\ & (n-1)k < t < n \quad k(n=1,2,\cdots) \end{cases}$
165.	$\frac{1}{s(e^{+ks}-a)}$	$S_k(t) = \begin{cases} 0 \quad \text{when } 0 < t < k \\ 1+a+a^2+\cdots+a^{n-1} \\ \text{when } nk < t < (n+k)k(n=1,2,\cdots) \end{cases}$
166.	$\frac{1}{s}\tanh ks$	$\begin{cases} M(2k,t) = (-1)^{n-1} \\ \quad \text{when } 2k(n-1) < t < 2nk \\ \quad (n=1,2,\cdots) \end{cases}$
167.	$\frac{1}{s(1+e^{-ks})}$	$\begin{cases} \frac{1}{2}M(k,t)+\frac{1}{2} = \frac{1-(1-1)^n}{2} \\ \quad \text{when } (n-1)k < t < nk \end{cases}$
168.	$\frac{1}{s^2}\tanh ks$	$\begin{cases} H(2k,t) \quad [H(2k,t) = k+(r-k)(-1)^n \quad \text{where } t = 2kn+r; \\ \quad 0 \le r \le 2k; n = 0,1,2,\cdots] \end{cases}$
169.	$\frac{1}{s\sinh ks}$	$\begin{cases} 2S(sk,t+k)-2 = 2(n-1) \\ \quad \text{when } (2n-3)k < t < (2n-1)k(t>0) \end{cases}$
170.	$\frac{1}{s\cosh ks}$	$\begin{cases} M(2k,t+3k)+1 = 1+(-1)^n \\ \quad \text{when } (2n-3)k < t < (2n-1)k(t>0) \end{cases}$
171.	$\frac{1}{s}\coth ks$	$\begin{cases} 2S(2k,t)-1 = 2n-1 \\ \quad \text{when } 2k(n+1) < t < 2kn \end{cases}$
172.	$\frac{k}{s^2+k^2}\coth\frac{\pi s}{2k}$	$\|\sin kt\|$
173.	$\frac{1}{(s^2+1)(1-e^{-\pi s})}$	$\begin{cases} \sin t & \text{when } (2n-2)\pi < t < (2n-1)\pi \\ 0 & \text{when } (2n-1)\pi < t < 2n\pi \end{cases}$
174.	$\frac{1}{s}e^{-k/s}$	$J_o(2\sqrt{kt})$
175.	$\frac{1}{\sqrt{s}}e^{-k/s}$	$\frac{1}{\sqrt{\pi t}}\cos 2\sqrt{kt}$
176.	$\frac{1}{\sqrt{s}}e^{k/s}$	$\frac{1}{\sqrt{\pi t}}\cosh 2\sqrt{kt}$
177.	$\frac{1}{s^{3/2}}e^{-k/s}$	$\frac{1}{\sqrt{\pi k}}\sin 2\sqrt{kt}$
178.	$\frac{1}{s^{3/2}}e^{k/s}$	$\frac{1}{\sqrt{\pi k}}\sinh 2\sqrt{kt}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
179.	$\frac{1}{s^{\mu}}e^{-k/s} \quad (\mu > 0)$	$\left(\frac{t}{k}\right)^{(\mu-1)/2} J_{\mu-1}\left(2\sqrt{kt}\right)$
180.	$\frac{1}{s^{\mu}}e^{k/s} \quad (\mu > 0)$	$\left(\frac{t}{k}\right)^{(\mu-1)/2} I_{\mu-1}\left(2\sqrt{kt}\right)$
181.	$e^{-k\sqrt{s}} \quad (k > 0)$	$\frac{k}{2\sqrt{\pi t^3}}\exp\left(-\frac{k^2}{4t}\right)$
182.	$\frac{1}{s}e^{-k\sqrt{s}} \quad (k \geq 0)$	$erfc\left(\frac{k}{2\sqrt{t}}\right)$
183.	$\frac{1}{\sqrt{s}}e^{-k\sqrt{s}} \quad (k \geq 0)$	$\frac{1}{\sqrt{\pi t}}\exp\left(-\frac{k^2}{4t}\right)$
184.	$s^{-3/2}e^{-k\sqrt{s}} \quad (k \geq 0)$	$2\sqrt{\frac{1}{\pi}}\exp\left(-\frac{k^2}{4t}\right) - k\, erfc\left(\frac{k}{2\sqrt{t}}\right)$
185.	$\frac{ae^{-k\sqrt{s}}}{s\left(a+\sqrt{s}\right)} \quad (k \geq 0)$	$-e^{ak}e^{a^2 t}\, erfc\left(a\sqrt{t} + \frac{k}{2\sqrt{t}}\right) + erfc\left(\frac{k}{2\sqrt{t}}\right)$
186.	$\frac{e^{-k\sqrt{s}}}{\sqrt{s}\left(a+\sqrt{s}\right)} \quad (k \geq 0)$	$e^{ak}e^{a^2 t}\, erfc\left(a\sqrt{t} + \frac{k}{2\sqrt{t}}\right)$
187.	$\frac{e^{-k\sqrt{s(s+a)}}}{\sqrt{s(s+a)}}$	$\begin{cases} 0 & \text{when } 0 < t < k \\ e^{-(1/2)at} I_o\left(\frac{1}{2}a\sqrt{t^2-k^2}\right) & \text{when } t > k \end{cases}$
188.	$\frac{e^{-k\sqrt{s^2+a^2}}}{\sqrt{\left(s^2+a^2\right)}}$	$\begin{cases} 0 & \text{when } 0 < t < k \\ J_o\left(a\sqrt{t^2-k^2}\right) & \text{when } t > k \end{cases}$
189.	$\frac{e^{-k\sqrt{s^2-a^2}}}{\sqrt{\left(s^2-a^2\right)}}$	$\begin{cases} 0 & \text{when } 0 < t < k \\ I_o\left(a\sqrt{t^2-k^2}\right) & \text{when } t > k \end{cases}$
190.	$\frac{e^{-k\left(\sqrt{s^2+a^2}-s\right)}}{\sqrt{\left(s^2+a^2\right)}} \quad (k \geq 0)$	$J_o\left(a\sqrt{t^2+2kt}\right)$
191.	$e^{-ks} - e^{-k\sqrt{s^2+a^2}}$	$\begin{cases} 0 & \text{when } 0 < t < k \\ \frac{ak}{\sqrt{t^2-k^2}} J_1\left(a\sqrt{t^2-k^2}\right) & \text{when } t > k \end{cases}$
192.	$e^{-k\sqrt{s^2+a^2}} - e^{-ks}$	$\begin{cases} 0 & \text{when } 0 < t < k \\ \frac{ak}{\sqrt{t^2-k^2}} I_1\left(a\sqrt{t^2-k^2}\right) & \text{when } t > k \end{cases}$
193.	$\frac{a^{\nu}e^{-k\sqrt{s^2-a^2}}}{\sqrt{\left(s^2+a^2\right)}\left(\sqrt{s^2+a^2}+s\right)^{\nu}} \quad (\nu > -1)$	$\begin{cases} 0 & \text{when } 0 < t < k \\ \left(\frac{t-k}{t+k}\right)^{(1/2)\nu} J_{\nu}\left(a\sqrt{t^2-k^2}\right) & \text{when } t > k \end{cases}$
194.	$\frac{1}{s}\log s$	$\Gamma'(1) - \log t \; [\Gamma'(1) = -0.5772]$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
195.	$\frac{1}{s^k}\log s \quad (k>0)$	$t^{k-1}\left\{\frac{\Gamma'(k)}{[\Gamma(k)]^2}\frac{\log t}{\Gamma(k)}\right\}$
196.	$\frac{\log s}{s-a} \quad (a>0)$	$e^{at}[\log a - \mathrm{Ei}(-at)]$
197.	$\frac{\log s}{s^2+1}$	$\cos t\ \mathrm{Si}(t) - \sin t\ \mathrm{Ci}(t)$
198.	$\frac{s\log s}{s+1}$	$-\sin t\ \mathrm{Si}(t) - \mathrm{cost}\ t\ \mathrm{Ci}(t)$
199.	$\frac{1}{s}\log(1+ks) \quad (k>0)$	$-\mathrm{Ei}\left(-\frac{t}{k}\right)$
200.	$\log\frac{s-a}{s-b}$	$\frac{1}{t}\left(e^{bt}-e^{at}\right)$
201.	$\frac{1}{s}\log(1+k^2s^2)$	$-2\mathrm{Ci}\left(\frac{t}{k}\right)$
202.	$\frac{1}{s}\log(s^2+a^2) \quad (a>0)$	$2\log a - 2\mathrm{Ci}(at)$
203.	$\frac{1}{s^2}\log(s^2+a^2) \quad (a>0)$	$\frac{2}{a}\left[at\log a + \sin at - at\ \mathrm{Ci}(at)\right]$
204.	$\log\frac{s^2+a^2}{s^2}$	$\frac{2}{t}(1-\cos at)$
205.	$\log\frac{s^2-a^2}{s^2}$	$\frac{2}{t}(1-\cosh at)$
206.	$\arctan\frac{k}{s}$	$\frac{1}{t}\sin kt$
207.	$\frac{1}{s}\arctan\frac{k}{s}$	$\mathrm{Si}(kt)$
208.	$e^{k^2s^2}\mathit{erfc}(ks) \quad (k>0)$	$\frac{1}{k\sqrt{\pi}}\exp\left(-\frac{t^2}{4k^2}\right)$
209.	$\frac{1}{s}e^{k^2s^2}\mathit{erfc}(ks) \quad (k>0)$	$\mathit{erf}\left(\frac{t}{2k}\right)$
210.	$e^{ks}\mathit{erfc}\left(\sqrt{ks}\right) \quad (k>0)$	$\frac{\sqrt{k}}{\pi\sqrt{t(t+k)}}$
211.	$\frac{1}{\sqrt{s}}\mathit{erfc}\left(\sqrt{ks}\right)$	$\begin{cases}0 & \text{when } 0<t<k\\ (\pi t)^{-1/2} & \text{when } t>k\end{cases}$
212.	$\frac{1}{\sqrt{s}}e^{ks}\mathit{erfc}\left(\sqrt{ks}\right) \quad (k>0)$	$\frac{1}{\sqrt{\pi(t+k)}}$
213.	$\mathit{erf}\left(\frac{k}{\sqrt{s}}\right)$	$\frac{1}{\pi t}\sin\left(2k\sqrt{t}\right)$
214.	$\frac{1}{\sqrt{s}}e^{k^2/s}\mathit{erfc}\left(\frac{k}{\sqrt{s}}\right)$	$\frac{1}{\sqrt{\pi t}}e^{-2k\sqrt{t}}$

Table of Laplace Transforms (continued)

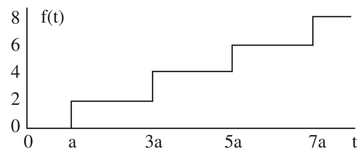
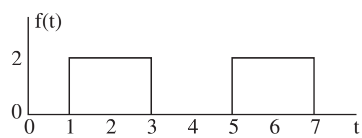
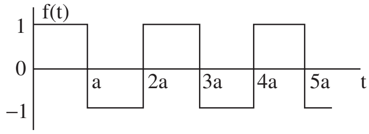
	$F(s)$	$f(t)$
215.	$-e^{as}\mathrm{Ei}(-as)$	$\frac{1}{t+a}$; $(a>0)$
216.	$\frac{1}{a}+se^{as}Ei(-as)$	$\frac{1}{(t+a)^2}$; $(a>0)$
217.	$\left[\frac{\pi}{2}-\mathrm{Si}(s)\right]\cos s+\mathrm{Ci}(s)\sin s$	$\frac{1}{t^2+1}$
218.	$K_o(ks)$	$\begin{cases} 0 & \text{when } 0<t<k \\ (t^2-k^2)^{-1/2} & \text{when } t>k \end{cases}$ $[K_n(t)$ is Bessel function of the second kind of imaginary argument$]$
219.	$K_o(k\sqrt{s})$	$\frac{1}{2t}\exp\left(-\frac{k^2}{4t}\right)$
220.	$\frac{1}{s}e^{ks}K_1(ks)$	$\frac{1}{k}\sqrt{t(t+2k)}$
221.	$\frac{1}{\sqrt{s}}K_1(k\sqrt{s})$	$\frac{1}{k}\exp\left(-\frac{k^2}{4t}\right)$
222.	$\frac{1}{\sqrt{s}}e^{k/s}K_o\left(\frac{k}{s}\right)$	$\frac{2}{\sqrt{\pi t}}K_o\left(2\sqrt{2kt}\right)$
223.	$\pi e^{-ks}I_o(ks)$	$\begin{cases} [t(2k-t)]^{-1/2} & \text{when } 0<t<2k \\ 0 & \text{when } t>2k \end{cases}$
224.	$e^{-ks}I_1(ks)$	$\begin{cases} \frac{k-t}{\pi k\sqrt{t(2k-t)}} & \text{when } 0<t<2k \\ 0 & \text{when } t>2k \end{cases}$
225.	$\frac{1}{s\sinh(as)}$	$2\sum_{k=0}^{\infty} u\,[t-(2k+1)a]$ 
226.	$\frac{1}{s\cosh s}$	$2\sum_{k=0}^{\infty}(-1)^k u\,(t-2k-1)$ 

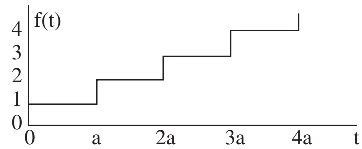
Table of Laplace Transforms (continued)

	F(*s*)	*f*(*t*)
227.	$\frac{1}{s}\tanh\left(\frac{as}{2}\right)$	$u(t)+2\sum_{k=1}^{\infty}(-1)^k u(t-ak)$ square wave
228.	$\frac{1}{2s}\left(1+\coth\frac{as}{2}\right)$	$\sum_{k=0}^{\infty} u(t-ak)$ stepped function
229.	$\frac{m}{s^2}-\frac{ma}{2s}\left(\coth\frac{as}{2}-1\right)$	$mt-ma\sum_{k=1}^{\infty} u(t-ka)$ saw – tooth function
230.	$\frac{1}{s^2}\tanh\left(\frac{as}{2}\right)$	$\frac{1}{a}\left[t+2\sum_{k=1}^{\infty}(-1)^k(t-ka)\,.\,u(t-ka)\right]$ triangular wave

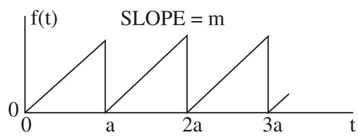
227. square wave



228. stepped function



229. saw – tooth function



230. triangular wave

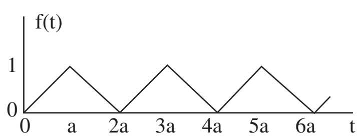


Table of Laplace Transforms (continued)

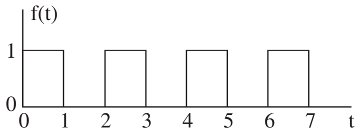
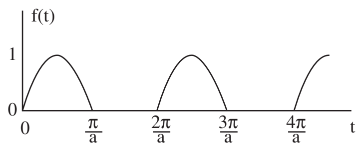
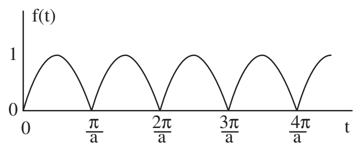
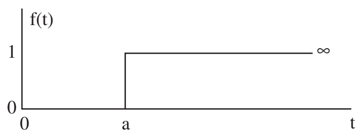
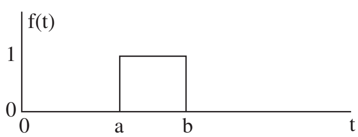
	$F(s)$	$f(t)$
231.	$\dfrac{1}{s\left(1+e^{-s}\right)}$	$\sum_{k=0}^{\infty}(-1)^k u\,(t-k)$ 
232.	$\dfrac{a}{\left(s^2+a^2\right)\left(1-e^{-\frac{\pi}{a}s}\right)}$	$\sum_{k=0}^{\infty}\left[\sin a\left(t-k\,\dfrac{\pi}{a}\right)\right].\,u\left(t-k\,\dfrac{\pi}{a}\right)$ half – wave rectification of sine wave 
233.	$\left[\dfrac{a}{\left(s^2+a^2\right)}\right]\coth\left(\dfrac{\pi s}{2a}\right)$	$[\sin\ (at)]\cdot u\,(t)+2\sum_{k=1}^{\infty}\left[\sin a\left(t-k\,\dfrac{\pi}{a}\right)\right]\cdot u\left(t-k\dfrac{\pi}{a}\right)$ full – wave rectification of sine wave 
234.	$\dfrac{1}{s}e^{-as}$	$u\,(t-a)$ 
235.	$\dfrac{1}{s}\left(e^{-as}-e^{-bs}\right)$	$u\,(t-a)-u\,(t-b)$ 

Table of Laplace Transforms (continued)

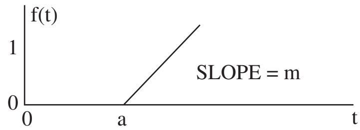
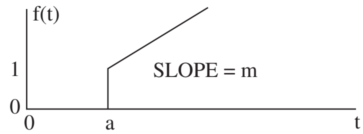
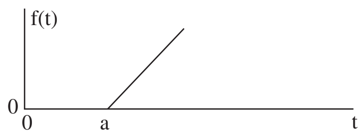
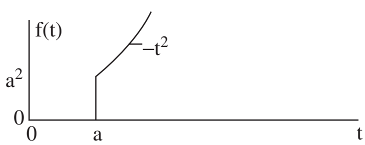
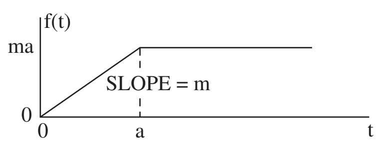
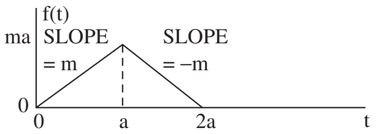
	$F(s)$	$f(t)$
236.	$\frac{m}{s^2}e^{-as}$	$m \cdot (t-a) \cdot u\,(t-a)$ 
237.	$\left[\frac{ma}{s}+\frac{m}{s^2}\right]e^{-as}$	$mt \cdot u(t-a)$ or $[ma + m\,(t-a)] \cdot u(t-a)$ 
238.	$\frac{2}{s^3}e^{-as}$	$(t-a)^2 \cdot u(t-a)$ 
239.	$\left[\frac{2}{s^3}+\frac{2a}{s^2}+\frac{a^2}{s}\right]e^{-as}$	$t^2 \cdot u(t-a)$ 
240.	$\frac{m}{s^2}-\frac{m}{s^2}e^{-as}$	$mt \cdot u(t) - m(t-a) \cdot u(t-a)$ 

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$

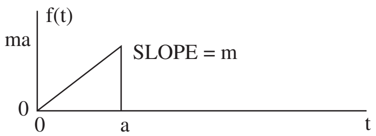
241. $\frac{m}{s^2} - \frac{2m}{s^2}e^{-as} + \frac{m}{s^2}e^{-2as}$

$mt - 2m(t-a) \cdot u(t-a) + m(t-2a) \cdot u(t-2a)$



242. $\frac{m}{s^2} - \left(\frac{ma}{s} + \frac{m}{s^2}\right)e^{-as}$

$mt - [ma + m(t-a)] \cdot u(t-a)$

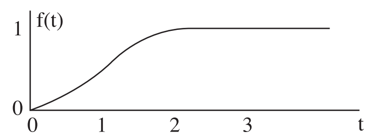


243. $\frac{\left(1-e^{-s}\right)^2}{s^3}$

$0.5t^2$ for $0 \le t < 1$

$1 - 0.5(t-2)^2$ for $0 \le t < 2$

1 for $2 \le t$



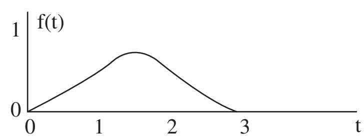
244. $\left[\frac{\left(1-e^{-s}\right)}{s}\right]^3$

$0.5t^2$ for $0 \le t < 1$

$0.75 - (t-1.5)^2$ for $1 \le t < 2$

$0.5(t-3)^2$ for $2 \le t < 3$

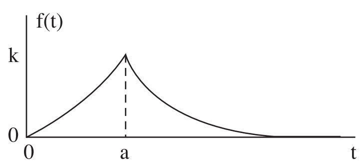
0 for $3 < t$



245. $\frac{b}{s(s-b)} + \left(e^{ba}-1\right)\left[\frac{1}{s+b} - \frac{s+\frac{b}{e^{ba}-1}}{s(s-b)}\right]e^{-as}$

$(e^{bt}-1) \cdot u(t) - (e^{bt}-1) \cdot u(t-a) + Ke^{-b(t-a)} \cdot u(t-a)$

where $K = (e^{ba}-1)$



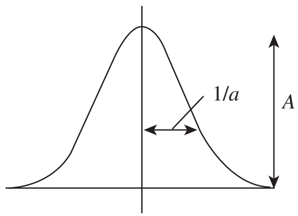
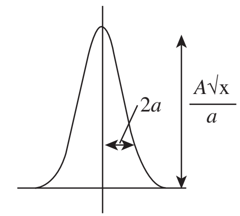
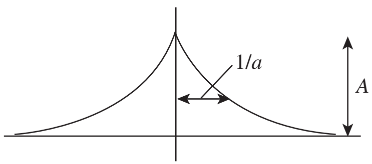
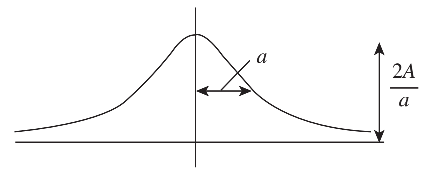
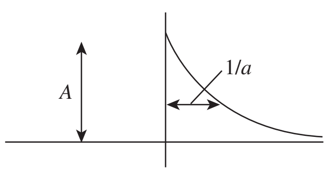
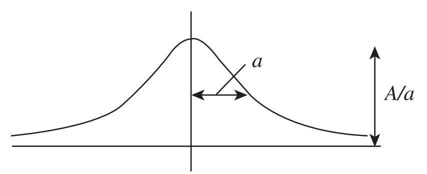
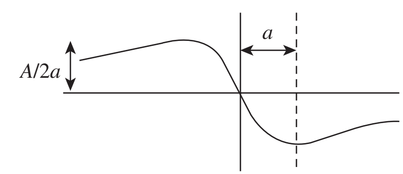
From Poularikas, A., Laplace transforms, in *The Handbook of Formulas and Tables for Signal Processing*, CRC Press, Boca Raton, FL, 1999, pp. **2**-7 to **2**-23.

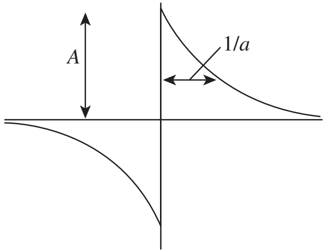
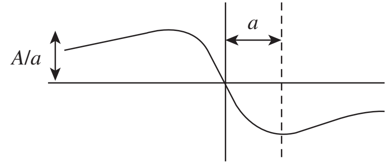
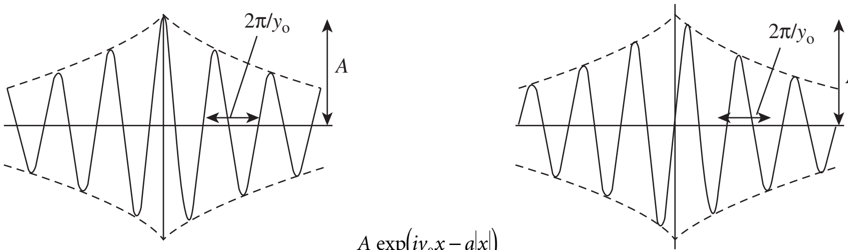
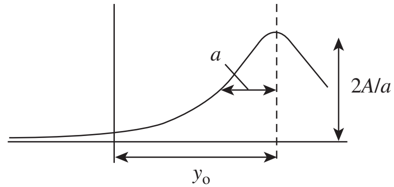
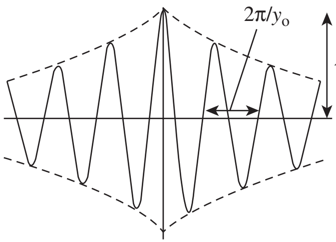
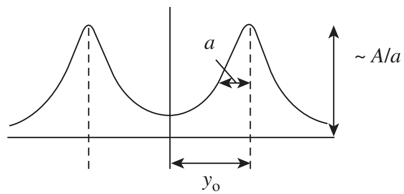
Properties of Fourier Transform

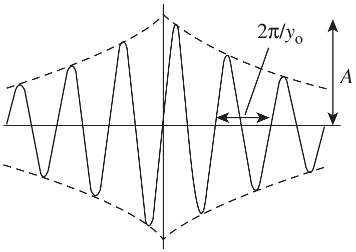
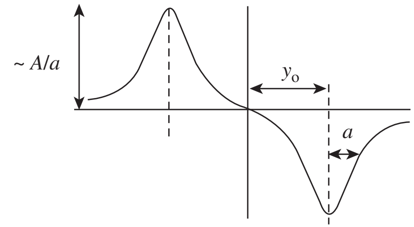
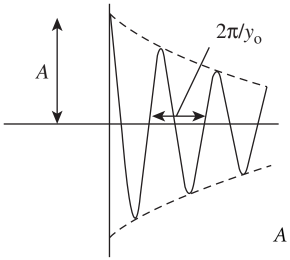
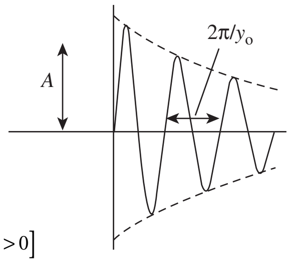
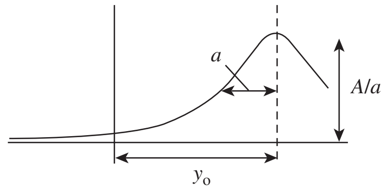
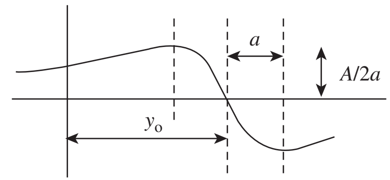
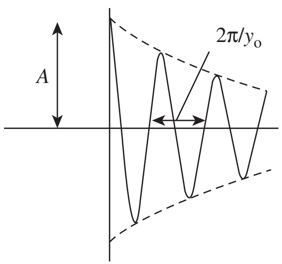
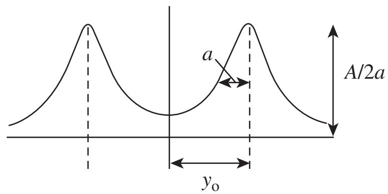
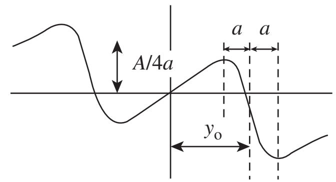
	Operation	$f(t)$	$F(\omega)$
1.	Transform-direct	$f(t)$	$\int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt$
2.	Inverse transform	$\frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{j\omega t}d\omega$	$F(\omega)$
3.	Linearity	$af_1(t) + bf_2(t)$	$aF_1(\omega) + bF_2(\omega)$
4.	Symmetry	$F(t)$	$2\pi f(-\omega)$
5.	Time shifting	$f(t \pm t_o)$	$e^{\pm j\omega t_o}F(\omega)$
6.	Scaling	$f(at)$	$\frac{1}{\lvert a\rvert}F\left(\frac{\omega}{a}\right)$
7.	Frequency shifting	$e^{\pm j\omega_o t}f(t)$	$F(\omega \mp \omega_o)$
8.	Modulation	$\begin{cases} f(t)\cos\omega_o t \\ f(t)\sin\omega_o t \end{cases}$	$\frac{1}{2}\left[F(\omega+\omega_o)+F(\omega-\omega_o)\right]$ $\frac{1}{2j}\left[F(\omega-\omega_o)-F(\omega+\omega_o)\right]$
9.	Time differentiation	$\frac{d^n}{dt^n}f(t)$	$(j\omega)^n F(\omega)$
10.	Time convolution	$f(t)*h(t)=\int_{-\infty}^{\infty} f(\tau)h(t-\tau)d\tau$	$F(\omega)\ H(\omega)$
11.	Frequency convolution	$f(t)\ h(t)$	$\frac{1}{2\pi}F(\omega)*H(\omega)=\frac{1}{2\pi}\int_{-\infty}^{\infty} F(\tau)H(\omega-\tau)d\tau$
12.	Autocorrelation	$f(t)\star f^*(t)=\int_{-\infty}^{\infty} f(\tau)f^*(\tau-t)d\tau$	$F(\omega)\ F^*(\omega) = \lvert F(\omega)\rvert^2$
13.	Parseval's formula	$E=\int_{-\infty}^{\infty}\lvert f(t)\rvert^2 dt$	$E=\frac{1}{2\pi}\int_{-\infty}^{\infty}\lvert F(\omega)\rvert^2 d\omega$
14.	Moments formula	$m_n=\int_{-\infty}^{\infty} t^n f(t)dt=\frac{F^{(n)}(0)}{(-j)^n}$ where	$F^{(n)}(0)=\left.\frac{d^n F(\omega)}{d\omega^n}\right\rvert_{\omega=0},\quad n=0,1,2\cdots$
15.	Frequency differentiation	$\begin{cases} (-jt)f(t) \\ (-jt)^n f(t) \end{cases}$	$\frac{dF(\omega)}{d\omega}$ $\frac{d^n F(\omega)}{d\omega^n}$
16.	Time reversal	$f(-t)$	$F(-\omega)$
17.	Conjugate function	$f^*(t)$	$F^*(-\omega)$
18.	Integral ($F(0) = 0$)	$\int_{-\infty}^{t} f(t)dt$	$\frac{1}{j\omega}F(\omega)$
19.	Integral ($F(0) \neq 0$)	$\int_{-\infty}^{t} f(t)dt$	$\frac{1}{j\omega}F(\omega)+\pi F(0)\delta(\omega)$

From Poularikas, A., Fourier transformation, in *The Handbook of Formulas and Tables for Signal Processing*, CRC Press, Boca Raton, FL, 1999, pp. **3**-3.

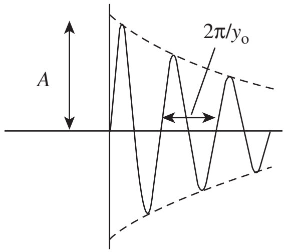
Table of Fourier Transforms ($x = t$, $y = w$)

$f(x)$ $\left[f(x) = (1/2\pi)\int_{-\infty}^{+\infty} F(y)e^{+lxy}\mathrm{dy}\right]$	$F(y)$ $\left[F(y) = \int_{-\infty}^{+\infty} f(x)e^{-txy}\mathrm{dx}\right]$
 $A\exp\left(-a^2x^2\right)$ [Gaussian]	 $\frac{A\sqrt{\pi}}{a}\exp\left(-y^2/4a^2\right)$ [Gaussian]
 $A\exp\left(-a\lvert x\rvert\right)$	 $\frac{2A}{a}\,\frac{a^2}{a^2+y^2}$ [Lorentzian]
 $A\exp(-ax)$ $[x > 0]$ 0 $[x < 0]$	  $A\left\{\frac{a-iy}{a^2+y^2}\right\}$

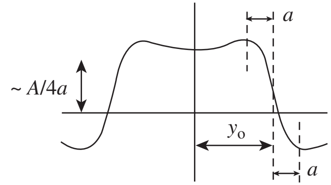
$f(x)$	$F(y)$
 $A\exp(-ax) \quad [x>0]$ $-A\exp(-a\lvert x\rvert) \quad [x<0]$	 $-2iA\dfrac{y}{a^2+y^2}$
 $A\exp(iy_0x - a\lvert x\rvert)$	 $\dfrac{2A}{a}\dfrac{a^2}{a^2+(y-y_0)^2}$
 $A\cos y_0x\exp(-a\lvert x\rvert)$	 $\dfrac{A}{a}\left\{\dfrac{a^2}{a^2+(y-y_0)^2}+\dfrac{a^2}{a^2+(y+y_0)^2}\right\}$ $=\dfrac{A}{a}\left\{\dfrac{2a^2(a^2+y_0{}^2+y^2)}{(a^2+y_0^2-y^2)^2+4a^2y^2}\right\}$

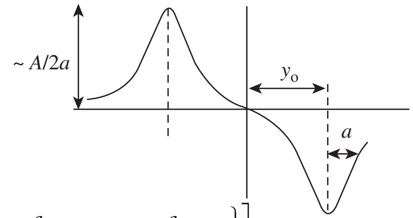
$f(x)$	$F(y)$
 $A \sin y_0 x \exp(-a\lvert x\rvert)$	$\frac{iA}{a}\left\{\frac{a^2}{a^2+(y+y_0)^2}-\frac{a^2}{a^2+(y-y_0)^2}\right\}$ $=\frac{iA}{a}\left\{\frac{-4a^2 y y_0}{(a^2+y_0^2-y^2)^2+4a^2y^2}\right\}$ 
  $A \exp(iy_0 x - ax)$ $[x>0]$; 0 $[x<0]$	  $A\left\{\frac{a+i(y_0-y)}{a^2+(y_0-y)^2}\right\}=A\left\{\frac{1}{a+i(y-y_0)}\right\}$
 $A \cos y_0 x \exp(-ax)$ $[x>0]$; 0 $[x<0]$	  $\frac{A}{2}\left[\left\{\frac{a}{a^2+(y+y_0)^2}+\frac{a}{a^2+(y-y_0)^2}\right\}+i\left\{\frac{y_0-y}{a^2+(y_0-y)^2}-\frac{y_0+y}{a^2+(y_0+y)^2}\right\}\right]$ $=A\left\{\frac{a(a^2+y_0^2+y^2)-iy(a^2+y^2-y_0^2)}{(a^2+y_0^2-y^2)^2+4a^2y^2}\right\}$

$f(x)$	$F(y)$

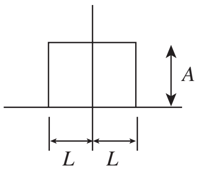


$$A \sin y_0 x \exp(-ax) \quad [x > 0]$$
$$0 \quad [x < 0]$$

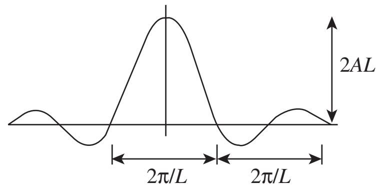




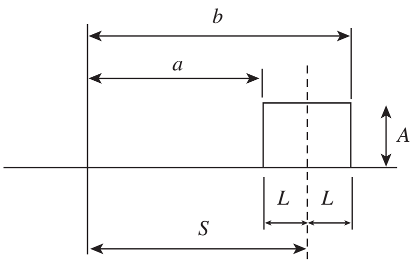
$$\frac{A}{2}\left[\left\{\frac{y_0 - y}{a^2 + (y_0 - y)^2} + \frac{y_0 + y}{a^2 + (y_0 + y)^2}\right\} + i\left\{\frac{a}{a^2 + (y_0 + y)^2} - \frac{a}{a^2 + (y_0 - y)^2}\right\}\right]$$
$$= Ay_0\left\{\frac{1}{(a^2 + y_0^{\,2} - y^2) + i2ay}\right\}$$



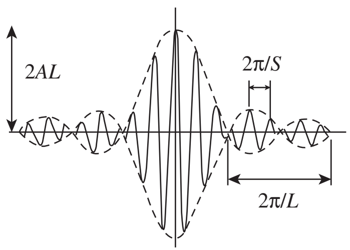
$$A \quad [|x| < L]$$
$$0 \quad [|x| > L]$$

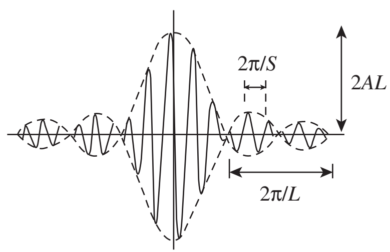


$$2A\frac{\sin Ly}{y}$$



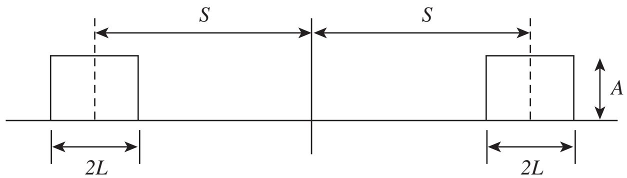
$$A \quad [a < x < b]$$
$$0 \quad [x < a;\ x > b]$$



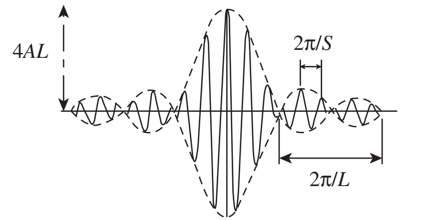


$$2A\frac{\sin Ly}{y}\exp(-iSy) = A\left[\frac{(\sin by - \sin ay) - i(\cos ay - \cos by)}{y}\right]$$
$$= 2A\left[\frac{(\sin Ly \cos Sy) - i(\sin Ly \sin Sy)}{y}\right] = \frac{iA}{y}\left[\exp(-iby) - \exp(-iay)\right]$$

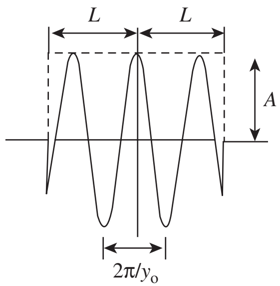
$f(x)$	$F(y)$

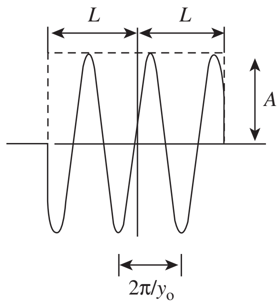


$$f(x) = \begin{cases} A & [(S-L) < |x| < (S+L)] \\ 0 & [\text{otherwise}] \end{cases}$$

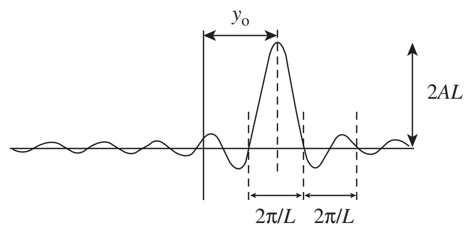


$$4A\frac{\cos Sy \sin Ly}{y}$$

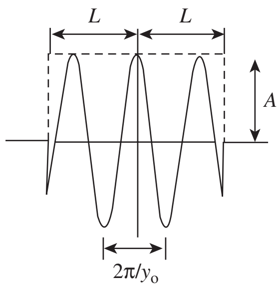




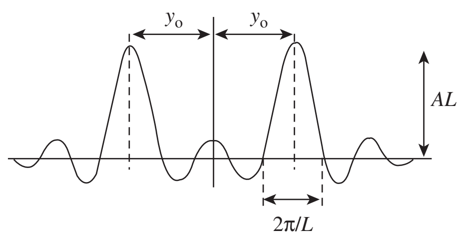
$$f(x) = \begin{cases} A\exp(iy_0 x) & [|x| < L] \\ 0 & [|x| > L] \end{cases}$$



$$2A\frac{\sin\{L(y_0 - y)\}}{(y_0 - y)}$$

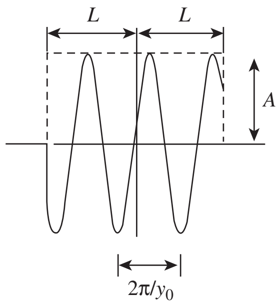


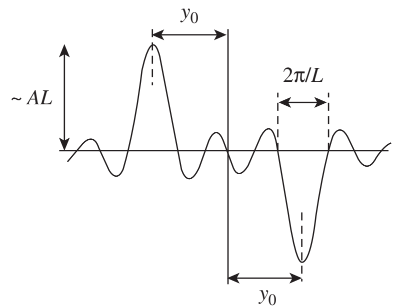
$$f(x) = \begin{cases} A\cos y_0 x & [|x| < L] \\ 0 & [|x| > L] \end{cases}$$

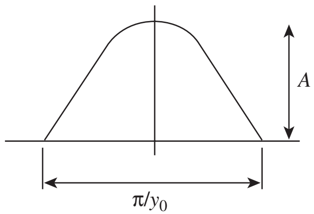


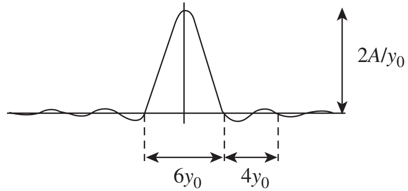
$$A\left[\frac{\sin L(y - y_0)}{(y - y_0)} + \frac{\sin L(y + y_0)}{(y + y_0)}\right]$$

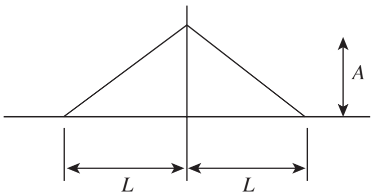
$f(x)$	$F(y)$
$A \sin y_0 x \quad [\lvert x\rvert < L]$; $0 \quad [\lvert x\rvert > L]$	$iA\left\{\dfrac{\sin L(y+y_0)}{(y+y_0)} - \dfrac{\sin L(y-y_0)}{(y-y_0)}\right\}$
$A \cos y_0 x \quad [\lvert x\rvert < (\pi/2y_0)]$; $0 \quad [\lvert x\rvert > (\pi/2y_0)]$	$2A\left(\dfrac{y_0}{y_0^2 - y^2}\right)\cos\left(\dfrac{\pi y}{2y_0}\right)$
$A\left(1 - \dfrac{\lvert x\rvert}{L}\right) \quad [\lvert x\rvert < L]$; $0 \quad [\lvert x\rvert > L]$	$AL\left(\dfrac{\sin(Ly/2)}{(Ly/2)}\right)^2$











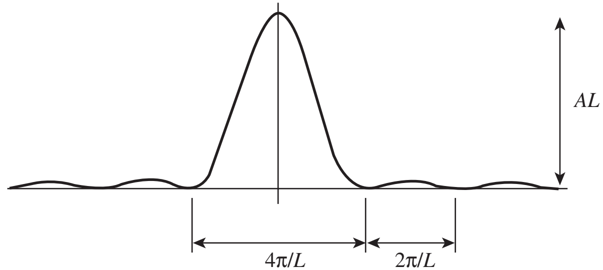
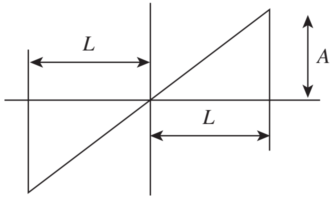
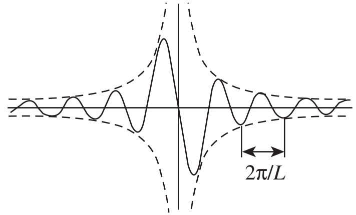
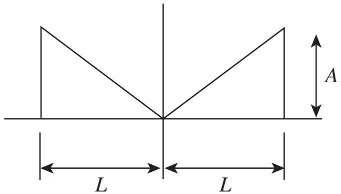
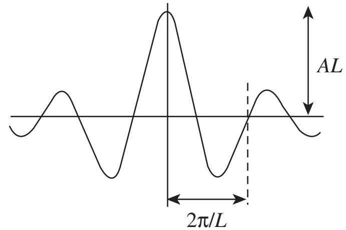
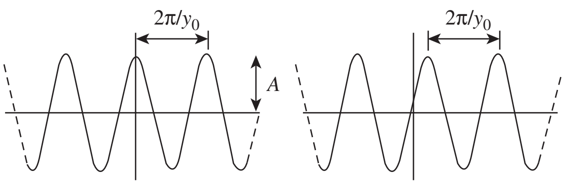
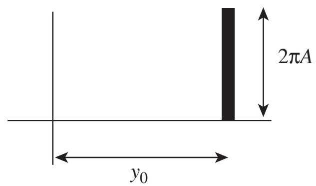


Table of Fourier Transforms ($x = t$, $y = w$) (continued)

$f(x)$	$F(y)$
	
$\frac{Ax}{L}\ \ [\lvert x\rvert < L]$ $0\ \ [\lvert x\rvert > L]$	$\frac{2iA}{y}\left(\cos Ly - \frac{\sin Ly}{Ly}\right)$
	
$\frac{A\lvert x\rvert}{L}\ \ [\lvert x\rvert < L]$ $0\ \ [\lvert x\rvert > L]$	$2AL\left\{\frac{\sin Ly}{Ly} - 2\left(\frac{\sin(Ly/2)}{Ly}\right)^2\right\}$
	
$A\exp(iy_0x)$	$2xA\delta(y-y_0)$

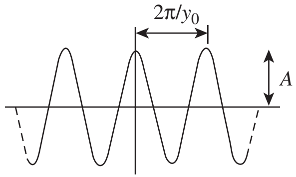
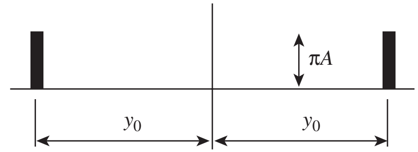
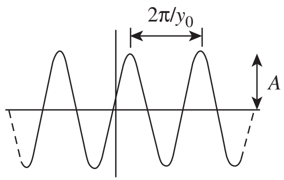
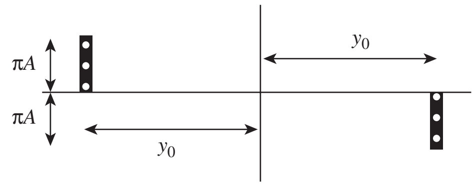
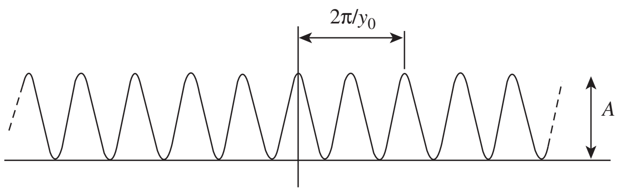
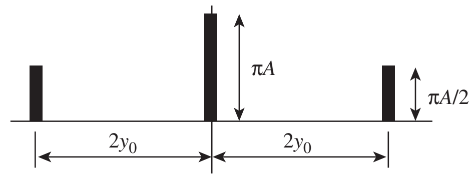
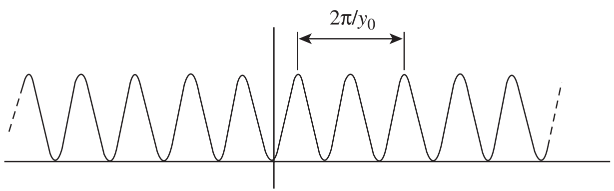
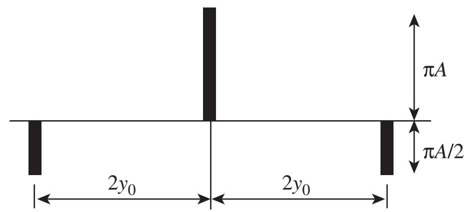
$f(x)$	$F(y)$
 $A\cos y_0 x$	 $xA\{\delta(y-y_0)+\delta(y+y_0)\}$
 $A\sin y_0 x$	 $\pi iA\{\delta(y+y_0)-\delta(y-y_0)\}$
 $A\sin^2 y_0 x$	 $\pi A\{-\tfrac{1}{2}\delta(y+2y_0)+\delta(y)+\tfrac{1}{2}\delta(y-2y_0)\}$
 $A\sin^2 y_0 x$	 $\pi A\{-\tfrac{1}{2}\delta(y+2y_0)+\delta(y)-\tfrac{1}{2}\delta(y-2y_0)\}$

Table of Fourier Transforms ($x = t$, $y = w$) (continued)

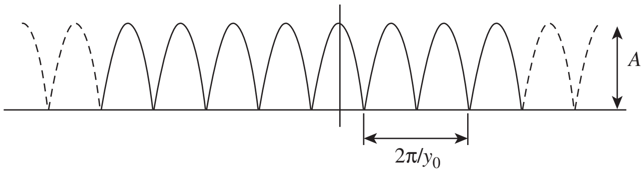
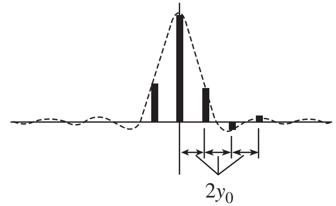
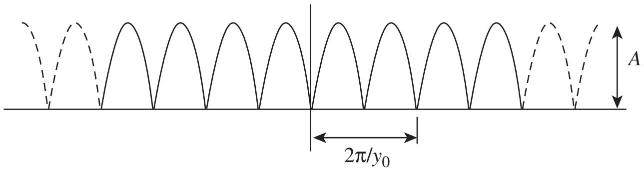
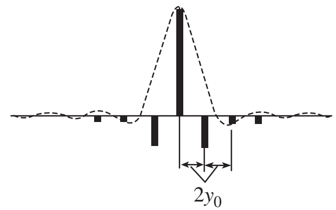
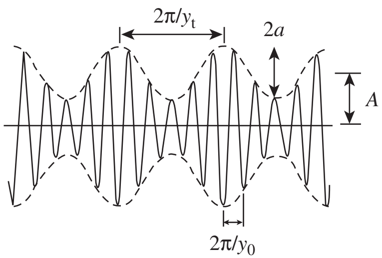
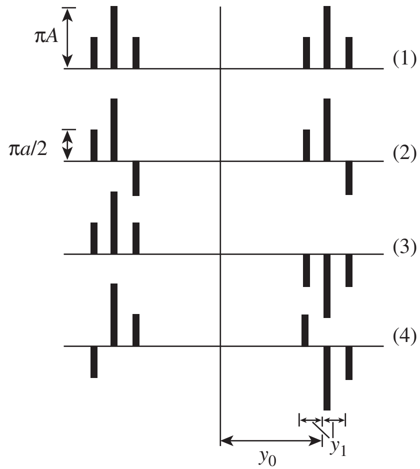
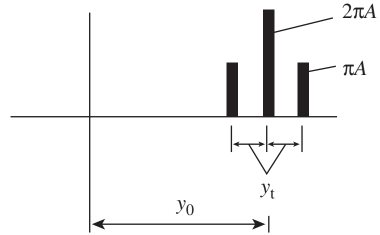
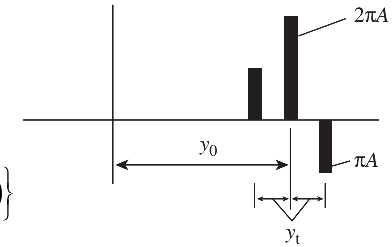
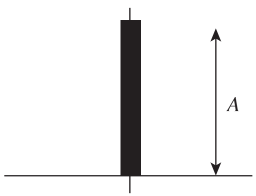
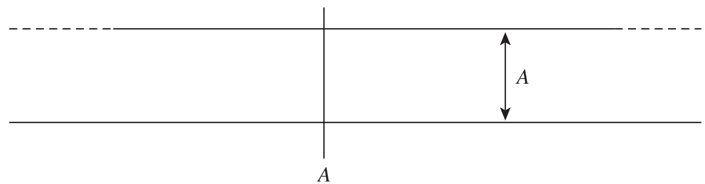
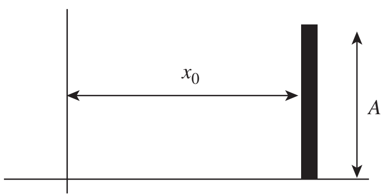
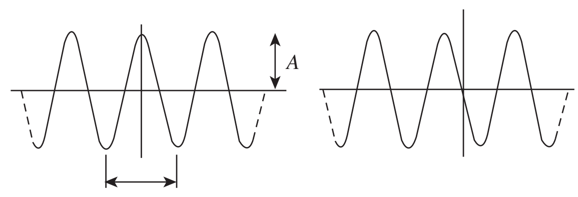
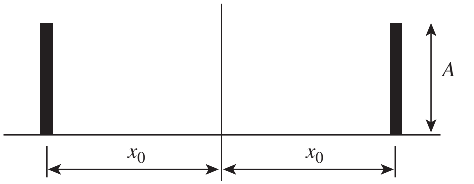
$f(x)$	$F(y)$
 $A\lvert\cos y_0 x\rvert$	$\sum_{n^{\pi y}-\infty}^{n^{\pi y}+\infty} 4A\left(\frac{y_0^2}{y_0^2-y^2}\right)\cos\left(\frac{xy}{2y_0}\right)\delta(y-2\pi y_0)$ $[n=0, \pm 1, \pm 2, \ldots]$ 
 $A[\sin y_0 x]$	$\sum_{n^{\pi y}-\infty}^{n^{\pi y}+\infty} (-1)^a 4A\left(\frac{y_0^2}{y_0^2-y^2}\right)\cos\left(\frac{xy}{2y_0}\right)\delta(y-2\pi y_0)$ $[n=0, \pm 1, \pm 2, \ldots]$ 
 $\cos y_0 x[A + a\cos y_1 x]\ldots(1)$ $\cos y_0 x[A + a\sin y_1 x]\ldots(2)$ $\sin y_0 x[A + a\cos y_1 x]\ldots(3)$ $\sin y_0 x[A + a\sin y_1 x]\ldots(4)$	 $F(y)$ consists of delta functions as shown

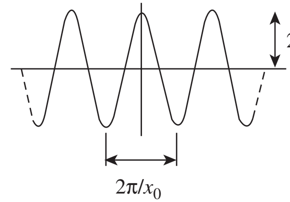
Table of Fourier Transforms ($x = t$, $y = w$) (continued)

$f(x)$	$F(y)$
$\exp(iy_0x)\,(A + a\cos y_1x)$	$2\pi\left\{A\delta(y-y_0)+\frac{a}{2}\delta(y-y_0+y_1)+\frac{a}{2}\delta(y-y_0-y_1)\right\}$ 
$\exp(iy_0x)\,(A + a\sin y_1x)$	$2\pi\left\{A\delta(y-y_0)+\frac{ia}{2}\delta(y-y_0+y_1)-\frac{ia}{2}\delta(y-y_0-y_1)\right\}$ 
 $A\delta(x)$	
 $A\delta(x-x_0)$	 $A\exp(-ix_0y)$

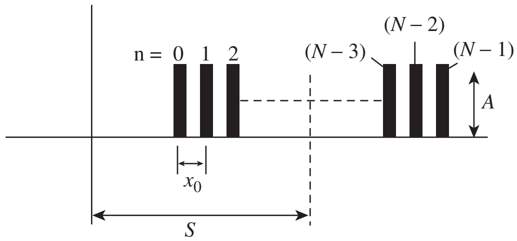
$f(x)$	$F(y)$



$A\{\delta(x - x_0) + \delta(x + x_0)\}$

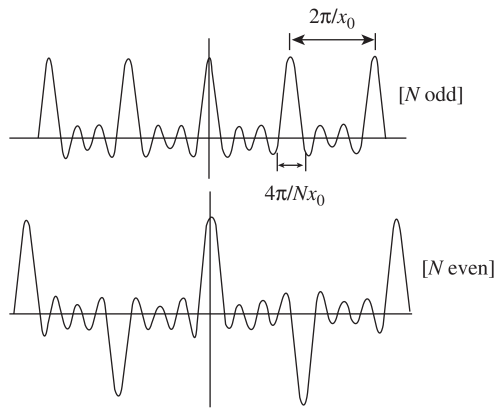


$2A \cos x_0 y$

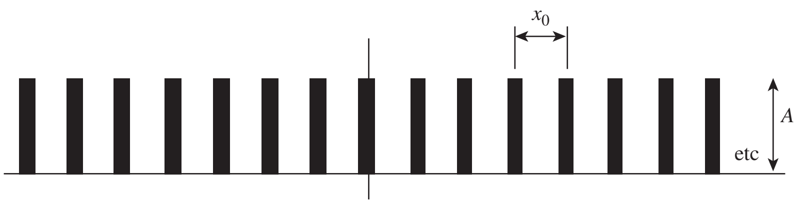


$$\sum_{n=0}^{N-1} A\delta\left\{x - nx_0 - S + \frac{(N-1)x_0}{2}\right\}$$

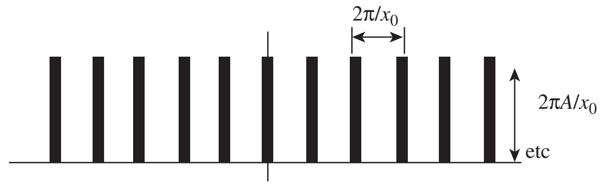
Set of N delta functions symmetrically placed about $x = S$.



$$A\frac{\sin(Nyx_0/2)}{\sin(yx_0/2)}\exp(-iSy)\ [\text{Drawn for } S = 0;\ N = 7 \text{ and } N = 8]$$

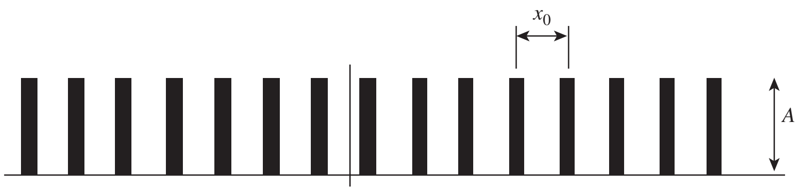


$$\sum_{n^{x_0}-\infty}^{+\infty} A\delta(x - nx_0)$$

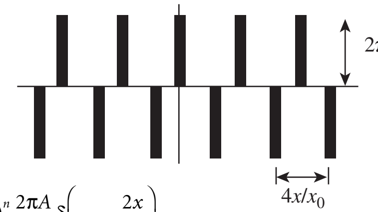


$$\sum_{n^{x_0}-\infty}^{+\infty} \frac{2\pi A}{x_0}\delta\left(y - n\frac{2\pi}{x_0}\right)$$

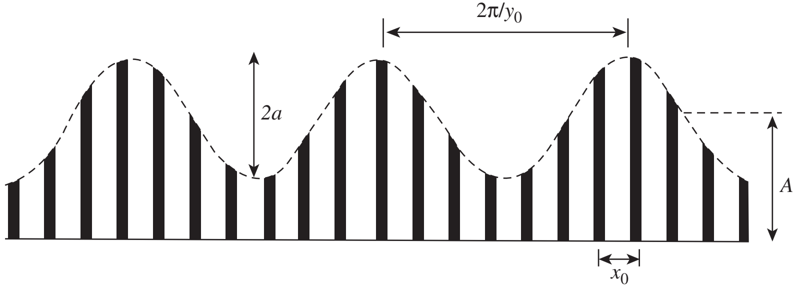
$f(x)$	$F(y)$



$$\sum_{n^{x_0}-\infty}^{+\infty} A\delta\left(x-\frac{x_0}{2}-nx_0\right)$$



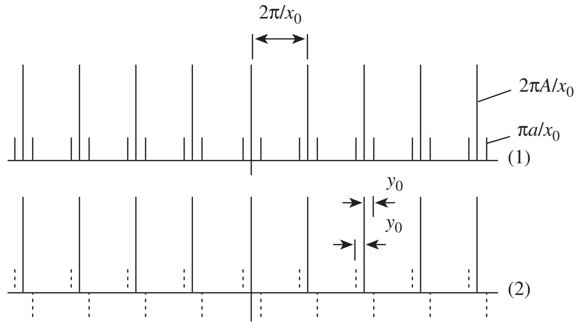
$$\sum_{n^{x_0}-\infty}^{+\infty} (-1)^n \frac{2\pi A}{x_0}\delta\left(y-n\frac{2x}{x_0}\right)$$



$$\sum \delta(x-nx_0)\{A+a\cos y_0x\} \quad (1)$$

$$\sum \delta(x-nx_0)\{A+a\sin y_0x\} \quad (2)$$

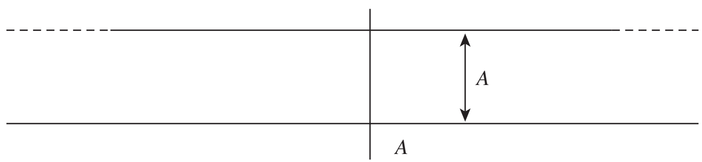
$$[n=0,\ \pm1, \pm2, \ldots]$$



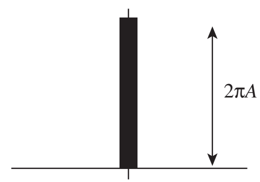
$$\sum_n \frac{2\pi}{x_0}\left\{A\delta\left(y-n\frac{2\pi}{x_0}\right)+\frac{a}{2}\delta\left(y-n\frac{2\pi}{x_0}+y_0\right)+\frac{a}{2}\delta\left(y-\frac{2\pi}{x_0}-y_0\right)\right\}$$

$$\sum_n \frac{2\pi}{x_0}\left\{A\delta\left(y-n\frac{2\pi}{x_0}\right)+\frac{ia}{2}\delta\left(y-n\frac{2\pi}{x_0}+y_0\right)-\frac{ia}{2}\delta\left(y-n\frac{2\pi}{x_0}-y_0\right)\right\}$$

$$[n=0, \pm1, \pm2, \ldots]$$

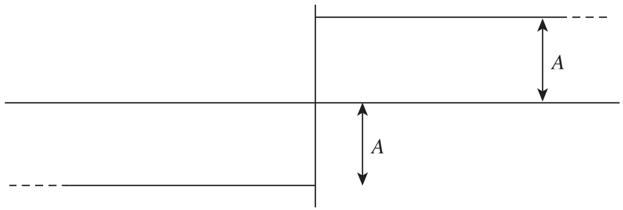
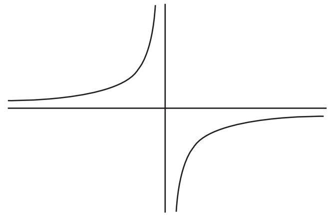
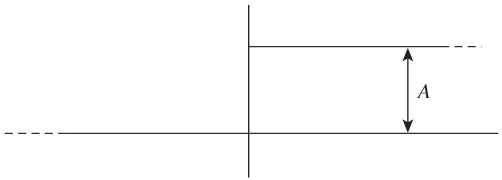
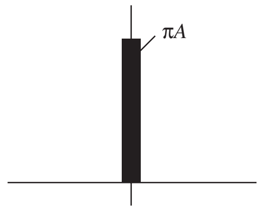
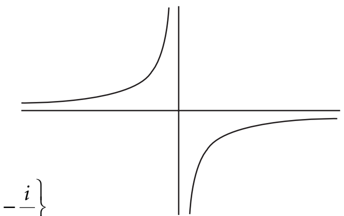
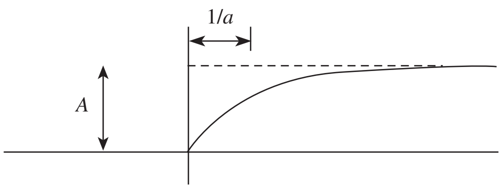
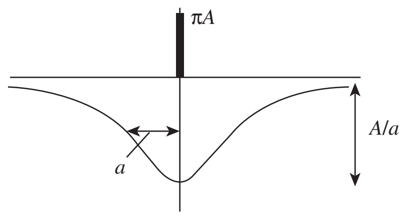
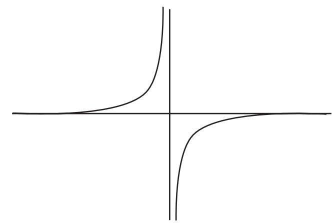


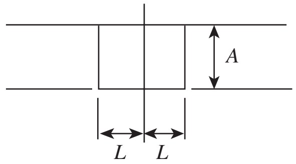
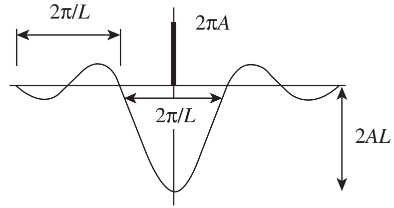
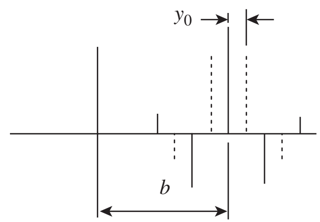
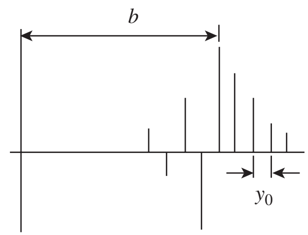
A



$2\pi A\delta(y)$

Table of Fourier Transforms ($x = t$, $y = w$) (continued)

$f(x)$	$F(y)$
 $+A \quad [x>0]$ $-A \quad [x<0]$ $\quad [f(x) = A\,\mathrm{sgn}(x)]$	 $-2iA\dfrac{1}{y}$
 $A \quad [x>0]$ $0 \quad [x<0]$ $\quad [f(x) = AU(x)]$	 $A\left\{\pi\delta(y) - \dfrac{i}{y}\right\}$
 $A\{1-\exp(-ax)\} \quad [x>0]$ $0 \quad [x<0]$	 $\pi A\delta(y) - A\left\{\dfrac{a}{a^2+y^2} + i\dfrac{a^2}{y(a^2+y^2)}\right\}$

$f(x)$	$F(y)$
 $A \quad [\lvert x \rvert > L]$ $0 \quad [\lvert x \rvert < L]$	 $2\pi A\delta(y) - 2A\frac{\sin Ly}{y}$
$A \exp\{i(a \cos y_0 x + bx)\}$	 $2\pi A \sum_{n=-\infty}^{+\infty} (i)^n J_n(a)\delta(y - b - ny_0)$
$A \exp\{i(a \sin y_0 x + bx)\}$	 $2\pi A \sum_{n=-\infty}^{+\infty} J_n(a)\delta(y - b - ny_0)$

Note: $J_n(-a) = J_{-n}(a) = (-1)^n J_n(a)$.

Table of Fourier Transforms ($x = t$, $y = w$) (continued)

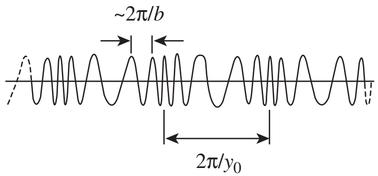
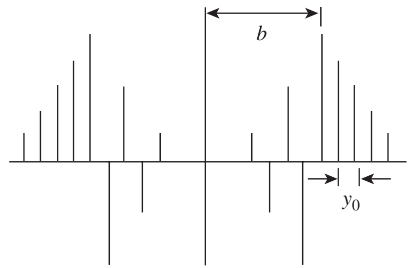
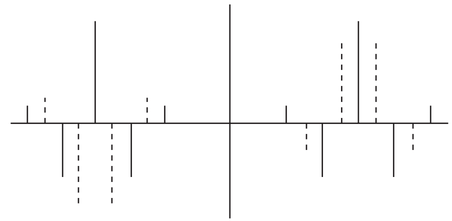
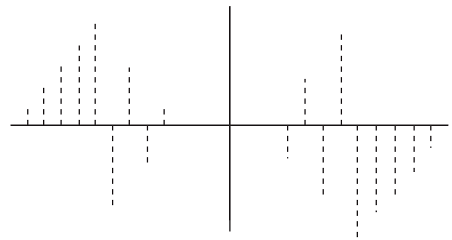
$f(x)$	$F(y)$
 $A\cos\left(a\sin y_0 x + bx\right)$	 $\pi A\sum_{n=-\infty}^{+\infty}\left\{J_n(a)\delta\left(y-b-ny_0\right)+J_n(a)\delta\left(y+b+ny_0\right)\right\}$
$A\cos\left(a\cos y_0 x + bx\right)$	 $\pi A\sum_{n=-\infty}^{+\infty}\left\{(+i)^n J_n(a)\delta\left(y-b-ny_0\right)+(-i)^n J_n(a)\delta\left(y+b+ny_0\right)\right\}$
$A\sin\left(a\sin y_0 x + bx\right)$	 $i\pi A\sum_{n=-\infty}^{+\infty}\left\{-J_n(a)\delta\left(y-b-ny_0\right)+J_n(a)\delta\left(y+b+ny_0\right)\right\}$

Table of Fourier Transforms ($x = t$, $y = w$) (continued)

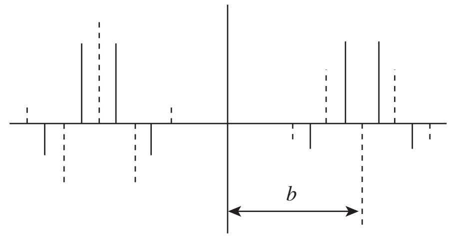
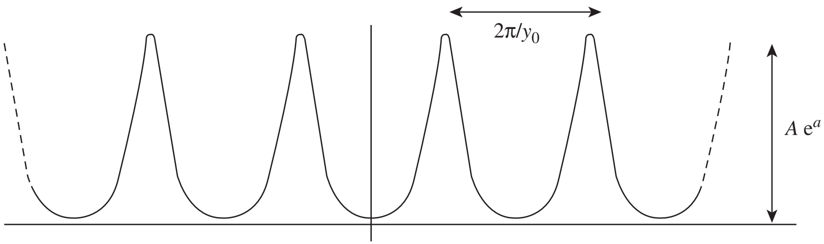
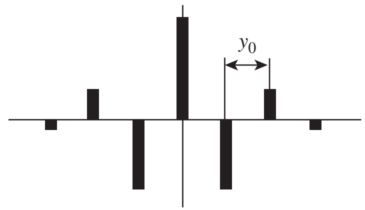
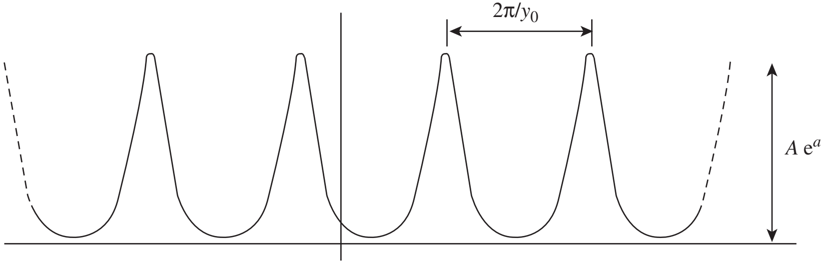
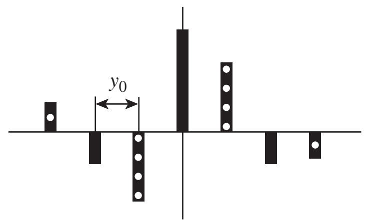
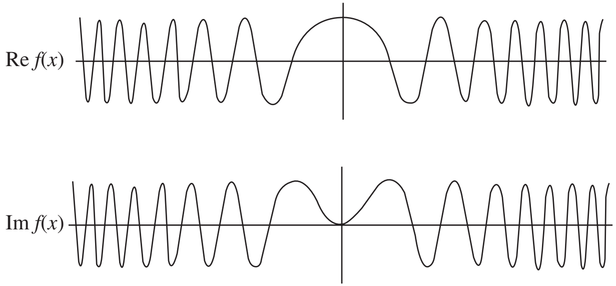
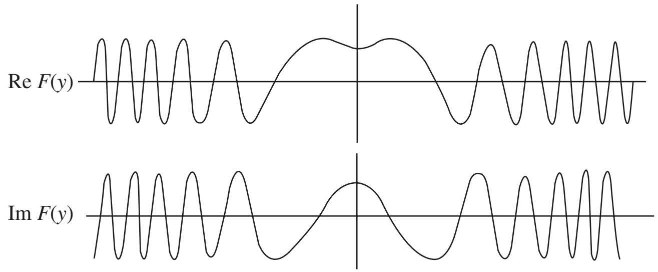
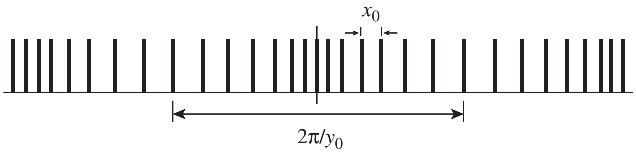
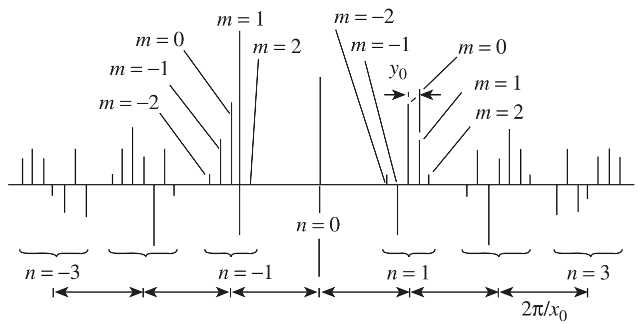
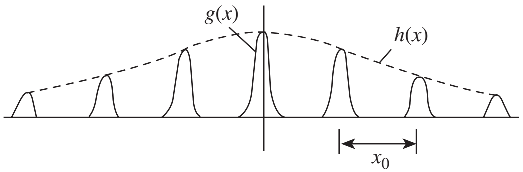
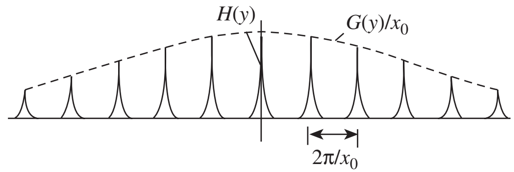
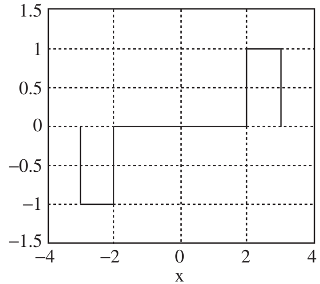
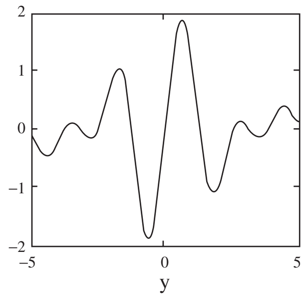
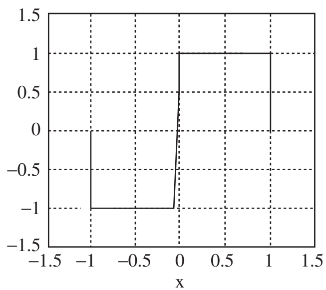
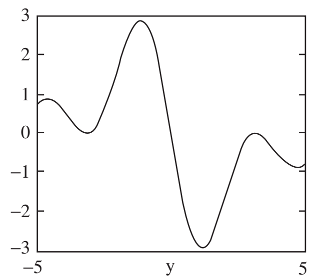
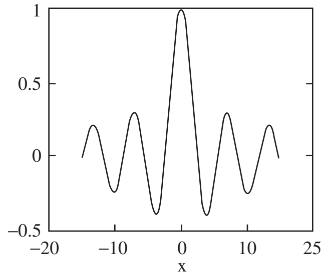
$f(x)$	$F(y)$
$A \sin(a \cos y_0 x + bx)$	 $i\pi A \sum_{n=-\infty}^{+\infty} \left\{(-i)^n J_n(a)\delta(y-b-ny_0) + (-i)^n J_n(a)\delta(y+b+ny_0)\right\}$
 $A \exp(-a \cos y_0 x)$	 $2\pi A \sum_{n=-\infty}^{+\infty} (-1)^n I_n(a)\delta(y-ny_0)$
 $A \exp(-a \sin y_0 x)$	 $2\pi A \sum_{n=-\infty}^{+\infty} (i)^n I_n(a)\delta(y-ny_0)$

Table of Fourier Transforms ($x = t$, $y = w$) (continued)

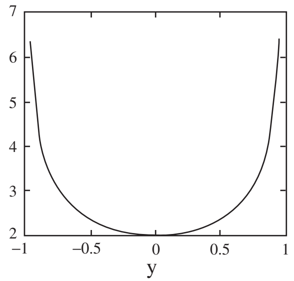
$f(x)$	$F(y)$
 $A\exp\left(\pm i a^2 x^2\right)$	 $\left(\frac{x}{2}\right)^{\frac{1}{2}} \frac{A(1-i)}{a}\exp\left(\mp i y^2/4a^2\right)$
 $f(x) = A\sum_n \delta\left(x - nx_0 + a\sin y_0 x\right)$	 $F(y) = \frac{2xA}{x_0}\sum_{m,n} J_m\left(n\frac{2\pi a}{x_0}\right)\delta\left(y - n\frac{2\pi}{x_0} - my_0\right)$ $(m = 0, \pm 1, \pm 2, \pm 3, \ldots)$ $(n = 0, \pm 1, \pm 2, \pm 3, \ldots)$

$f(x)$	$F(y)$
	
$f(x)=h(x)\sum_{n=-\infty}^{+\infty} g(x-nx_0)$	$F(y)=\frac{1}{x_0}\sum_{n=-\infty}^{+\infty}\left\{G\left(\frac{n2\pi}{x_0}\right)H\left(y-\frac{n2\pi}{x_0}\right)\right\}$
$f(x)=\sum_{n=-\infty}^{+\infty} h(nx_0)g(x-nx_0)$	$F(y)=\frac{1}{x_0}G(y)\sum_{n=-\infty}^{+\infty} H\left(y-\frac{n2\pi}{x_0}\right)$
 A $\quad s-a<x<s+a$ −A $\quad -s-a<x<-s+a$	 $-2Aj\frac{\sin ay}{y}\sin ys$
 A $\quad 0<x<2a$ −A $\quad -2a<x<0$	 $-4jA\sin ay\frac{\sin ay}{y}$

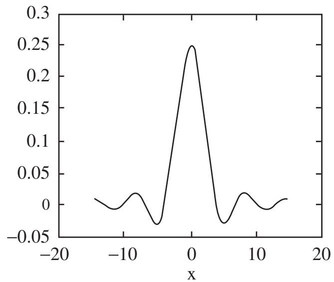
$f(x)$ / **$F(y)$**



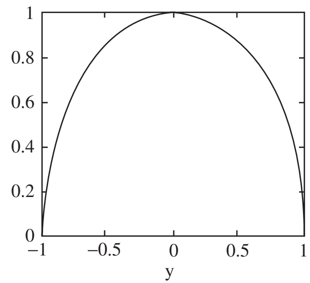
$J_0(x)$



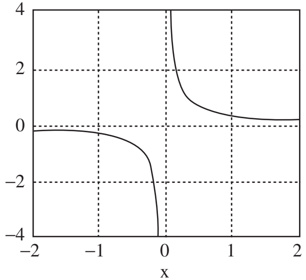
$\dfrac{2}{\sqrt{1-y^2}}$



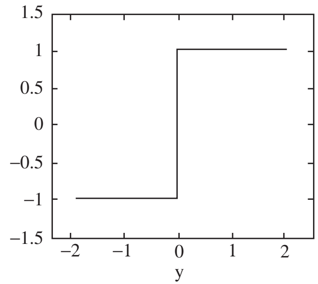
$\dfrac{J_1(x)}{2x}$



$\sqrt{1-y^2}$

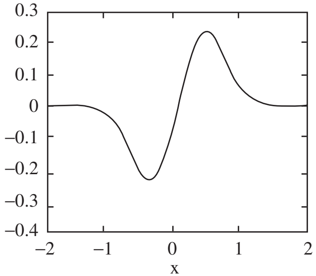


$\dfrac{1}{\pi x}$

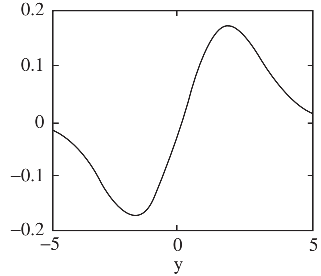


$$\text{sqn } y = \begin{cases} 1 & y > 0 \\ 0 & y = 0 \\ -1 & y < 0 \end{cases}$$

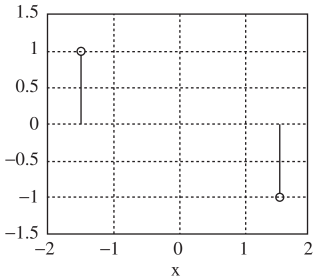
$f(x)$	$F(y)$



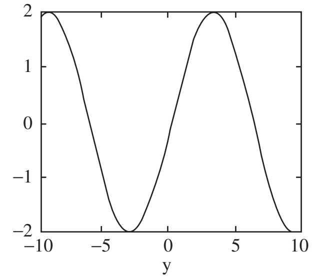
$xe^{-\pi x^2}$



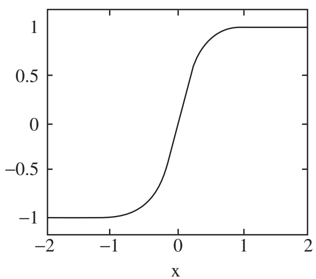
$-j\,\frac{y}{2\pi}\,e^{-\frac{y^2}{4\pi}}$



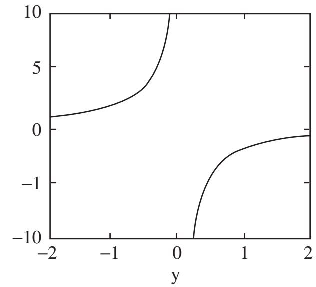
$\delta(x+a) - \delta(x-a)$



$2j \sin \frac{y}{2}$

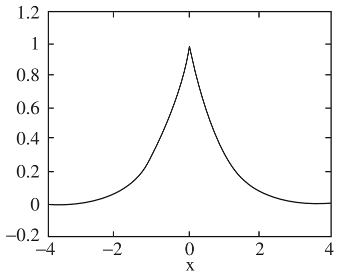


$\tanh \pi x$

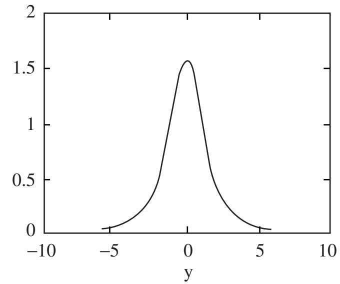


$-j\,\mathrm{cosech}\,\frac{y}{2}$

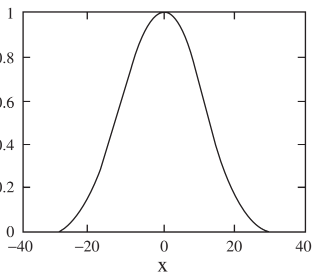
$f(x)$	$F(y)$



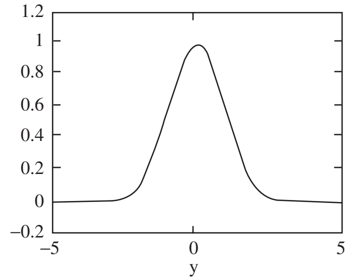
$e^{-|x|}\dfrac{\sin x}{x}$



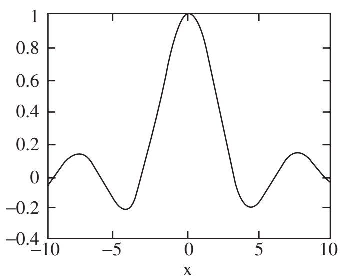
$\tan^{-1}\dfrac{2}{y^2}$



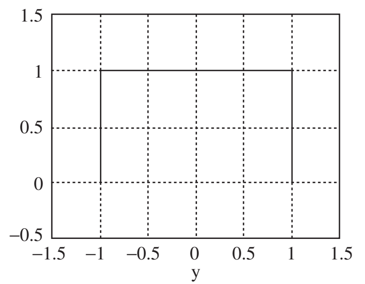
$p(x) * p(x) * p(x)$



$\left(\dfrac{\sin y}{y}\right)^3$

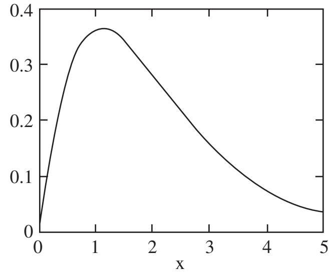


$\dfrac{\sin ax}{\pi x}$

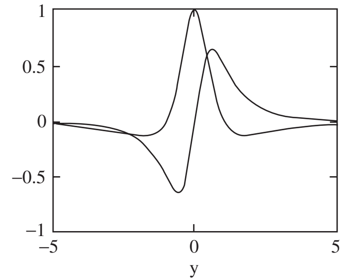


$P_a(x)$

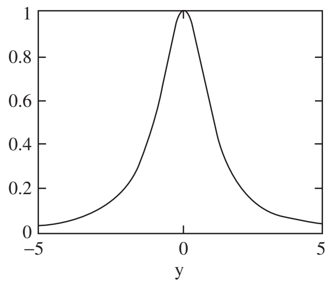
$f(x)$	$F(y)$



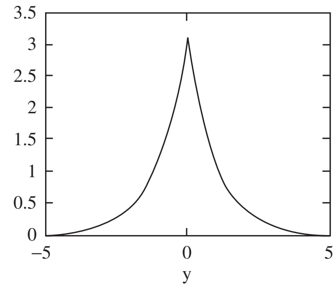
$x\,e^{-ax} \quad a > 0 \quad x \geq 0$



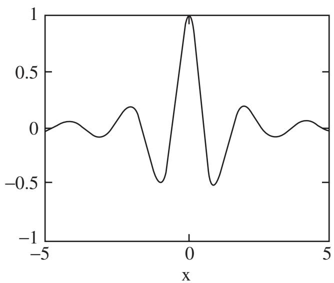
$$\frac{a^2 - y^2}{\left(a^2 + y^2\right)^2} - j\,\frac{2ay}{\left(a^2 + y^2\right)^2}$$



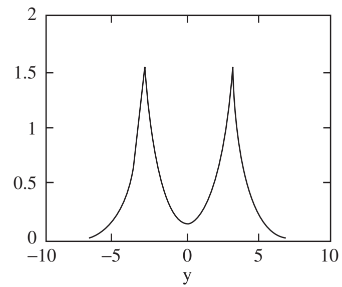
$$\frac{1}{a^2 + x^2}$$



$$\frac{\pi}{a}\,d^{-a|y|}$$

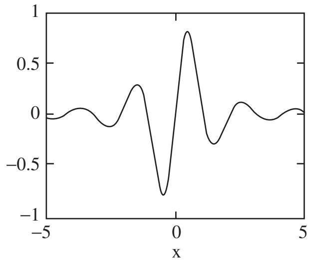
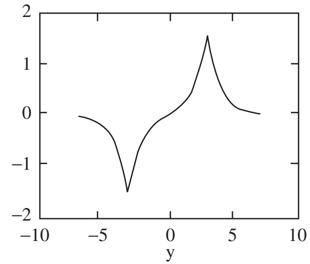
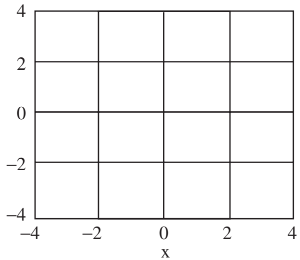
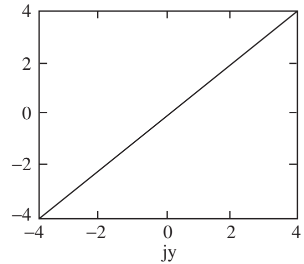
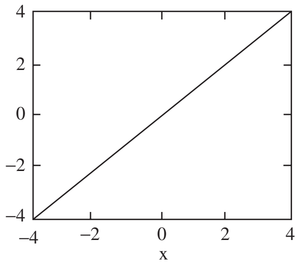
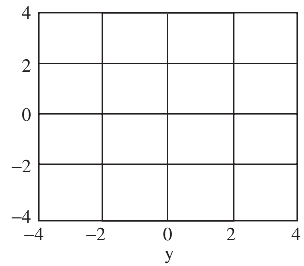


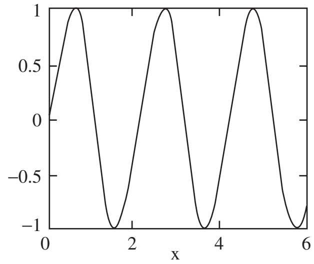
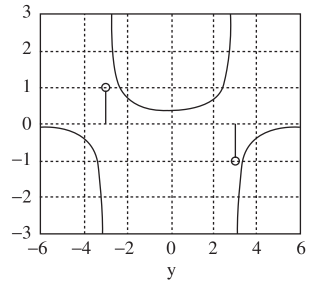
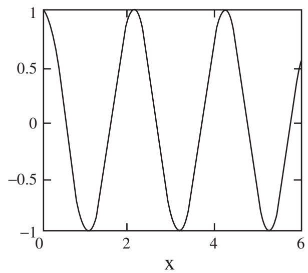
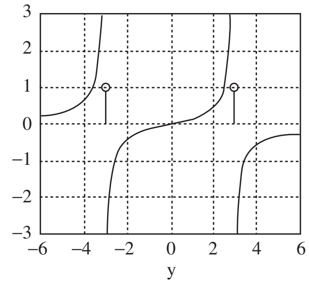
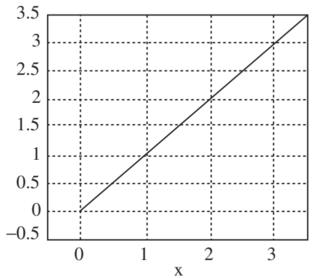
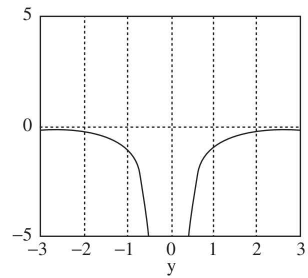
$$\frac{\cos bx}{a^2 + x^2}$$



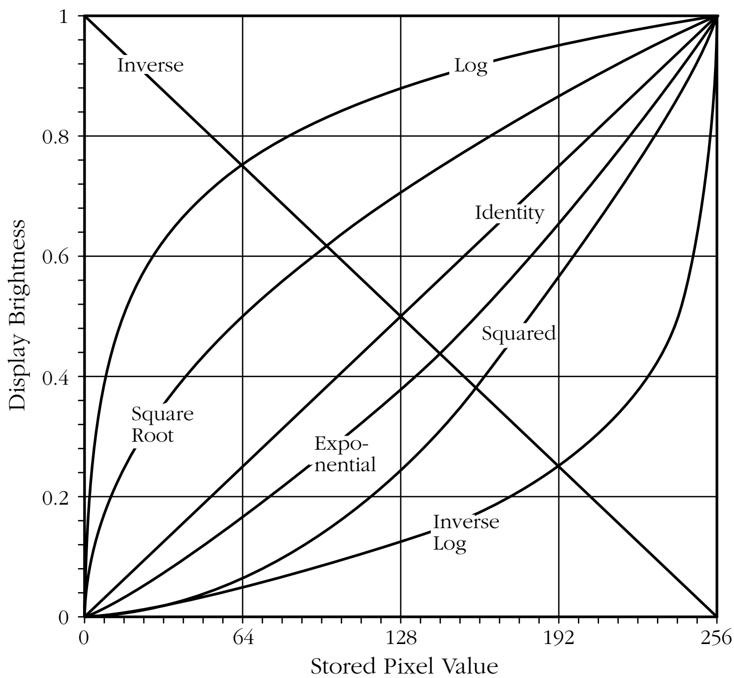
$$\frac{\pi}{2a}\left[e^{-a|y-b|} + e^{-a|y+b|}\right]$$

Table of Fourier Transforms ($x = t$, $y = w$) (continued)

$f(x)$		$F(y)$	
	$\frac{\sin bx}{a^2 + x^2}$		$\frac{\pi}{2aj}\left[e^{-a\lvert y-b\rvert} - e^{-a\lvert y+b\rvert}\right]$
	$\frac{d\delta(x)}{dx}$		jy
	x		$2\pi j \frac{d\delta(y)}{dy}$

$f(x)$		$F(y)$	
	$\sin w_0 x \quad x \ge 0$ $0 \quad x < 0$		$\dfrac{w_0}{w_0^2 - y^2} - j\dfrac{\pi}{2}\left[\delta(y - w_0) - \delta(y + w_0)\right]$
	$\cos w_0 x \quad x \ge 0$ $0 \quad x < 0$		$\dfrac{jy}{w_0^2 - y^2} + \dfrac{\pi}{2}\left[\delta(y - w_0) - \delta(y + w_0)\right]$
	$x \quad x \ge 0$ $0 \quad x < 0$		$j\pi\dfrac{d\delta(y)}{dy} - \dfrac{1}{y^2}$

From Poularikas, A., Fourier transformation, in *The Handbook of Formulas and Tables for Signal Processing*, CRC Press, Boca Raton, FL, 1999, pp. **3**-4 to **3**-27.



Examples of display transfer functions. (From Russ, J.C., Image enhancement: Processing in the spatial domain, in *The Image Processing Handbook,* 3rd ed., CRC Press, Boca Raton, FL, 1999, p. 232.)

Common Fourier Transforms

$x(t)$	$X(j\omega)$
$\delta(t)$	1
1	$2\pi\delta(\omega)$
$u(t)$	$\pi\delta(\omega) + \frac{1}{j\omega}$
$e^{-at}u(t)$, $a > 0$	$\frac{1}{a + j\omega}$
$te^{-at}u(t)$, $a > 0$	$\frac{1}{(a + j\omega)^2}$
$\sin(\omega_o t)$	$j\pi[\delta(\omega + \omega_o) - \delta(\omega - \omega_o)]$
$\cos(\omega_o t)$	$\pi[\delta(\omega + \omega_o) + \delta(\omega - \omega_o)]$

From Heinen, J.A. and Niederjohn, R.J., Signal processing, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 77.

Common Laplace Transforms

$x(t)$	$X(s)$
$d(t)$	1
$u(t)$	$\frac{1}{s}, \operatorname{Re}\{s\} > 0$
$e^{-at}u(t)$	$\frac{1}{s+a}, \operatorname{Re}\{s\} > -a$
$te^{-at}u(t)$	$\frac{1}{(s+a)^2}, \operatorname{Re}\{s\} > -a$
$\sin(\omega_o t)u(t)$	$\frac{\omega_o}{s^2+\omega_o^2}, \operatorname{Re}\{s\} > 0$
$\cos(\omega_o t)u(t)$	$\frac{s}{s^2+\omega_o^2}, \operatorname{Re}\{s\} > 0$

From Heinen, J.A. and Niederjohn, R.J., Signal processing, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 78.

Important Properties of Laplace Transforms

Signals	Laplace Transforms
$Ax_1(t) + Bx_2(t)$	$AX_1(s) + BX_2(s)$
$x(t - t_o),\ t_o \geq 0$	$X(s)e^{-st_o}$
$x(at),\ a > 0$	$\frac{1}{a}X\left(\frac{s}{a}\right)$
$\frac{dx(t)}{dt}$	$sX(s) - x(0-)$
$\int_{-\infty}^{t} x(\tau)d\tau$	$\frac{X(s)}{s}$
$x_1(t)*x_2(t)$	$X_1(s)X_2(s)$

Note: $x(t)$, $x_1(t)$, $x_2(t)$ are arbitrary signals with Laplace transforms $X(s)$, $X_1(s)$, $X_2(s)$, respectively. A, B, a, t_o are arbitrary constants.

From Heinen, J.A. and Niederjohn, R.J., Signal processing, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 79.

Representative Values of Absolute Seebeck Thermoelectric Coefficients of Some Materials Used in Industrial Electronic Circuits

	Seebeck Coefficient, μV/°C			
	0°C	20°C	100°C	400°C
Lead	0.03×10^{-3}	0.05×10^{-3}	0.08×10^{-3}	0.11×10^{-3}
Tin	0.03×10^{-3}	0.06×10^{-3}	0.09×10^{-3}	0.12×10^{-3}
Copper	1.72	1.82	2.23	3.85
Silver	1.42	1.50	1.84	4.07
Gold	2.3	2.12	2.0	2.3
Tungsten	1.9	4.1	6.7	12.1
Chromium	13.2	14.4	15.3	17.3
Nickel	–7.0	–9.7	–12.4	–15.0
Platinum	–4.2	–7.2	–9.7	–13.1
Brass	0.7	0.82	1.33	1.95
Kovar	0.20	0.20	0.19	0.02
Manganin	1.37	1.39	1.45	1.95
Nichrome	20.84	20.24	17.85	11.89
Silicon	–408	417	–455	–502
Germanium	–303			
CuO	–696			
Cu_2O	–474 – 1150			
Mn_2O_3	–385			

Note: Values reported in the literature are for nominal materials that may not be well documented as to composition and state. They are presented only to allow estimates of plausible Seebeck emf contributions. Specific values should be determined for critical applications.

From Reed, R.P., Measurement system architecture — Thermal effects in industrial electronic circuits, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 153.

Data originally from Reed, R.P. 1992. Absolute Seebeck thermoelectric characteristics—principles, significance, and applications, *Temperature, Its Measurement and Control in Science and Industry*, American Institute of Physics, 6(2):503–508.

Reed, R.P. 1993. *Manual on the Use of Thermocouples in Temperature Measurement, MNL-12, 4th edition*, Ch. 2, Park, R.W., ed., American Society for Testing and Materials, Philadelphia, PA.

Wang, T.P. 1992. Absolute Seebeck coefficients of metallic elements, *Temperature, Its Measurement and Control in Science and Industry*, American Institute of Physics, 6(2):509–514.

Kinzie, P.A. 1973. *Thermocouple Temperature Measurement*, Wiley-Interscience.

Power Definitions (Single-Phase Circuits)

Quantity (and Synonyms)	Symbol	Relationships	Units
Active power (real power, average power)	P	$P = \lvert V_{rms}\rvert \lvert I_{rms}\rvert \cos(\phi) = \lvert V_{rms}\rvert \lvert I_{rms}\rvert pf$ $= \sqrt{S^2 - Q^2}$	Watt (W)
Reactive power	Q	$Q = \lvert V_{rms}\rvert \lvert I_{rms}\rvert \sin(\phi) = \lvert V_{rms}\rvert \lvert I_{rms}\rvert rpf$ $= \sqrt{S^2 - P^2}$	VAr
Power factor	pf	$\cos(\phi)$	None, often represented as a percentage
Reactive power factor	rpf	$\sin(\phi)$	None
Complex power	S	$S = VI^*$	Voltamperes (VA)
Apparent power	|S|	$\lvert S\rvert = \lvert V_{rms}\rvert \lvert I_{rms}\rvert = \sqrt{P^2 + Q^2}$	Voltamperes (VA)

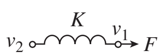
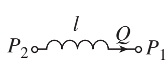
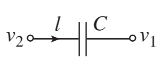
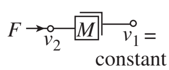
From Heydt, G., Main disturbances — Reactive power and harmonics compensation, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 357.

Power Definitions (Three-Phase Circuits)

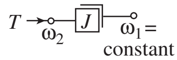
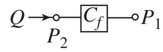
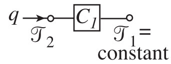
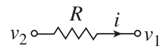
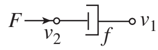
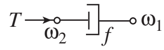
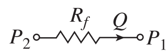
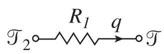
Quantity	Symbol	Relationships	Units
Active power (real power)	P	$P = 3\|V_{ln}\|\|I_{phase}\|\cos(\phi)$ $= 3\|V_{ln}\|\|I_{phase}\|pf$ $= \sqrt{3}\|V_{ll}\|\|I_{line}\|pf$ $= \sqrt{S^2 - Q^2}$	Watt (W)
Reactive power	Q	$Q = 3\|V_{ln}\|\|I_{phase}\|\sin(\phi)$ $= 3\|Vrubln\|\|I_{phase}\|rpf$ $= \sqrt{3}\|V_{ll}\|\|I_{line}\|rpf$ $= \sqrt{S^2 - p^2}$	VAr
Power factor	pf	cos(ϕ)	Often represented as a percentage
Reactive power factor	rpf	sin(ϕ)	None
Complex power	S	$S = 3V_{\text{ln}}I^*_{phase}$ $= \sqrt{3} - 30°V_{line}I^*_{line}$	Voltamperes (VA)
Apparent power	|S|	$\|S\| = 3\|V_{\text{ln}}\|\|I_{phase}\|$ $= 3\|V_{\text{ll}}\|\|I_{line}\|$ $= \sqrt{P^2 + Q^2}$	Voltamperes (VA)

From Heydt, G., Main disturbances — Reactive power and harmonics compensation, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 357.

Summary of Describing Differential Equations for Ideal Elements

Type of Element	Physical Elements	Describing Equation	Energy *E* or Power *P*	Symbol
	Electrical inductance	$v_{21} = L\frac{di}{dt}$	$E = \frac{1}{2}Li^2$	
Inductive storage	Translational spring	$v_{21} = \frac{1}{K}\frac{dF}{dt}$	$E = \frac{1}{2}\frac{F^2}{K}$	
	Rotational spring	$\omega_{21} = \frac{1}{K}\frac{dT}{dt}$	$E = \frac{1}{2}\frac{T^2}{K}$	
	Fluid inertia	$P_{21} = I\frac{dQ}{dt}$	$E = \frac{1}{2}IQ^2$	
	Electrical capacitance	$i = C\frac{dv_{21}}{dt}$	$E = \frac{1}{2}Cv_{21}^2$	
	Translational mass	$F = M\frac{dv_2}{dt}$	$E = \frac{1}{2}Mv_2^2$	

Summary of Describing Differential Equations for Ideal Elements (continued)

Type of Element	Physical Elements	Describing Equation	Energy E or Power P	Symbol
Capacitive storage	Rotational mass	$T = J\dfrac{d\omega_2}{dt}$	$E = \dfrac{1}{2}J\omega_2^2$	
	Fluid capacitance	$Q = C_f\dfrac{dP_{21}}{dt}$	$E = \dfrac{1}{2}C_f P_{21}^2$	
	Thermal capacitance	$q = C_t\dfrac{d\tau_2}{dt}$	$E = C_t\tau_2$	
	Electrical resistance	$i = \dfrac{1}{R}v_{21}$	$P = \dfrac{1}{R}v_{21}^2$	
	Translational damper	$F = fv_{21}$	$P = fv_{21}^2$	
Energy dissipators	Rotational damper	$T = f\omega_{21}$	$P = f\omega_{21}^2$	
	Fluid resistance	$Q = \dfrac{1}{R_f}P_{21}$	$P = \dfrac{1}{R_f}P_{21}^2$	
	Thermal resistance	$q = \dfrac{1}{R_t}T_{21}$	$P = \dfrac{1}{R_t}T_{21}$	

Nomenclature

- *Through-variable*: F = force, T = torque, i = current, Q = fluid volumetric flow rate, q = heat flow rate.
- *Across-variable*: v = translational velocity, ω = angular velocity, v = voltage, P = pressure, T = temperature.
- *Inductive storage*: L = inductance, $1/k$ = reciprocal translational or rotational stiffness, I = fluid inertance.
- *Capacitive storage*: C = capacitance, M = mass, J = moment of inertia, C_f = fluid capacitance, C_t = thermal capacitance.
- *Energy dissipators*: R = resistance, f = viscous friction, R_f = fluid resistance, R_t = thermal resistance.

From Boye, A.J. and Brogan, W.L., Modeling for system control, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 449. Originally from Dorf, R. and Bishop, R. 1995. *Modern Control Systems,* 7th ed. © 1995 by Addison-Wesley Publishing Company. Reprinted by permission.

Properties of the Wave Types for Time-of-Flight Measuring

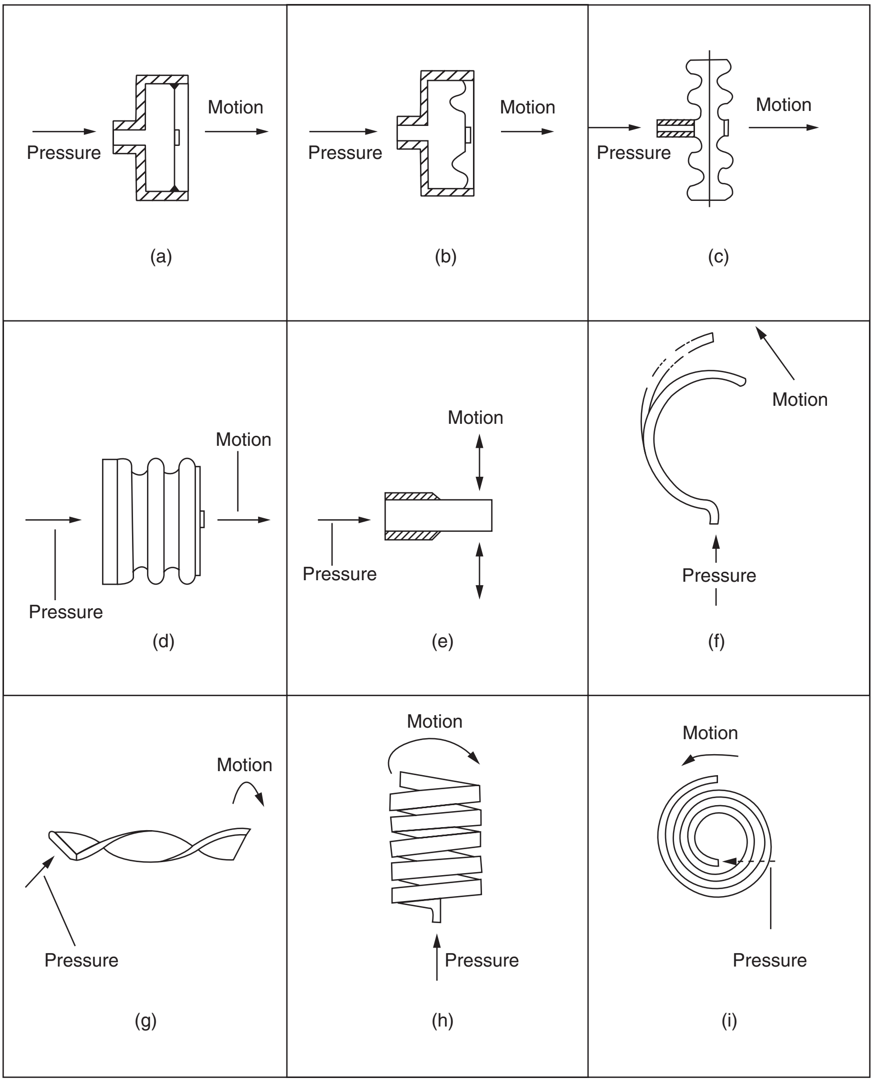
Principle	Wave Velocity	Avg. Carrier Frequency	Wavelength	Avg. Burst Time
Ultrasonic	340 m s^{-1}	50 kHz	7 mm	1 ms
Radar	300,000 km s^{-1}	10 GHz	3 cm	1 ns
Laser	300,000 km s^{-1}	300 THz	1 μm	1 ns

From Brumbi, D., Level measurement, in *The Measurement, Instrumentation and Sensors Handbook,* Webster, J.G., Ed., CRC Press, Boca Raton, FL, 1999, p. **11**-8.

Comparison of Strain Sensors

Description	Longitudinal strain sensitivity	Transverse strain sensitivity	Temperature sensitivity	Strain resolution	Spatial resolution	Time resolution	Measurable strain range
Piezoresistive constantan foil	$\Delta R/R/\Delta\varepsilon_L = 2.1$	$\Delta R/R/\Delta\varepsilon_t = <0.02$	$\Delta R/R/\Delta T = 2 \times 10^{-6}/°C$	<1 μstrain[a]	5–100 mm[b]	<1 μs[c]	0–3%
Annealed constantan foil[d]	$\Delta R/R/\Delta\varepsilon_L = 2.1$	$\Delta R/R/\Delta\varepsilon_t = <0.02$	$\Delta R/R/\Delta T = 2 \times 10^{-6}/°C$	<11 μstrain	5–100 mm	<1 μs	0–10%
Piezoresistive semiconductor	$\Delta R/R/\Delta\varepsilon_L = 150$	$\Delta R/R/\Delta\varepsilon_t$ = ???	$\Delta R/R/\Delta T = 1.7 \times 10^{-3}/°C$	<0.1 μstrain	1–15 mm	<1 μs	0–0.1%
Piezoelectric PVDF	$\Delta Q/A/\Delta\varepsilon_L = 120\ nC/m^2/\mu\varepsilon$	$\Delta Q/A/\Delta\varepsilon_t = 60\ nC/m^2/\mu\varepsilon$	$\Delta Q/A/\Delta T = -27\ \mu C/m^2/°C$	1–10 μstrain	Gage size	<1 μs	0–30%
Piezoelectric quartz	$\Delta Q/A/\Delta\varepsilon_L = 150\ nC/m^2/\mu\varepsilon$ bonded to steel		$\Delta Q/A/\Delta T = 0$	<0.01 μstrain 20 mm gage	Gage size	<10 μs	0–0.1%
Fiber optic Fabry-Perot	2 to 1000 μstrain/volt	Near zero		<1 μstrain	2–10 mm	<20 μs	
Birefringent Film	$K^e = 0.15–0.002$				0.5 mm[f]	<5 μs	0.05–5%
Moiré	1 fringe order/417 nm displ.	1 fringe order/417 nm displ.	Not defined	41.7 με over 10 mm	full field[g]	Limited by signal conditining	0.005–5%

[a] With good signal conditioning.
[b] Equal to grid area.
[c] Gage response is within 100 ns. Most signal conditioning limits response time to far less than this.
[d] Annealed foil has a low yield stress and a large strain to failure. It also has hysteresis in the unload and a zero shift under cyclic load.
[e] This technique measures a difference in principal strains. $\varepsilon_2 - \varepsilon_1 = N\lambda/2tK$
[f] Approximately the film thickness.
[g] The spatial strain resolution depends on the strain level. This is a displacement measurement technique.
From Lynch, C.S., Strain measurement, in *The Measurement, Instrumentation, and Sensors Handbook,* Webster, J.G., Ed., CRC Press, Boca Raton, FL, 1999, p. **22**-5.

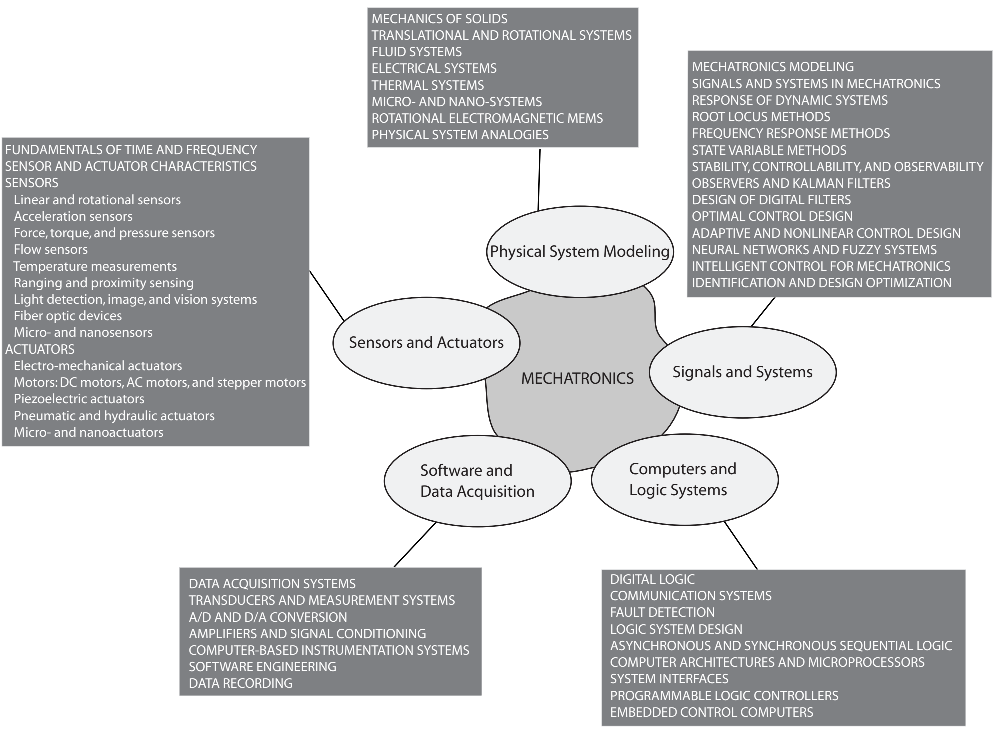


Pressure-sensing elements: (a) flat diaphragm; (b) corrugated diaphragm; (c) capsule; (d) bellows; (e) straight tube; (f) Cshaped Bourdon tube; (g) twisted Bourdon tube; (h) helical Bourdon tube; (i) spiral Bourdon tube. (From Norton, H.N., *Handbook of Transducers,* Englewood Cliffs, NJ: Prentice-Hall, 1989, 294–330. Reprinted with permission.) Previously published in Chau, K.H.L., Pressure and sound measurement, in *The Measurement, Instrumentation, and Sensors Handbook,* Webster, J.G., Ed., CRC Press, Boca Raton, FL, 1999, p. **26**-3.)

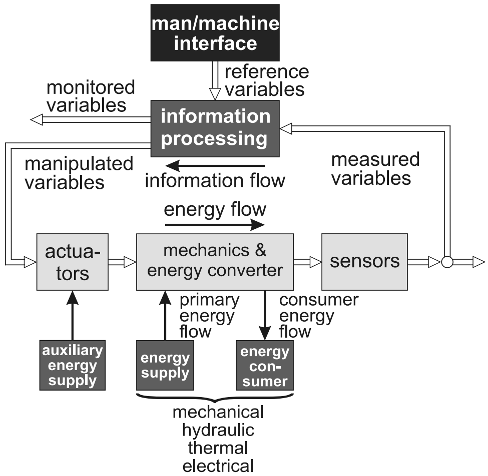
Permittivity (Dielectric Constants of Materials Used in Capacitors)

Material	Permittivity
Vacuum	1.0
Air	1.0006
Teflon	2.1
Polyethylene, etc.	2.0–3.0
Impregnated paper	4.0–6.0
Glass and mica	4.0–7.0
Ceramic (low *K*)	≤20.0
Ceramic (medium *K*)	80.0–100.0
Ceramic (high *K*)	≥1000,0

From Eren, H. and Goh, J., Capacitance and capacitance measurements, in *The Measurement, Instrumentation, and Sensors Handbook*, Webster, J.G., Ed., CRC Press, Boca Raton, FL, 1999, p. **45**-5.



The key elements of mechatronics. (From Bishop, R.H., What is mechatronics? in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-3.)



Mechanical process and information processing develop towards mechatronic systems. (From Iserman, R., Mechatronic design approach, in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **2**-3.)

Generalized Through and Across Variables for Processes with Energy Flow

System	Through Variables		Across Variables	
Electrical	Electric current	I	Electric voltage	U
Magnetic	Magnetic Flow	Φ	Magnetic force	Θ
Mechanical				
• translation	Force	F	Velocity	w
• rotation	Torque	M	Rotational speed	ω
Hydraulic	Volume flow	$\dot{V}$	Pressure	p
Thermodynamic	Entropy flow		Temperature	T

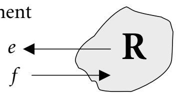
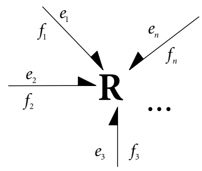
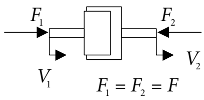
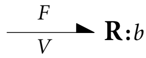
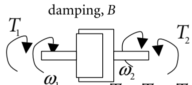
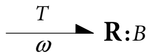
From Iserman, R., Mechatronic design approach, in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **2**-12.

Power and Energy Variables for Mechanical Systems

Energy Domain	Effort, e	Flow, f	Power, P
General	e	f	$e \cdot f$ [W]
Translational	Force, F [N]	Velocity, V [m/sec]	$F \cdot V$ [N m/sec, W]
Rotational	Torque, T or τ [N m]	Angular velocity, ω [rad/sec]	$T \cdot \omega$ [N m/sec, W]
Electrical	Voltage, v [V]	Current, i [A]	$v \cdot i$ [W]
Hydraulic	Pressure, P [Pa]	Volumetric flowrate, Q [m^3/sec]	$P \cdot Q$ [W]

From Longoria, R.G., Modeling of mechanical systems for mechatronics applications, in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-3.

Mechanical Dissipative Elements

Physical System	Fundamental Relations	Bond Graph
Generalized Dissipative Element  • Resistive element • **Resistance,** R	Dissipation: $\mathbf{e}\cdot\mathbf{f}=\sum_i e_i f_i = T\cdot f_s$ Resistive law: $e=\Phi_R(f)$ Conductive law: $f=\Phi_R^{-1}(e)$ Content: $P_f=\int e\cdot df$ Co-content: $P_e=\int f\cdot de$	 **Generalized multiport R-element**
Mechanical Translation  $F_1=F_2=F$ • Damper $V_1-V_2=V$ • **damping,** b	Constitutive: $F=\Phi(V)$ Content: $P_V=\int F\cdot dV$ Co-energy: $P_F=\int V\cdot dF$ Dissipation: $P_d=P_V+P_F$	 Linear: $F=b\cdot V$ Dissipation: $P_d=bV^2$
Mechanical Rotation  $T_1=T_2=T$ $\omega_1-\omega_2=\omega$ • Torsional damper • **damping,** B	Constitutive: $T=\Phi(\omega)$ Content: $P_\omega=\int T\cdot d\omega$ Co-energy: $P_T=\int \omega\cdot dT$ Dissipation: $P_d=P_\omega+P_T$	 Linear: $T=B\cdot\omega$ Dissipation: $P_d=B\omega^2$

From Longoria, R.G., Modeling of mechanical systems for mechatronics applications, in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-11.

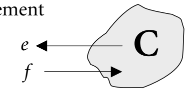
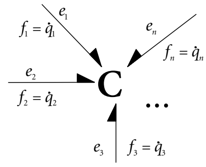
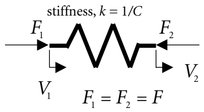
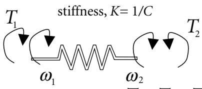
Typical Coefficient of Friction Values

Contacting Surfaces	Static, μ_s	Sliding or Kinetic, μ_k
Steel on steel (dry)	0.6	0.4
Steel on steel (greasy)	0.1	0.05
Teflon on steel	0.04	0.04
Teflon on teflon	0.04	—
Brass on steel (dry)	0.5	0.4
Brake lining on cast iron	0.4	0.3
Rubber on asphalt	—	0.5
Rubber on concrete	—	0.6
Rubber tires on smooth pavement (dry)	0.9	0.8
Wire rope on iron pulley (dry)	0.2	0.15
Hemp rope on metal	0.3	0.2
Metal on ice	—	0.02

Note: Actual values will vary significantly depending on conditions.

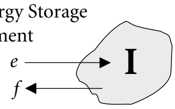
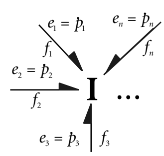
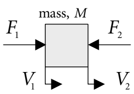
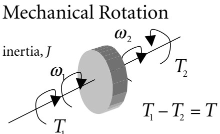
From Longoria, R.G., Modeling of mechanical systems for mechatronics applications, in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-11.

Mechanical Potential Energy Storage Elements (Integral Form)

Physical System	Fundamental Relations	Bond Graph
Generalized Potential Energy Storage Element  • Capacitive element • **Capacitance,** C	State: $\mathbf{q} = \text{displacement}$ Rate: $\dot{\mathbf{q}} = \mathbf{f}$ Constitutive: $\mathbf{e} = \Phi(\mathbf{q})$ Energy: $U_{\mathbf{q}} = \int \mathbf{e} \cdot d\mathbf{q}$ Co-energy: $U_{\mathbf{e}} = \int \mathbf{q} \cdot d\mathbf{e}$	 **Generalized multiport C-element**
Mechanical Translation  $F_1 = F_2 = F$ • spring $V_1 - V_2 = V$ • **stiffness,** k, **compliance,** C	State: $x = \text{displacement}$ Rate: $\dot{x} = V$ Constitutive: $F = F(x)$ Energy: $U_x = \int F \cdot dx$ Co-energy: $U_F = \int x \cdot dF$	$\xrightarrow[\dot{x}=V]{F}$ **C:** $1/C = k$ Linear: $F = k \cdot x$ Energy: $U_x = \frac{1}{2} k x^2$ Co-energy: $U_F = F^2 / 2k$
Mechanical Rotation  $T_1 = T_2 = T$ $\omega_1 - \omega_2 = \omega$ • Torsional spring • **stiffness,** K, **compliance,** C	State: $\theta = \text{angle}$ Rate: $\dot{\theta} = \omega$ Constitutive: $T = T(\theta)$ Energy: $U_\theta = \int T \cdot d\theta$ Co-energy: $U_T = \int \theta \cdot dT$	$\xrightarrow[\dot{\theta}=\omega]{T}$ **C:** $1/C = K$ Linear: $T = K \cdot \theta$ Energy: $U_\theta = \frac{1}{2} k \theta^2$ Co-energy: $U_T = T^2 / 2K$

From Longoria, R.G., Modeling of mechanical systems for mechatronics applications, in *The Mechantronics Handbook*, Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-13.

Mechanical Kinetic Energy Storage Elements (Integral Form)

Physical System	Fundamental Relations	Bond Graph
Generalized Kinetic Energy Storage Element  • Inertive element • **Inertance,** I	State: $\mathbf{p} = \text{momentum}$ Rate: $\dot{\mathbf{p}} = \mathbf{e}$ Constitutive: $\mathbf{f} = \Phi(\mathbf{p})$ Energy: $T_{\mathbf{p}} = \int \mathbf{f} \cdot d\mathbf{p}$ Co-energy: $T_{\mathbf{f}} = \int \mathbf{p} \cdot d\mathbf{f}$	 **Generalized multiport I-element**
Mechanical Translation  $F_1 - F_2 = F$ • Mass $V_1 = V_2 = V$ • **mass,** m	State: $p = \text{momentum}$ Rate: $\dot{p} = F$ Constitutive: $V = V(p)$ Energy: $T_p = \int f \cdot dp$ Co-energy: $T_V = \int p \cdot dV$	$\xrightarrow[V]{\dot{p}=F}$ **I:** M Linear: $V = p / M$ Energy: $T_p = p^2 / 2M$ Co-energy: $T_V = \frac{1}{2} M V^2$
Mechanical Rotation  $T_1 - T_2 = T$ $\omega_1 = \omega_2 = \omega$ • Rotational inertia • **mass moment of inertia,** J	State: $h = \text{angular momentum}$ Rate: $\dot{h} = T$ Constitutive: $\omega = \omega(h)$ Energy: $T_h = \int \omega \cdot dh$ Co-energy: $T_\omega = \int h \cdot d\omega$	$\xrightarrow[\omega]{\dot{h}=T}$ **I:** J Linear: $\omega = h / J$ Energy: $T_h = h^2 / 2J$ Co-energy: $T_\omega = \frac{1}{2} J \omega^2$

From Longoria, R.G., Modeling of mechanical systems for mechatronics applications, in *The Mechantronics Handbook*, Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-14.

Resistance of Copper Wire

AWG Size	Number of Strands	Diameter per Strand	Resistance per 1000 ft (Ω)
24	Solid	0.0201	28.4
24	7	0.0080	28.4
22	Solid	0.0254	18.0
22	7	0.0100	19.0
20	Solid	0.0320	11.3
20	7	0.0126	11.9
18	Solid	0.0403	7.2
18	7	0.0159	7.5
16	Solid	0.0508	4.5
16	19	0.0113	4.7

From Rizzoni, G., Electrical engineering, in *The Mechatronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **11**-9.

Type of Sensors for Various Measurement Objectives

Sensor	Features
	Linear/Rotational sensors
Linear/Rotational variable differential transducer (LVDT/RVDT)	High resolution with wide range capability Very stable in static and quasi-static applications
Optical encoder	Simple, reliable, and low-cost solution Good for both absolute and incremental measurements
Electrical tachometer	Resolution depends on type such as generator or magnetic pickups
Hall effect sensor	High accuracy over a small to medium range
Capacitive transducer	Very high resolution with high sensitivity Low power requirements Good for high frequency dynamic measurements
Strain gauge elements	Very high accuracy in small ranges Provides high resolution at low noise levels
Interferometer	Laser systems provide extremely high resolution in large ranges Very reliable and expensive
Magnetic pickup	Output is sinusoidal
Gyroscope	
Inductosyn	Very high resolution over small ranges
	Acceleration sensors
Seismic accelerometer	Good for measuring frequencies up to 40% of its natural frequency
Piezoelectric accelerometer	High sensitivity, compact, and rugged Very high natural frequency (100 kHz typical)
	Force, torque, and pressure sensors
Strain gauge	Good for both static and dynamic measurements
Dynamometers/load cells	They are also available as micro- and nanosensors
Piezoelectric load cells	Good for high precision dynamic force measurements
Tactile sensor	Compact, has wide dynamic range, and high
Ultrasonic stress sensor	Good for small force measurements
	Flow sensors
Pitot tube	Widely used as a flow rate sensor to determine speed in aircrafts
Orifice plate	Least expensive with limited range
Flow nozzle, venturi tubes	Accurate on wide range of flow More complex and expensive

Type of Sensors for Various Measurement Objectives (continued)

Sensor	Features
Rotameter	Good for upstream flow measurements
	Used in conjunction with variable inductance sensor
Ultrasonic type	Good for very high flow rates
	Can be used for both upstream and downstream flow measurements
Turbine flow meter	Not suited for fluids containing abrasive particles
	Relationship between flow rate and angular velocity is linear
Electromagnetic flow meter	Least intrusive as it is noncontact type
	Can be used with fluids that are corrosive, contaminated, etc.
	The fluid has to be electrically conductive
	Temperature sensors
Thermocouples	This is the cheapest and the most versatile sensor
	Applicable over wide temperature ranges (−200°C to 1200°C typical)
Thermistors	Very high sensitivity in medium ranges (up to 100°C typical)
	Compact but nonlinear in nature
Thermodiodes, thermo transistors	Ideally suited for chip temperature measurements
	Minimized self-heating
RTD—resistance temperature detector	More stable over a long period of time compared to thermocouple
	Linear over a wide range
Infrared type	Noncontact point sensor with resolution limited by wavelength
Infrared thermography	Measures whole-field temperature distribution
	Proximity sensors
Inductance, eddy current, hall effect, photoelectric, capacitance, etc.	Robust noncontact switching action
	The digital outputs are often directly fed to the digital controller
	Light sensors
Photoresistors, photodiodes, photo transistors, photo conductors, etc.	Measure light intensity with high sensitivity
	Inexpensive, reliable, and noncontact sensor
Charge-coupled diode	Captures digital image of a field of vision
	Smart material sensors
Optical fiber	
As strain sensor	Alternate to strain gages with very high accuracy and bandwidth
	Sensitive to the reflecting surface's orientation and status
As level sensor	Reliable and accurate
As force sensor	High resolution in wide ranges
As temperature sensor	High resolution and range (up to 2000°C)
Piezoelectric	
As strain sensor	Distributed sensing with high resolution and bandwidth
As force sensor	Most suitable for dynamic applications
As accelerometer	Least hysteresis and good setpoint accuracy
Magnetostrictive	
As force sensors	Compact force sensor with high resolution and bandwidth
	Good for distributed and noncontact sensing applications
As torque sensor	Accurate, high bandwidth, and noncontact sensor
	Micro- and nanosensors
Micro CCD image sensor	Small size, full field image sensor
Fiberscope	Small (0.2 mm diameter) field vision scope using SMA coil actuators
Micro-ultrasonic sensor	Detects flaws in small pipes
Micro-tactile sensor	Detects proximity between the end of catheter and blood vessels

From Anjanappa, M., Datta, K., and Song, T., Introduction to sensors and actuators, in *The Mechatronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, pp. **16**-2 to **16**-3.

Type of Actuators and Their Features

Actuator			Features
		Electrical	
Diodes, thyristor, bipolar transistor, triacs, diacs, power MOSFET, solid state relay, etc.			Electronic type Very high frequency response Low power consumption
		Electromechanical	
DC motor	Wound field	Separately excited	Speed can be controlled either by the voltage across the armature winding or by varying the field current
		Shunt	Constant-speed application
		Series	High starting torque, high acceleration torque, high speed with light load
		Compound	Low starting torque, good speed regulation Instability at heavy loads
	Permanent magnet	Conventional PM motor	High efficiency, high peak power, and fast response
		Moving-coil PM motor	Higher efficiency and lower inductance than conventional DC motor
		Torque motor	Designed to run for long periods in a stalled or a low rpm condition
	Electronic commutation (brushless motor)		Fast response High efficiency, often exceeding 75% Long life, high reliability, no maintenance needed Low radio frequency interference and noise production
AC motor	AC induction motor		The most commonly used motor in industry Simple, rugged, and inexpensive
	AC synchronous motor		Rotor rotates at synchronous speed Very high efficiency over a wide range of speeds and loads Need an additional system to start
	Universal motor		Can operate in DC or AC Very high horsepower per pound ratio Relatively short operating life
Stepper motor	Hybrid		Change electrical pulses into mechanical movement Provide accurate positioning without feedback
	Variable reluctance		Low maintenance
		Electromagnetic	
Solenoid type devices			Large force, short duration
Electromagnets, relay			On/off control
		Hydraulic and Pneumatic	
Cylinder			Suitable for liner movement
Hydraulic motor	Gear type		Wide speed range
	Vane type		High horsepower output
	Piston type		High degree of reliability
Air motor	Rotary type		No electric shock hazard
	Reciprocating		Low maintenance
Valves	Directional control valves		
	Pressure control valves		
	Process control valves		

Type of Actuators and Their Features (continued)

Actuator	Features
	Smart Material actuators
Piezoelectric & Electrostrictive	High frequency with small motion High voltage with low current excitation High resolution
Magnetostrictive	High frequency with small motion Low voltage with high current excitation
Shape Memory Alloy	Low voltage with high current excitation Low frequency with large motion
Electrorheological fluids	Very high voltage excitation Good resistance to mechanical shock and vibration Low frequency with large force
	Micro- and Nanoactuators
Micromotors	Suitable for micromechanical system
Microvalves	Can use available silicon processing technology, such as electrostatic motor
Micropumps	Can use any smart material

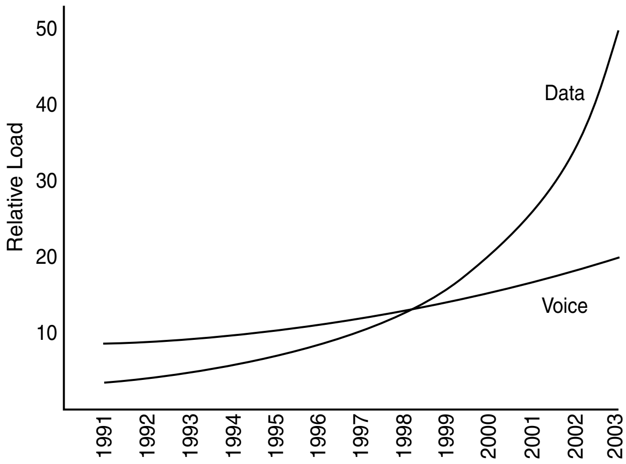
From Anjanappa, M., Datta, K., and Song, T., Introduction to sensors and actuators, in *The Mechatronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, pp. **16**-9 to **16**-10.

Performances of Two Deep-Sea Armored Coaxes

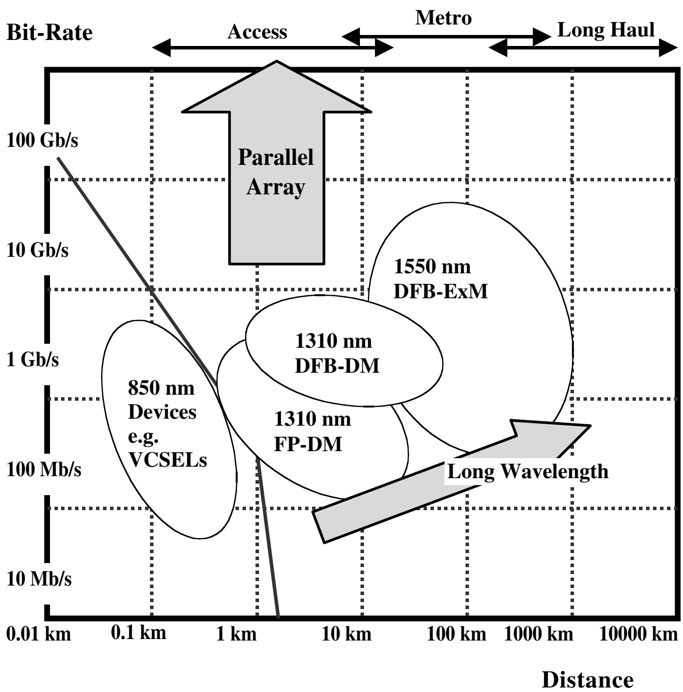
Cable Parameter	1972 Navy/SIO	1983 UNOLS
Diameter (mm)	17.3	17.3
Strength (kg)		
Ends fixed	17,000	17,800
One end free	11,900	17,300
Weight (kg/km)		
In air	1070	1020
In water	820	795
Free length (m)		
Ends fixed	20,800	22,300
One end free	14,500	21,800
Payload (kg)[a]		
Ends fixed	1880	2350
One end free	None	2150

[a]For operations to 6000 m, with the lower cable end free to rotate. The system's static strength/weight safety factor is 2.5.

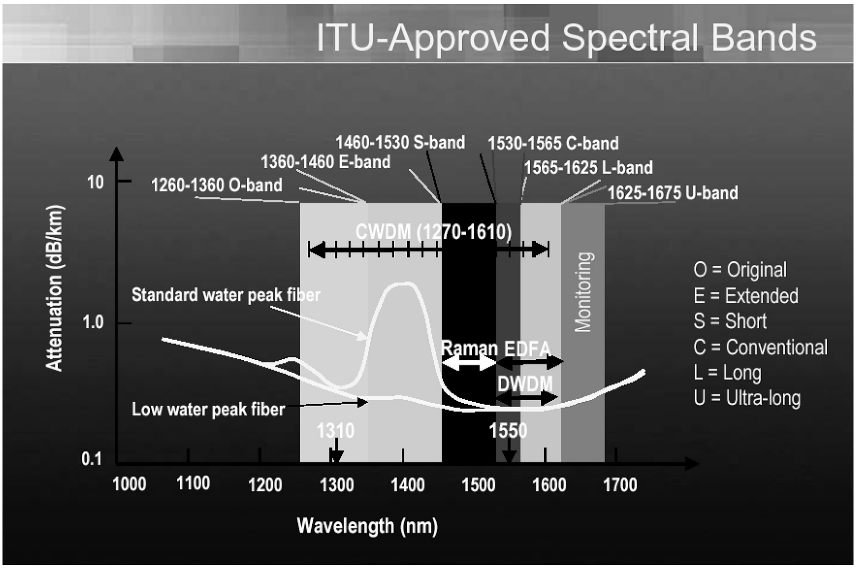
From Wilkins, G., Fiber optics telemetry in ocean cable systems, in *The Ocean Engineering Handbook,* El-Hawary, F., Ed., CRC Press, Boca Raton, FL, 2001, p. **5**-60.



Past and projected future growth of data and voice traffic. (From Gencata, A., Singhel, N., and Makherjee, B., Overview of optical communication networks, in *The Handbook of Optical Communication Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. 3.)



Nominal geographical spans of access, metro-core/regional, and long-haul networks as well as corresponding transmission rates with short- and long-wavelength transmitter devices. (From Raja, M.Y.A., Evolution of optical networks architecture, in *The Handbook of Optical Communication Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. 36.)



ITU-T-approved hand assignment in the low attenuation window of the silica fibers; the wavelength range involves 1260–1360 nm = O-band; 1360–1460 nm = E-band; 1460–1530 nm = S-band; 1530–1565 nm = C-band; 1565–1625 nm = L-band; and 1625–1675 nm = U-band (used in monitoring). (Courtesy EXFO Electro-Optical Engineering Inc. Printed with permission.) (From Raja, M.Y.A. and Ilyas, M., Optical transport networks: A physical layer perspective, in *The Handbook of Optical Communication Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. 391.)

Fiber Optics Chemical Sensors

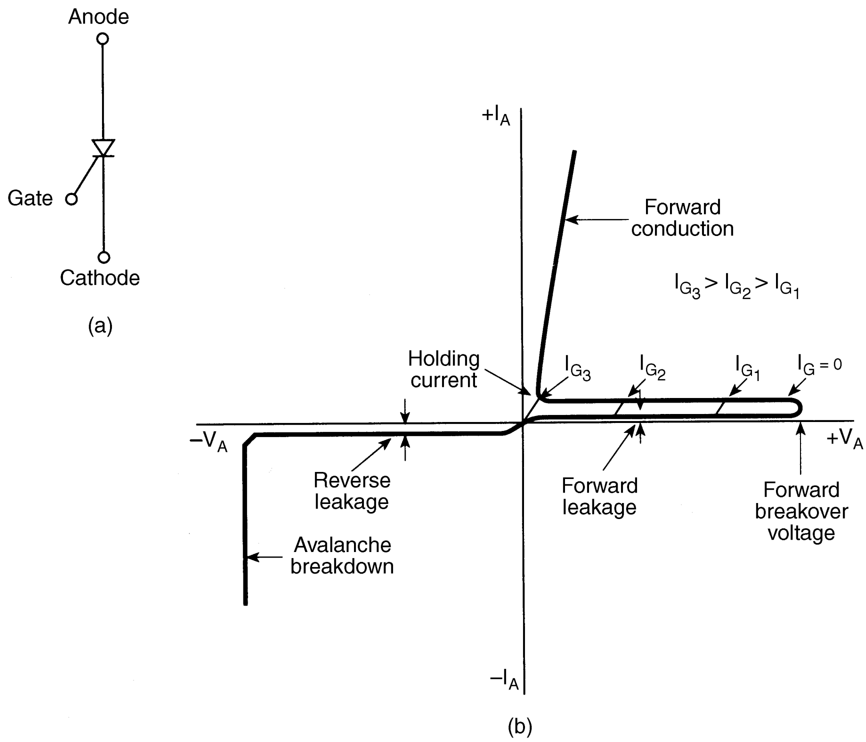
Sensor	Technique	Indicator	Principle	Wavelength (nm)			Detection limits	Sensitivity	Response Time	Ref.
				Excitation	Emission	Absorption				
Hydrogen sulphide	Porous fiber and sol-gel coating	Thionine	Florescence quenching	580	630	—	>50 ppb in H2S in water	~5 ppb	~5 S	57
pH	Porous fiber and sol-gel coating	Bromocresol green	Transmission/ absorption	—	615	—	3–6	~0.01 pH	~2 S	37
pH	Porous fiber and sol-gel coating	Bromocresol purple	Transmission/ absorption	—	—	580	6–9	~0.01 pH	~2 S	37
Hydrogen	Palladium coated fiber	Palladium thin films	Transmission/ absorption	—	—	650	0.2–0.6%	—	20–30 S	41
Carbon monoxide	Porous fiber	Organometallic complex in chloroform solution	Transmission/ absorption	—	—	450	9–28 vol.% in N_2 gas	~0.5 vol%	~ 100 S	27
Carbon dioxide dissolved in sea water	Fiber dipped in HPTS solution	Aqueous solution of 8-hydroxy-1,3,6-pyrenetrisulfonic acid-trisodium salt	Fluorescence	450	530	—	0–600 ppm	—	5 min	58
Oxygen dissolved oxygen	Porous fiber and sol-gel coating	Ruthenium complex	Fluorescence quenching	450	610	—	0–10% Oxygen 0.25–9 ppm dissolved oxygen	—	—	46
pH	Porous cellulose tricaetate fiber	Congo-red	Transmission	610	—	—	—	—	1–2 min	59

From Iqbal, T., Fiber optics sensors, in *The Handbook of Optical Communication Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. 428.

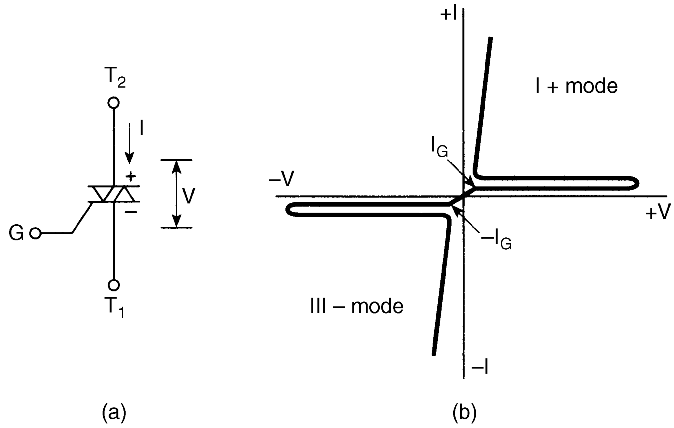
Typical Components of Various Glass Systems

Glass Type	Glass-Forming Systems
Silica glass	Na_2O - Ba_2O_3 -SiO_2
Fluoride glass (ZrF4-based)	$ZrF4_2$-BaF_2-LaF_3-$AlF3_2$-NaF
Fluoride glass (AlF3-based)	AlF_3-BaF_2-CaF_2-YF3-SrF_2-NaF-ZrF_4
Chalcogenide	Ge-As-Se
Chalcohalide	As-S-Cl
Sulphide glass	As_2S_3-La_2S_3

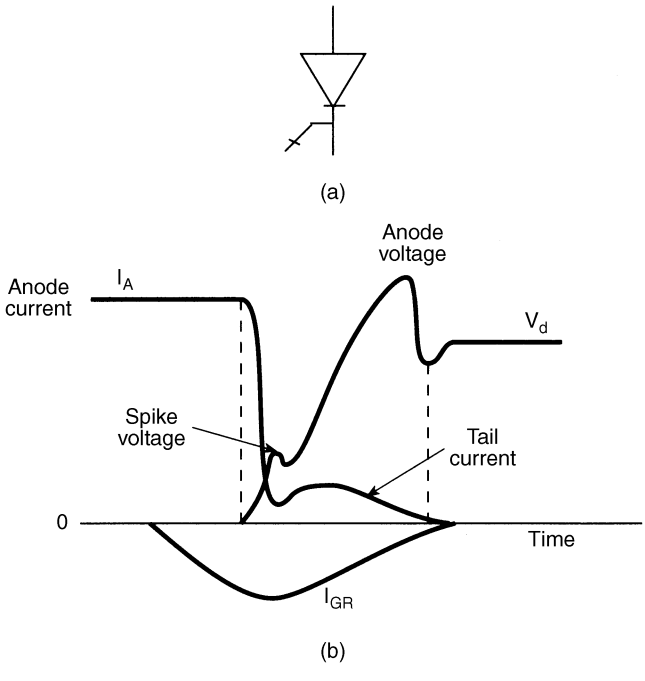
From Iqbal, T., Fiber optics sensors, in *The Handbook of Optical Communication Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. 411.



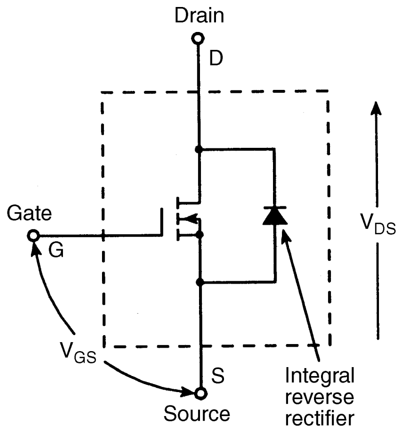
(a) Thyristor symbol and (b) volt-ampere characteristics. (From Rajashekara, K., Overview, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-2. Originally from Bose, B.K., *Modern Power Electronics: Evaluation, Technology, and Applications,* p. 5 © 1992 IEEE. With permission.)



(a) Triac symbol and (b) volt-ampere characteristics. (From Rajashekara, K., Overview, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-3. Originally from Bose, B.K., *Modern Power Electronics: Evaluation, Technology, and Applications,* p. 5 © 1992 IEEE. With permission.)



(a) GTO symbol and (b) turn-off characteristics. (From Rajashekara, K., Overview, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-4. Originally from Bose, B.K., *Modern Power Electronics: Evaluation, Technology, and Applications,* p. 5 © 1992 IEEE. With permission.)



Power MOSFET circuit symbol. (From Rajashekara, K., Overview, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-6. Originally from Bose, B.K., *Modern Power Electronics: Evaluation, Technology, and Applications,* p. 7 © 1992 IEEE. With permission.)

Total Elongation at Failure of Selected Polymers

Polymer	Elongation
ABS	5–20
Acrylic	2–7
Epoxy	4.4
HDPE	700–1000
Nylon, type 6	30–100
Nylon 6/6	15–300
Phenolic	0.4–0.8
Polyacetal	25
Polycarbonate	110
Polyester	300
Polypropylene	100–600
PTFE	250–350

From Whitaker, J.C., Fundamental electrical properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 10.

Tensile Strength of Selected Wrought Aluminum Alloys

Alloy	Temper	TS (MPa)
1050	0	76
1050	H16	130
2024	0	185
2024	T361	495
3003	0	110
3003	H16	180
5050	0	145
5050	H34	195
6061	0	125
6061	T6, T651	310
7075	0	230
7075	T6, T651	570

From Whitaker, J.C., Fundamental electrical properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 10.

Density of Selected Materials, mg/m^3

Metal		Ceramic		Glass		Polymer	
Ag	10.50	Al_2O_3	3.97–3.986	SiO_2	2.20	ABS	1.05–1.07
Al	2.7	BN(cub)	3.49	SiO_2 10 wt% Na_2O	2.291	Acrylic	1.17–1.19
Au	19.28	BeO	3.01–3.03	SiO_2 19.55 wt% Na_2O	2.383	Epoxy	1.80–2.00
Co	8.8	MgO	3.581	SiO_2 29.20 wt% Na_2O	2.459	HDPE	0.96
Cr	7.19	SiC(hex)	3.217	SiO_2 39.66 wt% Na_2O	2.521	Nylon, type 6	1.12–1.14
Cu	8.93	$Si_3N_4(\alpha)$	3.184	SiO_2 39.0 wt% CaO	2.746	Nylon 6/6	1.13–1.15
Fe	7.87	Si_3N_4 (β)	3.187			Phenolic	1.32–1.46
Ni	8.91	TiO_2 (rutile)	4.25			Polyacetal	1.425
Pb	11.34	UO_2	10.949–10.97			Polycarbonate	1.2
Pt	21.44	ZrO_2 (CaO)	5.5			Polyester	1.31
Ti	4.51	Al_2O_3 MgO	3.580			Polystyrene	1.04
W	19.25	$3Al_2O_3$ $2SiO_2$	2.6–3.26			PTFE	2.1–2.3

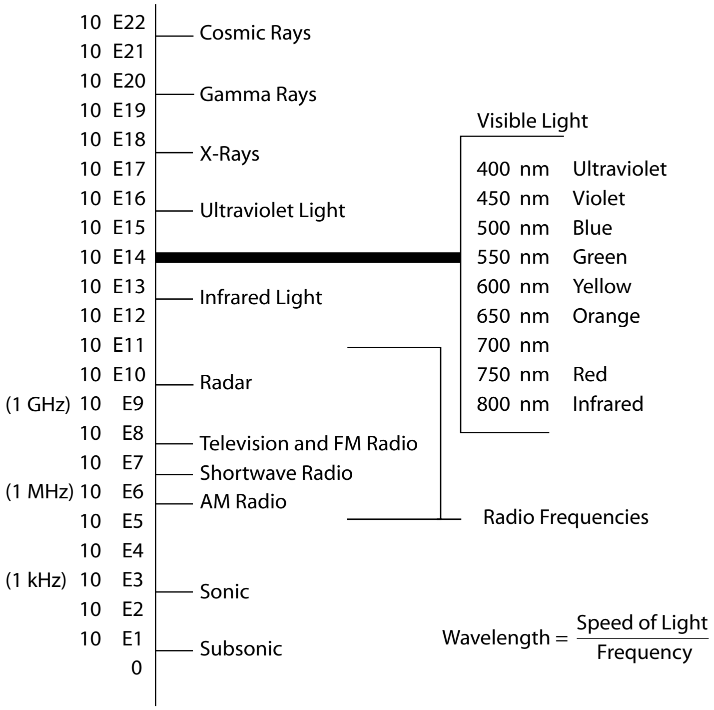
From Whitaker, J.C., Fundamental electrical properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p.11.

Applications in the Microwave Bands

Aeronavigation:	0.96–1.215 GHz
Global positioning system (GPS) down link:	1.2276 GHz
Military communications (COM)/radar:	1.35–1.40 GHz
Miscellaneous COM/radar:	1.40–1.71 GHz
L-band telemetry:	1.435–1.535 GHz
GPS downlink:	1.57 GHz
Military COM (troposcatter/telemetry):	1.71–1.85 GHz
Commercial COM and private line of sight (LOS):	1.85–2.20 GHz
Microwave ovens:	2.45 GHz
Commercial COM/radar:	2.45–2.69 GHz
Instructional television:	2.50–2.69 GHz
Military radar (airport surveillance):	2.70–2.90 GHz
Maritime navigation radar:	2.90–3.10 GHz
Miscellaneous radars:	2.90–3.70 GHz
Commercial C-band satellite (SAT) COM downlink:	3.70–4.20 GHz
Radar altimeter:	4.20–4.40 GHz
Military COM (troposcatter):	4.40–4.99 GHz
Commercial microwave landing system:	5.00–5.25 GHz
Miscellaneous radars:	5.25–5.925 GHz
C-band weather radar:	5.35–5.47 GHz
Commercial C-band SAT COM uplink:	5.925–6.425 GHz
Commercial COM:	6.425–7.125 GHz
Mobile television links:	6.875–7.125 GHz
Military LOS COM:	7.125–7.25 GHz
Military SAT COM downlink:	7.25–7.75 GHz
Military LOS COM:	7.75–7.9 GHz
Military SAT COM uplink:	7.90–8.40 GHz
Miscellaneous radars:	8.50–10.55 GHz
Precision approach radar:	9.00–9.20 GHz
X-band weather radar (and maritime navigation radar):	9.30–9.50 GHz
Police radar:	10.525 GHz
Commercial mobile COM [LOS and electronic news gathering (ENG)]:	10.55–10.68 GHz
Common carrier LOS COM:	10.70–11.70 GHz
Commercial COM:	10.70–13.25 GHz
Commercial Ku-band SAT COM downlink:	11.70–12.20 GHz
Direct broadcast satellite (DBS) downlink and private LOS COM:	12.20–12.70 GHz
ENG and LOS COM:	12.75–13.25 GHz
Miscellaneous radars and SAT COM:	13.25–14.00 GHz
Commercial Ku-band SAT COM uplink:	14.00–14.50 GHz
Military COM (LOS, mobile, and Tactical):	14.50–15.35 GHz
Aeronavigation:	15.40–15.70 GHz
Miscellaneous radars:	15.70–17.70 GHz
DBS uplink:	17.30–17.80 GHz

From Whitaker, J.C., Electromagnetic spectrum, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 31.

The Electromagnetic Spectrum



From Whitaker, J.C., Light, vision, and photometry, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 154.

Typical Luminance Values

Illumination	Illuminance, ft-L
Sun at zenith	4.82×10^8
Perfectly reflecting, diffusing surface in sunlight	9.29×10^3
Moon, clear sky	2.23×10^3
Overcast sky	$9–20 \times 10^2$
Clear sky	$6–17.5 \times 10^2$
Motion-picture screen	10

From Whitaker, J.C., Light, vision, and photometry, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 166. After Fink, D.G., *Television Engineering*, 2nd ed., McGraw-Hill, New York, 1952.

Resistivity of Selected Ceramics

Ceramic	Resistivity, Ω · cm
Borides	
Chromium diboride (CrB_2)	21×10^{-6}
Hafnium diboride (HfB_2)	$10 - 12 \times 10^{-6}$ at room temp.
Tantalum diboride (TaB_2)	68×10^{-6}
Titanium diboride (TiB_2) (polycrystalline)	
85% dense	$26.5–28.4 \times 10^{-6}$ at room temp.
85% dense	9.0×10^{-6} at room temp.
100% dense, extrapolated values	$8.7–14.1 \times 10^{-6}$ at room temp.
	3.7×10^{-6} at liquid air temp.
Titanium diboride (TiB2) (monocrystalline)	
Crystal length 5 cm, 39 deg. and 59 deg. orientation with respect to growth axis	$6.6 + 0.2 \times 10^{-6}$ at room temp.
Crystal length 1.5 cm, 16.5 deg. and 90 deg. orientation with respect to growth axis	$6.7 \pm 0.2 \times 10^{-6}$ at room temp.
Zirconium diboride (ZrB_2)	9.2×10^{-6} at 20°C
	1.8×10^{-6} at liquid air temp.
Carbides: boron carbide (B_4C)	0.3–0.8

From Whitaker, J.C., Resistors and resistive materials, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 187.

Properties of Magnetic Materials and Magnetic Alloys

Material (Composition)	Initial Relative Permeability, μ_i/μ_0	Maximum Relative Permeability, μ_{max}/μ_0	Coercive Force H_e, A/m (Oe)	Residual Field B_r, Wb/m² (G)	Saturation Field B_s, Wb/m² (G)	Electrical Resistivity $\rho \times 10^{-8}$ Ω · m	Uses
			Soft				
Commercial iron (0.2 imp.)	250	9000	≈80 (1)	0.77 (7700)	2.15 (21,500)	10	Relays
Purified iron (0.05 imp.)	10,000	200,000	4 (0.05)	—	2.15 (21,500)	10	
Silicon-iron (4 Si)	1500	7000	20 (0.25)	0.5 (5000)	1.95 (19,500)	60	Transformers
Silicon-iron (3 Si)	7500	55,000	8 (0.1)	0.95 (9500)	2 (20,000)	50	Transformers
Silicon-iron (3 Si)	—	116,000	4.8 (0.06)	1.22 (12,200)	2 (20,100)	50	Transformers
Mu metal (5 Cu, 2 Cr, 77 Ni)	20,000	100,000	4 (0.05)	0.23 (2300)	0.65 (6500)	62	Transformers
78 Peralloy (78.5 Ni)	8000	100,000	4 (0.05)	0.6 (6000)	1.08 (10,800)	16	Sensitive relays
Supermalloy (79 Ni, 5 Mo)	100,000	1,000,000	0.16 (0.002)	0.5 (5000)	0.79 (7900)	60	Transformers
Permendur (50 Cs)	800	5000	160 (2)	1.4 (14,000)	2.45 (24,500)	7	Electromagnets
Mn-Zn ferrite	1500	2500	16 (0.2)	—	0.34 (3400)	20×10^6	Core material for coils
Ni-Zn ferrite	2500	5000	8 (0.1)	—	0.32 (3200)	10^{11}	

From Whitaker, J.C., Inductors and magnetic properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 216. After Plonus, M.A., *Applied Electromagnetic*, McGraw-Hill, New York, 1978.

Thermal Conductivity of Common Materials

Material	Btu/(hu·ft·°F)	W/(m·°C)
Silver	242	419
Copper	228	395
Gold	172	298
Beryllia	140	242
Phosphor bronze	30	52
Glass (borosilicate)	0.67	1.67
Mylar	0.11	0.19
Air	0.015	0.026

From Whitaker, J.C., Thermal properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 234.

Relative Thermal Conductivity of Various Materials As a Percentage of the Thermal Conductivity of Copper

Material	Relative Conductivity
Silver	105
Copper	100
Berlox high-purity BeO	62
Aluminum	55
Beryllium	39
Molybdenum	39
Steel	9.1
High-purity alumina	7.7
Steatite	0.9
Mica	0.18
Phenolics, epoxies	0.13
Fluorocarbons	0.05

From Whitaker, J.C., Thermal properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 235.

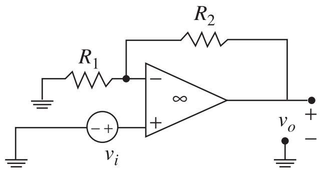
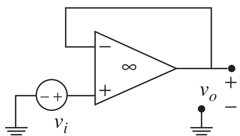
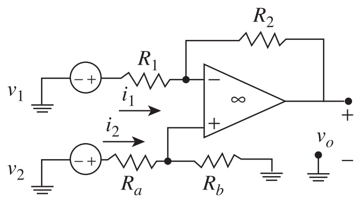
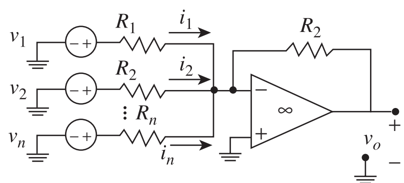
Variation of Electrical and Thermal Properties of Common Insulators As a Function of Temperature

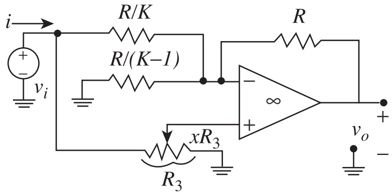
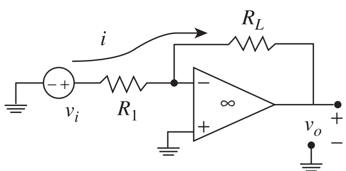
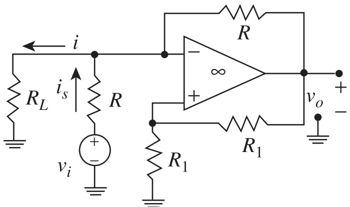
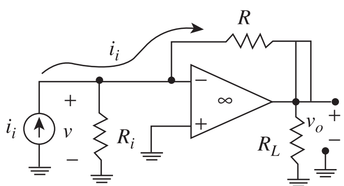
Parameters		20°C	120°C	260°C	400°C	538°C
Thermal conductivity[1]	99.5% BeO	140	120	65	50	50
	99.5% Al_2O_3	20	17	12	7.5	6
	95.0% Al_2O_3	13.5				
	Glass	0.3				
Power dissipation[2]	BeO	2.4	2.1	1.1	0.9	0.7
Electrical resistivity[3]	BeO	10^{16}	10^{14}	5×10^{12}	10^{12}	10^{11}
	Al_2O_3	10^{14}	10^{14}	10^{12}	10^{12}	10^{11}
	Glass	10^{12}	10^{10}	10^{8}	10^{6}	
Dielectric constant[4]	BeO	6.57	6.64	6.75	6.90	7.05
	Al_2O_3	9.4	9.5	9.6	9.7	9.8
Loss tangent[4]	BeO	0.00044	0.00040	0.00040	0.00049	0.00080

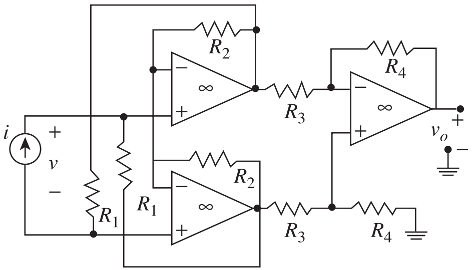
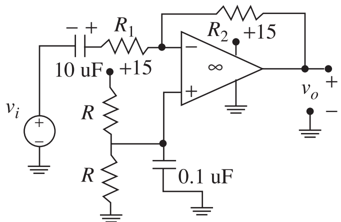
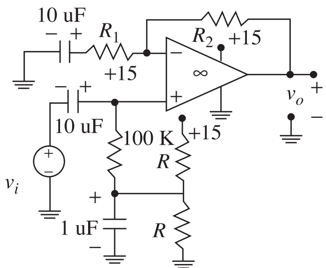
[1] Heat transfer in Btu/ft²/hr/°F
[2] Dissipation in W/cm/°C
[3] Resistivity in Ω-cm
[4] At 8.5 GHz

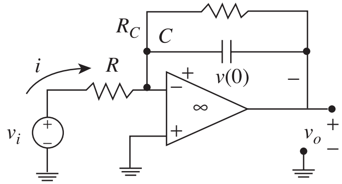
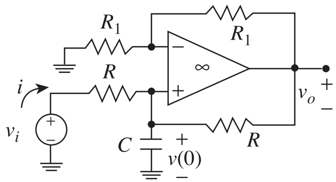
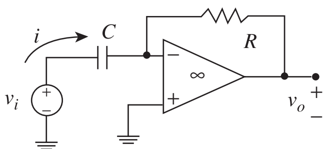
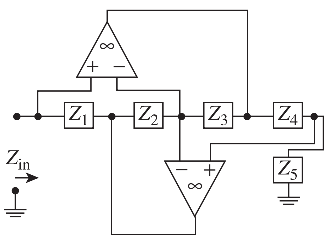
From Whitaker, J.C., Thermal properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 239.

Common Op-Amp Circuits

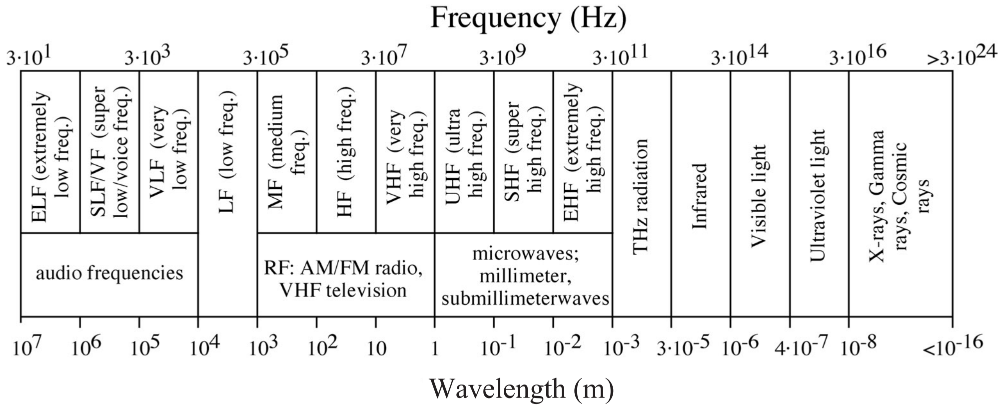
No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
1.	Noninverting amplifier		$\frac{v_o}{v_i} = 1 + \frac{R_2}{R_1}$	$R_{in} = \infty$ (ideally)	
2.	Buffer		$\frac{v_o}{v_i} = 1$	$R_{in} = \infty$ (ideally)	Special care of circuit 1
3.	Difference amplifier		$v_o = \frac{R_2}{R_1}(v_2 - v_1)$	$i_1 = \frac{v_1 - v_2 \frac{R_b}{(R_a + R_b)}}{R_1}$ $i_2 = \frac{v_2}{R_a + R_b}$	$\frac{R_1}{R_2} = \frac{R_a}{R_b}$
4.	Adder		$v_o = -\left\{ v_1 \frac{R_f}{R_1} + v_2 \frac{R_f}{R_2} + \cdots + v_n \frac{R_f}{R_n} \right\}$	$i_1 = \frac{v_1}{R_1}$ $i_2 = \frac{v_2}{R_2}$ $\vdots$ $i_n = \frac{v_n}{R_n}$	

No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
5.	Variable gain circuit		$\frac{v_o}{v_i} = (2Kx - K)$ $0 \le x \le 1, \quad K > 1$	$i = \frac{v_1}{R_3} + \frac{K v_i (1-x)}{R}$	Potentiometer R_3 adjusts the gain over the range –K to +K.
6.	Voltage-to-current converter		$i = \frac{v_1}{R_1}$		The current through R_L is independent of R_L
7.	Voltage-to-current converter with grounded load		$i = \frac{v_i}{R}$	$i_s = \frac{v_i}{R}\left(1 - \frac{R_L}{R}\right)$	$v_0 = v_i\ (2R_L/R)$. The current i is independent of R_L. Circuit has wide band-with for $R_L \ll R$.
8.	Current-to-voltage converter		$v_0 = Ri_i$	$v = 0$	The voltage v_0 is independent of R_L and R_i

No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
9.	Current-to-voltage converter		$v_o = -2iR_1 \frac{R_4}{R_3}$	$v = 0$	
10.	Inverting amplifier with single supply		$v_o = 7.5 - v_i \frac{R_2}{R_1}$		$R = 3.9\ k\Omega$
11.	Noninverting amplifier with single supply		$v_o = 7.5 + v_i\left(1+\frac{R_2}{R_1}\right)$		$R = 3.9\ k\Omega$

No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
12.	Integrator		$\nu_o = -V(0) - \frac{1}{RC}\int_0^t \nu_i(t)dt$ $V(0)$ is the initial voltage across the capacitor. RC is very large.	$i = \frac{\nu_i}{R}$	Negative feedback is required at DC. A large value of R_C can be used or a feedback path can be established through an external circuit.
13.	DeBoo integrator		$\nu_o = 2V(0) + \frac{2}{RC}\int_0^t \nu_i(t)dt$	$i = \frac{\nu_i}{R} - \frac{\nu_o}{2R}$	One end of capacitor is physically grounded.
14.	Differentiator		$\nu_o = -RC\frac{d\nu_i}{dt}$	$i = C\frac{d\nu_i}{dt}$	Differentiators are usually avoided in the design of circuits because they accentuate noise.
15.	Generalized impedance converter (GIC)		$Z_{in} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}$		

From Whitaker, J.C., Analog circuits, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, pp. 267–269.



Electromagnetic frequency spectrum and associated wavelengths. (From Fay, P., Introduction, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **1**-2.)

Modulation Schemes, Glossary of Terms

Abbreviation	Description	Remarks/Use
ACSSB	Amplitude Companded Single SideBand	Satellite transmission
AM	Amplitude Modulation	Broadcasting
APK	Amplitude Phase Keying modulation	
BLQAM	Blackman Quadrature Amplitude Modulation	
BPSK	Binary Phase Shift Keying	Spread spectrum systems
CPFSK	Continuous Phase Frequency Shift Keying	
CPM	Continuous Phase Modulation	
DEPSK	Differentially Encoded PSK (with carrier recovery)	
DPM	Digital Phase Modulation	
DPSK	Differential Phase Shift Keying (no carrier recovery)	
DSB-AM	Double SideBand Amplitude Modulation	
DSB-SC-AM	Double SideBand Suppressed Carrier AM	Includes digital schemes
FFSK	Fast Frequency Shift Keying ≡ MSK	NMT data and control
FM	Frequency Modulation	Broadcasting, AMPS, voice
FSK	Frequency Shift Keying	AMPS data and control
FSOQ	Frequency Shift Offset Quadrature modulation	
GMSK	Gaussian Minimum Shift Keying	GSM voice, data, and control
GTFM	Generalized Tamed Frequency Modulation	
HMQAM	Hamming Quadrature Amplitude Modulation	
IJF	Intersymbol Jitter Free ≡ SQORC	
LPAM	L-ary Pulse Amplitude Modulation	
LRC	LT symbols long Raised Cosine pulse shape	
LREC	LT symbols long Rectangularly EnCoded pulse shape	
LSRC	LT symbols long Spectrally Raised Cosine scheme	
MMSK	Modified Minimum Shift Keying ≡ FFSK	
MPSK	M-ary Phase Shift Keying	
MQAM	M-ary Quadrature Amplitude Modulation	A subclass of DSB-SC-AM
MQPR	M-ary Quadrature Partial Response	Radio-relay transmission
MQPRS	M-ary Quadrature Partial Response System ≡ MQPR	
MSK	Minimum Shift Keying	
m-*h*	multi-*h* CPM	
OQPSK	Offset (staggered) Quadrature Phase Shift Keying	
PM	Phase Modulation	Low capacity radio
PSK	Phase Shift Keying	4PSK ≡ QPSK
QAM	Quadrature Amplitude Modulation	

Modulation Schemes, Glossary of Terms (continued)

Abbreviation	Description	Remarks/Use
QAPSK	Quadrature Amplitude Phase Shift Keying	
QPSK	Quadrature Phase Shift Keying ≡ 4 QAM	Low capacity radio
QORC	Quadrature Overlapped Raised Cosine	
SQAM	Staggered Quadrature Amplitude Modulation	
SQPSK	Staggered Quadrature Phase Shift Keying	
SQORC	Staggered Quadrature Overlapped Raised Cosine	
SSB	Single SideBand	Low and High capacity radio
S3MQAM	Staggered class 3 Quadrature Amplitude Modulation	
TFM	Tamed Frequency Modulation	
TSI QPSK	Two-Symbol-Interval QPSK	
VSB	Vestigial SideBand	TV
WQAM	Weighted Quadrature Amplitude Modulation	Includes most digital schemes
XPSK	Crosscorrelated PSK	
π/4 DQPSK	π/4 shift DQPSK with $\alpha = 0.35$ raised cosine filtering	IS-54 TDMA voice and data
3MQAM	Class 3 Quadrature Amplitude Modulation	
4MQAM	Class 4 Quadrature Amplitude Modulation	
12PM3	12 state PM with 3 bit correlation	

Source: 4U Communications Research Inc., 2000.06.10~00:09, c:/tab/modulat.tab

From Kucar, A.D., Nomadic communications, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **2**-33.

Radar Bands

Band	Frequency Range	Principal Applications
HF	3–30 MHz	Over-the-horizon radar
VHF	30–300 MHz	Long-range search
UHF	300–1000 MHz	Long-range surveillance
L	1000–2000 MHz	Long-range surveillance
S	2000–4000 MHz	Surveillance
		Long-range weather characterization
		Terminal air traffic control
C	4000–8000 MHz	Fire control
		Instrumentation tracking
X	8–12 GHz	Fire control
		Air-to-air missile seeker
		Marine radar
		Airborne weather characterization
Ku	12–18 GHz	Short-range fire control
		Remote sensing
Ka	27– 40 GHz	Remote sensing
		Weapon guidance
V	40–75 GHz	Remote sensing
		Weapon guidance
W	75–110 GHz	Remote sensing
		Weapon guidance

From Belcher Jr., M.L. and Nessmith, J.T., Pulse radar, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **2**-183.

Thermal Conductivities of Typical Metals (W/m K) at Room Temperature

Metal	Thermal Conductivity
Silver	419
Copper	395
Gold	298
Aluminum	156
Brass	101
Lead	32
Kovar	17

From Golio, M., Materials properties — Metals, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **9**-68.

Thermal Coefficient of Linear Expansion of Some of the Materials Used in Microwave and RF Packaging Applications (at Room Temperature, in 10^{-6}/K)

Material	Thermal Coefficient of Expansion
Dielectrics	
Aluminum nitride	4
Alumina 96%	6
Beryllia	6.5
Diamond	1
Glass-ceramic	4–8
Quartz (fuzed)	0.54
Metals	
Aluminum	23
Beryllium	12
Copper	16.5
Gold	14.2
Kovar	5.2
Molybdenum	5.2
Nickel	13.3
Platinum	9
Silver	18.9
Semiconductors	
GaAs	5.9
Silicon	2.6
Silicon Carbide	2.2

From Golio, M., Materials properties — Metals, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **9**-69.

Properties of Some Typical Engineering Insulating Materials

Material	k	Loss	Frequency	Resistivity
Vacuum	1.00	0	All	Zero
Air	1.0006	0		
Glass Vycor 7910	3.8	$9.1*10^{-4}$		
Glass Corning 0080	6.75	$5.8*10^{-2}$		
Al_2O_3	8.5	10^{-3}	1 MHz	
Teflon (PTFE)	2.0	$2*10^{-4}$	1 MHz	10^{17}
Arlon 25N circuit board	3.28	$2.5*10^{-3}$	1 MHz	
Epoxy-glass circuit board	4.5			
Beryllium oxide	7.35			
Diamond	5.58			10^{16}
PZT (lead zirconium oxide)	~1000			
Undoped silicon	11.8			
TaO_5	28			
Quartz (SiO_2)	3.75–4.1	$2*10^{-4}$		
Mica (Ruby)	6.5–8.7	$3.5*10^{-4}$		
Water	78.2	0.04	1 MHz	

From Golio, M., Materials properties — Metals, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **9**-72.

Selected Material Properties of Semiconductors for Microwave and RF Applications

Property	Si	SiC	InP	GaAs	GaN
Atoms/cm^3	5.0×10^{22}	3.95×10^{22}	4.43×10^{22}	4.96×10^{22}	
Atomic weight	28.09	40.1	72.90	72.32	41.87
Breakdown Field (V/cm)	3×10^5 [32]	20×10^4 3C-SiC[27] 30×10^5 4H-SiC[27]	5×10^5 [32]	6×10^5	$>10 \times 10^5$
Crystal structure	Diamond	Zincblende	Zincblende	Zincblende	Wurtzite
Density (g/cm^3)	2.3283[23]	4.787[23]	5.316[33]	6.1[23]	
Dielectric constant	11.8[23]	9.75[17] 9.66[18]	12.4[23]	12.5[23]	9[35]
Effective mass m^*/m_0 Electron	1.1	0.37 3C-SiC[19] 0.45 6H-SiC[20]	0.067[23]	0.068[23]	0.22[35,36]
Electron Affinity, eV	4.05[31]	—	4.38[31]	4.07[31]	3.4[34]
Energy Gap (eV) at 300 K	1.107[23]	2.403 3C-SiC[23] 3.101 6H-SiC[23]	1.29[31]	1.35[31]	3.34[37]
Intrinsic carrier concentration (cm^{-3})	1.45×10^{10} [23]	3×10^6 3C-SiC[21] 10^{15}–10^{16} 6H-SiC[22]	1.6×10^7 [23]	1.8×10^6 [23]	$3\text{-}6 \times 10^9$ [23]
Lattice constant (Angstroms)	5.431[31]	4.3596[27]	5.860[31]	5.651[31]	3.190[38]
Linear Coeff. of thermal expansion (10^{-6} K^{-1})	2.49[23]	5.48[22]	4.6[23]	5.4[23]	5.6[27]
Melting point (K)	1685[23]	3070[23]	1335[31]	1511[31]	—
Electron mobility (cm^2/V-S) μ_m	1900[23]	1000 3C-SiC[24] 600 6H-SiC[24]	4600[23]	8800[23]	1000[39]
Holes mobility μ_p (cm^2/V-S)	500[23]	40 3C-SiC[24] 40 6H-SiC[24]	150[23]	400[23]	30[39]
Optical phonon energy (eV)	0.063 eV[31]	—	0.43[31]	0.35[31]	.912[40]
Refractive index	3.42[23]	2.65 3C-SiC[25] 2.72 6H-SiC[26]	3.1[31]	3.66[31]	2.7[41] (at band edge)
Resistivity, intrinsic (Ω-cm)	1000[31]	150 3C-SiC[27] $>10^{12}$ 4H-SiC[27]	8.2×10^7 [31]	3.8×10^8 [31]	$>10^{13}$ [27]
Specific heat (J/kg°K)	702[23]	640[28]	310[31]	325[32]	847.39[42]
Thermal conductivity at 300°K (Watt/cm°K)	1.24[23]	3.2 3C-SiC[29] 4.9 6H-SiC[30]	0.77[32]	0.56[31]	1.3[43]

From Harris, M., Materials properties — semiconductors, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **9**-105.

Channel Designations for VHF and UHF Television Stations in the U.S.

Channel Designation	Frequency Band (MHz)	Channel Designation	Frequency Band (MHz)	Channel Designation	Frequency Band (MHz)
2	54–60	30	566–572	57	728–734
3	60–66	31	572–578	58	734–740
4	66–72	32	578–584	59	740–746
5	76–82	33	584–590	60	746–752
6	82–88	34	590–596	61	752–758
7	174–180	35	596–602	62	758–764
8	180–186	36	602–608	63	764–770
9	186–192	37	608–614	64	770–776
10	192–198	38	614–620	65	776–782
11	198–204	39	620–626	66	782–788
12	204–210	40	626–632	67	788–794
13	210–216	41	632–638	68	794–800
14	470–476	42	638–644	69	800–806
15	476–482	43	644–650	70	806–812
16	482–488	44	650–656	71	812–818
17	488–494	45	656–662	72	818–824
18	494–500	46	662–668	73	824–830
19	500–506	47	668–674	74	830–836
20	506–512	48	674–680	75	836–842
21	512–518	49	680–686	76	842–848
22	518–524	50	686–692	77	848–854
23	524–530	51	692–698	78	854–860
24	530–536	52	698–704	79	860–866
25	536–542	53	704–710	80	866–872
26	542–548	54	710–716	81	872–878
27	548–554	55	716–722	82	878–884
28	554–560	56	722–728	83	884–890
29	560–566				

From Whitaker, J.C., Applications of RF technology, in *The RF Transmission Systems Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-16.

Radar Frequency Bands

Name	Frequency Range	Radiolocation Bands based on ITU Assignments in Region II
VHF	30–300 MHz	137–144 MHz
UHF	300–1,000 MHz	216–225 MHz
P-band[b]	230–1,000 MHz	420–450 MHz
		890–940[a] MHz
L-band	1,000–2,000 MHz	1,215–1,400 MHz
S-band	2,000–4,000 MHz	2,300–2,550 MHz
		2,700–3,700 MHz
C-band	4,000–8,000 MHz	5,255–5,925 MHz
X-band	8,000–12,500 MHz	8,500–10,700 MHz
Ku-band	12.5–18 GHz	13.4–14.4 GHz
		15.7–17.7 GHz
K-band	18–26.5 GHz	23–24.25 MHz
Ka-band	26.5–40 GHz	33.4–36 MHz
Millimeter	>40 GHz	

[a] Sometimes included in L-band.

[b] Seldom used nomenclature.

From Whitaker, J.C., Applications of RF technology, in *The RF Transmission Systems Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-31. Originally from Fink, D. and Christiansen, Eds., *Electronics Engineers' Handbook*, 3rd ed., McGraw-Hill, New York, 1989, Table 302. IEEE standard 521–1976.

Common-Carrier Microwave Frequencies Used in the U.S.

Band (GHz)	Allotted Frequencies (MHz)	Bandwidth (MHz)	Application
2	2110–2130	20	Limited
	2160–2180		
4	3700–4200	20	Major long-haul microwave relay band
6	5925–6425	500	Long and short haul
11	10,700–11,700	500	Short haul
18	17,700–19,700	1000	Short haul, limited use
30	27,500–29,500	2000	Short haul, experimental

From Whitaker, J.C., Applications of RF technology, in *The RF Transmission Systems Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-35.

Comparison of Amplitude Modulation Techniques

Modulation Scheme	Advantages	Disadvantages	Comments
DSB-SC	Good power efficiency. Good low-frequency response.	More difficult to generate than DSB+C. Detection requires coherent local oscillator, pilot, or phase-locked loop (PLL). Poor spectrum efficiency.	
DSB+C (AM)	Easier to generate than DSB-SC, especially at high-power levels. Inexpensive receivers using envelope detection.	Poor power efficiency. Poor spectrum efficiency. Poor low-frequency response. Exhibits threshold effect in noise.	Used in commercial AM.
SSB-SC	Excellent spectrum efficiency.	Complex transmitter design. Complex receiver design (same as DSB-SC). Poor low-frequency response.	Used in military communication systems, and to multiplex multiple phone calls onto long-haul microwave links.
SSB+SC	Good spectrum efficiency. Low receiver complexity.	Poor power efficiency. Complex transmitters. Poor low-frequency response. Poor noise performance.	
VSB-SC	Good spectrum efficiency. Excellent low-frequency response. Transmitter easier to build than for SSB.	Complex receivers (same as DSB-SC).	
VSB+C	Good spectrum efficiency. Good low-frequency response. Inexpensive receivers using envelope detection.	Poor power efficiency. Poor performance in noise.	Used in commercial TV.
QAM	Good low-frequency response. Good spectrum efficiency.	Complex receivers. Sensitive to frequency and phase errors.	Two SSB signals may be preferable.

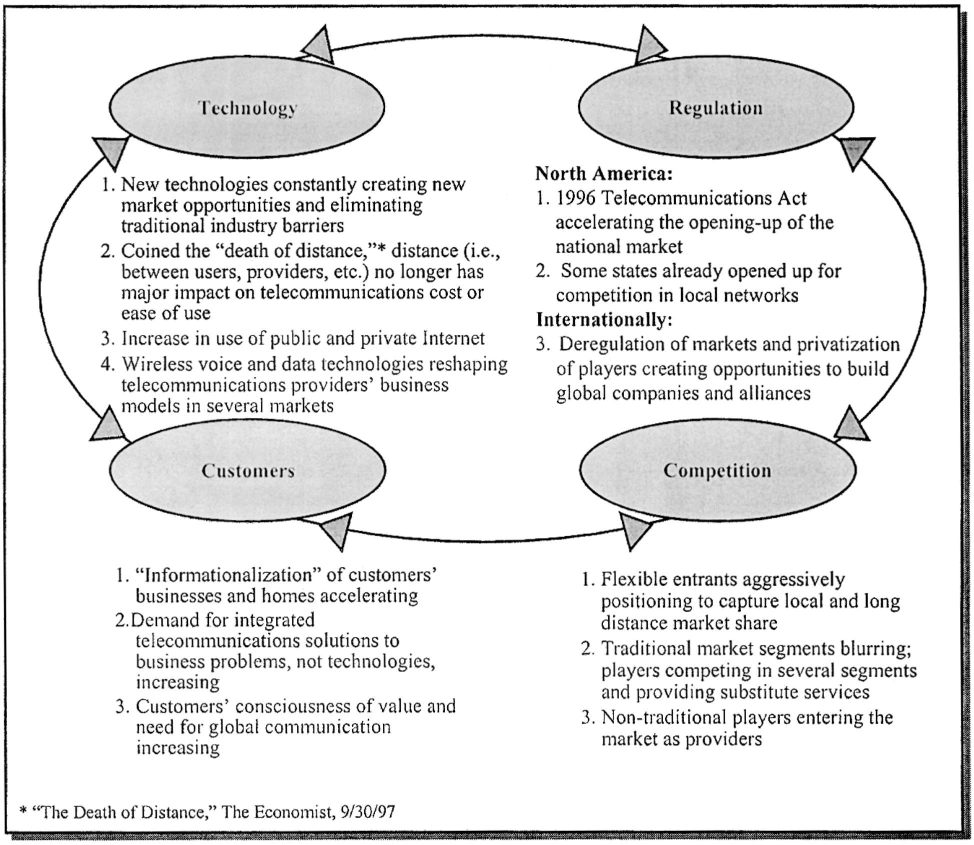
From Kubichek, R., Amplitude modulation, in *The RF Transmission Systems Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **3**-14.

Representative Specifications for Various Types of Flexible Air-Dielectric Coaxial Cable

Cable Size (in.)	Maximum Frequency (MHz)	Velocity (%)	Peak Power 1 MHz (kW)	Average Power 100 MHz (kW)	Average Power 1 MHz (kW)	Attenuation[a] 100 MHz (dB)	Attenuation[a] 1 MHz (dB)
$1\frac{5}{8}$	2.7	92.1	145	145	14.4	0.020	0.207
3	1.64	93.3	320	320	37	0.013	0.14
4	1.22	92	490	490	56	0.010	0.113
5	0.96	93.1	765	765	73	0.007	0.079

[a] Attenuation specified in dB/100 ft.

From Whitaker, J.C., Coaxial transmission lines, in *The RF Transmission Systems Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **12**-7.



Four drivers of change in telecommunications. (From Wery, B., Growth strategies for telecommunications operators, in *The Telecommunications Handbook,* Terplan, K. and Morreale, P., CRC Press, Boca Raton, FL, 2000, p. **1**-35.)

Summary and Comparison of Second-Generation TDMA-Based System Parameters

	Europe (GSM)	North America (IS-54/136)	Japan (PDC)
Access method	TDMA	TDMA	TDMA
Carrier spacing	200 kHz	30 kHz	25 kHz
Users per carrier	8 (16)	3 (6)	3 (tbd)
Modulation	GMSK	π/4-DQPSK	π/4-DQPSK
Voice codec	RPE 13 kbps	VSELP 7.95 kbps	VSELP 6.7 kbps
Voice frame	20 ms	20 ms	20 ms
Channel code	Convolutional	Convolutional	Convolutional
Coded bit rate	22.8 kbps	13 kbps	11.2 kbps
TDMA frame duration	4.6 ms	20 ms	20 ms
Interleaving	40 ms	27 ms	27 ms
ACCH	Extra slot	In slot	In slot
Handoff	MAHO	MAHO	MAHO

From Zori, M., Mobile and wireless telecommunications networks, in *The Telecommunications Handbook,* Terplan, K. and Morreale, P., Eds., CRC Press, Boca Raton, FL, 2000, p. **2**-48.

Some Milestones for Multimedia

1982	Introduction of compact disk — consumer audio
1984	Introduction of CD-ROMs; Macintosh GUIs
1986	Initial CD-I (Compact Disk Interactive) specification; Microsoft Windows
1987	DVI (digital video interactive) technology announced
1988	Erasable optical disks; initial ATM standards
1990	MPC (multimedia PC) standard; IMA (Interactive Multimedia Association) Compatibility Project; commercial multimedia applications
1992	ATM-based LAN development (155 Mbps to the desktop); FDDI 100 Mbps connections possible for less than $1000
1994	Wide-area ATM networks; networked multimedia systems and applications
1995	New low-speed voice compression standards (e.g., G.729, G.723.1, G.729A) and other interoperability standards for desktop multimedia are developed; also, DVD launched, H.323 developed
1998	Increased penetration of multimedia in corporate America for "mission-critical" applications; by then, IP had become ubiquitous in intranets and in the Internet; multimedia over LANs sees penetration

From Minoli, D., Minoli, E., and Sookchand, L., Video communications, in *The Telecommunications Handbook,* Terplan, K. and Morreale, P., Eds., CRC Press, Boca Raton, FL, 2000, p. **4**-8.

Comparison of Interconnect Characteristics for Al and Cu

Material	Specific Resistance (μΩ-cm)	Melting Point (°C)
Al	2.66	660
Cu	1.68	1073

From Shenai, K. and McShane, E., VLSI technology: A system perspective, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-8.

Comparison of High-Permittivity Constant Materials for DRAM Cell Capacitors

Material	Dielectric Constant	Minimum Equivalent Oxide Thickness (nm)
NO	7	3.5 to 4
Ta_2O_5	20–25	2 to 3
BST	200–400	?

From Shenai, K. and McShane, E., VLSI technology: A system perspective, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-11.

Summary of Some Architectures and Applications Possible from a Molecular Computing System

Mechanisms and Architectures	Applications
Light-energy transducing proteins	Biosensors
Light-energy transducing proteins (with controlled switching)	Organic memory storage
Optoelectronic transducing	Pattern recognition and processing
Evolutionary structures	Adaptive control

From Shenai, K. and McShane, E., VLSI technology: A system perspective, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-19.

Comparison of Selected Important Semiconductors of Major SiC Polytypes with Silicon and GaAs

Property	Silicon	GaAs	4H-SiC	6H-SiC	3C-SiC
Bandgap (eV)	1.1	1.42	3.2	3.0	2.3
Relative dielectric constant	11.9	13.1	9.7	9.7	9.7
Breakdown field $N_D = 10^{17}$ cm^{-3} (MV/cm)	0.6	0.6	//*c*-axis: 3.0	// *c*-axis: 3.2 ⊥*c*-axis: >1	>1.5
Thermal conductivity (W/cm-K)	1.5	0.5	3–5	3–5	3–5
Intrinsic carrier concentration (cm^{-3})	10^{10}	1.8×10^6	$\sim 10^{-7}$	$\sim 10^{-5}$	~10
Electron mobility @ $N_D = 10^{16}$ cm^{-3} (cm^2/V-s)	1200	6500	//*c*-axis: 800 ⊥*c*-axis: 800	//*c*-axis: 60 ⊥*c*-axis: 400	750
Hole mobility @ $N_A = 10^{16}$ cm^{-3} (cm^2/V-s)	420	320	115	90	40
Saturated electron velocity (10^7 cm/s)	1.0	1.2	2	2	2.5
Donor dopants and shallowest ionization energy (meV)	P: 45 As: 54	Si: 5.8	N: 45 P: 80	N: 85 P: 80	N: 50
Acceptor dopants and shallowest ionization energy (meV)	B: 45	Be, Mg, C: 28	Al: 200 B: 300	Al: 200 B: 300	Al: 270
1998 Commercial wafer diameter (cm)	30	15	5	5	None

From Neudeck, P.G., SiC technology, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **6**-3.

MEMS Processing Technologies

Process	Physical Dimension Range/ Aspect Ratio	Materials	Etch Stop Techniques	Through-put	Cost
		Subtractive processes			
Bulk micromachining	µm-cm/1:400	Single-crystal silicon, GaAs glass etching	Dopant-selective electrochemical Buried layer	High	Low
Reactive ion etch	µm-mm/1:100	Wide range of materials	Buried layer	Low	High
Laser ablation	1-100 µm/1:50	Various	Timed	Low	High
Electrodischarge machining	2 µm-mm/*	Si, metals	Timed	Low	Med
Precision mechanical cutting	nm-cm/*	PMMA	Tool position	Low	High
Focussed ion beam machining	nm-µm	various	Timed	Low	High
Chemical etching	µm/1:10	Metals, semiconductors, insulators	Timed	High	Low
Ultrasonic machining	25 µm-mm/*	Glass, ceramic, semiconductor, metals	Tool position	Moderate	Moderate
		Additive processes			
Physical vapor depositon	Wide range of materials	Electron beam or thermal evaporation/sputtering	—	Moderate	High
Chemical vapor deposition	Surface micromachining	LPCVD of polysilicon/PSG or sputtered aluminum/ photoresist	Selectivity of sacrificial etch to sacrificial layer to structural layer	High	Moderate
Laser-assisted CVD	nm-µm	Various	—	Low	High
Molecular beam epitaxy	nm	Semiconductors	—	Low	Very high
LIGA	µm-cm	PMMA	—	Low	High
Electroplating into a mold:	µm-mm	Cu, Ag, Au, Fe, permalloy	—	High	Low
	µm-mm/1:10	Polyimide	—	High	Moderate
	µm-mm	SU-8	—	High	Low
	µm-mm	Thick photoresist	—	High	Low

* Function of total geometry.
From Hesketh, P.J., Micromachining, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **10**-3.

Materials Properties of LPCVD Deposited MEMS Materials

Material	Growth Conditions	Film Thickness	Property	Value	Comments
			Polysilicon		
MUMPS process		3 μm	Young's modulus	169 ± 6.15 GPa	—
			Tensile strength	1.20 ± 0.15 GPa	
Thick polysilicon	1100°C, SiH_4/B_2H_6 or 610°C, Sitty	2.5-10 μm	Young's modulus Fracture toughness	150 ± 3- GPa 2.3 ± 0.1 MPa √m 280 MPa	Undoped film
Thin polysilicon	565°C, SiH_4, 620°C, SiH_4, 100 mTorr	1 μm	As-deposited residual stress		
CMOS		0.33 μm	Young's modulus	168 ± 7 GPa	—
			Tensile strength	2.11 ± 0.10 GPa	
			Young's modulus	162.8 ± 6 GPa	—
			Intrinsic stress	–350 ± 12 GPa	As deposited
			Intrinsicties	162.8 ± 6 GPa	After 1000°C anneal
			Silicon Nitride		
Standard process	800°C, $SiCl_2H_2lNH_3$	—	Intrinsic stress	~1.2 GPa	
Si-rich, variable stoichiometry	800, 850°C 200, 410 mTorr $SiCl_2H_2$/ NH_3	~0.1 μm	Intrinsic stress	(See Figure 10.10)	—
Silicon-rich, variable stoichiometry	850°C 200 mTorr $SiCl_2H_2/NH_3$	0.25–0.45 μm	Young's modulus		
PECVD				(190 GPa)	

From Hesketh, P.J., Micromachining, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **10**-18.

Wafer Bonding Techniques

Bonding Technique	Materials	Surface Treatment	Process	Time	Bond Strength/Comments
Anodic bonding	Silicon/7740 Pyrex glass	Clean	350–450°C ~500–1000V	~1–10 min	1–3 MPa[a]/uniform reliable hermetic bond formed
Silicon-silicon	Si-Si SiO_2-Si and SiO_2/SiO_2	Hydrophobic Hydrophilic	500–1100	hrs	Difficult to avoid voids unless processed at higher temperatures
Borosilicate glass	Si/$Si0_2$ and Si_3N_4		450	30 min	—
Eutectic	Si-Au-SiO_2	Clean and oxide-free	~350	—	148 MPa[b]/Nonuniform bonding area
Solder	SiO_2-Pb/Sn/Ag-SiO_2	Needs solder flux	250–400	min	Large difference in thermal expansion coefficient can lead to mechanical fracture
Glass frit	SiO_2-glass Ag mixture-SiO_2	Clean	~350	<hr	Difficult to form thin layers

From Hesketh, P.J., Micromachining, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **10**-32.

Microrelays

Application	Fabrication Process	Drive	Contact On-Resistance	Maximum Current	Off- Resistance/ Breakdown voltage	Switching Time	Insertion Loss
			Electrostatic				
Automated test equipment	Bulk micromachining and anodic bonding	<100 V	<3 Ω	—	—	<20 μs	
Switching	CMOS compatible	1-10 V with DC bias of 30-54 V	—	—	—	<1 ms	
RF to microwave	Surface micromachining	28 V at >50 nA	~0.22 Ω	200 mA	—	—	0.1 db at 4 GHz
RF to microwave	Surface micromachining on GaAs	~30 V	—	—	—	—	0.3 dB at 20 GHz
Switching	Electroplated metal films	24 V	0.05 Ω (initial)	5 mA (single contact); 150 mA (multiple contacts)	>100 V	—	—
Small-signal RF	Surface micromachining	20–100 V [10 μW]	10–80 Ω	1 mA	—	2.6– 20 μs	—
			Thermal				
Switching	MUMPS	7-12 V	2.4 Ω	80 mA	—	—	—
RF impedance matching	Surface micromachining in polysilicon	12 mW	2.1–35.6 Ω	>1 mA	>10^{12} Ω 400 V	<0.5 ms	—
			Magnetic				
Electrical control circuits	Polyimide mold and electroplated metals	180 mA (33 mW)	0.022 Ω	1.2 A	—	0.5–2.5 ms	—

From Hesketh, P.J., Micromachining, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **10**-46.

Electronic Packaging Requirements

Speed • Large bandwidth • Short inter-chip propagation delay	Size • Compact size
Thermal and Mechanical • High heat removal rate • A good match between the thermal coefficients of the dice and the chip carrier	Test and Reliability • Easy to test • Easy to modify • Highly reliable • Low cost
Pin Count and Wireability • Large I/O count per chip • Large I/O between the first and second level package	Noise • Low noise coupling among wires • Good-quality transmission line • Good power distribution

From Khandelwal, P. and Shenai, K., Microelectronics packaging, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **11**-2.

Thermal and Electrical Properties of Materials Used in Packaging

Metals

Metals	Coefficient of Thermal Expansion (CTE) (10^{-6} K^{-1})	Thermal Conductivity (W/cm-K)	Specific Electrical Resistance $10^{-6}\Omega$-cm
Aluminum	23	2.3	2.8
Silver	19	4.3	1.6
Copper	17	4.0	1.7
Molybdenum	5	1.4	5.3
Tungsten	4.6	1.7	5.3

Substrates

Insulating Substrates	Coefficient of Thermal Expansion (CTE) (10^{-6} K^{-1})	Thermal Conductivity (W/cm-K)	Dielectric Constant
Alumina (Al_2O_3)	6.0	0.3	9.5
Beryllia (BeO)	6.0	2.0	6.7
Silicon carbide (SiC)	3.7	2.2	42
Silicon dioxide (SiO_2)	0.5	0.01	3.9

Semiconductors

Semiconductors	Coefficient of Thermal Expansion (CTE) (10^{-6} K^{-1})	Thermal Conductivity (W/cm-K)	Dielectric Constant
Silicon	2.5	1.5	11.8
Germanium	5.7	0.7	16.0
Gallium arsenide	5.8	0.5	10.9

From Khandelwal, P. and Shenai, K., Microelectronics packaging, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **11**-6.

Some Properties of Ceramic Packaging Materials

Property	BeO	AlN	Al_2O_3 (96%)	Al_2O_3 (99.5%)
Density (g/cm^3)	2.85	3.28	3.75	3.8
CTE (ppm/K)	6.3	4.3	7.1	7.1
TC (W/cm-K)	285	180	21	25.1
Dielectric const.	6.7	10	9.4	10.2
Loss tangent	0.0001	0.0005	0.0001	0.0001

From Khandelwal, P. and Shenai, K., Microelectronics packaging, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **11**-6.

Interconnect Technologies

Interconnection Type	Line Width (µm)	Line Thickness (µm)	Line Resistance (ohm/cm)	Maximum Length (cm)
On-chip	0.5–2	0.7–2	100–1000	0.3–1.5
Thin-film	10–25	5–8	1.25–4	20–45
Ceramic	75–100	16–25	0.4–0.7	20–50
Printed circuit board	60–100	30–50	0.06–0.08	40–70
Shielded cables	100–450	35–450	0.0013–0.033	150–500

From Nakhla, M.S., Interconnect modeling and simulation, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **17**-5.

Voltage Buffer Performance

Power Supply	5 V	Dissipation	5 mW
DC gain (no load)	–3.3dB	Bandwidth	140 MHz
Output impedance	75Ω	Min. load resistance	10 KΩ
HD2 (V_{in} = 200 mV_{rms})	1 MHz	–50 dB	
	10 MHz	–49 dB	
	20 MHz	–45 dB	
IM3 (V_{in}=200 mV_{rms})	20 MHz, Δf = 200 KHz	–53 dB	
Slew rate	(Load = 10 pF)	+ 130 V/µs	–72 V/µs
Input referred noise	10 $nV\sqrt{Hz}$		

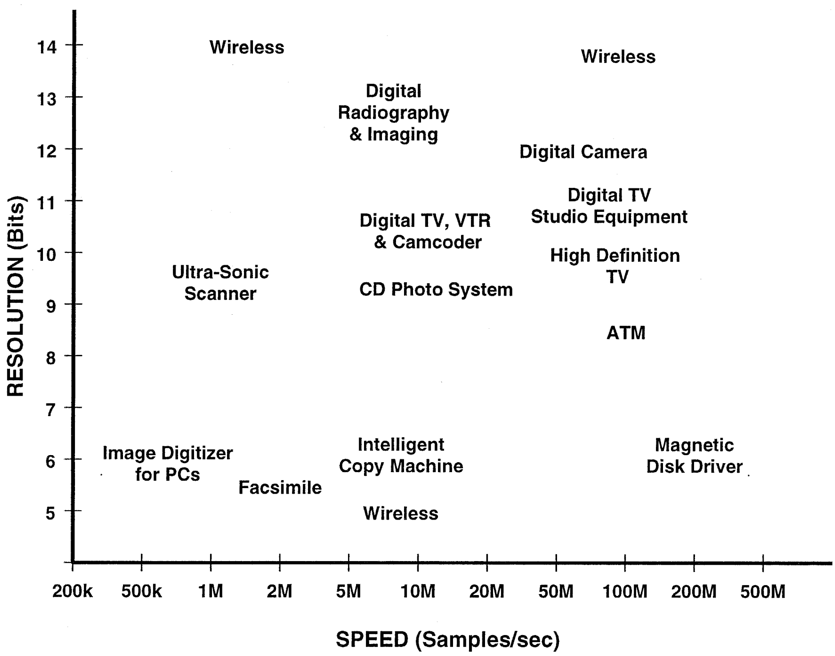
Note: Load = 10 kΩ/10 pF, except for slew rate measurement.

From Toumazou, C. and Payne, A., High-frequency amplifiers, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **21**-7.

Embedded Memory Technologies and Applications

Embedded Memory Technology	Compatibility to Logic Process	Applications
ROM	Diffusion, Vt, Contact programming High compatibility to logic process	Microcode, program storage PAL, ROM-based logic
E/E^{2}prom	High-voltage device, tunneling insulator required	Program, parameter storage, sequencer, learning machine
SRAM	6-Tr/4-Tr single/double poly load cells Wide range of compatibility	High-speed buffers, cache memory
DRAM	Gate capacitor/4-T/planar/stacked/trench cells Wide range of compatibility	High-density, high bit rate storage

From Wu, C.-Y., Embedded memory, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **50**-4. Originally from Iizuda, T., Embedded memory: A key to high-performance system VLSIs, *Proc. of 1990 Symp. on VLSI Circuts,* pp. 1–4, June 1990.



Recent high-speed ADC applications. (From Song, B.-S., Nyquist-rate ADC and DAC, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **54**-5.)

Microprocessor Statistics

Manufacturer	Part Name	# Transistors (millions)	Frequency (MHz)	Die Size (mm^2)	Technology (μm)
Compaq	Alpha 21264	15.2	600	314	0.35
IBM	PowerPC	6.35	250	66.5	0.3
HP	PA-8000	3.8	250	338	0.5
Sun	Ultrasparc-I	5.2	167	315	0.5
Intel	Pentium II	7.5	450	118	0.25

From Karnik, T., Microprocessor layout method, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **62**-1.

Comparing Electrical Parameters for BJT/HBT vs. FET

Parameter	BJT/HBT	FET
Input impedance Z	Low Z due to forward-biased junction; large diffusion capacitance C_{be}	High Z due to reverse biased junction or insulator; small depletion layer capacitance C_{gs}
Turn-on Voltage	Forward voltage V_{BE} highly repeatable; set by thermodynamics	Pinch-off voltage V_P not very repeatable; set by device design
Transconductance	High g_m [$= I_C/(kT/q)$]	Low g_m [$\cong v_{sat}C_{gs}$]
Current gain	β (or h_{FE}) = 50 to 150; β is important due to low input impedance	Not meaningful at low frequencies and falls as $1/\omega$ at high frequencies
Unity current gain cutoff frequency f_T	$f_T = g_m/2\pi C_{BE}$ is usually lower than for FETs	$f_T = g_m/2\pi C_{gs}$ ($= v_{sat}/2\pi L_g$) higher for FETs
Maximum frequency of oscillation f_{max}	$f_{max} = [f_T/(8\pi r_{b'} C_{bc}]^{1/2}$	$f_{max} = f_T\,[r_{ds}/R_{in}]^{1/2}$
Feedback capacitance	C_{bc} large because of large collector junction	Usually C_{gd} is much smaller than C_{bc}
1/*f* Noise	Low in BJT/HBT	Very high 1/*f* noise corner frequency
Thermal behavior	Thermal runaway and second breakdown	No thermal runaway
Other		Backgating is problem in semi-insulating substrates

From Estreich, O.B., Compound semiconductor devices for digital circuits, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **70**-13.

Status of Conventional and Renewable Power Sources

Conventional	Renewables
Coal, nuclear, oil, and natural gas	Wind, solar, biomass geothermal, and ocean
Fully matured technologies	Rapidly developing technologies
Numerous tax and investment subsidies embedded in national economies	Some tax credits and grants available from some federal and/or state governments
Accepted in society under the 'grandfather clause' as necessary evil	Being accepted on its own merit, even with limited valuation of their environmental and other social benefits

From Patel, M.R., *Wind and Solar Power Systems,* CRC Press, Boca Raton, FL, 1999, p. 3.

Benefits of Using Renewable Electricity

Traditional Benefits	Nontraditional Benefits Per Million kWh consumed
Monetary value of kWh consumed	Reduction in emission
U.S. average 12 cents/kWh	750–1000 tons of CO_2
U.K. average 7.5 pence/kWh	7.5–10 tons of SO_2
	3–5 tons of NOx
	50,000 kWh reduction in energy loss in power lines and equipment
	Life extension of utility power distribution equipment
	Lower capital cost as lower capacity equipment can be used (such as transformer capacity reduction of 50 kW per MW installed)

From Patel, M.R., *Wind and Solar Power Systems,* CRC Press, Boca Raton, FL, 1999, p. 3.

Electromagnetic Radiation and Stable Elementary Particles

	Charge	Mass	Examples or Sources
Alpha particle	+2	4	Alpha "rays" emitted by heavy radioisotopes; cosmic rays
Electron	–1	1/1836	Ionosphere; atoms of matter; beta rays from radioactive elements
Gamma ray	0	0	Radioactive decay; nuclear transitions; nuclear reactors; cosmic rays
Neutrino	0	0	Emitted by sun, stars, nuclear reactors. Accompanies radioactive emission (beta decay)
Neutron†	0	1	Vicinity of planets and sun; atomic nuclei; nuclear reactors
Photon	0	0	All light flux from sun, stars, etc.; radiation belts
Positron	+1	1/1836	Fast anti-electrons emitted from radioactive materials
Proton	+1	1	Cosmic rays; radiation belts; atomic nuclei
X-ray	0	0	Radiation belts; solar radiation; high-voltage vacuum tubes

† Secondary particle; not stable; life about 1,000 seconds.

Electrons are negatively-charged "atoms of electricity"; in ordinary matter they form an ordered "cloud" surrounding the heavy, positively-charged atomic nuclei.

Photons are electromagnetic waves; they carry energy in discrete quantity, proportional to the frequency of the associated wave.

Beta decay involves the emission of an electron or positron. (The terms *beta-ray* and *beta-particle* are sometimes used.)

Gamma rays consist of high-energy photons (electromagnetic waves); they are emitted in radioactive decay.

X-rays consist of photons emitted in the acceleration (deceleration) of charged particles, as when high-speed electrons strike a heavy, metal target.

Atomic nucleus is the heavy core of the atom, consisting of protons and neutrons. The number of protons is called the *atomic number*. The number of neutrons plus protons is called the *mass number*. The energy required to separate all of the neutrons and protons of the nucleus is called the *binding energy*.

Radioactive nucleus is one that spontaneously changes by radioactive decay, electron capture, or fission. It becomes ultimately transformed into a different kind of nucleus.

Isotopes of an element contain the same number of protons but slightly different numbers of neutrons. They are chemically indistinguishable, except by very much refined procedures and in some biological reactions.

Ions are electrically-charged atoms. If the negative electron charges just balance the total positive charge of the nucleus, the atom is neutral; with more electrons the atom becomes a negative ion, and with fewer electrons it becomes a positive ion.

Fission is the breakup of nuclei into fragments that are themselves nuclei. Mass is usually lost; hence energy is released.

Fusion is the coalescing of two nuclei to form a heavier one.

From Bolz, R.E. and Tuve, G.L., Electromagnetic radiation, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 205.

Electromagnetic Frequency Spectra

Ranges and Applications

Application or Common Name	Typical Frequency, cps†	Typical Wavelength‡	Approximate Frequency Range, cps†
Electric a-c power	60	5×10^6 m	25–60
Eddy-current heating (metals)	60	5×10^6 m	50–1000
Servo and instrument power	400	7.5×10^5 m	100–1000
Audio frequency standard	440	6.8×10^5 m	440 and 600
Induction furnace power	2000	1.5×10^5 m	500–3000
R-F heating of metals	10 kc	3×10^4 m	1 kc–1 mc
Power-line communication	30 kc	10^4 m	wide
Maritime and radio beacon	400 kc	750 m	20–550 kc
Radio broadcasting	1000 kc	300 m	550–1600 kc
Shortwave radio	20 mc	15 m	3–300 mc
Microwave diathermy	27 mc	11 m	—
Dielectric heating and drying	40 mc	7.5 m	10–200 mc
F-M radio	100 mc	3m	91–108 mc
Television (channels 2–13)	180 mc	1.67 m	54–216 mc
Radar	500 mc	60.0 cm	200–1200 mc
Television (channels 14–83)	800 mc	37.5 cm	470–890 mc
Tracking stations	960 mc	31.3 cm	440–5600 mc
Intercity relay	2000 mc	15.0 cm	1200–20,000 mc
Radar	10,000 mc	3.0 cm	1200–20,000 mc
Super high frequency	20,000 mc	1.5 cm	3000–30,000 mc
Far infrared (germanium detector)	3×10^{13}	10 μm	
Infrared (PbS detector)	1.25×10^{14}	2.4 μm	
Infrared heaters	1.5×10^{14}	2 μm	
Night infrared searchlight	3×10^{14}	1 μm	
Near infrared photography	3.75×10^{14}	0.8 μm	
Cadmium red line	4.65×10^{14}	.64385 μm	
Yellow (max visual)	5.3×10^{14}	.56 μm	
Solar max intensity	7.1×10^{14}	.42 μm	
Germicidal lamps—ultraviolet	10^{15}	.3 μm	
Soft X-rays	10^{18}	3 Å	
Hard X-rays	10^{20}	.03 Å	
Gamma rays	10^{21}	.003 Å	
Cosmic rays	3×10^{23}	10^{-5} Å	

† The name *hertz* is widely used by electrical engineers for cycles per second.
‡ Units: 1 meter = 100 cm = 39.37 in. = 10^6 micrometers (μm) = 10^{10} angstrom units (Å). Velocity = 186,290 mi/s = 2.99793×10^8 m/s = frequency × wavelength.

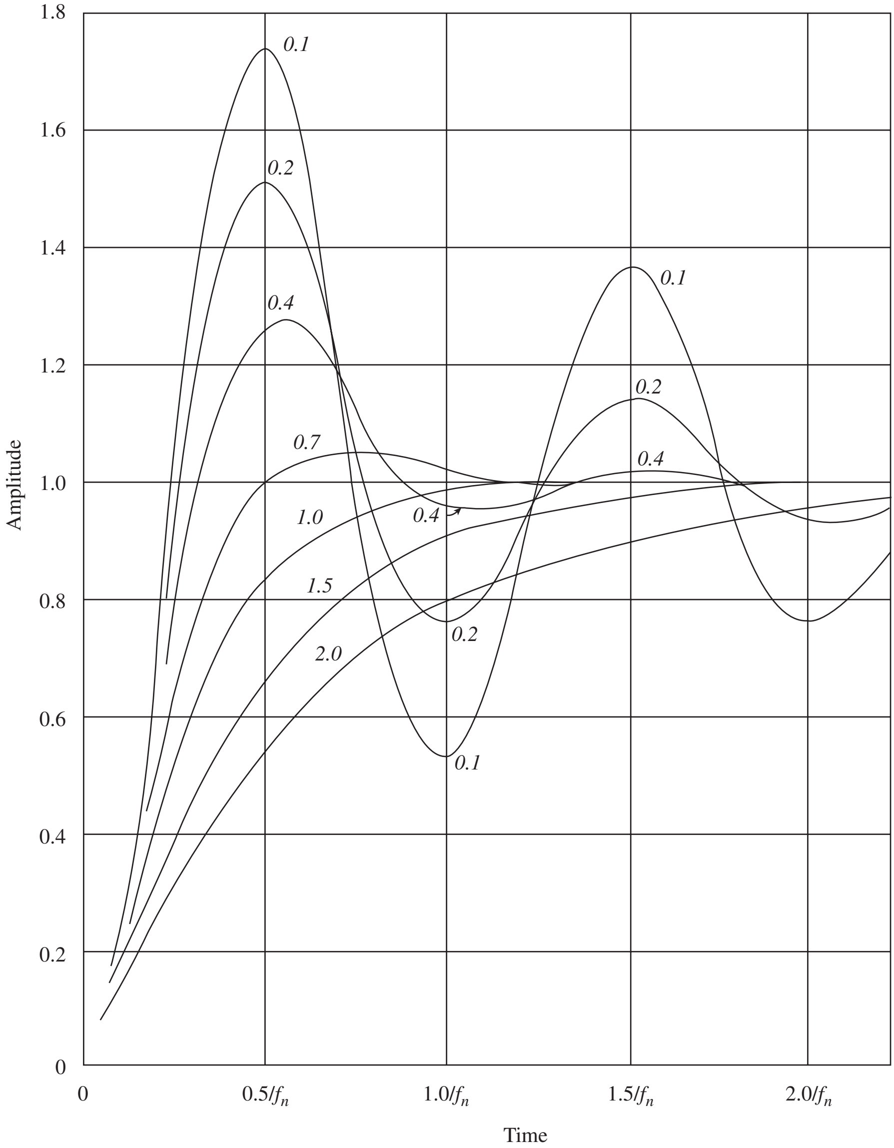
Visible Spectrum — Representative Colors

Color	Frequency	Wavelength
Violet	7.3×10^{14}	0.41
Blue	6.38×10^{14}	0.47
Green	5.75×10^{14}	0.52
Yellow	5.17×10^{14}	0.58
Orange	5.0×10^{14}	0.60
Red	4.6×10^{14}	0.65

From Bolz, R.E. and Tuve, G.L., Electromagnetic radiation, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 206.

Dynamic Response of RCL System to a Step-Change Input

With little or no damping a step-change input will cause an oscillatory RCL system to respond at its natural frequency f_n. The oscillations decrease with time, and this decay may be defined in terms of the logarithmic decrement or exponential decay ratio. At critical damping the response is similar to that of a linear system subjected to the same step input. With large amounts of damping, the response is non-oscillatory



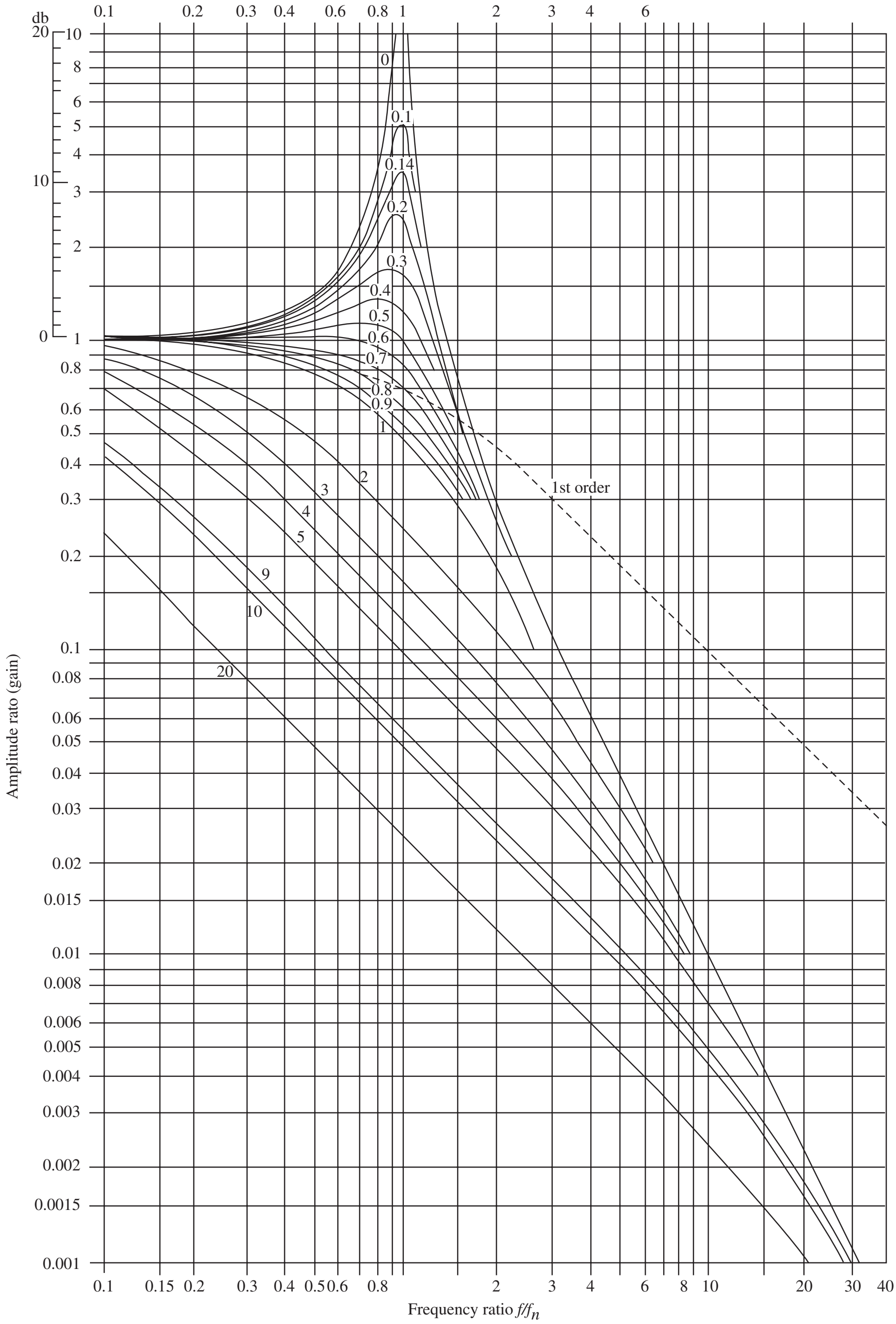
Response of a simple oscillatory system to a unit step input. Damping ratios, $z = c/c_c$, from 0.1 to 2.0.

From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 598. Originally from Tuve, G.L. and Domholdt, L.C., *Engineering Experimentation*, McGraw-Hill, New York, 1966.

Amplitude Response — Second-Order System

If the input frequency is low, the response of an oscillatory system will almost duplicate the input. At the higher frequencies the response will depend on the ratio of actual damping c to critical damping c_c. For the electrical system critical damping is $2\sqrt{L/C}$; for the mechanical mass-spring-damper system the critical damping is $2\sqrt{km}$, where k is the spring constant and m is the mass.

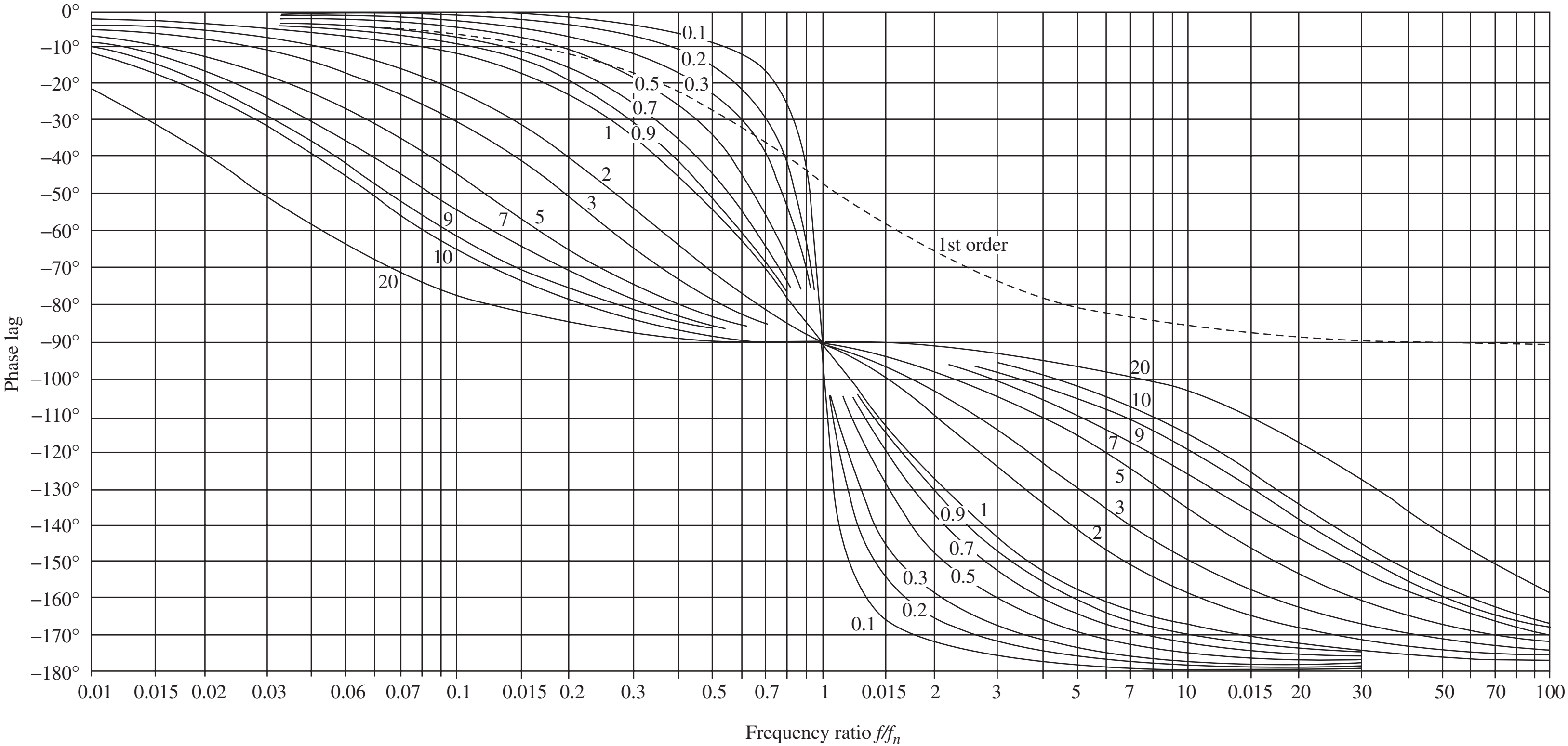
These figures show the response of a simple oscillatory (RCL) system to a sine-wave input, with damping ratios c/c_c from 0.1 to 20.0.



From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 599.

Phase Response—Second-Order System

This figure shows phase lag vs. frequency ratio for a second-order system (RCL) in response to a sine-wave input (semilog coordinates). Damping ratios of 0.1 to 20.0 are given.



Reference

For large-scale curves giving values for damping ratios to 20, frequency ratios to 40, and gains as low as 0.001, see *Handbook of the Engineering Sciences,* J.H. Potter, Ed., Vol. 2, D. Van Nostrand Co., 1967. pp. 786–787.

From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 600.

Frequency-Response Approximations and Corrections

When the magnitude of the output–input ratio and the phase-angle response are each plotted against frequency on logarithmic coordinates, the work of obtaining the transfer function becomes largely a matter of graphical addition and subtraction. (Semilog plots may also be used.)

A simplification is attained by treating separately each of the four basic types of factors in the transfer function and by starting with straight-line approximations of the actual curves.*

Corrections from the straight-line approximations, to obtain the actual curves, are given in the following table and also in the following figure.

Values of Log Magnitude and Angles of $(1 + j\omega T)^{-1}$

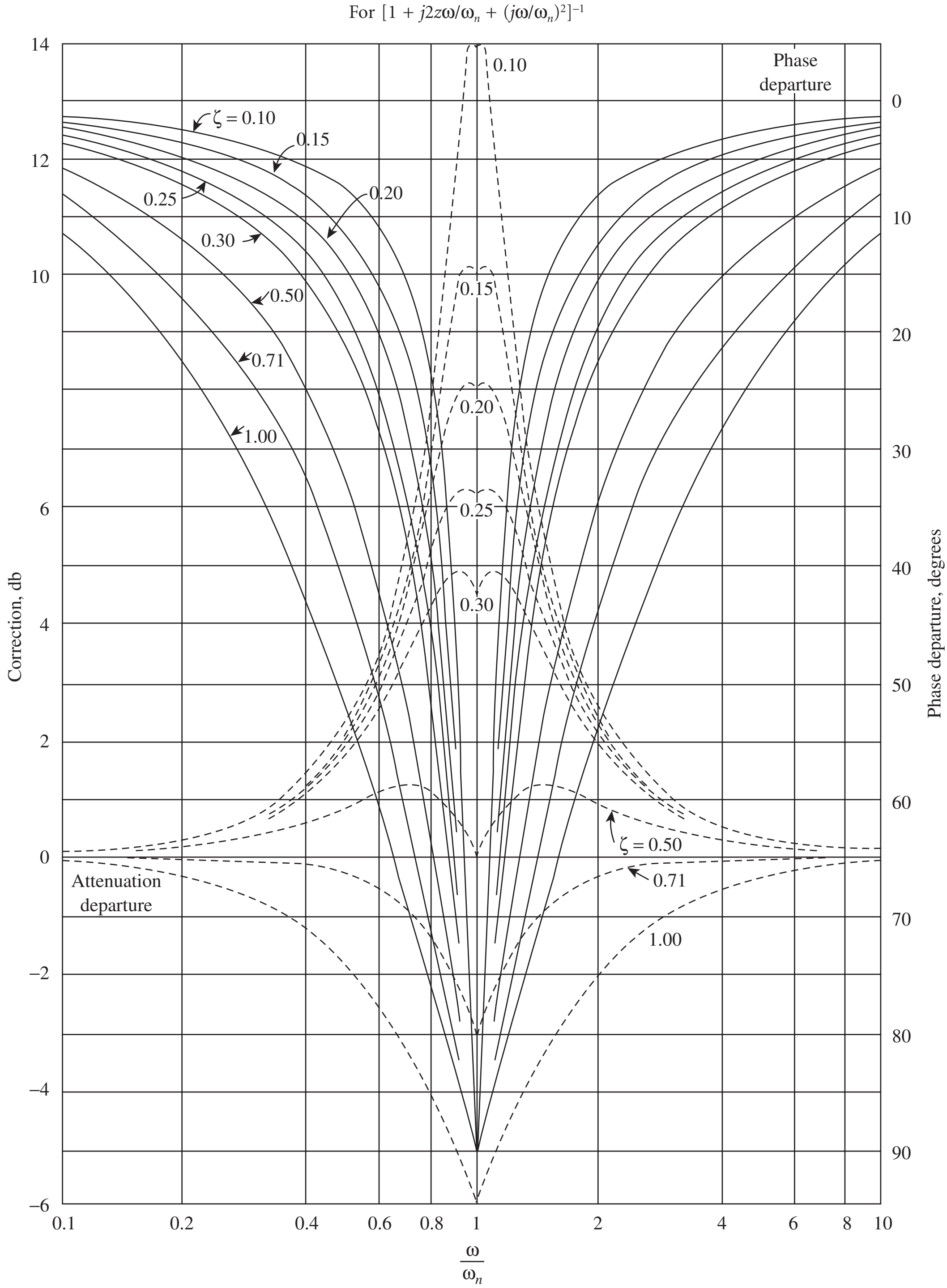
The corner frequency ω_{cf} is used as the index, i.e., $1/(1 + j\omega T) = 1/(1 + j\omega/\omega_{cf})$. Range is one decade above and below ω_{cf}.

ω_{cf}	Exact Magnitude, db	Value of the Asymptote, db	Error, db	Angle, Degrees
0.10	–0.04	0	–0.04	–5.7
0.50	–0.97	0	–0.97	–26.6
0.76	–2.00	0	–2.00	–45.0
1.00	–3.01	0	–3.01	
1.31	–4.35	–2.35	–2.00	
2.00	–6.99	-6.02	–0.97	–63.4
4.00	–12.30	–12.04	–0.26	
10.00	–20.04	–20.00	–0.04	–84.3

* For a full discussion of the method, with examples, see: *Feedback Control System Analysis and Synthesis,* 2nd ed., J.J. D'Azzo and C.H. Houpis, McGraw-Hill Book Company, New York, 1966, pp. 278–303.

From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 601.

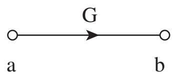
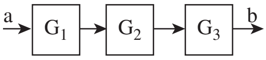
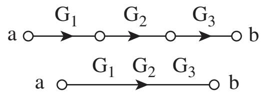
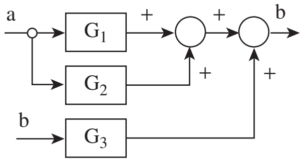
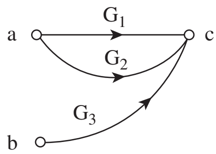
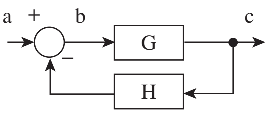
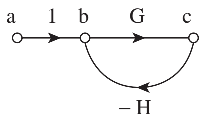
Corrections to the Log Magnitude and Phase Diagram



From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 602. Originally from H.M. James, N.B. Nichols, and R.S. Phillips, *Theory of Servomechanisms*, McGraw-Hill Book Company, New York, 1947.

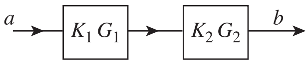
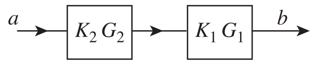
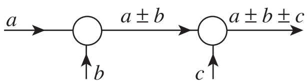
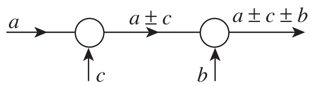
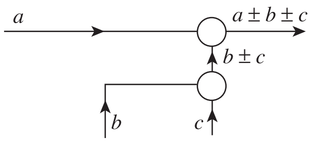
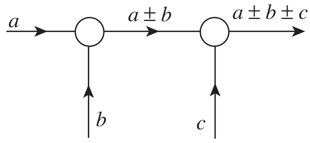
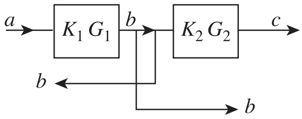
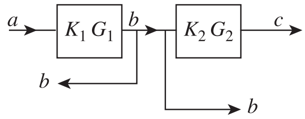
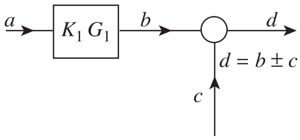
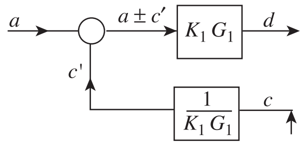
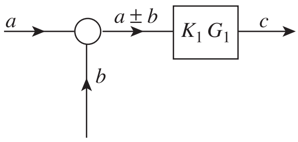
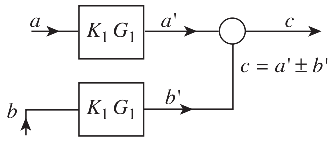
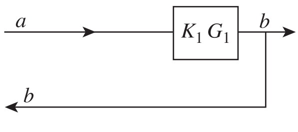
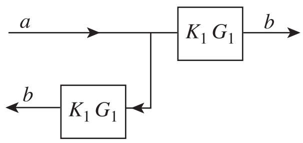
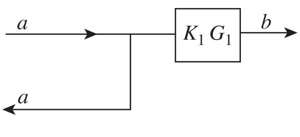
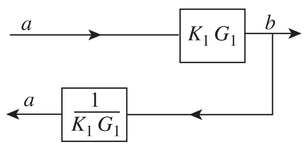
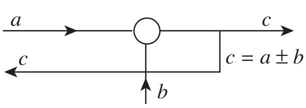
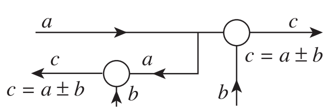
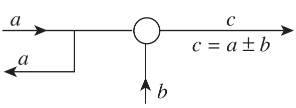
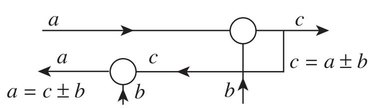
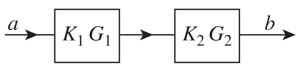
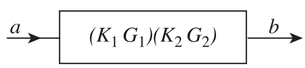
Block and Signal-Flow Diagrams

SYMBOLS: a = input
b = output
G = transfer function

Operation	Block Diagram	Signal-Flow Diagram	Equation
Basic element			$b=Ga$
Elements in cascade			$b=G_1\ G_2\ G_3a$
Elements in parallel			$C=\left(G_1+G_2\right)a+G_3b-$
Feedback			$C=\dfrac{G}{1+GH}a$

From Bolz, R.E. and Tove, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science,* CRC Press, Boca Raton, FL, 1973, p. 1061.

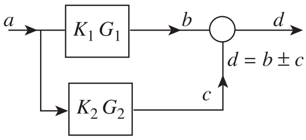
Block-Diagram Manipulations

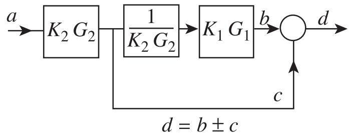
Manipulation	Original Network	Equivalent Network
1. Interchange of elements		
2. Interchange of summing points		
3. Rearrangement of summing points		
4. Interchange of takeoff points		
5. Moving a summing point ahead of an element		
6. Moving a summing point beyond an element		
7. Moving a takeoff point ahead of an element		
8. Moving a takeoff point beyond an element		
9. Moving a takeoff point ahead of a summing point		
10. Moving a takeoff point beyond a summing point		
11. Combining cascade elements		

Block-Diagram Manipulations (continued)

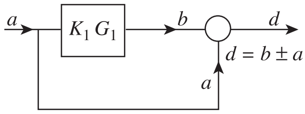
Manipulation	Original Network	Equivalent Network

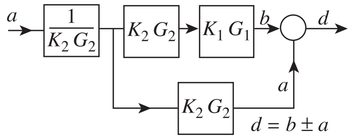
12. Removing an element from a forward loop



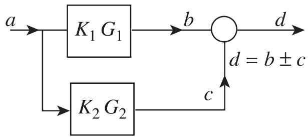


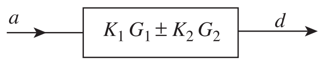
13. Inserting an element in a forward loop



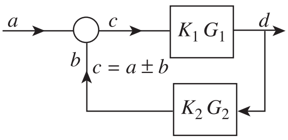


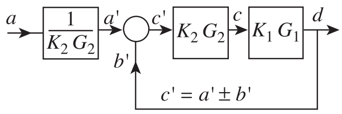
14. Eliminating a forward loop



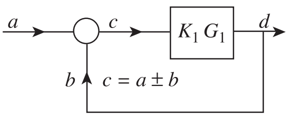


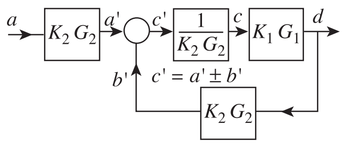
15. Removing an element from a feedback loop



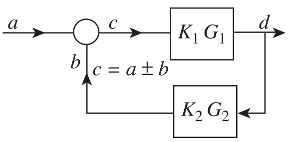


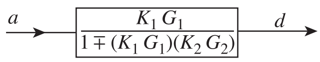
16. Inserting an element in a feedback loop



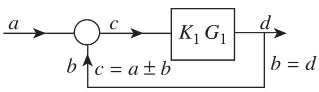


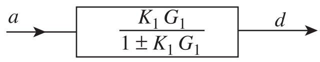
17. Elminating a feedback loop



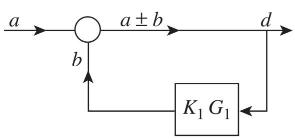


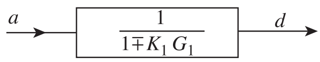
18. Special form of 17



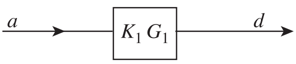


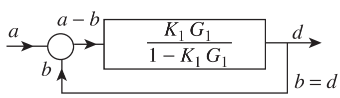
19. Special form of 17



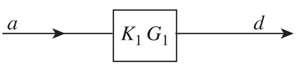


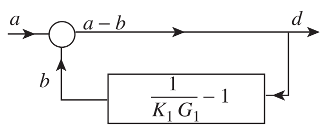
20. Inserting a feedback loop to replace an element





21. Different form of 20

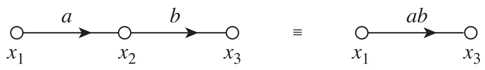




From Bolz, R.E. and Tove, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science,* CRC Press, Boca Raton, FL, 1973, pp. 1062–1063. Originally from E.M. Grabbe, S. Ramo, and D.E. Wooldridge, Eds., *Handbook of Automation, Computation, and Control,* Vol. 1, John Wiley & Sons, New York, 1958, pp. **20**-62 and **20**-63.

Signal-Flow Diagrams

Cascade

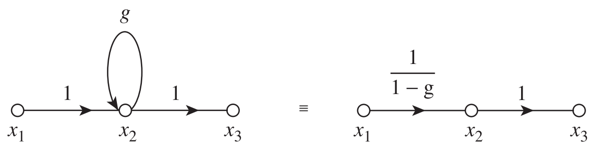
1. 

$x_3 = bx_2 = bax_1$

Parallel

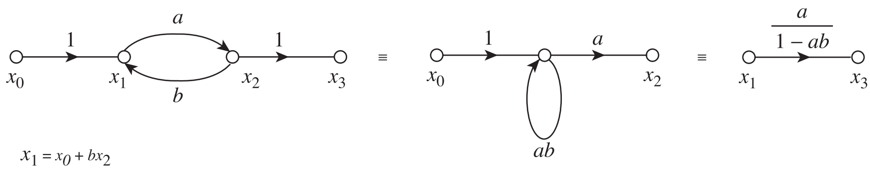
2. 

$x_2 = (a + b)x_1$

3. 

$x_2 = x_1 + gx_2$

$x_2 = x_1\ (1/1\text{-}g)$

4. 

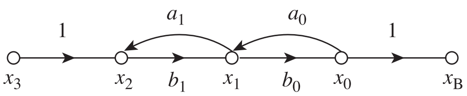
$x_1 = x_0 + bx_2$

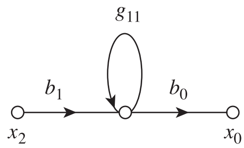
$x_2 = ax_1 = ax_0 + abx_2$

$x_3/x_0 = a/1\text{-}ab$

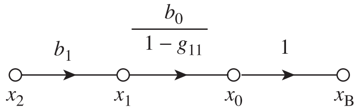
Signal-Flow Diagrams (continued)

5.



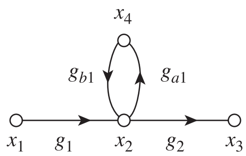


$$g_{11} = a_1b_1 + a_0b_0$$

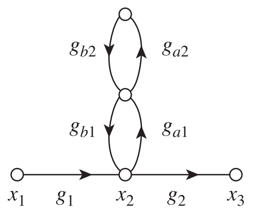


$$\frac{x_B}{x_3} = \frac{b_1b_0}{1 - g_{11}} = \frac{b_1b_0}{1 - a_1b1 - a_0b_0}$$

6.

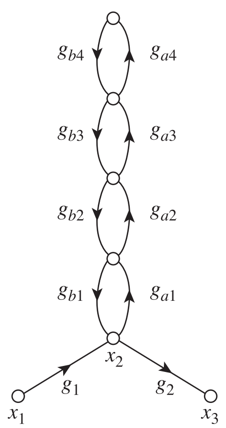


$$\frac{x_3}{x_1} = G = \frac{g_1g_2}{1 - g_{a1}g_{b1}}$$



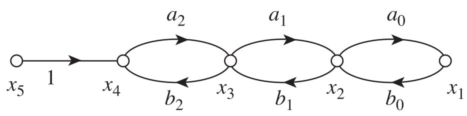
$$\mathrm{G} = \frac{x_3}{x_1} = \cfrac{g_1g_2}{1 - \cfrac{g_{a1}g_{b1}}{1 - g_{a2}g_{b2}}}$$

7.

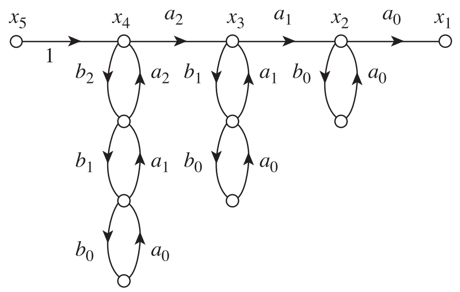


$$\mathrm{G} = \frac{x_3}{x_1} = \cfrac{g_1g_2}{1 - \cfrac{g_{a1}g_{b1}}{1 - \cfrac{g_{a2}g_{b2}}{1 - \cfrac{g_{a3}g_{b3}}{1 - g_{a4}g_{b4}}}}}$$

Signal-Flow Diagrams (continued)

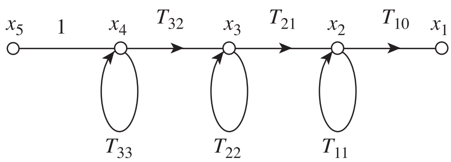


reduces to



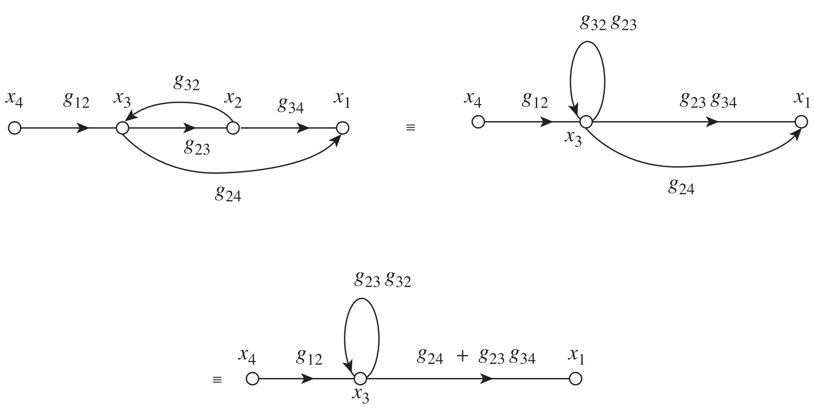
8.

which reduces to



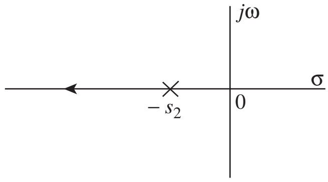
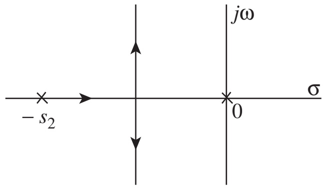
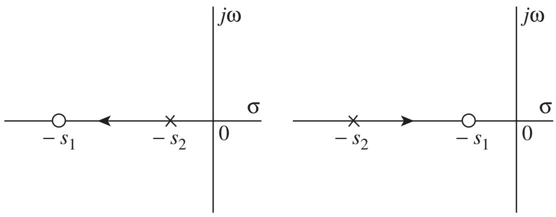
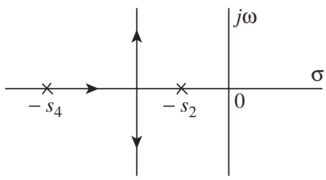
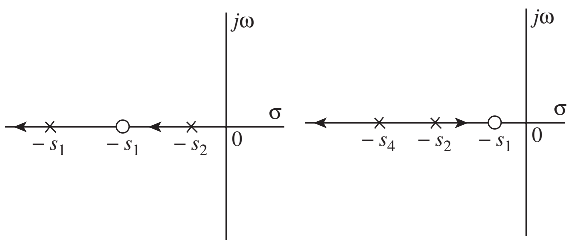
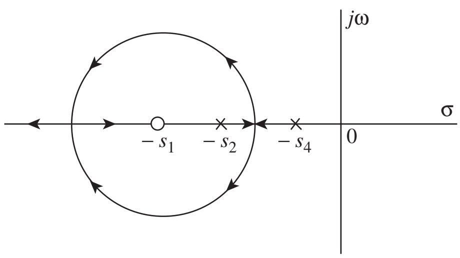
then $$\frac{x_1}{x_5} = a_0\left[\frac{1}{1-a_0b_0}\right]a_1\left[\frac{1}{1-\frac{a_1b_1}{1-a_0b_0}}\right]a_2\left[\frac{1}{1-\frac{a_2b_2}{1-\frac{a_1b_1}{1-a_0b_0}}}\right]$$

9.



From Bolz, R.E. and Tove, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science,* CRC Press, Boca Raton, FL, 1973, pp. 1064–1066. Originally from D.P. Campbell, *Process Dynamics,* John Wiley & Sons, New York, 1958.

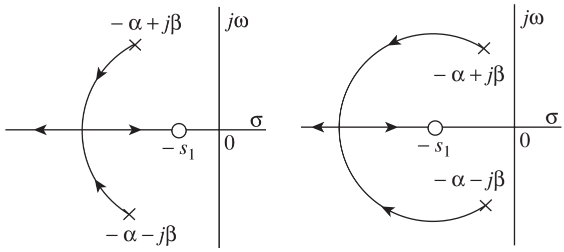
Root Loci

Continuous Systems	
Overall Transfer Function	Sketch of Root Locus
1. $\dfrac{k}{s+s_2}$	
2. $\dfrac{k}{s(s+s_2)}$	
3. $k\dfrac{s+s_1}{s+s_2}$	
4. $\dfrac{k}{(s+s_2)(s+s_4)}$	
5. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)}$	
6. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)}$	

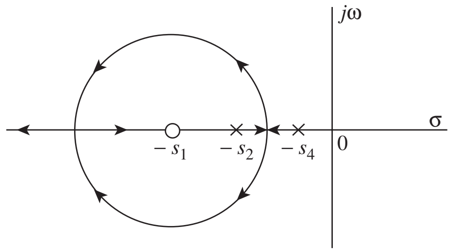
Root Loci (continued)

Overall Transfer Function	Sketch of Root Locus

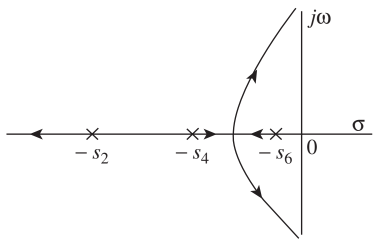
7. $\dfrac{k(s+s_1)}{(s+\alpha+j\beta)(s+\alpha-j\beta)}$



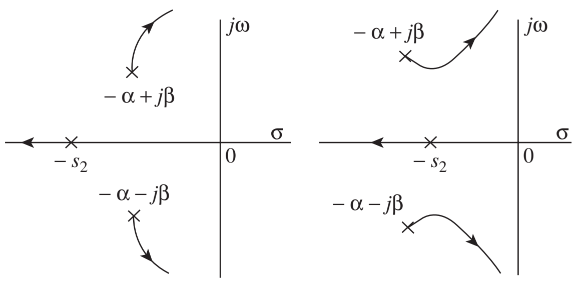
8. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)}$



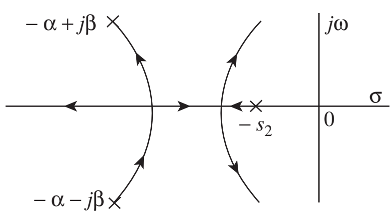
9. $\dfrac{k}{(s+s_2)(s+s_4)(s+s_5)}$



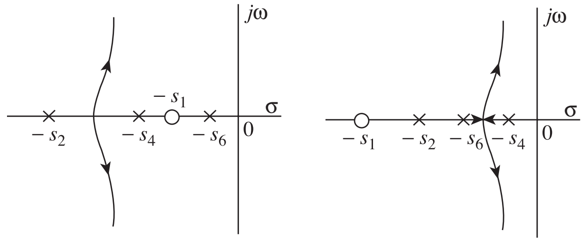
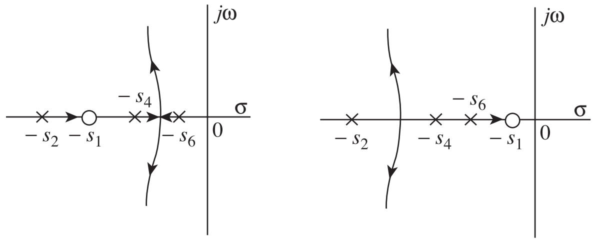
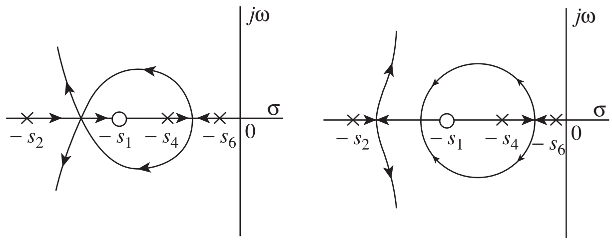
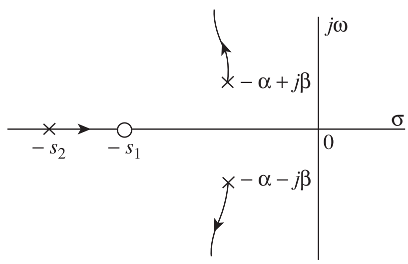
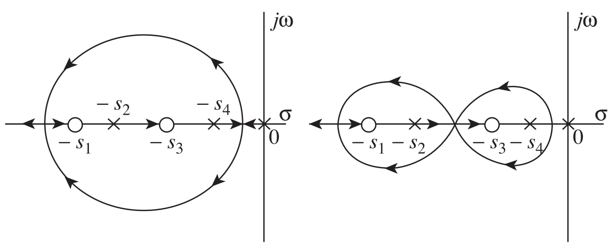
10. $\dfrac{k}{(s+s_2)(s+\alpha+j\beta)(s+\alpha-j\beta)}$



11. $\dfrac{k}{(s+s_2)(s+\alpha+j\beta)(s+\alpha-j\beta)}$



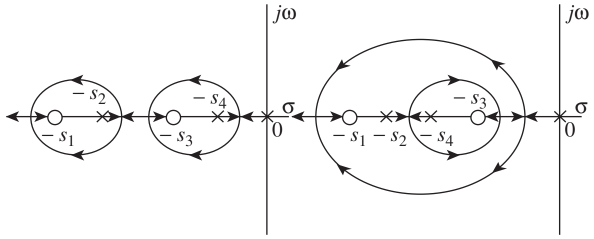
Root Loci (continued)

Overall Transfer Function	Sketch of Root Locus
12. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)(s+s_6)}$	
13. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)(s+s_6)}$	
14. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)(s+s_6)}$	
15. $\dfrac{k(s+s_1)}{(s+s_2)(s+\alpha+j\beta)(s+\alpha-j\beta)}$	
16. $\dfrac{k(s+s_1)(s+s_2)}{s(s+s_2)(s+s_4)}$	

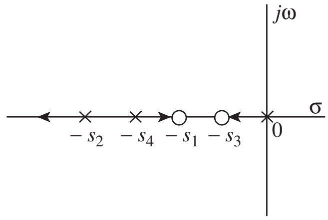
Root Loci (continued)

Overall Transfer Function	Sketch of Root Locus

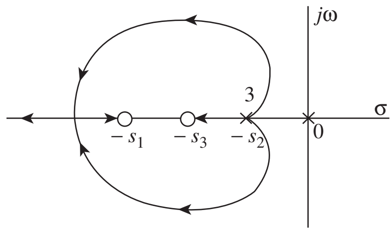
17. $\dfrac{k(s+s_1)(s+s_3)}{s(s+s_2)(s+s_4)}$



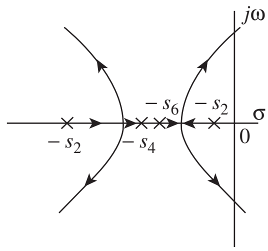
18. $\dfrac{k(s+s_1)(s+s_3)}{s(s+s_2)(s+s_4)}$



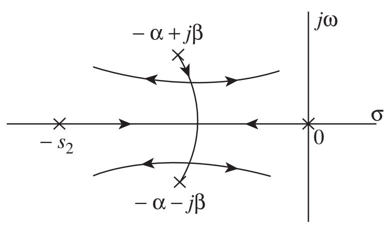
19. $\dfrac{k(s+s_1)(s+s_3)}{(s+s_2)}$



20. $\dfrac{k}{(s+s_2)(s+s_4)(s+s_6)(s+s_8)}$



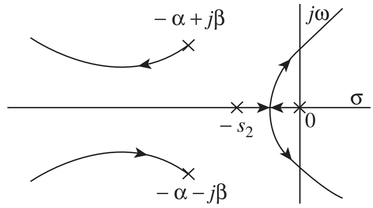
21. $\dfrac{k}{s(s+s_2)(s+\alpha+j\beta)(s+\alpha-j\beta)}$



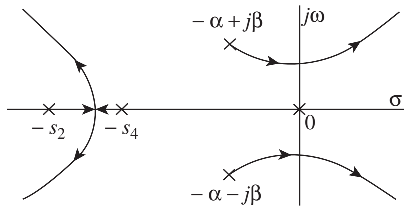
Root Loci (continued)

Overall Transfer Function	Sketch of Root Locus

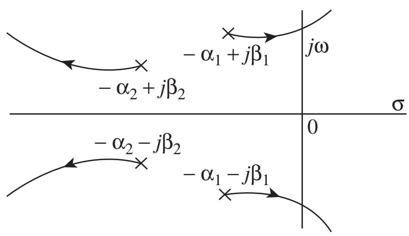
22. $$\frac{k}{s(s+s_2)(s+\alpha+j\beta)(s+\alpha-j\beta)}$$



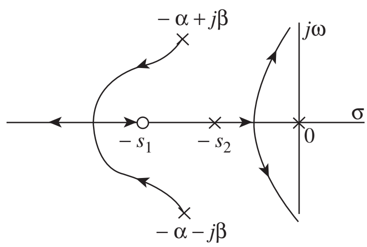
23. $$\frac{k}{\left\{\begin{array}{r}(s+s_2)(s+s_4)(s+\alpha+j\beta)\\ \times(s+\alpha-j\beta)\end{array}\right\}}$$



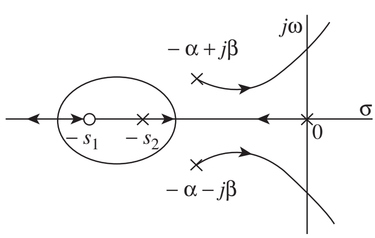
24. $$\frac{k}{\left\{\begin{array}{r}(s+\alpha_1+j\beta)(s+\alpha-j\beta_1)\\ \times(s+\alpha_2+j\beta_2)(s+\alpha_2-j\beta_2)\end{array}\right\}}$$



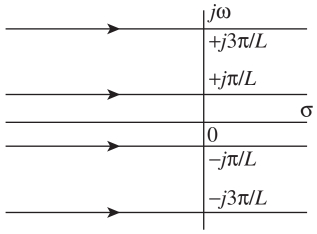
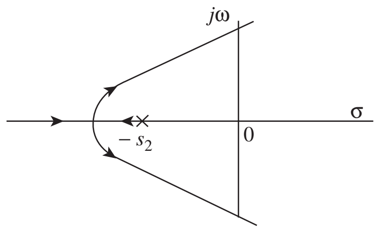
25. $$\frac{k(s+s_1)}{\left\{\begin{array}{r}s(s+s_2)(s+\alpha+j\beta)\\ \times(s+\alpha-j\beta)\end{array}\right\}}$$



26. $$\frac{k(s+s_1)}{\left\{\begin{array}{r}s(s+s_2)(s+\alpha+j\beta)\\ \times(s+\alpha+j\beta)\end{array}\right\}}$$



Root Loci (continued)

Overall Transfer Function	Sketch of Root Locus
27. ke^{-sL}	
28. $\frac{ke^{-sL}}{s+s_2}$	

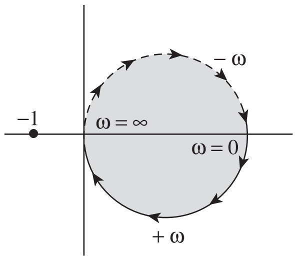
Handbook of Automation, Computation and Control, E.M. Grabbe, S. Ramo, and D.E. Wooldridge, Eds., Vol. 1, John Wiley & Sons, New York, 1958.

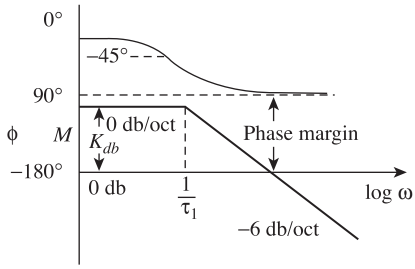
From Bolz, R.E. and Tuve, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 1073–1078. Originally from *Mathematics of Automatic Control*, Takahashi, T. (translation edited by George M. Kranc), English translation, Holt, Rinehart and Winston, Inc., New York, 1966.

Transfer Function Plots for Typical Transfer Function

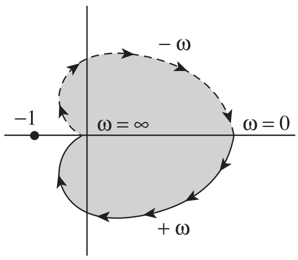
G(s)	Polar Plot	Bode Diagram

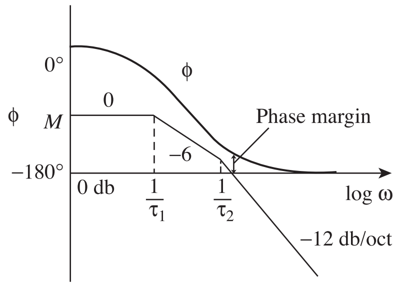
1. $\dfrac{K}{s\tau_1 + 1}$



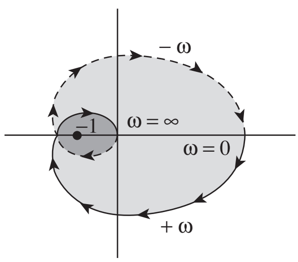


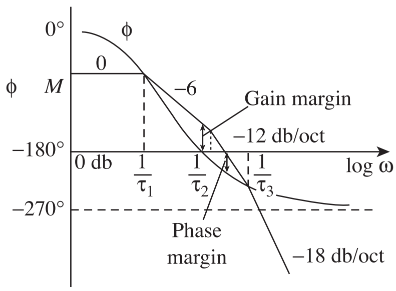
2. $\dfrac{K}{(s\tau_1 + 1)(s\tau_2 + 1)}$



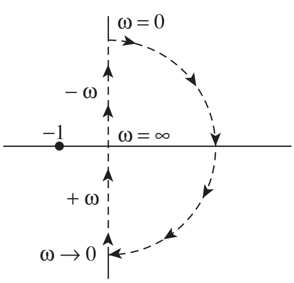


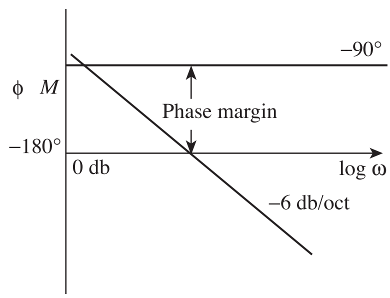
3. $\dfrac{K}{(s\tau_1 + 1)(s\tau_2 + 1)(s\tau_3 + 1)}$

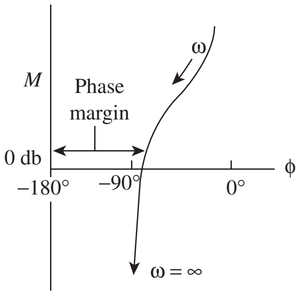
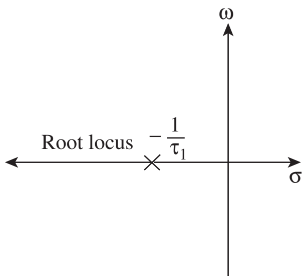
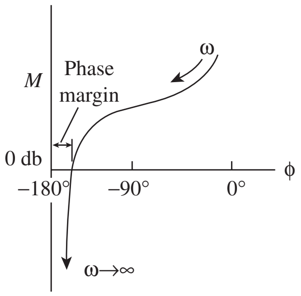
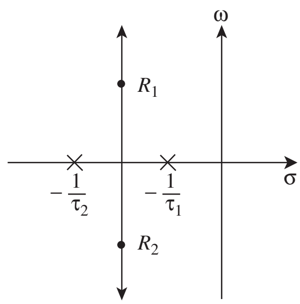
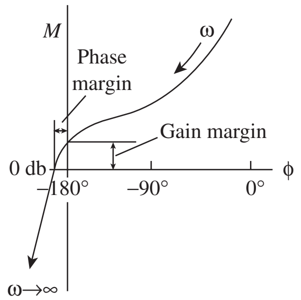
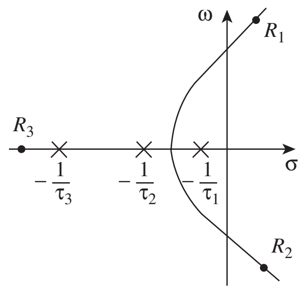
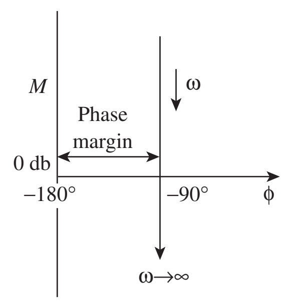
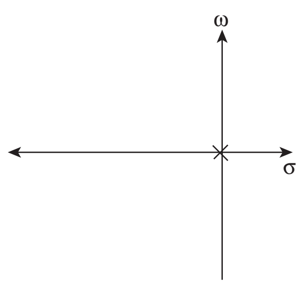




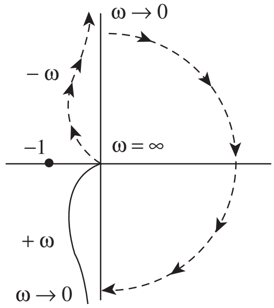
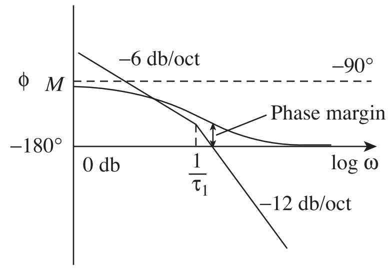
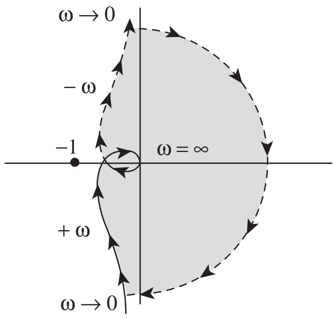
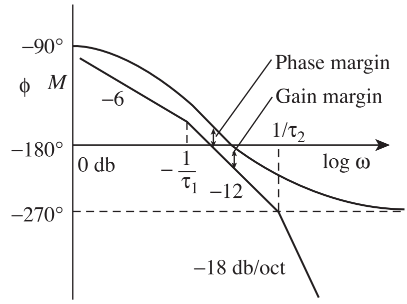
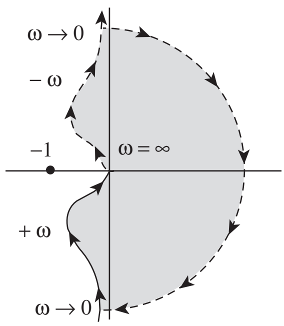
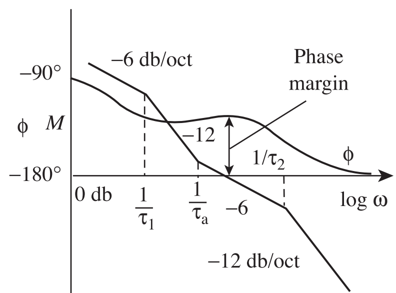
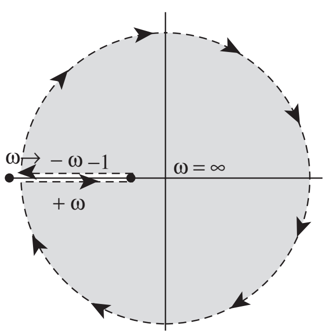
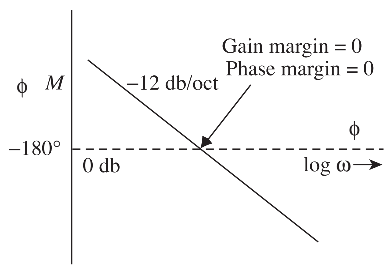
4. $\dfrac{K}{S}$

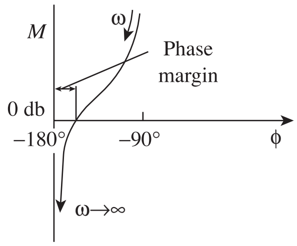
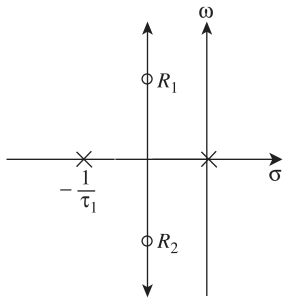
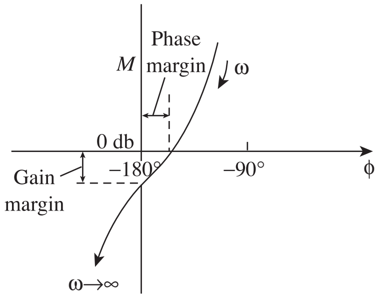
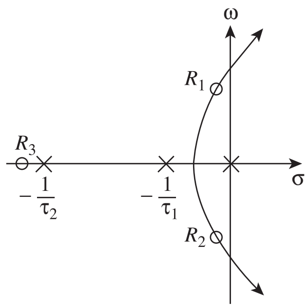
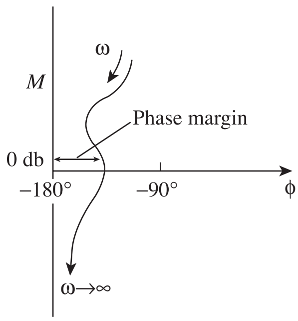
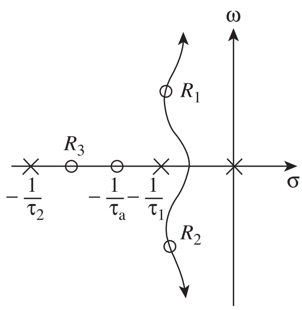
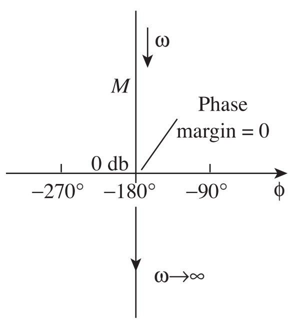
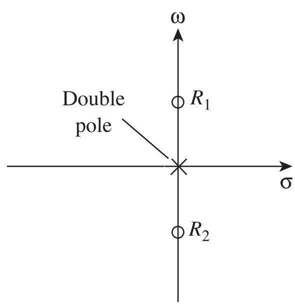




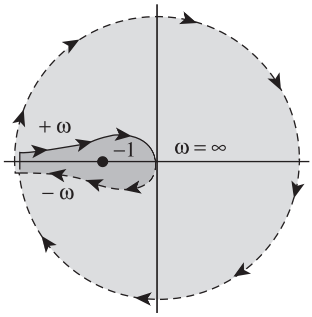
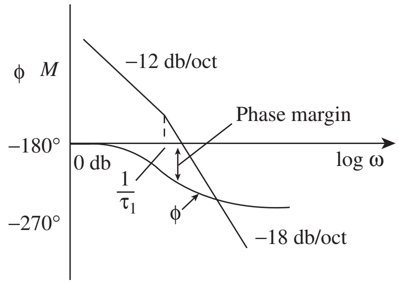
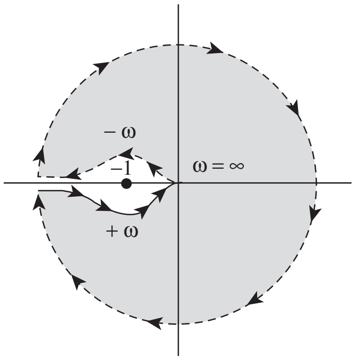
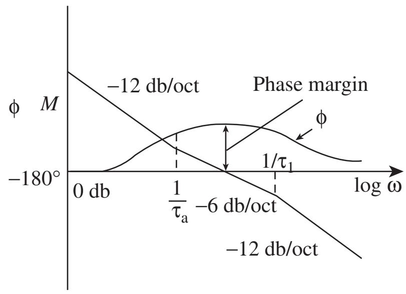
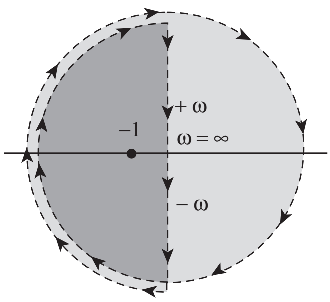
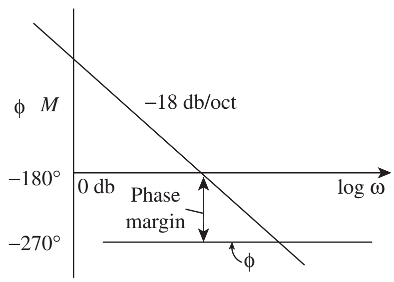
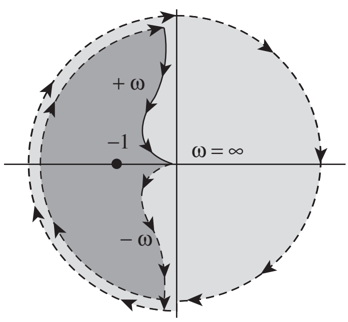
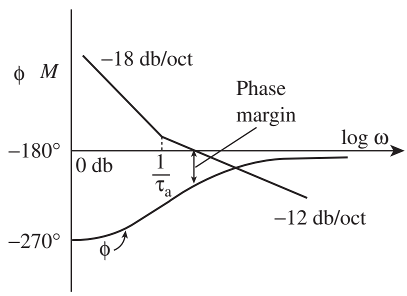
Nichols Diagram	Root Locus	Comments
		Stable; gain margin = ∞
		Elementary regulator; stable; gain margin = ∞
		Regulator with additional energy-storage component; unstable, but can be made stable by reducing gain
		Ideal integrator; stable

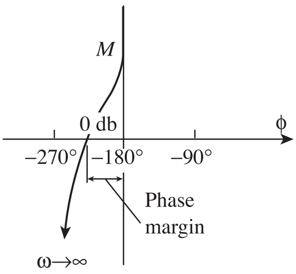
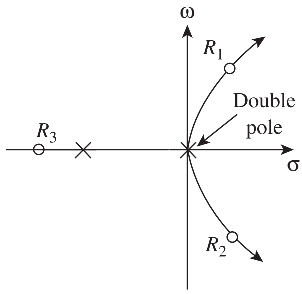
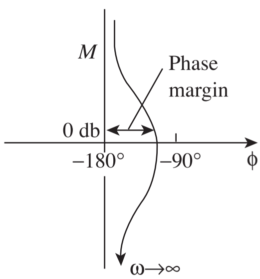
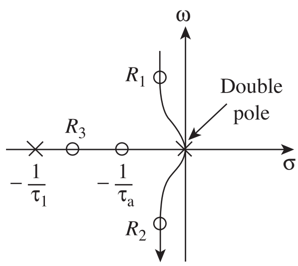
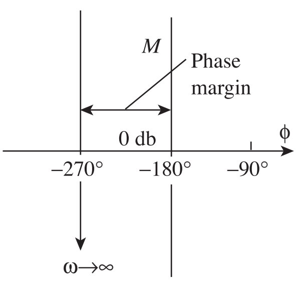
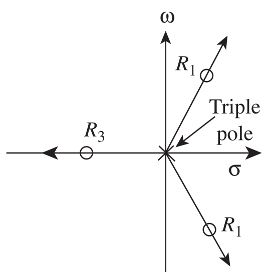
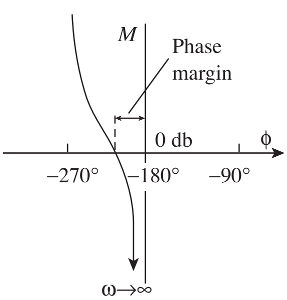
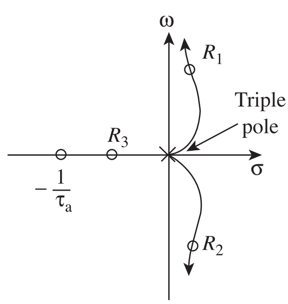
Transfer Function Plots for Typical Transfer Function (continued)

	G(s)	Polar Plot	Bode Diagram
5.	$\dfrac{K}{s(s\tau_1+1)}$		
6.	$\dfrac{K}{s(s\tau_1+1)(s\tau_2+1)}$		
7.	$\dfrac{K(s\tau_a+1)}{s(s\tau_1+1)(s\tau_2+1)}$		
8.	$\dfrac{K}{s^3}$		

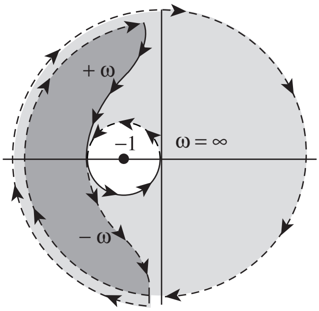
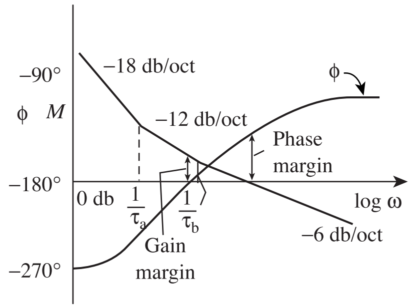
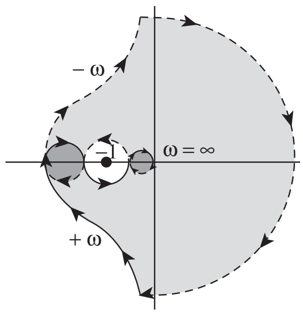
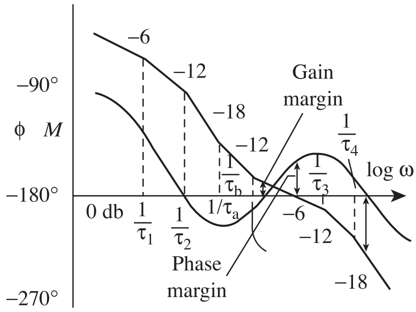
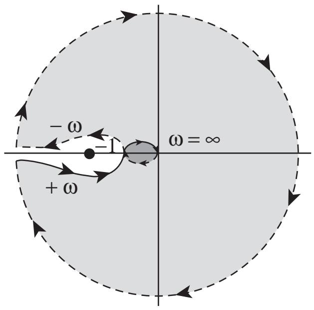
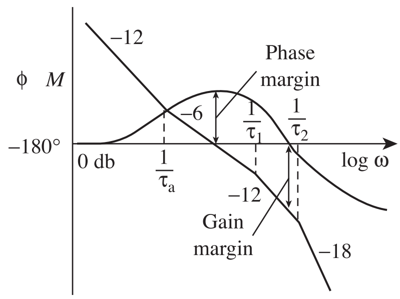
Nichols Diagram	Root Locus	Comments
		Elementary instrument servo; inherently stable; gain margin = ∞
		Instrument servo with field-control motor or power servo with elementary Ward-Leonard drive; stable as shown, but may become unstable with increased gain
		Elementary instrument servo with phase-lead (derivative) compensator; stable
		Inherently unstable; must be compensated

Transfer Function Plots for Typical Transfer Function (continued)

	G(s)	Polar Plot	Bode Diagram
9.	$\frac{K}{s^2(s\tau_1+1)}$		
10.	$\frac{K(s\tau_a+1)}{s^2(s\tau_1+1)}$		
11.	$\frac{K}{s^3}$		
12.	$\frac{K(s\tau_a+1)}{s^3}$		

Nichols Diagram	Root Locus	Comments
		Inherently unstable; must be compensated
		Stable for all gains
		Inherently unstable
		Inherently unstable

Transfer Function Plots for Typical Transfer Function (continued)

	G(s)	Polar Plot	Bode Diagram
13.	$\dfrac{K(s\tau_a+1)(s\tau_b+1)}{s^3}$		
14.	$\dfrac{K(s\tau_a+1)(s\tau_b+1)}{s(s\tau_1+1)(s\tau_2+1)(s\tau_3+1)(s\tau_4+1)}$		
15.	$\dfrac{K(s\tau_a+1)}{s^2(s\tau_1+1)(s\tau_2+1)}$		

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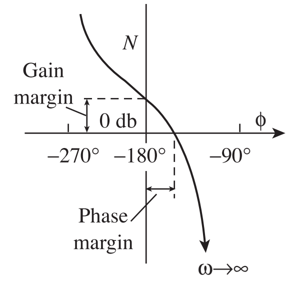
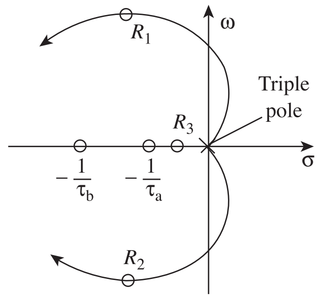
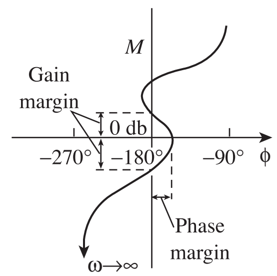
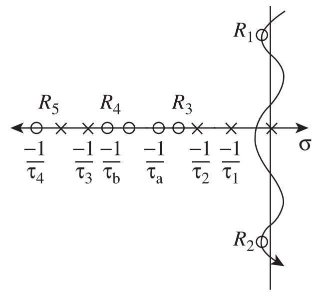
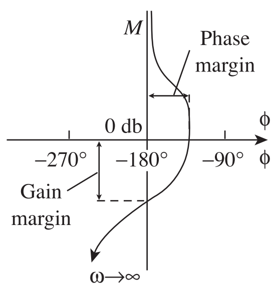
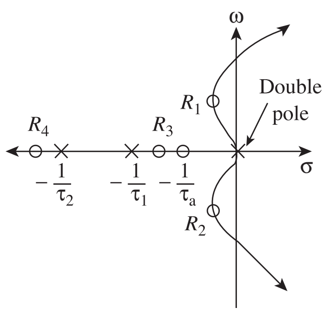
<tr><th>Nichols Diagram</th><th>Root Locus</th><th>Comments</th></tr>
<tr><td>
</td><td>
</td><td>Conditionally stable; becomes unstable if gain is too low</td></tr>
<tr><td>
</td><td>
</td><td>Conditionally stable; stable at low gain, becomes unstable as gain is raised, again becomes stable as gain is further increased, and becomes unstable for very high gains</td></tr>
<tr><td>
</td><td>
</td><td>Conditionally stable; becomes unstable at high gain</td></tr>
</table>

From Bolz, R.E. and Tuve, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 1080–1087. Originally from G.J. Thaler and R.G. Brown, *Analysis and Design of Feedback Control Systems*, 2nd ed., McGraw-Hill Book Company, New York, 1960.

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Properties of Dressed Lumber

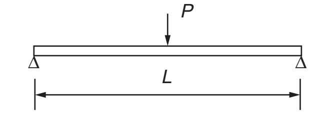
Standard Size Width × Depth	S4S Dressed Size Width × Depth	Cross-Sectional Area *A* (in.²)	Moment of Inertia I (in.⁴)	Section Modulus *S* (in.³)	Weight in Pounds per Lineal Foot[a]
1 × 4	¾ × 3½	2.63	2.68	1.53	0.64
1 × 6	¾ × 5¼	4.13	10.40	3.78	1.00
1 × 8	¾ × 7¼	5.44	23.82	6.57	1.32
1 × 12	¾ × 11¼	8.44	88.99	15.82	2.01
2 × 4	1½ × 3½	5.25	5.36	3.06	1.28
2 × 6	1½ × 5½	8.25	20.80	7.56	2.01
2 × 8	1½ × 7¼	10.88	47.64	13.14	2.64
2 × 10	1½ × 9¼	13.88	98.93	21.39	3.37
2 × 12	1½ × 11¼	16.88	177.98	31.64	4.10
4 × 2	3½ × 1½	5.25	.98	1.31	1.28
4 × 4	3½ × 3½	12.25	12.51	7.15	2.98
4 × 6	3½ × 5½	19.25	48.53	17.65	4.68
4 × 8	3½ × 7¼	25.38	111.15	30.66	6.17
6 × 2	5½ × 1½	8.25	1.55	2.06	2.01
6 × 4	5½ × 3½	19.25	19.65	11.23	4.68
6 × 6	5½ × 5½	30.25	76.26	27.73	7.35
6 × 8	5½ × 7¼	41.25	193.36	51.53	10.03
8 × 2	7¼ × 1½	10.88	2.04	2.72	2.64
8 × 4	7¼ × 3½	25.38	25.90	14.80	6.17
8 × 6	7¼ × 5½	41.25	103.98	37.81	10.03
8 × 8	7¼ × 7¼	56.25	263.67	70.31	13.67

[a] Weights are for wood with a density of 35 pounds per cubic foot.

From Alexander, A., Design and construction of concrete formwork, in *The Civil Engineering Handbook*, 2nd ed., Chen, W.-F. and Liew, J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **4**-4.

Beam Formulas

Simply Supported Beam with Concentrated Load at Center

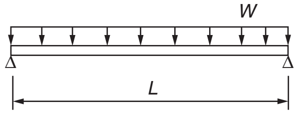


$$M_{max} = \frac{PL}{4}$$

$$\Delta = \frac{PL^3}{48EI}$$

$$V_{max} = \frac{P}{2}$$

Simply Supported Beam with Uniformly Distributed Load

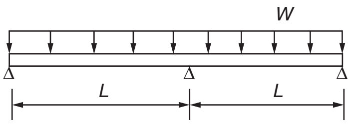


$$M_{max} = \frac{wL^2}{8}$$

$$\Delta_{max} = \frac{5wL^4}{384\,EI}$$

$$V_{max} = \frac{wL}{2}$$

Two Span Continuous Beam with Uniformly Distributed Load

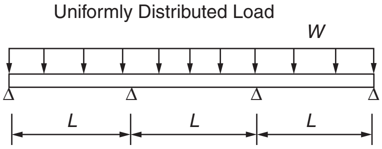


$$M_{max} = \frac{wL^2}{8}$$

$$\Delta_{max} = \frac{wL^4}{185EI}$$

$$V_{max} = \frac{5wL}{8}$$

Three Span Continuous Beam with Uniformly Distributed Load

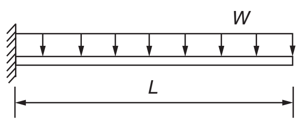


$$M_{max} = \frac{wL^2}{10}$$

$$\Delta_{max} = \frac{wL^4}{145EI}$$

$$V_{max} = .6wL$$

Cantilever Beam with Uniformly Distributed Load

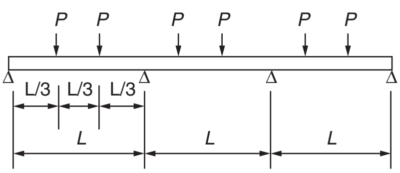


$$M_{max} = \frac{wL^2}{2}$$

$$\Delta_{max} = \frac{wL^4}{8EI}$$

$$V_{max} = wL$$

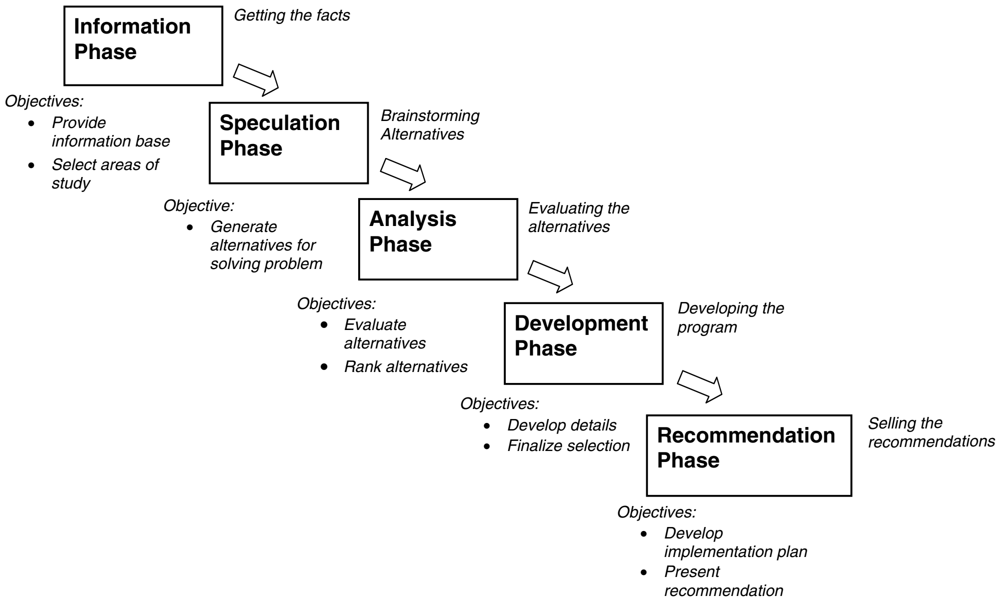
Three Span Continuous Beam with Concentrated Loads at Span Third Points



$$M_{max} = .267PL$$

$$V_{max} = 1.27P$$

From Alexander, A., Design and construction of concrete formwork, in *The Civil Engineering Handbook*, 2nd ed., Chen, W.-F. and Liew, J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **4**-23.



Phases in the value engineering job plan. From Chua, D.K.H., Value improvement methods, in *The Civil Engineering Handbook,* 2nd ed., Chen, W.F. and Liew, J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **7**-2.

Maximum Contaminant Concentrations Allowable in Drinking Water (Action Levels)

Parameter	Authority U.S. PHS[a]	U.S. EPA[b,c]	WHO[d]
		Pathogens and Parasites	
Total coliform bacteria (no./100mL)	1	<5% positive samples in a set of = 40 per month, or <1 sample positive in a set of <40 per month	0
		Inorganic Poisons (mg/L)	
Antimony	—	0.006	—
Arsenic	0.05	0.05 (Interim)	0.05
Asbestos (Million fibers > 10 μM per liter)	—	7	—
Barium	1	2	—
Beryllium	—	0.004	—
Cadmium	0.01	0.005	0.005
Chromium (Total)	0.05	0.1	0.05
Copper	—	1.3 90th percentile action level, requires corrosion control	—
Cyanide	0.2	0.2	0.1
Fluoride	See nuisances	4	—
Lead	0.05	0.015 90th percentile action level, requires corrosion control	0.05
Mercury (inorganic)	—	0.002	0.001
Nickel	—	0.1	—
Nitrate (as N)	10	10	10
Nitrite (as N)	—	1	—
Nitrate plus nitrite (as N)	—	10	—
Selenium	0.01	0.05	0.01
Sulfate	—	Deferred (400 to 500?)	—
Thallium	—	0.002	—
		Organic Poisons (μg/L, Except as Noted)	
Acrylamide	—	Use in treatment, storage, and distribution; restricted	—
Alachor	—	2	—
Aldicarb	—	3	—
Aldicarb sulfoxide	—	4	—
Aldicarb Sulfone	—	3	—
Aldrin and Dieldrin	—	—	0.03
Atrazine	—	3	—
Benzene	—	5	10
Benzo[a]pyrene	—	0.2	0.01
Bromobenzene	—	Monitor	—
Bromochloromethane	—	Monitor if ordered	—
Bromodichloromethane	—	Monitor	—
Bromoform	—	Monitor	—
Bromomethane	—	Monitor	—
n-Butylbenzene	—	Monitor if ordered	—
sec-Butylbenzene	—	Monitor if ordered	—
tert-Butylbenzene	—	Monitor if ordered	—
Carbofuran	—	40	—
Carbon chloroform extract	200	—	—

Maximum Contaminant Concentrations Allowable in Drinking Water (Action Levels) (continued)

Parameter	Authority		
	U.S. PHS[a]	U.S. EPA[b,c]	WHO[d]
Carbon tetrachloride	—	5	—
Chlordane	—	2	0.3
Chlorobenzene	—	100	—
Chlorodibromomethane	—	Monitor	—
Chloroethane	—	Monitor	—
Chloroform	—	Monitor	30
Chloromethane	—	Monitor	—
m-Chlorotoluene	—	Monitor	—
p-Chlorotoluene	—	Monitor	—
2,4-D	—	70	100
Dalapon	—	200	—
DDT	—	—	1
1,2-Dibromo-3-chloropropane (DBCP)	—	0.2	—
Dibromomethane	—	Monitor	—
m-Dichlorobenzene	—	Monitor	—
o-Dichlorobenzene	—	600	—
p-Dichlorobenzene	—	75	—
Dichlorodifluoromethane	—	Monitor if ordered	—
1,1-Dichloroethane	—	Monitor	—
1,2-Dichloroethane	—	5	10
1,1-Dichloroethylene	—	7	0.3
cis-1,2-Dichloroethylene	—	70	—
trans-1,2-Dichloroethylene	—	100	—
Dichloromethane	—	5	—
1,2-Dichloropropane	—	5	—
1,3-Dichloropropane	—	Monitor	—
2,2-Dichloropropane	—	Monitor	—
1,1-Dichloropropene	—	Monitor	—
1,3-Dichloropropene	—	Monitor	—
Di(2-ethylhexyl)adipate	—	400	—
Di(2-ethylhexyl)phthalate	—	6	—
Dinoseb	—	7	—
Dioxin (2,3,7,8-TCDD)	—	30×10^{-9}	—
Diquat	—	20	—
Endothall	—	100	—
Endrin	—	2	—
Epichlorhydrin	—	Use in treatment, storage, and distribution; restricted	—
Ethylbenzene	—	700	—
Ethylene dibromide (EDB)	—	0.05	—
Fluorotrichloromethane	—	Monitor if ordered	—
Glyphosate (aka Rodeo™ and Roundup™)	—	700	—
Heptachlor	—	0.4	0.1
Heptachlor epoxide	—	0.2	—
Hexachlorobenzene	—	1	0.01
Hexachlorobutadiene	—	Monitor if ordered	—
Hexachlorocyclopentadiene (HEX)	—	50	—
Isopropylbenzene	—	Monitor if ordered	—
p-Isopropyltolulene	—	Monitor if ordered	—
Lindane	—	0.2	3
Methoxychlor	—	40	30
Naphthalene	—	Monitor if ordered	—
Oxamyl (Vydate)	—	200	—
Pentachlorophenol	—	1	10

Maximum Contaminant Concentrations Allowable in Drinking Water (Action Levels) (continued)

Parameter	Authority U.S. PHS[a]	U.S. EPA[b,c]	WHO[d]
PCB (polychlorinate biphenyl)	—	0.5	—
Picloram	—	500	—
n-Propylbenzene	—	Monitor if ordered	—
Silvex (2,4,5-TP)	—	50	—
Simazine	—	4	—
Styrene	—	100	—
2,3,7,8-TCDD (Dioxin)	—	30×10^{-6}	—
1,1,1,2-Tetrachloroethane	—	Monitor	—
1,1,2,2-Tetrachloroethane	—	Monitor	—
Tetrachloroethylene	—	5	—
Toluene	—	1000	—
Toxaphene	—	3	—
1,2,3-Trichlorobenzene	—	Monitor if ordered	—
1,2,4-Trichlorobenzene	—	70	—
1,1,1-Trichloroethane	—	200	—
1,1,2-Trichloroethane	—	5	—
Trichloroethylene	—	5	—
1,2,3-Trichloropropane	—	Monitor	—
2,4,6-Trichlorophenol	—	—	10
Trihalomethanes (Total)	—	100	—
2,4-Trimethylbenzene	—	Monitor if ordered	—
1,3,5-Trimethylbenzene	—	Monitor if ordered	—
Vinyl chloride	—	2	—
Xylene (Total)	—	10,000	—
m-Xylene	—	Monitor	—
o-Xylene	—	Monitor	—
p-Xylene	—	Monitor	—
Radioactivity (pCi/L, except as noted)			
Gross alpha (excl. Ra, u)	—	15	2.7
Gross beta	1000	—	27
Gross beta/photon (mrem/yr)	—	4	—
Radium-226	10		—
Radium-226 and 228	—	5	—
Radon-222	—	300	—
Strontium-90	3	—	—
Uranium (mg/L)	—	.03	—
Nuisances (mg/L, except as noted)			
Alkyl benzene sulfonate	0.5	—	—
Aluminum	—	—-	0.2
Chloride	250	250	250
Color (Pt-Co Units)	15	15	15
Copper	1	See above	1
Corrosivity (Langelier Index)	—	—[e]	—
Fluoride	0.8–1.7 Depending on air temperature	See above	—
Hardness (as $CaCO_3$)	—	—	500
Hydrogen sulfide	—	—	—[f]
Iron	0.3	0.3	0.3
Manganese	0.05	0.05	0.1
Methylene blue active substances	—	0.5	—

Maximum Contaminant Concentrations Allowable in Drinking Water (Action Levels) (continued)

	Authority		
Parameter	U.S. PHS[a]	U.S. EPA[b,c]	WHO[d]
Odor (threshold odor no.)	3	3	—[g]
pH	—	6.5/8.5	6.5/8.5
Phenol (μg/L)	1	—	—
Silver	0.05	0.05	—
Sodium	—	—[e]	200
Sulfate	250	500	400
Taste	—	—	—[g]
Total dissolved solids	500	500	1000
Turbidity (nephelometric units)	5	All samples = ≤5; 95% of samples ≤ 0.5	5
Zinc	5	5	5
Disinfectants and Disinfection Byproducts (mg/L)			
Chlorine	—	4.	—
Chloramines		4.	—
Chlorine dioxide	—	0.8	—
Total trihalomethanes	—	0.080	—
Haloacetic acids	—	0.060	—
Chlorite	—	1.0	—
Bromate	—	0.010	—
Total organic carbon	—	Treatment	—

[a] Hopkins, O. C. 1962. *Public Health Service Drinking Water Standards 1962*. U.S. Department of Health Education, and Welfare, Public Health Service, Washington, DC.
[b] Pontius, F. W. 1990. "Complying with the New Drinking Water Quality Regulations," *Journal of the American Water Works Association,* 82(2): 32.
[c] Auerbach, J. 1994. "Cost and Benefits of Current SDWA Regulations," *Journal of the American Water Works Association,* 86(2): 69.
[d] Anonymous. 1984. *Guidelines For Drinking Water Quality*: Volume 1. Recommendations. World Health Organization, Geneva, Switzerland.
[e] To be monitored and reported to appropriate agency and/or public.
[f] Not detectable by consumer.
[g] Not offensive for most consumers.

From Sykes, R.M., Water and wastewater planning, in *The Civil Engineering Handbook,* 2nd ed., Chen, W.-F. and Liew, J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, pp. **8**-3 to **8**-6.

National Ambient Air Quality Standards

Criteria Pollutant	Averaging Period	Primary NAAQS (μg/m^3)	Secondary NAAQS (μg/m^3)
PM_{10}	Annual	50	150
	24 hours	150	150
$PM_{2.5}$	Annual[a]	15	15
	24 hours[a]	65	65
Sulfur dioxide (SO_2)	Annual	80	
	24 hours	365	
	3 hours		1300
Nitrogen dioxide (NO_2)	Annual	100	100
Ozone	1 hour	235	235
	8 hours[a]	157	157
Carbon monoxide (CO)	8 hours	10,000	10,000
	1 hour	40,000	40,000
Lead	Quarterly	1.5	1.5

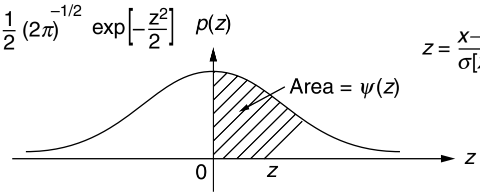
[a] The 1997 Revised $PM_{2.5}$ and 8-hour ozone were challenged in court and were the subject of a significant question regarding the constitutionality of EPA's power to make policy without legislative review and EPA's responsibility to consider economic implications of policymaking. A February 27, 2001, ruling by the Supreme Court found the EPA could move forward with the $PM_{2.5}$ standard but must review the proposed ozone standard. The revised standards were cleared of remaining legal hurdles in March 2002.

From Jacko, R.B. and LaBreche, T.M.C., Air pollution, in *The Civil Engineering Handbook*, 2nd ed., Chen, W.-F. and Liew, J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **12**-4.

Standard Normal Probability

for $z > 2.2$, $\psi(z) \approx \frac{1}{2} - \frac{1}{2}(2\pi)^{-1/2} \exp\left[-\frac{z^2}{2}\right]$

$z = \frac{x - \bar{x}}{\sigma[x]}$



z	0	1	2	3	4	5	6	7	8	9
0	0	.003969	.007978	.011966	.015953	.019939	.023922	.027903	.031881	.035856
.1	.039828	.043795	.047758	.051717	.055670	.059618	.063559	.067495	.071424	.075345
.2	.079260	.083166	.087064	.090954	.094835	.098706	.102568	.106420	.110251	.114092
.3	.117911	.121720	.125516	.129300	.133072	.136831	.140576	.144309	.148027	.151732
.4	.155422	.159097	.162757	.166402	.170031	.173645	.177242	.180822	.184386	.187933
.5	.191462	.194974	.198466	.201944	.205401	.208840	.212260	.215661	.219043	.222405
.6	.225747	.229069	.232371	.235653	.238914	.242154	.245373	.248571	.251748	.254903
.7	.258036	.261148	.264238	.267305	.270350	.273373	.276373	.279350	.282305	.285236
.8	.288145	.291030	.293892	.296731	.299546	.302337	.305105	.307850	.310570	.313267
.9	.315940	.318589	.321214	.323814	.326391	.328944	.331472	.333977	.336457	.338913
1.0	.341345	.343752	.346136	.348495	.350830	.353141	.355428	.357690	.359929	.362143
1.1	.364334	.366500	.368643	.370762	.372857	.374928	.376976	.379000	.381000	.382977
1.2	.384930	.386861	.388768	.390651	.392512	.394350	.396165	.397958	.399727	.401475
1.3	.403200	.404902	.406582	.408241	.409877	.411492	.413085	.414657	.416207	.417736
1.4	.419243	.420730	.422196	.423641	.425066	.426471	.427855	.429219	.430563	.431888
1.5	.433193	.434476	.435745	.436992	.438220	.439429	.440620	.441792	.442947	.444083
1.6	.445201	.446301	.447384	.448449	.449497	.450529	.451543	.452540	.453521	.454486
1.7	.455435	.456367	.457284	.458185	.459070	.459941	.460796	.461636	.462462	.463273
1.8	.464070	.464852	.465620	.466375	.467116	.467843	.468557	.469258	.469946	.470621
1.9	.471283	.471933	.472571	.473197	.473610	.474412	.475002	.475581	.476148	.476705
2.0	.477250	.477784	.478308	.478822	.479325	.479818	.480301	.480774	.481237	.481691
2.1	.482136	.482571	.482997	.483414	.483823	.484222	.484614	.484997	.485371	.485738
2.2	.486097	.486447	.486791	.487126	.487455	.487776	.488089	.488396	.488696	.488989
2.3	.489276	.489556	.489830	.490097	.490358	.490613	.490863	.491106	.491344	.491576
2.4	.491802	.492024	.492240	.492451	.492656	.492857	.493053	.493244	.493431	.493613
2.5	.493790	.493963	.494132	.494297	.494457	.494614	.494766	.494915	.495060	.495201
2.6	.495339	.495473	.495604	.495731	.495855	.495975	.496093	.496207	.496319	.496427
2.7	.496533	.496636	.496736	.496833	.496928	.497020	.497110	.497197	.497282	.497365
2.8	.497445	.497523	.497599	.497673	.497744	.497814	.497882	.497948	.498012	.498074
2.9	.498134	.498193	.498250	.498305	.498359	.498411	.498462	.498511	.498559	.498605
3.0	.498650	.498694	.498736	.498777	.498817	.498856	.498893	.498930	.498965	.498999
3.1	.499032	.499065	.499096	.499126	.499155	.499184	.499211	.499238	.499264	.499289
3.2	.499313	.499336	.499359	.499381	.499402	.499423	.499443	.499462	.499481	.499499
3.3	.499517	.499534	.499550	.499566	.499581	.499596	.499610	.499624	.499638	.499651
3.4	.499663	.499675	.499687	.499698	.499709	.499720	.499730	.499740	.499749	.499758
3.5	.499767	.499776	.499784	.499792	.499800	.499807	.499815	.499822	.499828	.499835
3.6	.499841	.499847	.499853	.499858	.499864	.499869	.499874	.499879	.499883	.499888
3.7	.499892	.499896	.499900	.499904	.499908	.499912	.499915	.499918	.499922	.499925
3.8	.499928	.499931	.499933	.499936	.499938	.499941	.499943	.499946	.499948	.499950
3.9	.499952	.499954	.499956	.499958	.499959	.499961	.499963	.499964	.499966	.499967

From Harr, M.E., Accounting for variability, in *The Civil Engineering Handbook,* 2nd ed., Chen. W.F. and Liew, J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **16**-11.

Typical Values of Elastic Modulus and Poisson's Ratio for Granular Soils

Type of Soil	Elastic Modulus, E_s MPa	Elastic Modulus, E_s lb/in.^{2}	Poisson's ratio, μ
Loose sand	10–24	1,500–3,500	0.20–0.40
Medium dense sand	17–28	2,500–4,000	0.25–0.40
Dense sand	35–55	5,000–8,000	0.30–0.45
Silty sand	10–17	1,500–2,500	0.20–0.40
Sand and gravel	69–170	10,000–25,000	0.15–0.35

From Humphrey, D.N., Strength and deformation, in *The Civil Engineering Handbook,* 2nd ed., Chen, W.-F. and Liew J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **17**-8. Originally from Das, B. M. 1990. *Principles of Foundation Engineering,* 2nd ed., p. 161. PWS-Kent Publishing Co., Boston. With permission.

Representative Applications and Controlling Functions of Geotextiles

Primary Function	Application	Secondary Functions
Separation	Unpaved roads (temporary and permanent)	Filter, drains, reinforcement
	Paved roads (secondary and primary)	Filter, drains
	Construction access roads	Filter, drains, reinforcement
	Working platforms	Filter, drains, reinforcement
	Railroads (new construction)	Filter, drains, reinforcement
	Railroads (rehabilitation)	Filter, drains, reinforcement
	Landfill covers	Drains, reinforcement
	Preloading (stabilization)	Drains, reinforcement
	Marine causeways	Filter, drains, reinforcement
	General fill areas	Filter, drains, reinforcement
	Paved and unpaved parking facilities	Filter, drains, reinforcement
	Cattle corrals	Filter, drains, reinforcement
	Coastal and river protection	Filter, drains, reinforcement
	Sports fields	Filter, drains
Drainage-transmission	Retaining walls	Separation, filter
	Vertical drains	Separation, filter
	Horizontal drains	Reinforcement
	Below membranes (drainage of gas and water)	Reinforcement
	Earth dams	Filter
	Below concrete (decking and slabs)	—
Reinforcement	Pavement overlays	—
	Concrete overlays	—
	Subbase reinforcement in roadways and railways	Filter
	Retaining structures	Drains
	Membrane support	Separation, drains, filter
	Embankment reinforcement	Drains
	Fill reinforcement	Drains
	Foundation support	Drains
	Soil encapsulation	Drains, filter separation
	Net against rockfalls	Drains
	Fabric retention systems	Drains
	Sandbags	—
	Reinforcement of membranes	—
	Load redistribution	Separation
	Bridging nonuniformity soft soil areas	Separation
	Encapsulated hydraulic fills	Separation
	Bridge piles for fill placement	—
Filter	Trench drains	Separation, drains
	Pipe wrapping	Separation, drains
	Base course drains	Separation, drains
	Frost protection	Separation, drainage, reinforcement
	Structural drains	Separation, drains
	Toe drains in dams	Separation, drains
	High embankments	Drains
	Filter below fabric-form	Separation, drains
	Silt fences	Separation, drains
	Silt screens	Separation
	Culvert outlets	Separation
	Reverse filters for erosion control:	
	Seeding and mulching	
	Beneath gabions	
	Ditch amoring	
	Embankment protection, coastal	
	Embankment protection, rivers and streams	
	Embankment protection, lakes	
	Vertical drains (wicks)	Separation

From Holtz, R.D., Geosynthetics, in *The Civil Engineering Handbook*, 2nd ed., Chen, W.-F. and Liew J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **24**-3. Originally from Christopher, B. R., and Holtz, R. D. 1989. *Geotextile Design and Construction Guidelines.*, U.S. Federal Highway Administration, National Highway Institute, Report No. FHWA-HI-90-001.

Physical Properties of Water in SI Units*

Temperature, °F	Specific Weight y, lb/ft³	Density ρ, slugs/ft³	Viscosity $\mu \times 10^5$, lb·s/ft²	Kinematic Viscosity $\nu \times 10^5$, ft²/s	Surface Tension $\sigma \times 10^2$ lb/ft	Vapor Pressure p_u, psia	Vapor Pressure Head p_u/γ, ft	Bulk Modulus of Elasticity $E_u \times 10^{-3}$, psi
0	9.805	999.8	1.781	1.785	0.0756	0.61	0.06	2.02
5	9.807	1000.0	1.518	1.519	0.0749	0.87	0.09	2.06
10	9.804	999.7	1.307	1.306	0.0742	1.23	0.12	2.10
15	9.798	999.1	1.139	1.139	0.0735	1.70	0.17	2.14
20	9.789	998.2	1.002	1.003	0.0728	2.34	0.25	2.18
25	9.777	997.0	0.890	0.893	0.0720	3.17	0.33	2.22
30	9.764	995.7	0.798	0.800	0.0712	4.24	0.44	2.25
40	9.730	992.2	0.653	0.658	0.0696	7.38	0.76	2.28
50	9.689	988.0	0.547	0.553	0.0679	12.33	1.26	2.29
60	9.642	983.2	0.466	0.474	0.0662	19.92	2.03	2.28
70	9.589	977.8	0.404	0.413	0.0644	31.16	3.20	2.25
80	9.530	971.8	0.354	0.364	0.0626	47.34	4.96	2.20
90	9.466	965.3	0.315	0.326	0.0608	70.10	7.18	2.14
100	9.399	958.4	0.282	0.294	0.0589	101.33	10.33	2.07

* In this table and in the others to follow, if $\mu \times 10^5 = 3.746$ then $\mu = 3.746 \times 10^{-5}$ lb·s/ft², etc. For example, at 80°F, $\sigma \times 10^2 = 0.492$ or $\sigma = 0.00492$ lb/ft and $E_u \times 10^{-3} = 322$ or $E_u = 322{,}000$ psi.

From Lyn, D.A., Fundamentals of hydraulics, in *The Civil Engineering Handbook*, 2nd ed., Chen, W.-F. and Liew J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **29**-27. Originally from Daugherty, R.L., Franzini, J.B., and Finnemore, E.J. (1985) *Fluid Mechanics with Engineering Applications*, 8th ed., McGraw-Hill, New York. With permission.

Physical Properties of Air at Standard Atmospheric Pressure in English Units

Temperature T, °F	T, °C	Density $\rho \times 10^3$, slugs/ft³	Specifc Weight $\gamma \times 10^2$, lb/ft³	Viscosity $\mu \times 10^7$, lb·s/ft²	Kinematic Viscosity $\nu \times 10^4$, ft²/s
–40	–40.0	2.94	9.46	3.12	1.06
–20	–28.9	2.80	9.03	3.25	1.16
0	–17.8	2.68	8.62	3.38	1.26
10	–12.2	2.63	8.46	3.45	1.31
20	–6.7	2.57	8.27	3.50	1.36
30	–1.1	2.52	8.11	3.58	1.42
40	4.4	2.47	7.94	3.62	1.46
50	10.0	2.42	7.79	3.68	1.52
60	15.6	2.37	7.63	3.74	1.58
70	21.1	2.33	7.50	3.82	1.64
80	26.7	2.28	7.35	3.85	1.69
90	32.2	2.24	7.23	3.90	1.74
100	37.8	2.20	7.09	3.96	1.80
120	48.9	2.15	6.84	4.07	1.89
140	60.0	2.06	6.63	4.14	2.01
160	71.1	1.99	6.41	4.22	2.12
180	82.2	1.93	6.21	4.34	2.25
200	93.3	1.87	6.02	4.49	2.40
250	121.1	1.74	5.60	4.87	2.80

From Lyn, D.A., Fundamentals of hydraulics, in *The Civil Engineering Handbook*, 2nd ed., Chen, W.-F. and Liew J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **29**-28. Originally from Daugherty, R.L., Franzini, J.B., and Finnemore, E.J. (1985) *Fluid Mechanics with Engineering Applications*, 8th ed., McGraw-Hill, New York. With permission.

Physical Properties of Common Liquids at Standard Atmospheric Pressure in SI Units

Liquid	Temperature T, °F	Density ρ, kg/m^3	Specific Gravity, s	Viscosity $\mu \times 10^4$, N·s/m^2	Surface Tension σ, N/m	Vapor Pressure p_u, kN/m^2, abs	Modulus of Elasticity $E_u \times 10^{-6}$, N/m^2
Benzene	20	895	0.90	6.5	0.029	10.0	1030
Carbon tetrachloride	20	1588	1.59	9.7	0.026	12.1	1100
Crude oil	20	856	0.86	72	0.03		
Gasoline	20	678	0.68	2.9	……	55	
Glycerin	20	1258	1.26	14,900	0.063	0.000014	4350
Hydrogen	–257	72	0.072	0.21	0.003	21.4	
Kerosene	20	808	0.81	19.2	0.025	3.20	
Mercury	20	13,550	13.56	15.6	0.51	0.00017	26,200
Oxygen	–195	1206	1.21	2.8	0.015	21.4	
SAE 10 oil	20	918	0.92	820	0.037		
SAE 30 oil	20	918	0.92	4400	0.036		
Water	20	998	1.00	10.1	0.073	2.34	2070

From Lyn, D.A., Fundamentals of hydraulics, in *The Civil Engineering Handbook*, 2nd ed., Chen, W.-F. and Liew J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **29**-29. Originally from Daugherty, R.L., Franzini, J.B., and Finnemore, E.J. (1985) *Fluid Mechanics with Engineering Applications*, 8th ed., McGraw-Hill, New York. With permission.

Physical Properties of Common Gases at Standard Sea-Level Atmosphere and 68°F in English Units

Liquid	Chemical Formula	Molecular Weight	Specific Weight, γ, lb/ft^3	Viscosity $\mu \times 10^7$, lb·s/ft^2	Gas Constant R, ft·lb/(slug·°R) [= ft^2/(s^2·°R)]	Specific Heat, ft·lb/(slug·°R) [= ft^2/(s^2·°R)] c_p	c_u	Specific Heat Ratio $k = c_p/c_u$
Air		29.0	0.0753	3.76	1715	6000	4285	1.40
Carbon dioxide	CO_2	44.0	0.114	3.10	1123	5132	4009	1.28
Carbon monoxide	CO	28.0	0.0726	3.80	1778	6218	4440	1.40
Helium	He	4.00	0.0104	4.11	12,420	31,230	18,810	1.66
Hydrogen	H_2	2.02	0.00522	1.89	24,680	86,390	61,710	1.40
Methane	CH_4	16.0	0.0416	2.80	3100	13,400	10,300	1.30
Nitrogen	N_2	28.0	0.0728	3.68	1773	6210	4437	1.40
Oxygen	O_2	32.0	0.0830	4.18	1554	5437	3883	1.40
Water vapor	H_2O	18.0	0.0467	2.12	2760	11,110	8350	1.33

From Lyn, D.A., Fundamentals of hydraulics, in *The Civil Engineering Handbook*, 2nd ed., Chen, W.-F. and Liew J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **29**-30. Originally from Daugherty, R.L., Franzini, J.B., and Finnemore, E.J. (1985) *Fluid Mechanics with Engineering Applications*, 8th ed., McGraw-Hill, New York. With permission.

Typical Physical Properties of and Allowable Stresses for Some Common Materials (in U.S. Customary System Units)

Material	Unit Weight (lb/in.^{3})	Ultimate Strength (ksi)			Yield Strength (ksi)		Allow Stresses (psi)		Elastic Moduli ($\times 10^{-6}$ psi)		Coefficient of Thermal Expansion ($\times 10^6$/°F)
		Tension	Compression	Shear	Tension	Shear	Tension or Compression	Shear	Tension or Compression	Shear	
Aluminum alloy (extruded)											
2024-T4	0.100	60	—	32	44	25			10.6	4.00	12.9
6061-T6		38	—	24	35	20			10.0	3.75	13.0
Cast iron											
gray	0.276	30	120	—	—	—			13	6	5.8
malleable		54	—	48	36	24			25	12	6.7
Concrete											
8 gal/sack	0.087	—	3	—	—	—	–1350	66	3	—	6.0
6 gal/sack		—	5	—	—	—	–2250	86	5	—	—
Magnesium alloy, AM100A	0.065	40	—	21	22	—	—	—	6.5	2.4	14.0
Steel											
0.2% carbon (hot rolled)		65	—	48	36	24	±24,000	14,500			
0.6% carbon (hot rolled)	0.283	100	—	80	60	36			30	12	6.5
0.6% carbon (quenched)		120	—	100	75	45					
3½% Ni, 0.4% C		200	—	150	150	90					
Wood											
Douglas fir (coast)	0.018	—	7.4	1.1	—	—	±1900	120	1.76	—	—
Southern pine (longleaf)	0.021	—	8.4	1.5	—	—	±2250	135	1.76	—	—

From Pan, A.D.E. and Popov, E.P., Mechanics of materials, in *The Civil Engineering Handbook,* 2nd ed., Chen, W.-F. and Liew, J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **46**-7.

Typical Physical Properties of and Allowable Stresses for Some Common Materials (in SI System Units)

Material	Unit Mass ($\times 10^3$ kg/m^3)	Ultimate Strength (MPa)			Yield Strength (MPa)		Allow Stresses (MPa)		Elastic Moduli (GPa)		Coefficient of Thermal Expansion ($\times 10^{-6}$/°C)
		Tension	Compression	Shear	Tension	Shear	Tension or Compression	Shear	Tension or Compression	Shear	
Aluminum alloy (extruded)											
2014-T6	2.77	414	—	220	300	170			73	27.6	23.2
6061-T6		262	—	165	241	138			70	25.9	23.4
Cast iron											
gray	7.64	210	825	—	—	—			90	41	10.4
malleable		370	—	330	250	165			170	83	12.1
Concrete											
0.70 water-cement ratio	2.41	—	20	—	—	—	–9.31	0.455	20	—	10.8
0.53 water-cement ratio		—	35	—	—	—	–15.5	0.592	35	—	
Magnesium alloy, AM100A	1.80	275	—	145	150	—	—	—	45	17	25.2
Steel											
0.2% carbon (hot rolled)		450	—	330	250	165	+165.0	100			
0.6% carbon (hot rolled)	7.83	690	—	550	415	250			200	83	11.7
0.6% carbon (quenched)		825	—	690	515	310					
3½% Ni, 0.4% C		1380	—	1035	1035	620					
Wood											
Douglas fir (coast)	0.50	—	51	7	—	—	+13.1	0.825	12.1	—	—
Southern pine (longleaf)	0.58	—	58	10	—	—	+15.5	0.930	12.1	—	—

From Pan, A.D.E. and Popov, E.P., Mechanics of materials, in *The Civil Engineering Handbook,* 2nd ed., Chen, W.-F. and Liew, J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **46**-8.

Some Distribution Types

Distribution	PMF ($p_X(x)$) or PDF ($f_X(x)$)	Mean, $E[X]$	Variance, Var$[X]$
Binomial	$p_X(x)=\binom{n}{x}p^x(1-p)^{n-x}$ $x=0,1,2,\ldots,n$	np	$np(1-p)$
Poisson	$p_X(x)=\frac{(\nu t)^x}{x!}e^{-\nu t}$	νt	νt
Normal	$f_X(x)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]$ $-\infty<x<\infty$	μ	σ^2
Lognormal	$f_X(x)=\frac{1}{x\zeta\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{\ln x-\lambda}{\zeta}\right)^2\right]$ $0<x<\infty$	$e^{\left(\lambda+\frac{1}{2}\zeta^2\right)}$	$e^{\left(2\lambda+\zeta^2\right)}\left[e^{\zeta^2}-1\right]$
Rayleigh	$f_X(x)=\frac{x}{\alpha^2}\exp\left[-\frac{1}{2}\left(\frac{x}{\alpha}\right)^2\right]$ $0\le x<\infty$	$\alpha\sqrt{\frac{\pi}{2}}$	$\left(2-\frac{\pi}{2}\right)\alpha^2$
Exponential	$f_X(x)=\lambda\exp[-\lambda(x-\tau)]$ $\tau\le x<\infty$	$\tau+\frac{1}{\lambda}$	$\frac{1}{\lambda^2}$
Gumbel type I maximum	$f_X(x)=\alpha\exp\left[-\alpha(x-u)-e^{-\alpha(x-u)}\right]$ $-\infty<x<\infty$	$u+\frac{0.5772}{\alpha}$	$\frac{\pi^2}{6\alpha^2}$
Fretchet type II maximum	$f_X(x)=\frac{k}{\nu-\tau}\left(\frac{\nu-\tau}{x-\tau}\right)^{k+1}\exp\left[-\left(\frac{\nu-\tau}{x-\tau}\right)^k\right]$ $\varepsilon<x<\infty$	$(\nu-\tau)\Gamma\left(1-\frac{1}{k}\right)+\tau$	$(\nu-\tau)^2\left[\Gamma\left(1-\frac{2}{k}\right)\right]-\Gamma^2\left(1-\frac{1}{k}\right)$
Weibull type III minimum	$f_X(x)=\frac{k}{w-\varepsilon}\left(\frac{x-\varepsilon}{w-\varepsilon}\right)^{k-1}\exp\left[-\left(\frac{x-\varepsilon}{w-\varepsilon}\right)^k\right]$ $\varepsilon<x<\infty$	$(w-\varepsilon)\Gamma\left(1-\frac{1}{k}\right)+\varepsilon$	$(w-\varepsilon)^2\left[\Gamma\left(1-\frac{2}{k}\right)+\Gamma^2\left(1-\frac{1}{k}\right)\right]$

From Quek, S.-T., Structural reliability, in *The Civil Engineering Handbook,* 2nd ed., Chen, W.-F. and Liew, J.Y.R., Eds., CRC Press, Boca Raton, FL, 2003, p. **52**-4.

Typical Compound Composition of Ordinary Portland Cement

Chemical Formula	Shorthand Notation	Chemical Name	Weight Percent
$3CaO \cdot SiO_2$	C_3S	Tricalcium silicate	50
$2CaO \cdot SiO_2$	C_2S	Dicalcium silicate	25
$3CaO \cdot Al_2O_3$	C_3A	Tricalcium aluminate	12
$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF	Tetracalcium aluminoferrite	8
$CaSO_4 \cdot 2H_2O$	CSH_2	Calcium sulfate dihydrate (gypsum)	3.5

From Mindness, S., Concrete constituent matenaus, in *Concrete Construction Engineering Handbook*, Nawy, E.G., Ed., CRC Press, Boca Raton, FL, 1998, p. **1**–4.

Properties of Some Lightweight Concretes

Type of Lightweight Concrete	Type of Aggregate	Aggregate Density, kg/m^3	Concrete Density, kg/m^3
Aerated	—	—	400–600
Partially compacted	Expanded vermiculite and perlite	5–240	400–1150
	Foamed slag	480–960	960–1500
	Sintered pulverized-fuel ash	640–960	1100–1300
	Expanded clay or shale	560–1040	950–1200
Structural lightweight aggregate concrete	Foamed slag	480–960	1650–2050
	Sintered pulverized-fuel ash	640–960	1350–1750
	Expanded clay or shale	560–1040	1350–1850

From Mindness, S., Concrete constituent matenaus, in *Concrete Construction Engineering Handbook*, Nawy, E.G., Ed., CRC Press, Boca Raton, FL, 1998, p. **1**–16.

Mechanical Properties of Hardened Concrete

Mix	MK Content, %	Silica Fume Content, %	W/C or W/C + MK or W/C + SF	Unit Weight, kg/m³	Strength, MPa								E Modulus,[§] GPa
					Compressive[*]						Splitting-tensile[†]	Flexura[‡]	
					1 Day	3 Days	7 Days	28 Days	90 Days	180 Days	28 Days	28 Days	28 Days
CO	0	0	0.40	2350	20.9	25.5	28.9	36.4	42.5	44.2	2.7	6.3	29.6
MK10	10	—	0.40	2330	25.0	32.9	37.9	39.9	43.0	46.2	3.1	7.4	32.0
SF10	—	10	0.40	2320	23.2	28.6	34.7	44.4	48.0	50.2	2.8	7.0	31.1

Note: MK, Metakaolin: W/C, water/cementitous material ratio; SF, silica fume.

[*] Average of three 102 × 203-mm cylinders.

[†] Average of two 152 × 305-mm cylinders.

[‡] Average of two 102 × 76 × 406-mm prims.

[§] Average of two 152 × 305-mm cylinders.

From Malhotra, V.M., Mineral admixtures, in *Concrete Construction Engineering Handbook*, Nawy, E.G., Ed., CRC Press, Boca Raton, FL, 1998, p. **2**-38. Originally from Zhang, M.H. and Malhotra, V.M. 1995. Characteristics of a thermally activated alumina-silicate pozzolanic material and its use in concrete. *Cement Concrete Res.* 25(8):1713–1725.

ACI 318 Maximum Chloride-Ion Content for Corrosion Protection

Type of Application	Maximum Water-Soluble Chloride Ion (Cl^-) in Concrete, Percent by Weight of Cement
Prestressed concrete	0.06
Reinforced concrete exposed to chloride in service	0.15
Reinforced concrete that will be dry or protected from moisture in serviced	1.00
Other reinforced concrete construction	0.30

From Whitney, D.P., Chemical admixtures, in *Concrete Construction Engineering Handbook*, Nawy, E.G., Ed., CRC Press, Boca Raton, FL, 1998, p. **3**-9. Originally from ACI 318-95/318R-95 Building Code and Commentary.

Properties of Typical Air-Entraining Admixtures

Name Brand	Manufacturer	Active Ingredient	Dosage	Sp. Gr.
Protex regular	Protex Industries	Neutral vinusol resin	0.3–1.0	1.044
Darex AEA	WR Grace & Co.	Organic acid salts	0.65–1.95	1.00–1.05
Airex “D”	Mulco, Inc.	Sulfonated HC salt	1.5–1.85	1.01–1.03
Plastair	SikaChemical Corp.	Vinusol resin	1.4	—
Plastade	Sternson	Coconut acid amide	0.6–1.9	1.0

From Whitney, D.P., Chemical admixtures, in *Concrete Construction Engineering Handbook*, Nawy, E.G., Ed., CRC Press, Boca Raton, FL, 1998, p. **3**-11. Originally from Dolch, W.I. 1984. Air-entraining admixtures. In *Concrete Admixtures Handbook Properties, Science, and Technology*, V.S. Ramachandran, ed., pp. 269–302. Noyes Publications, Park Ridge, NJ.

Total Target Air Content for Concrete

Nominal Maximum Aggregate Size, in.	Air Content, %*		
	Severe Exposure†	Moderate Exposure†	Mild Exposure†
⅜	7½	6	4½
½	7	5½	4
¾	6	5	3½
1	6	4½	3
1½	5½	4½	2½
2‡	5	4	2
3‡	4½	3½	1½

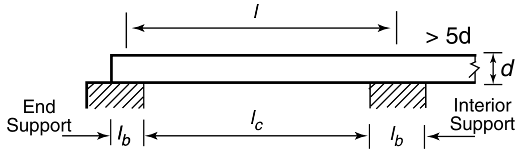
* Project specifications often allow the air content of the delivered concrete to be within –1 to +2 percentage points of the table target values.

† Severe exposure is an environment in which concrete is exposed to wet freeze-thaw conditions, deicers, or other aggressive agents. Moderate exposure is an environment in which concrete is exposed to freezing but will not be continually moist, will not be exposed to water for long periods before freezing, and will not be in contact with deicers or aggressive chemicals. Mild exposure is an environment in which concrete is not exposed to freezing conditions, deicers or aggressive agents.

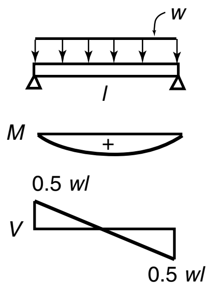
‡ These air contents apply to total mix, as for the preceding aggregate sizes. When testing these concretes, however, aggregate larger than 1½ in. is removed by hand-picking or sieving and air content is determined on the minus 1½ in. fraction of mix. (Tolerance on air content as delivered applies to this value.) Air content of the total mix is computed from the value determined on the minus 1½ in. fraction.

From Whitney, D.P., Chemical admixtures, in *Concrete Construction Engineering Handbook*, Nawy, E.G., Ed., CRC Press, Boca Raton, FL, 1998, p. **3**-13. Originally from Kosmatka, S.H. and Panarese, W.C. 1988. *Design and Control of Concrete Mixtures,* 13th ed., Portland Cement Association, Skokie, Ill.

UNIFORMLY LOADED BEAM FORMULAS FOR WOOD DESIGN



ONE SPAN



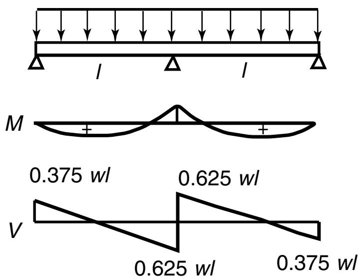
$$\Delta_{max} = \frac{5}{384}\ \frac{wl^4}{E'I}$$

$$M_{max} = wl^2/8$$

$$V_{EM} = \left[0.5\ wl - w\left(d + \frac{l_b}{2}\right)\right]$$

(end, modified)

TWO SPANS



$$\Delta_{max} = \frac{1}{185}\ \frac{wl^4}{E'I}$$

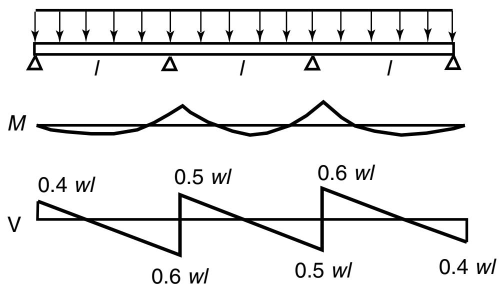
$$M_{max} = wl^2/8$$

$$V_{EM} = \left[0.375\ wl - w\left(d + \frac{l_b}{2}\right)\right]$$

$$V_{IM} = \left[0.625\ wl - w\left(d + \frac{l_b}{2}\right)\right]$$

(interior, modified)

THREE (or more) SPANS



$$\Delta_{max} = \frac{1}{145}\ \frac{wl^4}{E'I}$$

$$M_{max} = wl^2/10$$

$$V_{EM} = \left[0.4\ wl - w\left(d + \frac{l_b}{2}\right)\right]$$

$$V_{IM} = \left[0.6\ wl - w\left(d + \frac{l_b}{2}\right)\right]$$

DESIGN NOTES:

1. If l_b is unknown, use $l_b = 0$ for shear calculations.
2. If d is unknown when calculating shear force, either:
   a) Assume $d = 0$ in calc. and re-evaluate with d determined if shear controls.
   b) Assume a likely value of d and check with an additional iteration when d is determined.

Beam formulas for one-, two-, and three-span conditions. (From Johnston, D.W., Design and construction of concrete formwork, in *Concrete Construction Engineering Handbook,* Nawy, E.G., Ed., CRC Press, Boca Raton, FL, 1998, p. 7-33.)

Theoretical Maximum Load Ratios on Floor and Prop for Various Shore/Reshore Combinations

Shore + Reshore	Absolute Maximum Load Ratio		Converged Maximum Load Ratio	
	On Floor Slab	On Prop	On Floor Slab	On Prop
1 + 1	1.50	1.0	1.50	1.0
1 + 2	1.34	1.0	1.34	1.0
1 + 3	1.25	1.0	1.25	1.0
1 + 4	1.20	1.0	1.20	1.0
1 + 5	1.17	1.0	1.17	1.0
2 + 0	2.25	2.0	2.00	1.0
2 + 1	1.83	2.0	1.78	1.11
2 + 2	1.75	2.0	1.67	1.17
2 + 3	1.61	2.0	1.60	1.21
2 + 4	1.60	2.0	1.56	1.25
2 + 5	1.55	2.0	1.53	1.24
3 + 0	2.36	3.0	2.00	1.34
3 + 1	2.10	3.0	1.87	1.37
3 + 2	1.97	3.0	1.80	1.40
3 + 3	1.84	3.0	1.76	1.42
3 + 4	1.77	3.0	1.72	1.43
3 + 5	1.77	3.0	1.70	1.43

From Ghosh, S.K., Construction loading in high-rise buildings, in *Concrete Construction Engineering Handbook*, Nawy, E.G., Ed., CRC Press, Boca Raton, FL, 1998, p. **8**-7. Originally from Lasisi, M.Y. and Ng, S.F. 1979. Construction loads imposed on high-rise floor slabs. *Concrete Int.* 1(2):24–29.

Selected Earthquakes Since 1900 (Fatalities Greater than 1,000)[a]

Year	Day-Month	Location	Latitude	Longitude	Deaths	M	Comments/Damage ($ millions)
1902	19-Apr	Guatemala	14N	91W	2,000	7.5	
	16-Dec	Turkestan	40.8N	72.6E	4,500	6.4	
1903	19-Apr	Turkey	39.1N	42.4E	1,700		
	28-Apr	Turkey	39.1N	42.5E	2,200	6.3	
1905	04-Apr	India, Kangra	33.0N	76.0E	19,000	8.6	
	08-Sep	Italy, Calabria	39.4N	16.4E	2,500	7.9	
1906	31-Jan	Colombia	1N	81.5W	1,000	8.9	
	16-Mar	Taiwan, Kagi	23.6N	120.5E	1,300	7.1	
	18-Apr	San Francisco, CA	38N	123W	2,000+	8.3	Conflagration
	17-Aug	Chile, Santiago	33S	72W	20,000	8.6	Conflagration
1907	14-Jan	Jamaica, Kingston	18.2N	76.7W	1,600	6.5	Conflagration
	21-Oct	Central Asia	38N	69E	12,000	8.1	
1908	28-Dec	Italy, Messina	38N	15.5E	70,000	7.5	Deaths possibly 100,000
1909	23-Jan	Iran	33.4N	49.1E	5,500	7.3	
1912	09-Aug	Turkey, Marmara Sea	40.5N	27E	1,950	7.8	
1915	13-Jan	Italy, Avezzano	42N	13.5E	29,980	7.5	
1917	21-Jan	Indonesia, Bali	8.0S	115.4E	15,000		
	30-Jul	China	28.0N	104.0E	1,800	6.5	
1918	13-Feb	China, Canton	23.5N	117.0E	10,000	7.3	
1920	16-Dec	China, Gansu	35.8N	105.7E	200,000	8.6	Major fractures, landslides
1923	24-Mar	China	31.3N	100.8E	5,000	7.3	
	25-May	Iran	35.3N	59.2E	2,200	5.7	
	01-Sep	Japan, Kanto	35.0N	139.5E	143,000	8.3	$2800, conflagration

Selected Earthquakes Since 1900 (Fatalities Greater than 1,000)[a] (continued)

Year	Day-Month	Location	Latitude	Longitude	Deaths	M	Comments/Damage ($ millions)
1925	16-Mar	China, Yunnan	25.5N	100.3E	5,000	7.1	
1927	07-Mar	Japan, Tango	35.8N	134.8E	3,020	7.9	
	22-May	China, nr Xining	36.8N	102.8E	200,000	8.3	Large fractures
1929	01-May	Iran	38N	58E	3,300	7.4	
1930	06-May	Iran	38.0N	44.5E	2,500	7.2	
	23-Jul	Italy	41.1N	15.4E	1,430	6.5	
1931	31-Mar	Nicaragua	13.2N	85.7W	2,400	5.6	
1932	25-Dec	China, Gansu	39.7N	97.0E	70,000	7.6	
1933	02-Mar	Japan, Sanriku	39.0N	143.0E	2,990	8.9	
	25-Aug	China	32.0N	103.7E	10,000	7.4	
1934	15-Jan	India, Bihar-Nepal	26.6N	86.8E	10,700	8.4	
1935	20-Apr	Formosa	24.0N	121.0E	3,280	7.1	
	30-May	Pakistan, Quetta	29.6N	66.5E	30,000	7.5	Deaths possibly 60,000
	16-Jul	Taiwan	24.4N	120.7E	2,700	6.5	
1939	25-Jan	Chile, Chillan	36.2S	72.2W	28,000	8.3	$100
	26-Dec	Turkey, Erzincan	39.6N	38E	30,000	8	
1940	10-Nov	Romania	45.8N	26.8E	1,000	7.3	
1942	26-Nov	Turkey	40.5N	34.0E	4,000	7.6	
	20-Dec	Turkey, Erbaa	40.9N	36.5E	3,000	7.3	Some reports of 1,000 killed
1943	10-Sep	Japan, Tottori	35.6N	134.2E	1,190	7.4	
	26-Nov	Turkey	41.0N	33.7E	4,000	7.6	
1944	15-Jan	Argentina, San Juan	31.6S	68.5W	5,000	7.8	Deaths possibly 8,000
	01-Feb	Turkey	41.4N	32.7E	2,800	7.4	Deaths possibly 5,000
	07-Dec	Japan, Tonankai	33.7N	136.2E	1,000	8.3	
1945	12-Jan	Japan, Mikawa	34.8N	137.0E	1,900	7.1	
	27-Nov	Iran	25.0N	60.5E	4,000	8.2	
1946	31-May	Turkey	39.5N	41.5E	1,300	6	
	10-Nov	Peru, Ancash	8.3S	77.8W	1,400	7.3	Landslides, great destruction
	20-Dec	Japan, Tonankai	32.5N	134.5E	1,330	8.4	
1948	28-Jun	Japan, Fukui	36.1N	136.2E	5,390	7.3	Conflagration
	05-Oct	Turkmenistan	38.0N	58.3E	110,000	7.3	
1949	05-Aug	Ecuador, Ambato	1.2S	78.5E	6,000	6.8	Large landslides
1950	15-Aug	India, Assam; Tibet	28.7N	96.6E	1,530	8.7	Great topographical changes
1954	09-Sep	Algeria, Orleansvl.	36N	1.6E	1,250	6.8	
1957	27-Jun	USSR (Russia)	56.3N	116.5E	1,200		
	02-Jul	Iran	36.2N	52.7E	1,200	7.4	
	13-Dec	Iran	34.4N	47.6E	1,130	7.3	
1960	29-Feb	Morocco, Agadir	30N	9W	10,000	5.9	Deaths possibly 15,000
	22-May	Chile	39.5S	74.5W	4,000	9.5	Deaths possibly 5,000
1962	01-Sep	Iran, Qazvin	35.6N	49.9E	12,230	7.3	
1963	26-Jul	Yugoslavia, Skopje	42.1N	21.4E	1,100	6	Shallow depth just under city
1966	19-Aug	Turkey, Varto	39.2N	41.7E	2,520	7.1	
1968	31-Aug	Iran	34.0N	59.0E	12,000	7.3	Deaths possibly 20,000
1969	25-Jul	Eastern China	21.6N	111.9E	3,000	5.9	
1970	04-Jan	Yunnan, China	24.1N	102.5E	10,000	7.5	
	28-Mar	Turkey, Gediz	39.2N	29.5E	1,100	7.3	
	31-May	Peru	9.2S	78.8W	66,000	7.8	Great rockslide; $500
1972	10-Apr	Iran, southern	28.4N	52.8E	5,054	7.1	
	23-Dec	Nicaragua	12.4N	86.1W	5,000	6.2	Managua
1974	10-May	China	28.2N	104.0E	20,000	6.8	
	28-Dec	Pakistan	35.0N	72.8E	5,300	6.2	

Selected Earthquakes Since 1900 (Fatalities Greater than 1,000)[a] (continued)

Year	Day-Month	Location	Latitude	Longitude	Deaths	M	Comments/Damage ($ millions)
1975	04-Feb	China	40.6N	122.5E	10,000	7.4	
	06-Sep	Turkey	38.5N	40.7E	2,300	6.7	
1976	04-Feb	Guatemala	15.3N	89.1W	23,000	7.5	$6,000
	06-May	Italy, northeastern	46.4N	13.3E	1,000	6.5	
	25-Jun	New Guinea	4.6S	140.1E	422	7.1	West Irian
	27-Jul	China, Tangshan	39.6N	118.0E	255,000	8	Deaths possibly 655,000; $2,000
	16-Aug	Philippines	6.3N	124.0E	8,000	7.9	Mindanao
	24-Nov	Iran-USSR border	39.1N	44.0E	5,000	7.3	
1977	04-Mar	Romania	45.8N	26.8E	1,500	7.2	
1978	16-Sep	Iran, Tabas	33.2N	57.4E	15,000	7.8	$11
1980	10-Oct	Algeria, El Asnam	36.1N	1.4E	3,500	7.7	
	23-Nov	Italy, southern	40.9N	15.3E	3,000	7.2	
1981	11-Jun	Iran, southern	29.9N	57.7E	3,000	6.9	
	28-Jul	Iran, southern	30.0N	57.8E	1,500	7.3	
1982	13-Dec	W. Arabian Peninsula	14.7N	44.4E	2,800	6	
1983	30-Oct	Turkey	40.3N	42.2E	1,342	6.9	
1985	19-Sep	Mexico, Michoacan	18.2N	102.5W	9,500	8.1	Deaths possibly 30,000
1986	10-Oct	El Salvador	13.8N	89.2W	1,000	5.5	
1987	06-Mar	Colombia-Ecuador	0.2N	77.8W	1,000	7	
1988	20-Aug	Nepal-India border	26.8N	86.6E	1,450	6.6	
	07-Dec	Armenia, Spitak	41.0N	44.2E	25,000	7	$16,200
1990	20-Jun	Iran, western	37.0N	49.4E	40,000	7.7	Deaths possibly 50,000
	16-Jul	Philippines, Luzon	15.7N	121.2E	1,621	7.8	Landslides, subsidence
1991	19-Oct	India, northern	30.8N	78.8E	2,000	7	
1992	12-Dec	Indonesia, Flores	8.5S	121.9E	2,500	7.5	Tsunami wave height 25 m
1993	29-Sep	India, southern	18.1N	76.5E	9,748	6.3	
1995	16-Jan	Japan, Kobe	34.6N	135E	6,000	6.9	$100,000, conflagration
	27-May	Sakhalin Island	52.6N	142.8E	1,989	7.5	
1997	10-May	Iran, northern	33.9N	59.7E	1,560	7.5	4,460 injured; 60,000 homeless
1998	04-Feb	Afghanistan	37.1N	70.1E	2,323	6.1	Also Tajikistan
	30-May	Afghanistan	37.1N	70.1E	4,000	6.9	Also Tajikistan
	17-Jul	Papua New Guinea	2.96S	141.9E	2,183	7.1	Tsunami
1999	25-Jan	Colombia	4.46N	75.82W	1,185	6.3	
	17-Aug	Turkey	40.7N	30.0E	17,118	7.4	50,000 injured; $7,000
	20-Sep	Taiwan	23.7N	121.0E	2,297	7.6	8,700 injured; 600,000 homeless
2001	26-Jan	India, Bhuj	23.3 N	70.3 E	19,988	7.7	166,812 injured; 600,000 homeless
Total Events = 108			Total Deaths = 1,762,802				

[a] Magnitude scale varies.

From Scawthorn, C., Earthquakes: A historical perspective, in *Earthquake Engineering Handbook*, Chen, W.-F. and Scawthorn, C., Eds., CRC Press, Boca Raton, FL, 2003, pp. **1**-2 to **1**-4. Originally from National Earthquake Information Center, Golden, CO, http://neic.usgs.gov/neis/eqlists/eqsmajr.html.

Selected U.S. Earthquakes[a]

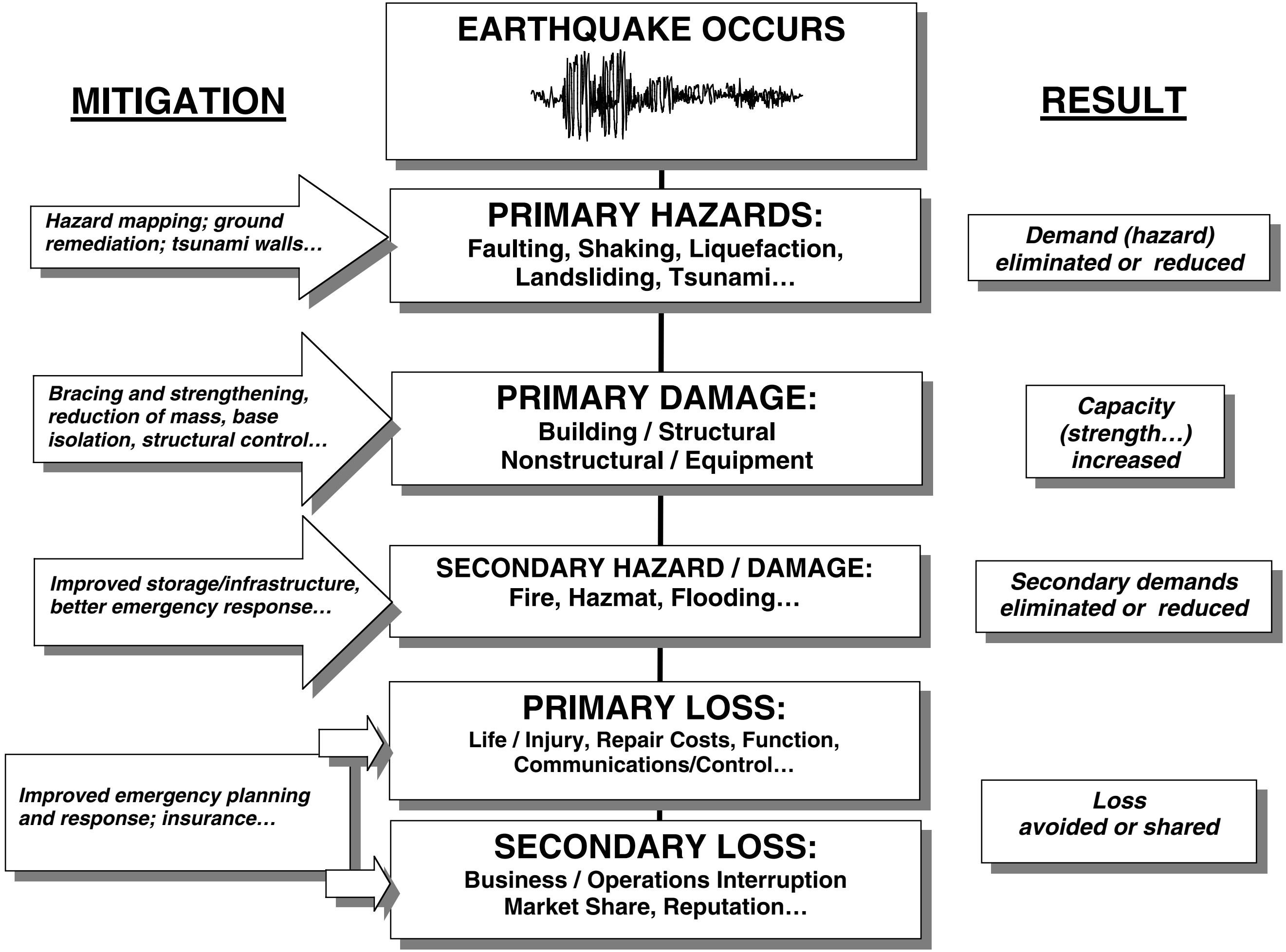
Year	Month	Day	Latitude	Longitude	M	MMI	Fatalities	Damage US $ (millions)	Locale
1755	11	18				8			Massachusetts, Nr Cape Ann
1774	2	21				7			Eastern Virginia (MMI from Sta)
1791	5	16				8			Connecticut, E. Haddam (MMI from Sta)
1811	12	16	36N	90W	8.6				Missouri, New Madrid
1812	1	23	36.6N	89.6W	8.4	12			Missouri, New Madrid
	2	7	36.6N	89.6W	8.7	12			Missouri, New Madrid
1817	10	5				8			Massachusetts, Woburn (MMI from Sta)
1836	6	10	38N	122W		10			California
1838	6	0	37.5N	123W		10			California
1857	1	9	35N	119W	8.3	7			California, Central
1865	10	8	37N	122W		9			California, San Jose, Santa Cruz
1868	4	3	19N	156W		10	81		Hawaii
	10	21	37.5N	122W	6.8	10	3		California, Hayward
1872	3	26	36.5N	118W	8.5	10	50		California, Owens Valley
1886	9	1	32.9N	80W	7.7	9	60	5	South Carolina, Charleston
1892	2	24	31.5N	117W		10			California, San Diego County
	4	19	38.5N	123W		9			California, Vacaville, Winters
	5	16	14N	143W					Guam, Agana
1897	5	31			5.8	8			Virignia, Giles County (M_b from Sta)
1899	9	4	60N	142W	8.3				Alaska, Cape Yakataga
1906	4	18	38N	123W	8.3	11	2,000	400	California, San Francisco (fire)
1915	10	3	40.5N	118W	7.8				Nevada, Pleasant Valley
1925	6	29	34.3N	120W	6.2		13	8	California, Santa Barbara
1927	11	4	34.5N	121W	7.5	9			California, Lompoc
1933	3	11	33.6N	118W	6.3		115	40	California, Long Beach
1934	12	31	31.8N	116W	7.1	10			California, Baja, Imperial Valley
1935	10	19	46.6N	112W	6.2		2	19	Montana, Helena
1940	5	19	32.7N	116W	7.1	10	9	6	California, southeast of El Centro
1944	9	5	44.7N	74.7W	5.6			2	New York, Massena
1949	4	13	47.1N	123W	7	8	8	25	Washington, Olympia
1951	8	21	19.7N	156W	6.9				Hawaii
1952	7	21	35N	119W	7.7	11	13	60	California, Kern County
1954	12	16	39.3N	118W	7	10			Nevada, Dixie Valley
1957	3	9	51.3N	176W	8.6			3	Alaska
1958	7	10	58.6N	137W	7.9		5		Alaska, Lituyabay (landslide)
1959	8	18	44.8N	111W	7.7				Montana, Hebgen Lake
1962	8	30	41.8N	112W	5.8			2	Utah
1964	3	28	61N	148W	8.3		131	540	Alaska
1965	4	29	47.4N	122W	6.5	7	7	13	Washington, Seattle
1971	2	9	34.4N	118W	6.7	11	65	553	California, San Fernando
1975	3	28	42.1N	113W	6.2	8		1	Idaho, Pocatello Valley
1975	8	1	39.4N	122W	6.1			6	California, Oroville Reservoir
	11	29	19.3N	155W	7.2	9	2	4	Hawaii
1980	1	24	37.8N	122W	5.9	7	1	4	California, Livermore
	5	25	37.6N	119W	6.4	7		2	California, Mammoth Lakes
	7	27	38.2N	83.9W	5.2			1	Kentucky, Maysville
	11	8	41.2N	124W	7	7	5	3	California, northern coast
1983	5	2	36.2N	120W	6.5	8		31	California, central, Coalinga
	10	28	43.9N	114W	7.3		2	13	Idaho, Borah Peak
	11	16	19.5N	155W	6.6	8		7	Hawaii, Kapapala
1984	4	24	37.3N	122W	6.2	7		8	California, Morgan Hill
1986	7	8	34N	117W	6.1	7		5	California, Palm Springs
1987	10	1	34.1N	118W	6	8	8	358	California, Whittier
	11	24	33.2N	116W	6.3	6	2		California, Superstition Hills
1989	6	26	19.4N	155W	6.1	6			Hawaii
	10	18	37.1N	122W	7.1	9	62	6,000	California, Loma Prieta
1990	2	28	34.1N	118W	5.5	7		13	California, southern, Claremont, Covina

Selected U.S. Earthquakes[a] (continued)

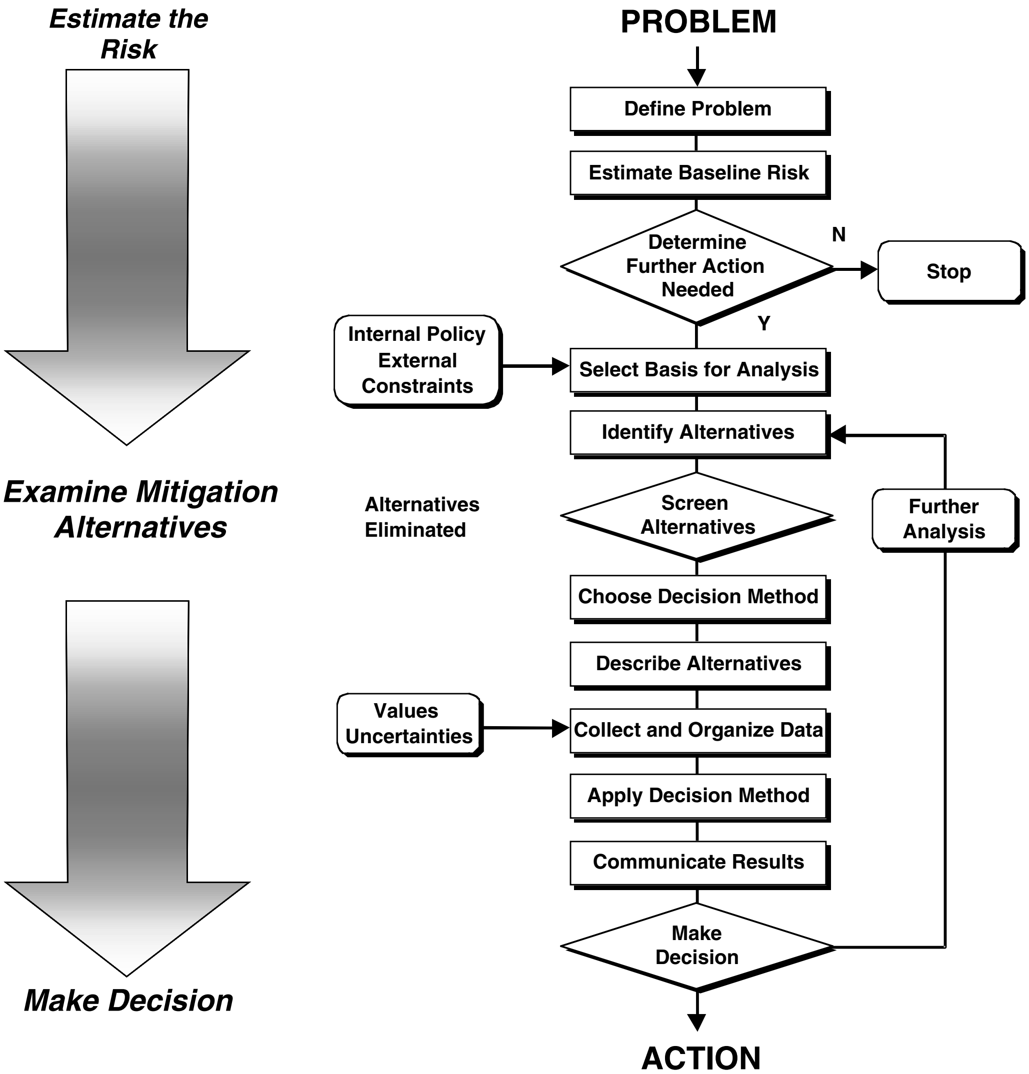
Year	Month	Day	Latitude	Longitude	M	MMI	Fatalities	Damage US $ (millions)	Locale
1992	4	23	34N	116W	6.3	7			California, Joshua Tree
	4	25	40.4N	124W	7.1	8		66	California, Humboldt, Ferndale
	6	28	34.2N	117W	6.7	8			California, Big Bear
	6	28	34.2N	116W	7.6	9	3	92	California, Landers, Yucca Valley
	6	29	36.7N	116W	5.6				California-Nevada border T.S.
1993	3	25	45N	123W	5.6	7			Washington-Oregon
	9	21	42.3N	122W	5.9	7	2		Oregon, Klamath Falls
1994	1	16	40.3N	76W	4.6	5			Pennsylvania (felt Canada)
	1	17	34.2N	119W	6.8	9	57	30,000	California, Northridge
	2	3	42.8N	111W	6	7			Wyoming, Afton
1995	10	6	65.2N	149W	6.4				Alaska (oil pipeline damaged)

[a] Magnitude scale varies.

From Scawthorn, C., Earthquakes: A historical perspective, in *Earthquake Engineering Handbook*, Chen, W.-F. and Scawthorn, C., Eds., CRC Press, Boca Raton, FL, 2003, pp. **1**-4 to **1**-5. Originally from National Earthquake Information Center (1996). Database of Significant Earthquakes Contained in Seismicity Catalogs, Golden, CO.



Earthquake loss process. (From Scawthorn, C., Earthquake risk management: An overview, in *Earthquake Engineering Handbook*, Chen, W.-F. and Scawthorn, C., Eds., CRC Press, Boca Raton, FL, 2003, p. **2**-7.)

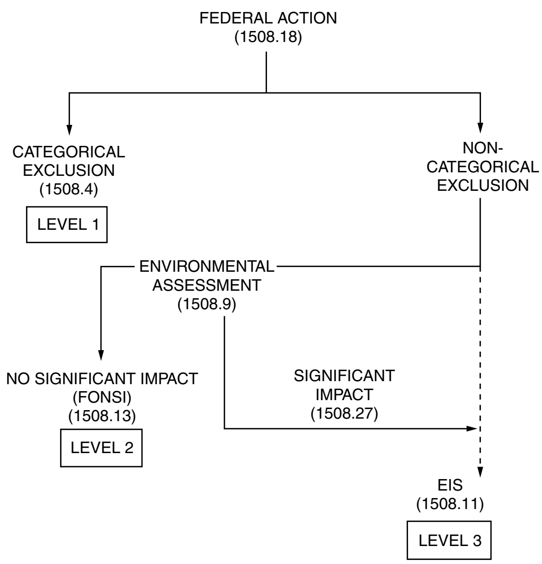


Earthquake risk management decision process. (From Scawthorn, C., Earthquake risk management: An overview, in *Earthquake Engineering Handbook,* Chen, W.-F. and Scawthorn, C., Eds., CRC Press, Boca Raton, FL, 2003, p. **2**-9.)

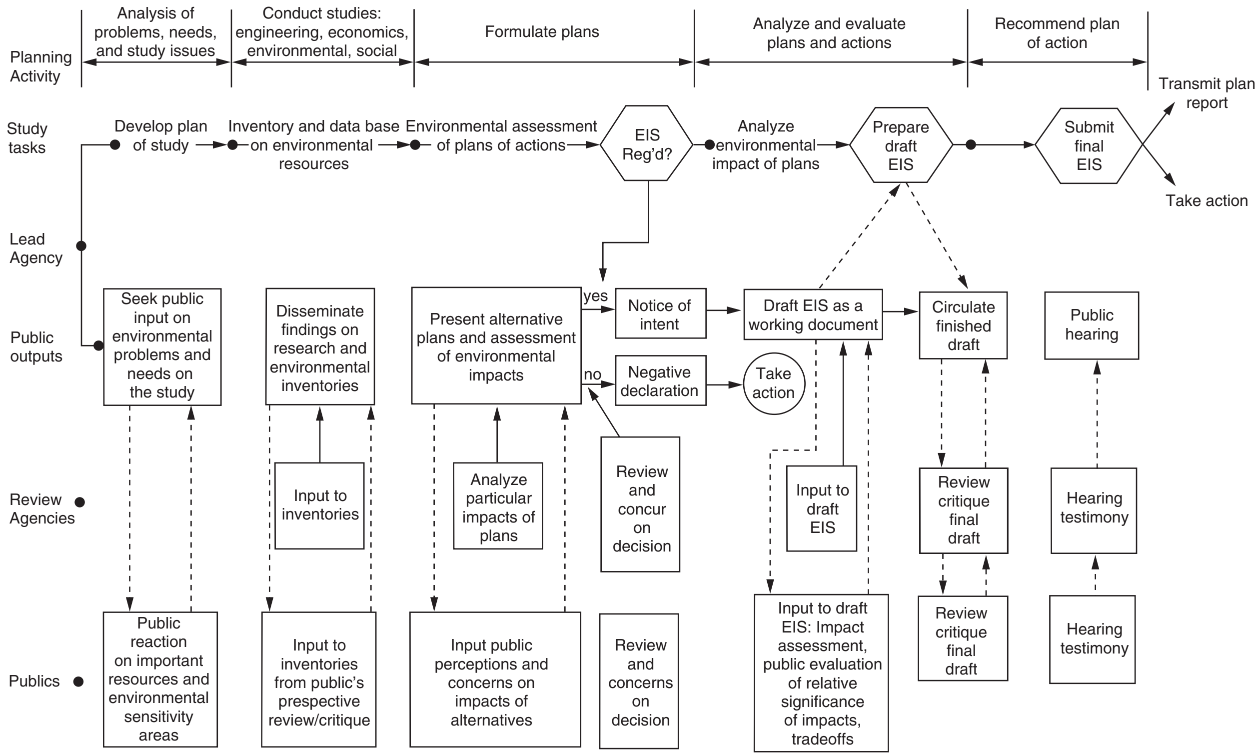
Principle Elemental Components of Structural Steel

Carbon	Principal hardening element in steel, increases strength and hardness, decreases ductility, toughness, and weldability Moderate tendency to segregate
Manganese	Increases strength and toughness Controls negative effects of sulfur
Phosphorus	Increases strength and hardness, decreases ductility and toughness Considered as an impurity, but sometimes added for atmospheric corrosion resistance Strong tendency to segregate
Sulfur	Considered undesirable except for machineability. Decreases ductility, toughness, and weldability Adversely affects surface quality Strong tendency to segregate
Silicon	Used to deoxidize or "kill" molten steel Increases strength
Aluminum	Used to deoxidize or "kill" molten steel Refines grain size, thus increasing strength and toughness
Vanadium and Columbium	Small additions increase strength Refines grain size, thus increasing strength and toughness
Titanium	Small amounts refine the grain size, thus increasing toughness
Nickel	Increases strength and toughness
Chromium	Increases strength Increases atmospheric corrosion resistance
Copper	Primary contributor to atmospheric corrosion resistance Increases strength
Nitrogen	Increases strength and hardness May decrease ductility and toughness
Boron	Small amounts increase hardenability, used only in aluminum-killed steels Most cost effective at low carbon levels

From Hamburger, R.O. and Nazir, N.A., Seismic design of steel structures, in *Earthquake Engineering Handbook*, Chen, W.-F. and Scawthorn, C., CRC Press, Boca Raton, FL, 2003, p. 12-10.



Three levels of analysis in the EIA process. Number in parentheses denotes paragraph in CEQ regulations which contains definition. (From Canter, L.W., Background conceptual and administrative information, in *Environmental Engineers' Handbook,* 2nd ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, p. 43.)



Public participation in environmental impact assessment. (From Canter, L.W., Background conceptual and administrative information, in *Environmental Engineers' Handbook,* 2nd ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, p. 45.)

Priority Chemicals Targeted in the 33/50 Project for the Industrial Sector Pollution Prevention Strategy

Target Chemicals	Million Pounds Released in 1988
Benzene	33.1
Cadmium	2.0
Carbon Tetrachloride	5.0
Chloroform	26.9
Chromium	56.9
Cyanide	13.8
Dichloromethane	153.4
Lead	58.7
Mercury	0.3
Methyl Ethyl Ketone	159.1
Methyl Isobutyl Ketone	43.7
Nickel	19.4
Tetrachloroethylene	37.5
Toluene	344.6
1,1,1-Trichloroethane	190.5
Trichloroethylene	55.4
Xylene	201.6

From Liu, D.H.F., Regulations and definitions, in *Environmental Engineers' Handbook*, 2nd ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, p. 85. Originally from U.S. Environmental Protection Agency, 1992, *Pollution prevention 1991: Research program*, EPA/600/R-92/189 (September). (Washington, D.C.: Office of Research and Development).

Main Membrane Separation Processes: Operating Principles and Application

Separation Process	Membrane Type	Driving Force	Method of Separation	Range of Application
Microfiltration	Symmetric microporous membrane, 0.1 to 10 μA pore radius	Hydrostatic pressure difference, 0.1 to 1 bar	Sieving mechanism due to pore radius and adsorption	Sterile filtration clarification
Ultrafiltration	Asymmetric microporous membrane, 1 to 10 μA pore radius	Hydrostatic pressure difference, 0.5 to 5 bar	Sieving mechanism	Separation of macromolecular solutions
Reverse osmosis	Symmetric skin-type membrane	Hydrostatic pressure, 20 to 100 bar	Solution–diffusion mechanism	Separation of salt and microsolutes from solutions
Dialysis	Symmetric microporous membrane, 0.1 to 10 μA pore size	Concentration gradient	Diffusion in convection-free layer	Separation of salts and microsolutes from macromolecular solutions
Electrodialysis	Cation and anion exchange membranes	Electrical potential gradient	Electrical charge of particle and size	Desalting of ionic solution
Gas operation	Homogeneous or porous polymer	Hydrostatic pressure concentration gradient	Solubility, diffusion	Separation from gas mixture
Supported liquid membranes	Symmetric microporous membrane with adsorbed organic liquid	Chemical gradient	Solution diffusion via carrier	Separation
Membrane distillation	Microporous membrane	Vapor-pressure	Vapor transport into hydrophobic membrane	Ultrapure water concentration of solutions

From Liu, D.H.F., Separation and recycling systems, in *Environmental Engineers' Handbook*, 2nd ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, p. 140. Originally from E. Orioli, R. Molinari, V. Calabrio, and A.B. Gasile, 1989, Membrane technology for production—integrated pollution control systems, Seminar on the Role of the Chemical Industry in Environmental Protection, CHEM/SEM. 18/R. 19, Geneva.

Summary of NAAQSs

Pollutant	Averaging Time	Standard (@ 25°C and 760 mm Hg) Primary	Secondary
Particulate matter	Annual arithmetic mean	50 μg/m³	Same as primary
10 micrometers (PM_{10})	24-hour	150 μg/m³	Same as primary
Sulfur dioxide (SO_2)	Annual arithmetic mean	0.03 ppm (80 μg/m³)	Same as primary
	24-hour	0.14 ppm (365 μg/m³)	Same as primary
	3-hour	None	0.5 ppm (1300 μg/m³)
Carbon monoxide (CO)	8-hour	9 ppm (10 mg/m³)	Same as primary
	1-hour	35 ppm (40 mg/m³)	Same as primary
Ozone (O_3)	1-hour per day	0.12 ppm (235 μg/m³)	Same as primary
Nitrogen dioxide (NO_2)	Annual arithmetic mean	0.053 ppm (100 μg/m³)	Same as primary
Lead (Pb)	Quarterly arithmetic mean	1.5 μg/m³	Same as primary

Notes: All standards with averaging times of 24 hours or less, and all gaseous fluoride standards, are not to have more than one actual or expected exceedance per year.

μg/m³ or mg/m³ = microgram or milligram per cubic meter

From Zegel, W.C., Setting standards, in *Environmental Engineers' Handbook*, 2nd Ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, p. 189. Originally from CFR Title 40, Part 50. Environmental Protection Agency, U.S. Government Printing Office, 1993.

National Emission Standards for Hazardous Air Pollutants

Affected Facility	Emission Level	Monitoring
	Asbestos	
Asbestos mills	No visible emissions or meet equipment standards	No requirement
Roadway surfacing	Contain no asbestos, except temporary use	No requirement
Manufacturing	No visible emissions or meet equipment standards	No requirement
Demolition/renovation	Wet friable asbestos or equipment standards and no visible emissions	No requirement
Spraying friable asbestos		
Equipment and machinery	No visible emissions or meet equipment standards	No requirement
Buildings, structures, etc.	<1 percent asbestos dry weight	No requirement
Fabricating products	No visible emissions or meet equipment standards	No requirement
Friable insulation	No asbestos	No requirement
Waste disposal	No visible emissions or met equipment and work practice requirements	No requirement
Waste disposal sites	No visible emissions; design and work practice requirements	No requirement
	Beryllium	
Extraction plants	1. 10 g/hour, or	1. Source test
Ceramic plants	2. 0.01 μ/m³ (thirty-day)	2. Three years CEM[a]
Foundries		
Incinerators		
Propellant plants		
Machine shops (Alloy >5 percent by weight beryllium)		

National Emission Standards for Hazardous Air Pollutants (continued)

Affected Facility	Emission Level	Monitoring
Rocket motor test sites		
Closed tank collection of combustion products	75 μg min/m^3 of air within 10 to 60 minutes during two consecutive weeks	Ambient concentration during and after test
	2 g/hour, maximum 10 g/day	Continuous sampling during release
	Mercury	
Ore processing	2300 g/24 hour	Source test
Chlor-alkali plants	2300 g/24 hour	Source test or use approved design, maintenance and housekeeping
Sludge dryers and incinerators	3200 g/24 hour	Source test or sludge test
	Vinyl Chloride (VC)	
Ethylene dichloride (EDC) manufacturing	1. EDC purification: 10 ppm[b]	Source test/CEM[a]
	2. Oxychlorination: 0.2 g/kg of EDC product	Source test
VC manufacturing	10 ppm[b]	Source test/CEM[a]
Polyvinyl chloride (PVC) manufacturing		
Equipment	10 ppm[b]	Source test/CEM[a]
Reactor opening loss	0.02 g/kg	Source test
Reactor manual vent valve	No emission except emergency	
Sources after stripper	Each calendar day:	Source test
	1. Strippers—2000 ppm (PVC disposal resins excluding latex); 400 ppm other	
	2. Others—2 g/kg (PVC disposal resins excluding latex); 0.4 g/kg other	Source test
EDC/VC/PVC manufacturing		
Relief valve discharge	None, except emergency	
Loading/unloading	0.0038 m^3 after load/unload or 10 ppm when controlled	Source test
Slip gauge	Emission to control	
Equipment seals	Dual seals required	
Relief valve leaks	Rupture disc required	
Manual venting	Emissions to control	
Equipment opening	Reduce to 2.0 percent VC or 25 gallon	
Sampling (>10 percent by weight VC)	Return to process	
LDAR[d]	Approved program required	Approved program
In-process wastewater	10 ppm VC before discharge	Source test
	Inorganic Arsenic	
Glass melting furnace	Existing: <2.5 Mg/year[c] or 85 percent control	Method 108
	New or modified: <0.4 Mg/year or 85 percent control	Continuous opacity and temperature monitor for control
Copper converter	Secondary hooding system	Methods 5 and 108A
	Particle limit 11.6 mg/dscm[d]	Continuous opacity for control

National Emission Standards for Hazardous Air Pollutants (continued)

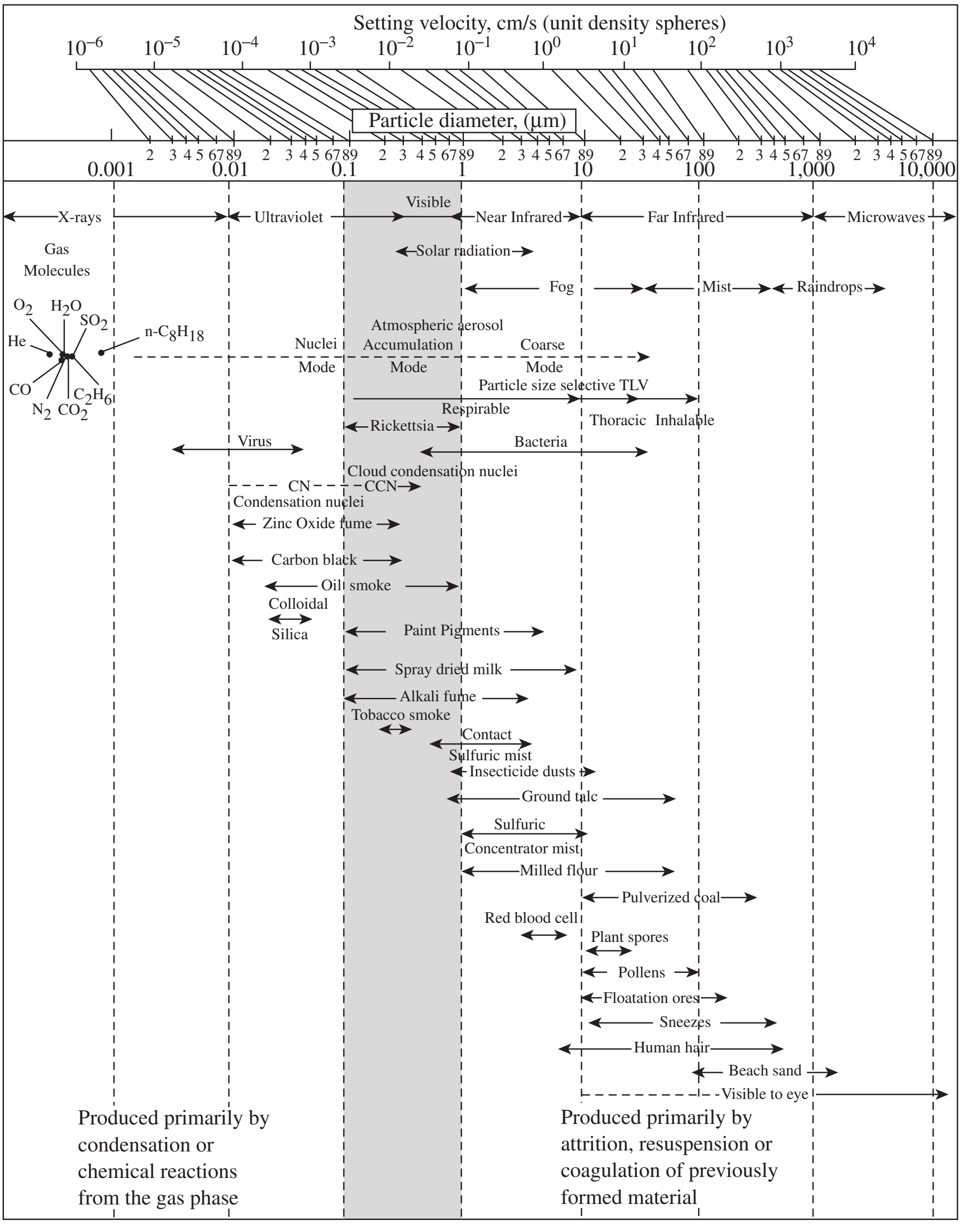
Affected Facility	Emission Level	Monitoring
	Approved operating plan	Airflow monitor for secondary hood
Arsenic trioxide and metallic arsenic plants using roasting/condensation process	Approved plan for control of emissions	Opacity monitor for control
		Ambient air monitoring
	Benzene	
Equipment leaks (Serving liquid or gas ⩾10 percent by weight benzene; facilities handling 1000 Mg/year and coke oven by-product exempt)	Leak is 10,000 ppm using Method 21; no detectable emissions (NDE) is 500 ppm using Method 21	
Pumps	Monthly LDAR,[e] dual seals, 95 percent control or NDE[f]	Test of NDE[f]
Compressors	Seal with barrier fluid, 95 percent control or NDE[f]	Test for NDE[f]
Pressure relief valves	NDE[f] or 95 percent control	Test for NDE[f]
Sampling connection systems	Closed purge or closed vent	
Open-end valves/lines	Cap, plug, or second valve	
Valves	Monthly LDAR[e] (quarterly if not leaking for two consecutive months) or NDE[f]	Test for NDE[f]
Pressure relief equipment	LDAR[e]	
Product accumulators	95 percent control	
Closed-vent systems and control devices	NDE or 95 percent control	Monitor annually
Coke by-product plants		
Equipment and tanks	Enclose source, recover, or destroy. Carbon adsorber or incinerator alternate	Semiannual LDAR,[e] annual maintenance
Light-oil sumps	Cover, no venting to sump	Semiannual LDAR[e]
Napthalene equipment	Zero emissions	
Equipment leaks (serving ⩾10 percent by weight)	See 40 CFR 61, subpart J.	
Exhauster (⩾1 percent by weight)	Quarterly LDAR[e] or 95 percent control or NDE[f]	Test for NDE[f]
Benzene storage vessels		
Vessels with capacity >10,000 gallon	Equipped with:	
	1. Fixed roof with internal floating roof-seals, or	Periodic inspection
	2. External floating roof with seals, or	Periodic inspection
	3. Closed vent and 95 percent control	Maintenance plant and monitoring
Benzene transfer		
Producers and terminals (loading >1,300,000/year)	Vapor collection and 95 percent control	Annual recertification
Loading racks (marine rail, truck)	Load vapor-tight vessels only	Yes
Exemptions:		
Facilities loading <70 percent benzene		
Facilities loading less than required of >70 percent benzene		
Both of above subject to record-keeping		
Waste Operations		

National Emission Standards for Hazardous Air Pollutants (continued)

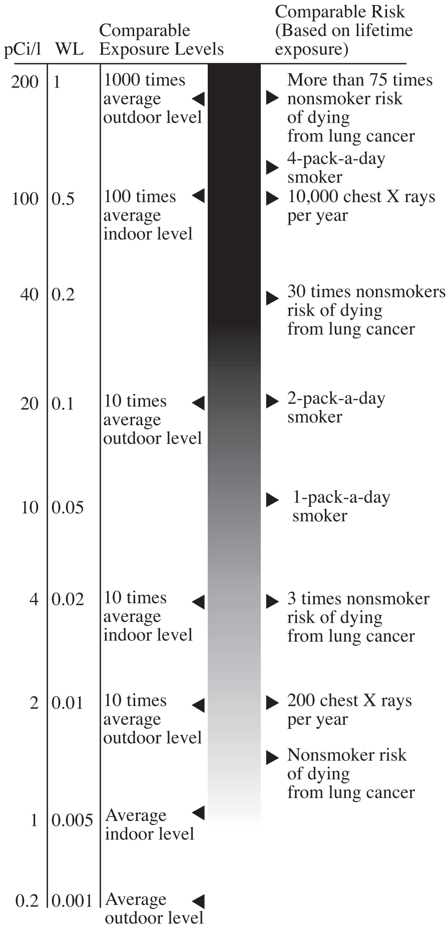
Affected Facility	Emission Level	Monitoring
Chemical manufacturing plants	1. Facilities ≥10 Mg/year in aqueous wastes must control streams ≥10 ppm. Control to 99 percent or <10 ppm	Monitor control and treatment. Also, periodically monitor certain equipment for emissions >500 ppm and inspect equipment
Petroleum refineries	2. If >10 ppm in wastewater treatment system: Wastes in <10 ppm Total in <1 Mg/year	
Coke by-product plants	3. >1 Mg/year to <10 Mg/year	Report annually
TSDF[g] treating wastes from the three preceding	4. <1 Mg facilities	One-time report
	Radionuclides	
DOE facilities (radon not included)	10 mrem/year[b] radionuclides (any member of the public)	Approved EPA computer model and Method 114 or direct monitoring (ANSIN13.1-1969)
NRC licensed facilities and facilities not covered by subpart H	10 mrem/year[h] radionuclides (any member of the public)	Approved EPA computer model or Appendix E
	3 mrem/year iodine (any member of the public)	Emissions determined by Method 114 or direct monitoring (ANSIN13.1-1969)
Calciners and nodulizing kilns at elemental phosphorus plants	2 curies per year (polonium-210)	Method 111
Storage and disposal facilities for radium-containing material, owned/operated by DOE	20 pCi/m² per second[i] (radon-222)	None specified
Phosphogypsum stacks (waste from phosphorus fertilizer production)	20 pCi/m² per second[i] (radon-222)	Method 115
Disposal of uranium mill trailings (operational)	20 pCi/m² per second[i] (radon-222)	Method 115

[a] CEM = continuous emission monitor.
[b] Before opening equipment, VC must be reduced to 2.0 percent (volume) or 25 gallons, whichever is larger.
[c] Mg/year = megagrams per year.
[d] mg/dscm = milligrams per dry standard cubic meter.
[e] LDAR = leak detection and repair.
[f] NDE = no detectable emissions.
[g] TSDF = treatment, storage, and disposal facilities.
[h] mrem/year = millirems per year (the rem is the unit of effective dose equivalent for radiation exposure).
[i] pCi/m² per second = picocuries per square meter per second.

From Zegel, W.C., Technology standards, in *Environmental Engineers' Handbook*, 2nd ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, pp. 193–196. Originally adapted from David R. Patrick, Ed., *Toxic Air Pollution Handbook*, Van Nostrand Reinhold, New York, 1994.



Molecular and aerosol particle diameters, copyright © P.C. Reist. Molecular diameters calculated from viscosity data. From Altwicker, E.R. et al., Air pollution, in *Environmental Engineers' Handbook,* 2nd ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, p. 334. Originally adapted from Lapple, 1961, *Stanford Research Institute Journal,* 3rd quarter; and J.S. Eckert and R.F. Strigle, Jr., 1974, *JAPCA,* 24:961–965.



Radon risk evaluation chart. This chart shows how the lung cancer risks of radon exposure compare to other causes of the disease. For example, breathing 20 pCi/l poses about the same lung cancer risk as smoking two packs of cigarettes a day. From Altwicker, E.R. et al., Air pollution, in *Environmental Engineers' Handbook,* 2nd ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, p. 437. Originally reprinted from U.S. Environmental Protection Agency.

Mechanical Characteristics of Sound Waves

	RMS Sound Pressure (dynes/cm^2)	RMS Sound Particle Velocity (cm/sec)	RMS Sound Particle Motion at (1,000 Hz cm)	Sound Pressure Level (dB 0.0002 bar)
Threshold of hearing	0.0002	0.0000048	0.76×10^{-9}	0
	0.002	0.000048	7.6×10^{-9}	20
Quiet room	0.02	0.00048	76.0×10^{-9}	40
	0.2	0.0048	760×10^{-9}	60
Normal speech at 3′	2.0	0.048	7.6×10^{-6}	80
Possible hearing impairment	20.0	0.48	76.0×10^{-6}	100
	200	4.80	760×10^{-6}	120
Threshold of pain	2000	48.0	7.6×10^{-3}	140
Incipient mechanical damage	20×10^3	480	76.0×10^{-3}	160
	200×10^3	4800	760×10^{-3}	180
Atmospheric pressure	2000×10^3	48000	7.6	200

From Liu, D.H.F. and Roberts, H.C., The physics of sound and hearing, in *Environmental Engineers' Handbook*, 2nd ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, p. 452.

Representative Sound Pressures and Sound Levels

Source and Distance	Sound Pressure (dynes/cm^2)	Sound Level (decibels 0.0002 μ bar
Saturn rocket motor, close by	1,100,000	195
Military rifle, peak level at ear	20,000	160
Jet aircraft takeoff; artillery, 2500′	2000	140
Planing mill, interior	630	130
Textile mill	63	110
Diesel truck, 60′	6	90
Cooling tower, 60′	2	80
Private business office	.06	50

Source	Acoustic Power of Source
Saturn rocket motor	30,000,000 watts
Turbojet engine	10,000 watts
Pipe organ, forte	10 watts
Conventional voice	10 microwatts
Soft whisper	1 millimicrowatt

From Liu, D.H.F. and Roberts, H.C., The physics of sound and hearing, in *Environmental Engineers' Handbook*, 2nd ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, p. 454.

Typical Wastewater Flow Rates from Residential Sources

Source	Unit	Flow, gal/unit·d Range	Typical
Apartment:			
High-rise	Person	35–75	50
Low-rise	Person	50–80	65
Hotel	Guest	30–55	45
Individual residence:			
Typical home	Person	45–90	70
Better home	Person	60–100	80
Luxury home	Person	75–150	95
Older home	Person	30–60	45
Summer cottage	Person	25–50	40
Motel:			
With kitchen	Unit	90–180	100
Without kitchen	Unit	75–150	95
Trailer park	Person	30–50	40

Note: 1 = gal × 3.7854.

From Adams Jr., C.E. et al., Nature of wastewater, in *Environmental Engineers' Handbook*, 2nd ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, p. 517. Originally from Metcalf and Eddy, Inc., *Wastewater Engineering*, 3rd ed., McGraw-Hill, New York, 1991.

Estimated Distribution of World's Water

	Volume 1000 km^3	Percentage of Total Water
Atmospheric water	13	0.001
Surface water		
Salt water in oceans	1,320,000	97.2
Salt water in lakes and inland seas	104	0.008
Fresh water in lakes	125	0.009
Fresh water in stream channels (average)	1.25	0.0001
Fresh water in glaciers and icecaps	29,000	2.15
Water in the biomass	50	0.004
Subsurface water		
Vadose water	67	0.005
Groundwater within depth of 0.8 km	4200	0.31
Groundwater between 0.8 and 4 km depth	4200	0.31
Total (rounded)	1,360,000	100

From Chae, Y.C. and Hamidi, A., Groundwater and aquifers, in *Environmental Engineers' Handbook*, 2nd ed., Liu, D.H.F. and Liptak, B.G., Eds., CRC Press, Boca Raton, FL, 1997, p. 1009. Originally from Bouwer, H., *Groundwater Hydrology*, McGraw-Hill, Inc., New York, 1978.

Currently Developed Types of Fuel Cells and Their Characteristics and Applications

Fuel Cell Type	Electrolyte	Charge Carrier	Operating Temperature	Fuel	Electric Efficiency (System)	Power Range/Application
Alkaline FC (AFC)	KOH	OH^-	60–120°C	Pure H_2	35–55%	<5 kW, niche markets (military, space)
Proton exchange membrane FC (PEMFC)[a]	Solid polymer (such as Nafion)	H^+	50–100°C	Pure H_2 (tolerates CO_2)	35–45%	Automotive, CHP (5–250 kW), portable
Phosphoric acid FC (PAFC)	Phosphoric acid	H^+	~220°C	Pure H_2 (tolerates CO_2, approx. 1% CO)	40%	CHP (200 kW)
Molten carbonate FC (MCFC)	Lithium and potassium carbonate	CO_3^{2-}	~650°C	H_2, CO, CH_4, other hydrocarbons (tolerates CO_2)	>46%	200 kW–MW range, CHP and stand-alone
Solid oxide FC (SOFC)	Solid oxide electrolyte (yttria, zirconia)	O^{2-}	~1000°C	H_2, CO, CH_4, other hydrocarbons (tolerates CO_2)	>46%	2 kW–MW range, CHP and stand-alone

[a] Also known as a solid polymer fuel cell (SPFC).

From Hoogers, G., Introduction, in *Fuel Cell Technology Handbook*, Hoogers, G., Ed., CRC Press, Boca Raton, FL, 2003, p. **1**-4.

Hydrogen Storage Properties for a Range of Metal Hydrides

Metal Hydride System	Mg/MgH_2	Ti/TiH_2	V/VH_2	Mg_2Ni/Mg_2NiH_4	$FeTi/FeTiH_{1.95}$	$LaNi_5/LaNi_5H_{5.9}$	LH_2[b]
Hydrogen content as mass fraction (%)	7.7	4.0	2.1	3.2	1.8	1.4	100.0
Hydrogen content by volume (kg/dm^3)	0.101	0.15	0.09	0.08	0.096	0.09	0.077
Energy content (MJ/kg) (based on HHV)	9.9	5.7	3.0	4.5	2.5[a]	1.95	143.0
Energy content (MJ/kg) (LHV)[a]	8.4	4.8	2.5	3.8	2.1	1.6	120.0
Heat of reaction (kJ/Nm^3) (H_2)	3360	5600	—	2800	1330	1340	—
Heat of reaction (kJ/mol)[a]	76.3	127.2	—	63.6	30.2	30.4	—
Heat of reaction (as fraction of HHV, %)[a]	26.7	44.5	—	22.2	10.6	10.6	—
Heat of reaction (as fraction of LHV, %)[a]	31.6	52.6	—	26.3	12.5	12.6	—

[a] Raw data taken from *Ullmann's Encyclopedia of Industrial Chemistry*, Sixth ed., Wiley-VCH, 2001. Data recalculated by the author.

[b] LH_2: liquid hydrogen.

From Hoogers, G., The fueling problem: Fuel cell systems, in *Fuel Cell Technology Handbook*, Hoogers, G., Ed., CRC Press, Boca Raton, FL, 2003, p. **5**-6.

Typical Gas Composition of Biogas from Organic Household Waste

Component	Concentration (Wet Gas)
Methane	60–75%
Carbon dioxide	< 35%
Water vapor	0–10%
Nitrogen	< 5%
Oxygen	< 1%
Carbon monoxide	0.2%
Siloxanes	<10 mg per m^3 CH_4
Hydrogen sulfide	150 ppm

From Hoogers, G., The fueling problem: Fuel cell systems, in *Fuel Cell Technology Handbook*, Hoggers, G., Ed., CRC Press, Boca Raton, FL, 2003, p. **5**-20.

Performance of Different Battery Types

Battery Type	Specific Energy Storage (Wh/kg)	Specific Power (for 30 sec at 80% capacity) (W/kg)	Specific Cost, ($/kWh)	Cycle Life (Charges and Discharges to 80% of Capacity)
Lead–acid	35 (55)[a] [171][b]	200 (450)	125 (75)	450 (2000)
Nickel–cadmium	40 (57) [217]	175 (220)	600 (110)	1250 (1650)
Nickel–metal hydride	70 (120)	150 (220)	540 (115)	1500 (2200)
Lithium ion	120 (200)	300 (350)	600 (200+)	1200 (3500)

[a] Values in parentheses represent projections for the next five years.
[b] Values in brackets represent the theoretical limit on specific energy.

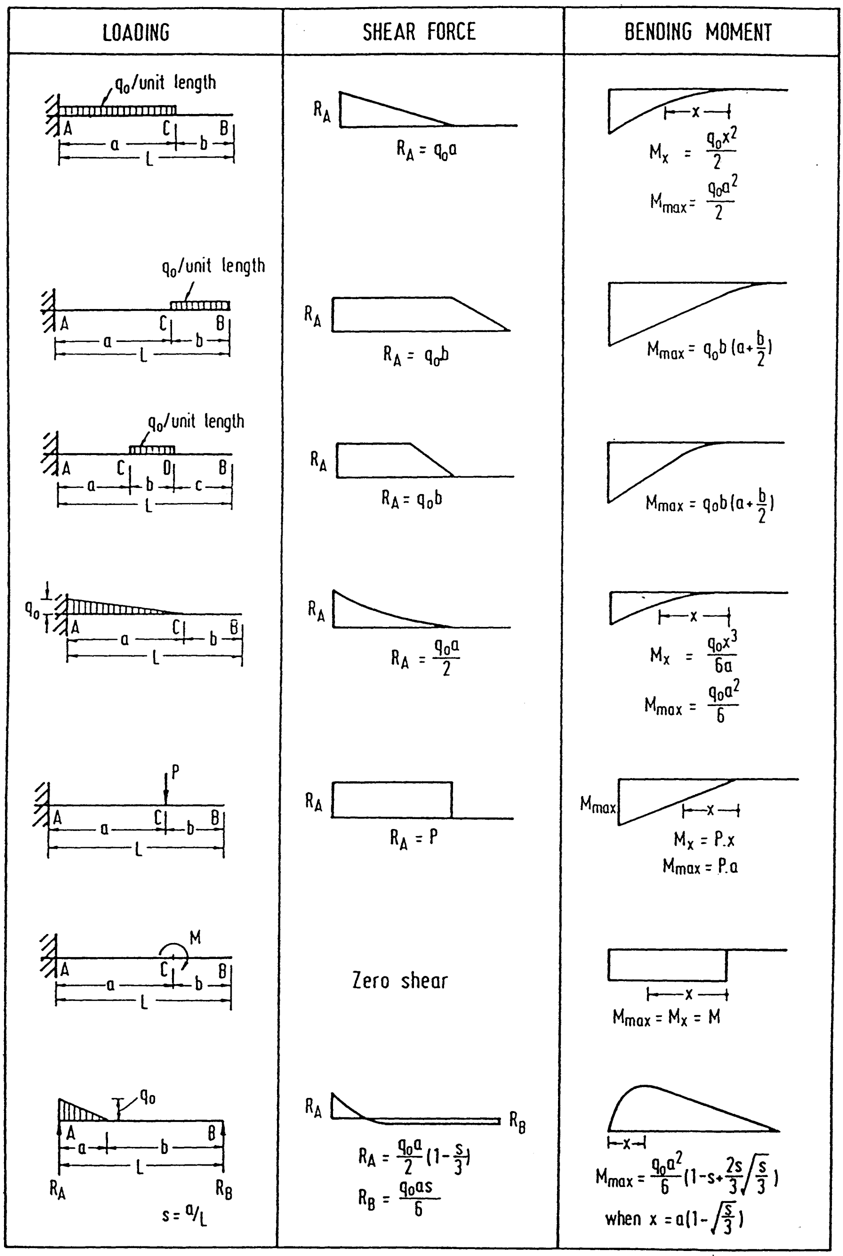
From Stone, R., Competing technologies for transportation, in *Fuel Cell Technology Handbook*, Hoogers, G., Ed., CRC Press, Boca Raton, FL, 2003, p. **11**-17. Theoretical limits on specific energy from Rand, R.A.J. et al., *Batteries for Electric Vehicles*, Research Studies Press, Baldock, U.K., 1998; other data from Ashton, R., in *Design of a Hybrid Electric Vehicle*, University of Oxford, Oxford, 1998.

Thermodynamic Data for Selected Chemical Compounds

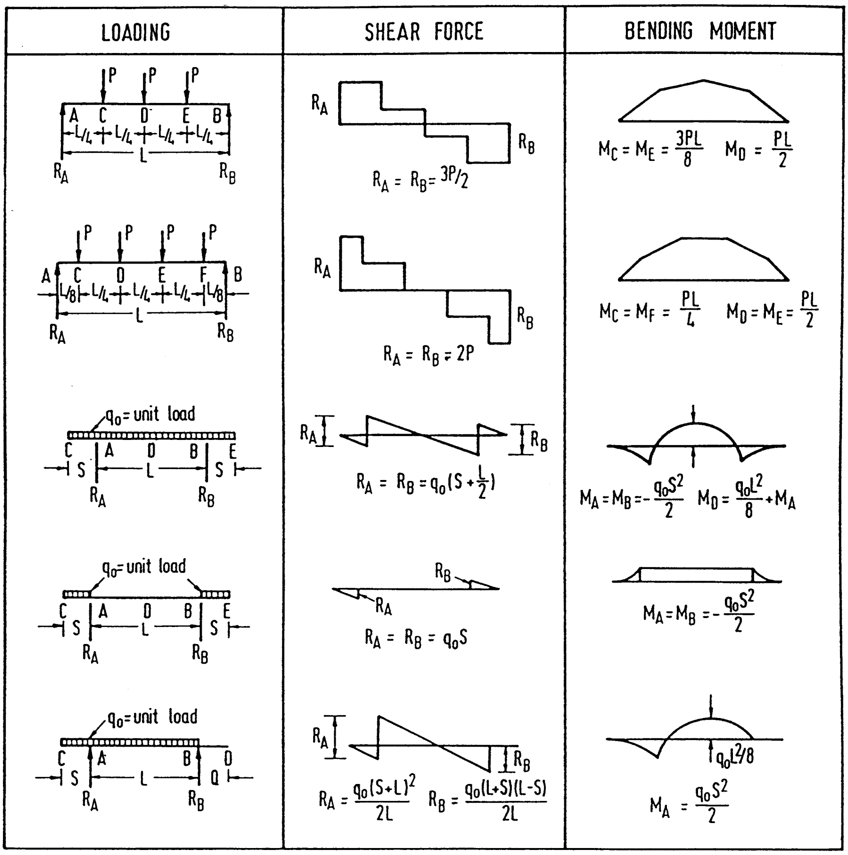
Compound (gaseous/liquid)	Common Name	Molar Mass (g/mol)	ΔH_f (kJ/mol)	ΔG_f (kJ/mol)
H_2O (l)	water	18,02	–285,83	–237,13
H_2O (g)	water (steam)	18,02	–241,82	–228,57
CH_4	methane	16,04	–74,81	–50,72
C_3H_6 (g)	propane	42,08	20,42	62,78
C_4H_{10} (g)	butane	58,13	–126,15	–17,03
C_8H_{18} (l)	octane	114,23	–249,90	6,40
C_8H_{18} (l)	iso-octane	114,23	–255,10	—
CH_3OH (l)	methanol	32,04	–238,66	–166,27
CH_3OH (g)	methanol	32,04	–200,66	–161,96
C_2H_5OH (l)	ethanol	46,07	–277,69	–174,78
C_2H_5OH (g)	ethanol	46,07	–235,10	–168,49
CO	carbon monoxide	28,01	–110,53	–137,17
CO_2	carbon dioxide	44,01	–393,51	–394,36
H_2	hydrogen	2,02	0	0
O_2	oxygen	32,00	0	0

Note: Tabulated are the standard heat of formation, ΔH_f, and the Gibbs free energy, ΔG_f, at 10^5 Pa and 298 K.

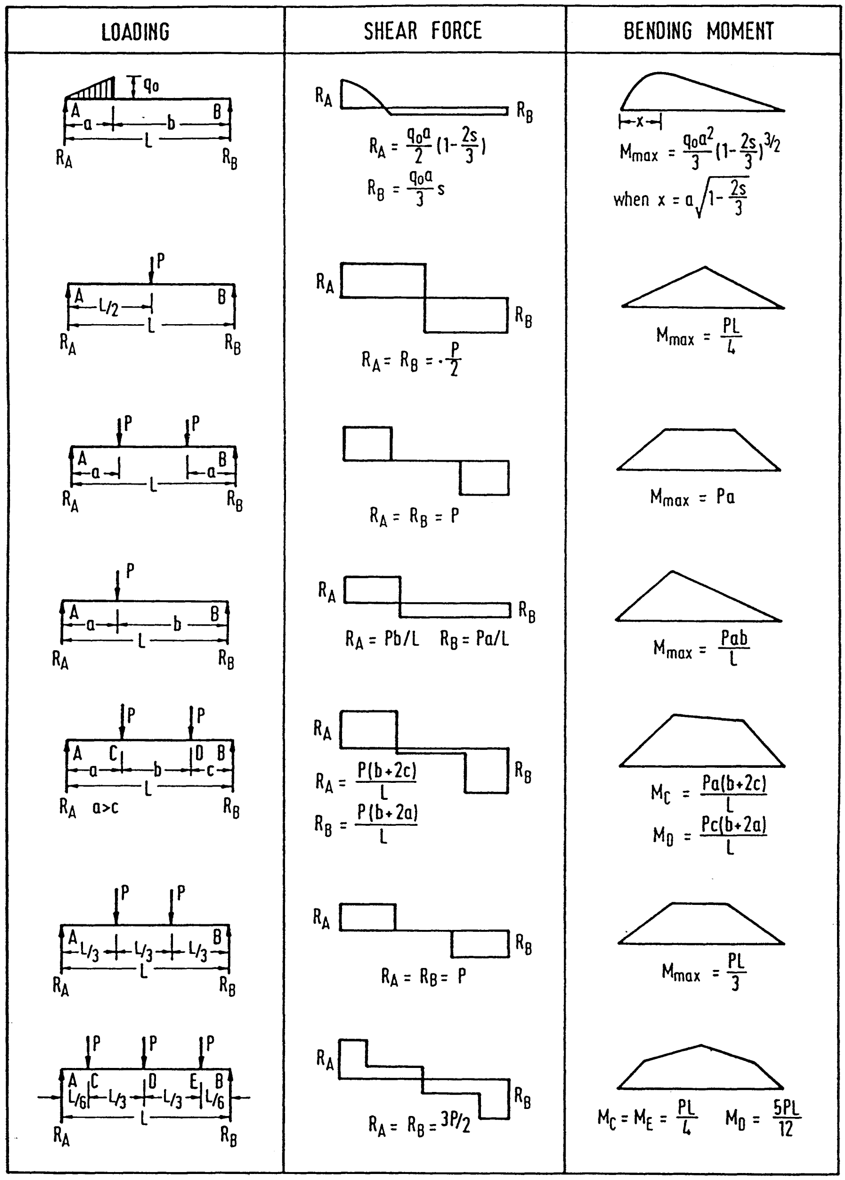
From Hoogers, G., Ed., Appendix 1: Thermodynamic data for selected chemical compounds, in *Fuel Cell Technology Handbook*, Hoggers, G., Ed., CRC Press, Boca Raton, FL, 2003, p. **A1**-1.



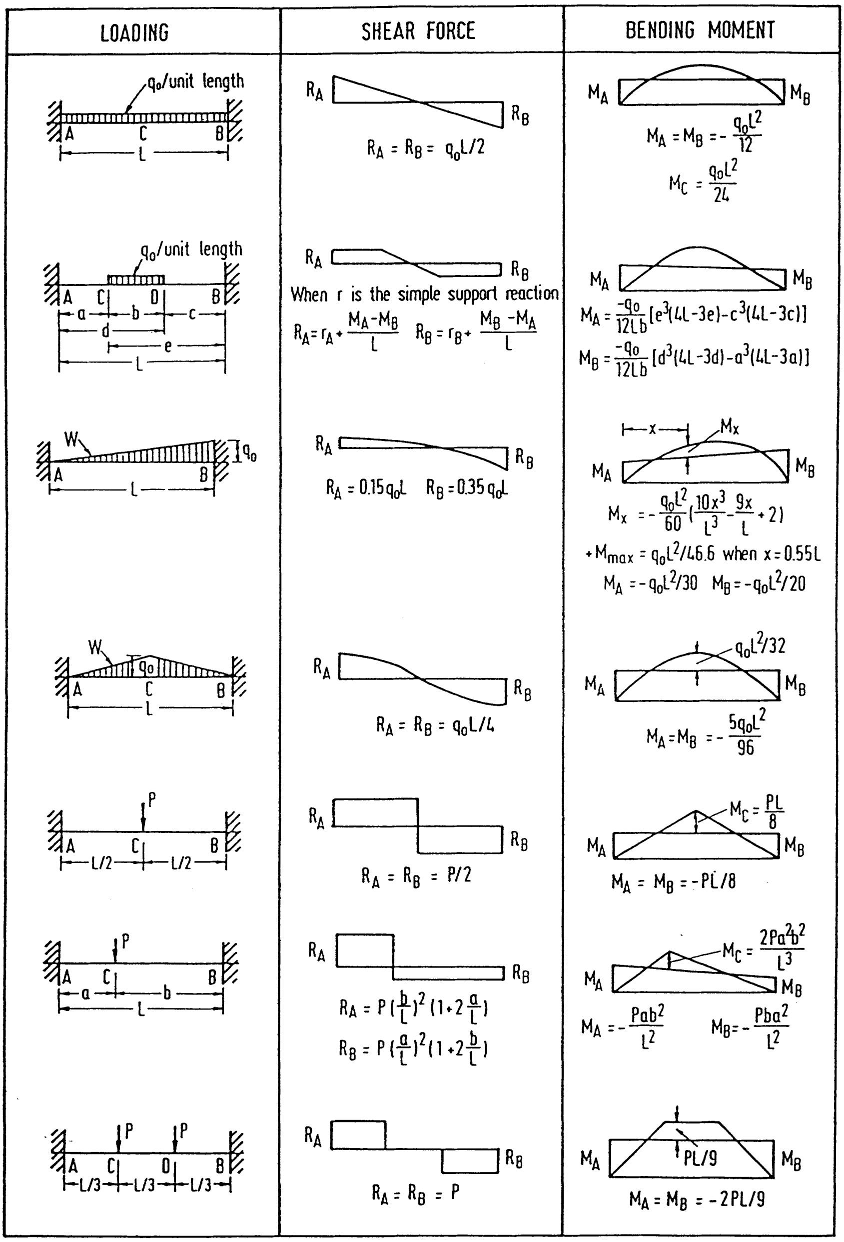
Shear force and bending moment diagrams for beams with simple boundary conditions subjected to selected loading cases. (From Liew, J.Y.R., Shanmugam, E., and Yu, C.H., Structural analysis, in *Handbook of Structural Engineering,* Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, pp. **2**-8 to **2**-10.)



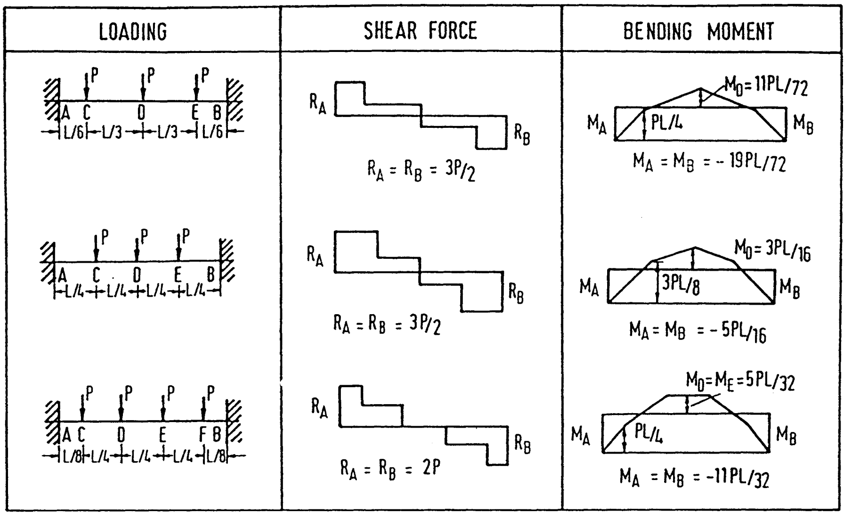
(*Continued*) Shear force and bending moment diagrams for beams with simple boundary conditions subjected to selected loading cases.



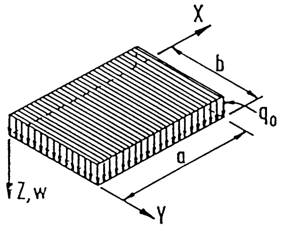
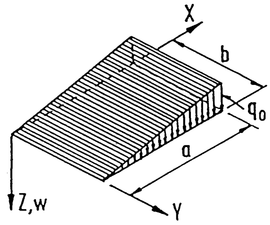
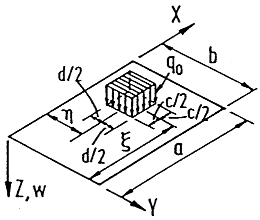
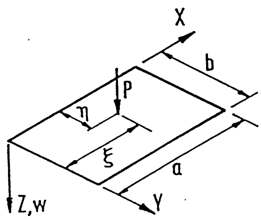
(*Continued*) Shear force and bending moment diagrams for beams with simple boundary conditions subjected to selected loading cases.



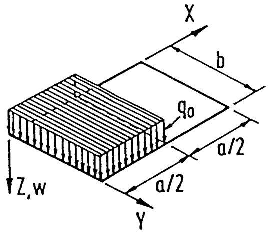
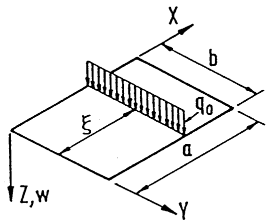
Shear force and bending moment diagrams for built-up beams subjected to typical loading cases. (From Liew, J.Y.R., Shanmugam, E., and Yu, C.H., Structural analysis, in *Handbook of Structural Engineering,* Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, pp. **2**-12 to **2**-13.)



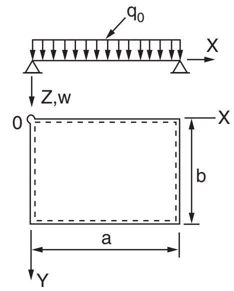
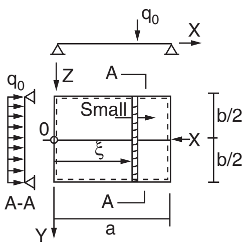
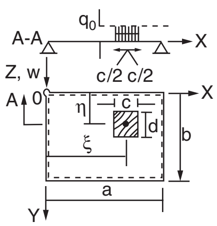
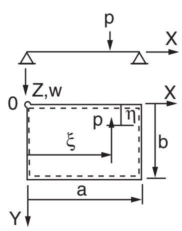
(*Continued*) Shear force and bending moment diagrams for built-up beams subjected to typical loading cases.

No.	Load $q(x,y) = \sum_m \sum_n q_{mn} \sin\frac{m\pi x}{a} \sin\frac{n\pi y}{b}$	Expansion Coefficients q_{mn}
1		$q_{mn} = \frac{16q_0}{\pi^2 mn}$ $(m, n = 1, 3, 5, \ldots.)$
2		$q_{mn} = \frac{-8q_0 \cos m\pi}{\pi^2 mn}$ $(m, n = 1, 3, 5, \ldots.)$
3		$p_{mn} = \frac{16q_0}{\pi^2 mn} \sin\frac{m\pi\xi}{a} \sin\frac{n\pi\eta}{b}$ $\times \sin\frac{m\pi c}{2a} \sin\frac{n\pi d}{2b}$ $(m, n = 1, 3, 5, \ldots.)$
4		$q_{mn} = \frac{4q_0}{ab} \sin\frac{m\pi\xi}{a} \sin\frac{n\pi\eta}{b}$ $(m, n = 1, 2, 3, \ldots.)$

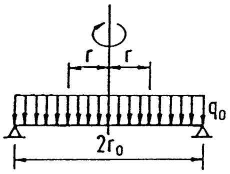
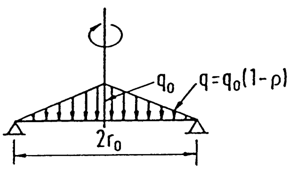
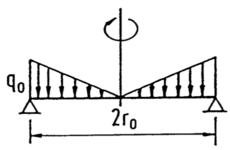
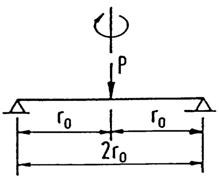
Typical loading on plates and loading functions. (From Liew, J.Y.R., Shanmugam, E., and Yu, C.H., Structural analysis, in *Handbook of Structural Engineering*, Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, pp. **2**-46 to **2**-47.)

No.	Load $q(x,y) = \sum_M \sum_n q_{mn} \sin\frac{m\pi x}{a} \sin\frac{n\pi y}{b}$	Expansion coefficients q_{mn}
5		$q_{mn} = \frac{8q_0}{\pi^2 mn}$ for $m,n = 1,3,5,\ldots.$ $q_{mn} = \frac{16q_0}{\pi^2 mn}$ for $\begin{cases} m = 2,6,10,\ldots. \\ n = 1,3,5,\ldots \end{cases}$
6		$q_{mn} = \frac{4q_0}{\pi a n} \sin\frac{m\pi\xi}{a}$ $(m,n = 1,2,3,\ldots.)$

(*Continued*) Typical loading on plates and loading functions.

Case No.	Sructural System and Static Loading	Deflection and Internal Forces
1		$w=\frac{16q_0}{\pi^6 D}\sum_m\sum_a\frac{\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}}{mn\left(\frac{m^2}{a^2}+\frac{n^2}{b^2}\right)^2}$ $m_x=\frac{16q_0a^2}{\pi^4}\sum_m\sum_n\frac{\left(m^2+v\frac{n^2}{\varepsilon^2}\right)\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}}{mn\left(m^2+\frac{n^2}{\varepsilon^2}\right)^2}$ $m_y=\frac{16q_0a^2}{\pi^4}\sum_m\sum_n\frac{\left(\frac{n^2}{\varepsilon^2}+vm^2\right)\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}}{mn\left(m^2+\frac{n^2}{\varepsilon^2}\right)^2}$ $\varepsilon=\frac{b}{a}$, $m=1, 3, 5, \ldots, \infty$; $n=1, 3, 5, \ldots, \infty$
2		$w=\frac{a^4}{D\pi^4}\sum_{m=1}^{\infty}\frac{P_m}{m^4}\left(1-\frac{2+\alpha_m\tanh\alpha_m}{2\cosh\alpha_m}\cos\lambda_m y\right.$ $\left.+\frac{\lambda_m y\sinh\lambda_m y}{2\cosh\alpha_m}\right)\sin\lambda_m x$ where $P_m=\frac{2q_0}{a}\sin\frac{m\pi\xi}{a}$ $\lambda_m=\frac{m\pi}{a}$ $m=1, 2, 3, \ldots$ $\alpha_m=\frac{m\pi b}{2a}$
3		$w=\frac{16q_0}{D\pi^6}\sum_m\sum_n\frac{\sin\frac{m\pi\xi}{a}\sin\frac{n\pi\eta}{b}\sin\frac{m\pi c}{b}\sin\frac{n\pi d}{2b}}{mn\left(\frac{m^2}{a^2}+\frac{n^2}{b^2}\right)^2}$ $\times\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}$ $m=1, 2, 3, \ldots$ $n=1, 2, 3, \ldots$
4		$w=\frac{4P}{D\pi^4 ab}\sum_m\sum_n\frac{\sin\frac{m\pi\xi}{a}\sin\frac{n\pi\eta}{b}\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}}{\left(\frac{m^2}{a^2}+\frac{n^2}{b^2}\right)^2}$ $m=1, 2, 3, \ldots$ $n=1, 2, 3, \ldots$

Typical loading and boundary conditions for rectangular plates. (From Liew, J.Y.R., Shanmugam, E., and Yu, C.H., Structural analysis, in *Handbook of Structural Engineering,* Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, pp. **2**-49.)

Case No.	Structural System and Static Loading	Deflection and Internal Forces
1		$w = \frac{q_0 r_0^4}{64D(1+\nu)}[2(3+\nu)C_1 - (1+\nu)C_0]$ $m_r = \frac{q_0 r_0^2}{16}(3+\nu)C_1$ $\rho = \frac{r}{r_0}$ $m_\theta = \frac{q_0 r_0^2}{16}[2(1-\nu) - (1+3\nu)C_1]$ $C_0 = 1 - \rho^4$ $q_r = \frac{q_0 r_0}{2}\rho$ $C_1 = 1 - \rho^2$
2		$w = \frac{q_0 r_0^4}{14400D}\left[\frac{3(183+43\nu)}{1+\nu} - \frac{10(71+29\nu)}{1+\nu}\rho^2 + 225\rho^4 - 64\rho^5\right]$ $(m_r)_{\rho=0} = (m_\varphi)_{\rho=0} = \frac{q_0 r_0^2}{720}(71+29\nu);$ $(q_r)_{\rho=1} = -\frac{q_0 r_0}{6}$ $\rho = \frac{r}{r_0}$
3		$w = \frac{q_0 r_0^4}{450D}\left[\frac{3(6+\nu)}{1+\nu} - \frac{5(4+\nu)}{1+\nu}\rho^2 + 2\rho^5\right]$ $(m_r)_{\rho=0} = (m_\varphi)_{\rho=0} = \frac{q_0 r_0^2}{45}(4+\nu);$ $(q_r)_{\rho=1} = -\frac{q_0 r_0}{3}$ $\rho = \frac{r}{r_0}$
4		$w = \frac{P r_0^2}{16\pi D}\left[\frac{3+\nu}{1+\nu}C_1 + 2C_2\right]$ $C_1 = 1 - \rho^2$ $m_r = \frac{P}{4\pi}(1+\nu)C_3$ $C_2 = \rho^2 \ln \rho$ $m_\varphi = \frac{P}{4\pi}[(1-\nu) - (1+\nu)C_3]$ $C_3 = \ln \rho$ $q_r = \frac{P}{2\pi r_0 \rho}$ $\rho = \frac{r}{r_0}$

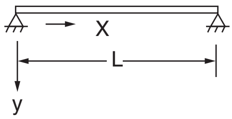
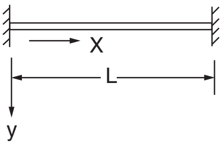
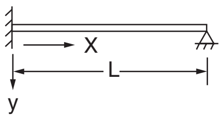
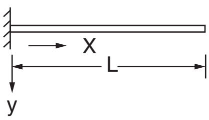
Typical loading and boundary conditions for circular plates. (From Liew, J.Y.R., Shanmugam, E., and Yu, C.H., Structural analysis, in *Handbook of Structural Engineering*, Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, pp. **2**-52.)

Frequencies and Mode Shapes of Beams in Flexural Vibration

$$f_n = \frac{k_n}{2\pi}\sqrt{\frac{EI}{mL^4}}\ \text{HZ}$$

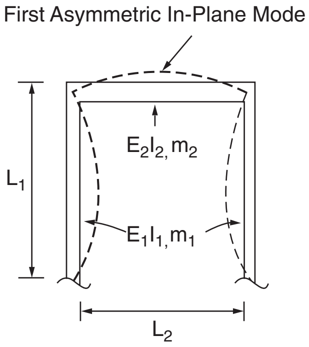
n = 1, 2, 3…

L = Length (m)
EI = Flexural Rigidity (Nm^2)
M = Mass per unit length (kg/m)

Boundary Conditions	K_n; n = 1, 2, 3	Mode Shape $y_n\left(\frac{x}{L}\right)$	A_n; n = 1, 2, 3…
Pinned - Pinned 	$(n\pi)^2$	$\sin\frac{n\pi x}{L}$	
Fixed - Fixed 	22.37 61.67 120.90 199.86 298.55 $(2n+1)\frac{\pi^2}{4}$; n > 5	$\cosh\frac{\sqrt{K_n}x}{L} - \cos\frac{\sqrt{K_n}x}{L} - A_n\left(\sinh\frac{\sqrt{K_n}x}{L} - \sin\frac{\sqrt{K_n}x}{L}\right)$	0.98250 1.00078 0.99997 0.99999 1.0; n > 5
Fixed - Pinned 	15.42 49.96 104.25 178.27 272.03 $(4n+1)^2\frac{\pi^2}{4}$; n > 5	$\cosh\frac{\sqrt{K_n}x}{L} - \cos\frac{\sqrt{K_n}x}{L} - A_n\left(\sinh\frac{\sqrt{K_n}x}{L} - \sin\frac{\sqrt{K_n}x}{L}\right)$	1.00078 1.00000 1.0; n > 3
Cantilever 	3.52 22.03 61.69 120.90 199.86 $(2n+1)^2\frac{\pi^2}{4}$; n > 5	$\cosh\frac{\sqrt{K_n}x}{L} - \cos\frac{\sqrt{K_n}x}{L} - A_n\left(\sinh\frac{\sqrt{K_n}x}{L} - \sin\frac{\sqrt{K_n}x}{L}\right)$	0.73410 1.01847 0.99922 1.00003 1.0; n > 4

From Liew, J.Y.R., Shanmugan, E., and Yu, C.H., Structural analysis, in *Handbook of Structural Engineering,* Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, p. **2**-173.

Fundamental Frequencies of Portal Frames in Asymmetrical Mode of Vibration

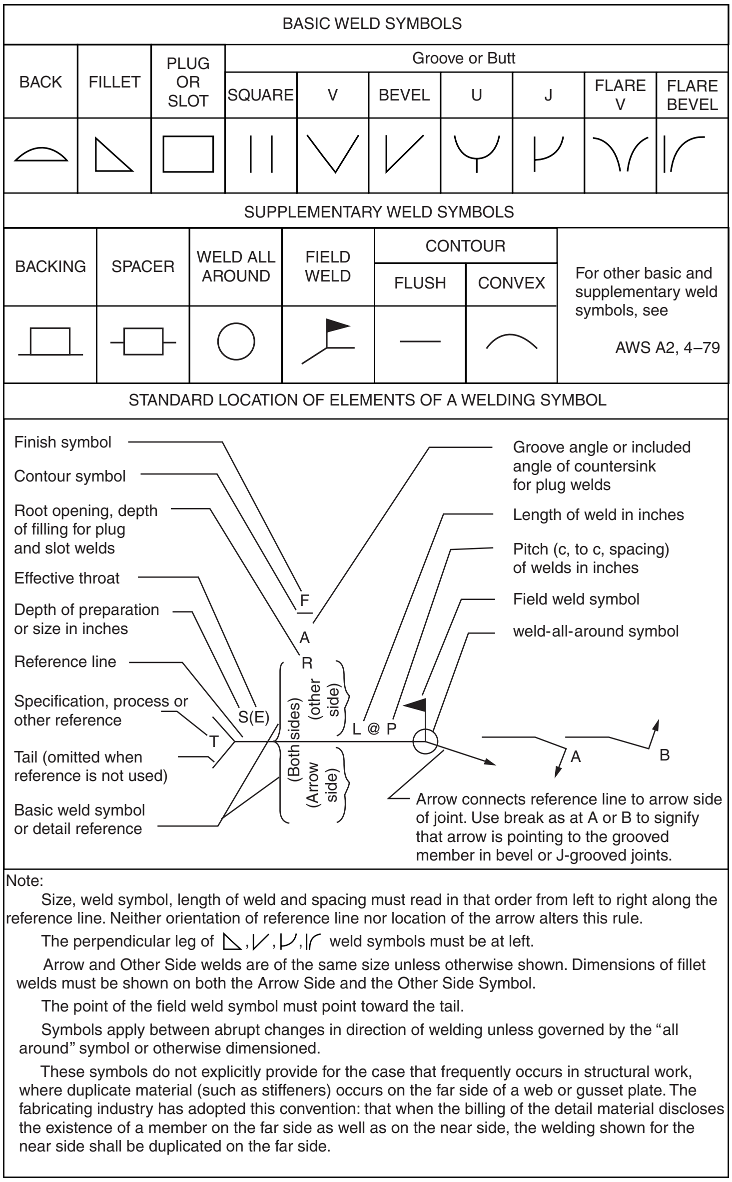


$$f = \frac{\lambda^2}{2\pi L_1^2}\left(\frac{E_1I_1}{m_1}\right)^{1/2} \text{HZ}$$

E = Modulus of elasticity
I = Area moment of inertia
m = mass per unit length

$\frac{m_1}{m_2}$	$\frac{E_1I_1}{E_2I_2}$	λ value: Pinned Bases, L_1/L_2 = 0.25	0.75	1.5	3.0	6.0	Clamped Bases, L_1/L_2 = 0.25	0.75	1.5	3.0	6.0
0.25	0.25	0.6964	0.9520	1.1124	1.2583	1.3759	0.9953	1.3617	1.6003	1.8270	2.0193
	0.75	0.6108	0.8961	1.0764	1.2375	1.3649	0.9030	1.2948	1.5544	1.7999	2.0051
	1.5	0.5414	0.8355	1.0315	1.2093	1.3491	0.8448	1.2323	1.5023	1.7649	1.9853
	3.0	0.4695	0.7562	0.9635	1.1610	1.3201	0.7968	1.1648	1.4329	1.7096	1.9504
	6.0	0.4014	0.6663	0.8737	1.0870	1.2702	0.7547	1.1056	1.3573	1.6350	1.8946
0.75	0.25	0.8947	1.1740	1.3168	1.4210	1.4882	1.2873	1.7014	1.9262	2.0994	2.2156
	0.75	0.7867	1.1088	1.2776	1.3998	1.4773	1.1715	1.6242	1.8779	2.0733	2.2026
	1.5	0.6983	1.0368	1.2281	1.3707	1.4617	1.0979	1.5507	1.8218	2.0390	2.1843
	3.0	0.6061	0.9413	1.1516	1.3203	1.4327	1.0373	1.4698	1.7454	1.9838	2.1516
	6.0	0.5186	0.8314	1.0485	1.2414	1.3822	0.9851	1.3981	1.6601	1.9072	2.0983
1.5	0.25	1.0300	1.2964	1.4103	1.4826	1.5243	1.4941	1.9006	2.0860	2.2090	2.2819
	0.75	0.9085	1.2280	1.3707	1.4616	1.5136	1.3652	1.8214	2.0390	2.1842	2.2695
	1.5	0.8079	1.1514	1.3203	1.4326	1.4982	1.2823	1.7444	1.9837	2.1515	2.2521
	3.0	0.7021	1.0482	1.2414	1.3821	1.4694	1.2141	1.6583	1.9070	2.0983	2.2206
	6.0	0.6011	0.9279	1.1335	1.3024	1.4191	1.1570	1.5808	1.8198	2.0234	2.1693
3.0	0.25	1.1597	1.3898	1.4719	1.5189	1.5442	1.7022	2.0612	2.1963	2.2756	2.3190
	0.75	1.0275	1.3202	1.4326	1.4981	1.5336	1.5649	1.9834	2.1515	2.2520	2.3070
	1.5	0.9161	1.2412	1.3821	1.4694	1.5182	1.4752	1.9063	2.0982	2.2206	2.2899
	3.0	0.7977	1.1333	1.3024	1.4191	1.4896	1.4015	1.8185	2.0233	2.1693	2.2595
	6.0	0.6838	1.0058	1.1921	1.3391	1.4395	1.3425	1.7382	1.9366	2.0964	2.2094
6.0	0.25	1.2691	1.4516	1.5083	1.5388	1.5545	1.8889	2.1727	2.2635	2.3228	2.3385
	0.75	1.1304	1.3821	1.4694	1.5181	1.5440	1.7501	2.0980	2.2206	2.2899	2.3268
	1.5	1.0112	1.3023	1.4191	1.4896	1.5287	1.6576	2.0228	2.1693	2.2595	2.3101
	3.0	0.8827	1.1919	1.3391	1.4395	1.5002	1.5817	1.9358	2.0963	2.2095	2.2802
	6.0	0.7578	1.0601	1.2277	1.3595	1.4502	1.5244	1.8550	2.0110	2.1380	2.2309

From Liew, J.Y.R., Shanmugam, E., and Yu, C.H., Structural analysis, in *Handbook of Structural Engineering,* Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, pp. **2**-176.



Basic weld symbols. (From Lui, E.M., Structural steel design, in *Handbook of Structural Engineering,* Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, p. **3**-74.)

Strength of Welds

Types of Weld and Stress	Material	ASD Allowable Stress	LRFD ϕF_{BM} or ϕF_W	Required Weld Strength Level[a,b]
		Full Penetration Groove Weld		
Tension normal to effective area	Base	Same as base metal	0.90 F_y	“Matching” weld must be used
Compression normal to effective area	Base	Same as base metal	0.90 F_y	Weld metal with a strength level equal to or less than “matching” must be used
Tension of compression parallel to axis of weld	Base	Same as base metal	0.90 F_y	
Shear on effective area	Base weld electrode	0.30 × nominal tensile strength of weld metal	0.90[0.60 f_y] 0.80[0.60 F_{EXX}]	
		Partial Penetration Groove Welds		
Compression normal to effective area	Base	Same as base metal	0.90 F_y	Weld metal with a strength level equal to or less than “matching” weld metal may be used
Tension or compression parallel to axis of weld[c]				
Shear parallel to axis of weld	Base weld electrode	0.30 × nominal tensile strength of weld metal	0.75[0.60 F_{EXX}]	
Tension normal to effective area	Base weld electrode	0.30 × nominal tensile strength of weld metal ≤0.18 × yield stress of base metal	0.90 F_y 0.80[0.60 F_{EXX}]	
		Fillet Welds		
Stress on effective area	Base weld electrode	0.30 × nominal tensile strength of weld metal	0.75[0.60 F_{EXX}] 0.90 F_y	Weld metal with a strength level equal to or less than “matching” weld metal may be used
Tension or compression parallel to axis of weld[c]	Base	Same as base metal	0.90 *Fy*	
		Plug or Slot Welds		
Shear parallel to faying surfaces (on effective area)	Base weld electrode	0.30 × nominal tensile strength of weld metal	0.75[0.60 F_{EXX}]	Weld metal with a strength level equal to or less than “matching” weld metal may be used

[a] See AWS D1.1 for “matching” weld material.

[b] Weld metal one strength level stronger than “matching” weld metal will be permitted.

[c] Fillet welds partial-penetration groove welds joining component elements of built-up members such as flange-to-web connections may be designed without regard to the tensile or compressive stress in these elements parallel to the axis of the welds.

From Lui, E.M., Structural steel design, in *Handbook of Structural Engineering*, Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, p. **3**–75.

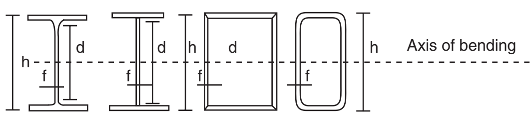
Reinforcing Bar Dimensions and Weights

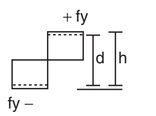
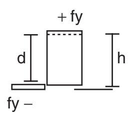
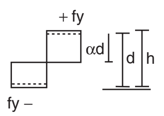
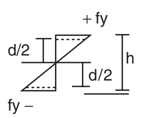
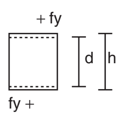
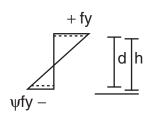
Bar Number	Nominal Dimensions: Diameter (in.)	Diameter (nm)	Area (in.²)	Area (cm²)	Weight (lb/ft)	Weight (kg/m)
3	0.375	9.5	0.11	0.71	0.376	0.559
4	0.500	12.7	0.20	1.29	0.668	0.994
5	0.625	15.9	0.31	2.00	1.043	1.552
6	0.750	19.1	0.44	2.84	1.502	2.235
7	0.875	22.2	0.60	3.87	2.044	3.041
8	1.000	25.4	0.79	5.10	2.670	3.973
9	1.128	28.7	1.00	6.45	3.400	5.059
10	1.270	32.3	1.27	8.19	4.303	6.403
11	1.410	35.8	1.56	10.06	5.313	7.906
14	1.693	43.0	2.25	14.52	7.65	11.38
18	2.257	57.3	4.00	25.81	13.60	20.24

From Grider, A., Ramirez, J.A., and Yun, Y.M., Structural concrete design, in *Handbook of Structural Engineering*, Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, p. **4**–6.

Eurocode 4 Maximum Width-to-Thickness Ratios for Steel Webs

Webs: elements perpendicular to axis of bending



Class	Web subject to bending	Web subject to compression	Web subject to bending and compression
Stress distribution (Compression positive)			
1	d/t ≤ 72 ε	d/t ≤ 33 ε	when α > 0.5 d/t ≤ 396 ε/(13α–1) when α < 0.5 d/t ≤ 36 ε/α
2	d/t ≤ 83 ε	d/t ≤ 38 ε	when α > 0.5 d/t ≤ 456 ε/(13α–1) when α < 0.5 d/t ≤ 41.5 ε/α
Stress distribution (compression positive)			
3	d/t ≤ 124 ε	d/t ≤ 42 ε	when ψ > –1 d/t ≤ 42 ε/(0.67+0.33 ψ) when ψ ≤ –1 d/t ≤ 62 ε/(1–ψ)/ψ

$\varepsilon = 235/f_y$	f_y (N/mm[1])	235	275	355
	ε	1.0	0.92	0.81

From Consenza, E. and Zandonini, R., Composite construction, in *Handbook of Structural Engineering*, Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, p. **6**-29.

Mechanical Properties of Steels Referred to in the AISI 1996 Specification

Steel Designation	ASTM Designation	Yield Point, F_y (ksi)	Tensile Strength, F_u (ksi)	Elongation (%) In 2-in. Gage Length	Elongation (%) In 8-in. Gage Length
Structural steel	A36	36	58–80	23	—
High-strength low-allow structural steel	A242 (3/4 in. and under)	50	70	—	18
	(3/4 in. to 1-1/2 in.)	46	67	21	18
Low and intermediate tensile strength carbon plates, shapes and bars	A283 Gr. A	24	45–60	30	27
	B	27	50–65	28	25
	C	30	55–75	25	22
	D	33	60–80	23	20
Cold-formed welded and seamless carbon steel structural tubing in rounds and shapes	A500				
	Round tubing				
	A	33	45	25	—
	B	42	58	23	—
	C	46	62	21	—
	D	36	58	23	—
	Shaped tubing				
	A	39	45	25	—
	B	46	58	23	—
	C	50	62	21	—
	D	36	58	23	—
Structural steel with 42 ksi minimum yield point	A529 Gr. 42	42	60–85	—	19
	50	50	70–100	—	18
Hot-rolled carbon steel sheets and stripes of structural quality	A570 Gr. 30	30	49	21–25	—
	33	33	52	18–23	—
	36	36	53	17–22	—
	40	40	55	15–21	—
	45	45	60	13–19	—
	50	50	65	11–17	—
High-strength low-alloy columbium-vanadium steels of structural quality	A572 Gr. 42	42	60	24	20
	50	50	65	21	18
	60	60	75	18	16
	65	65	80	17	15
High-strength low-alloy structural steel with 50 ksi minimum yield point	A588	50	70	21	18
Hot-rolled and cold-rolled high-strength low-alloy steel sheet and strip with improved corrosion resistance	A60				
	Hot-rolled as rolled coils; annealed or normalized; and cold-rolled	45	65	22	—
	Hot-rolled as rolled cut lengths	50	70	22	—
Hot-rolled and cold-rolled high-strength low-alloy columbium and/or vanadium steel sheet and strip	A607 Gr. 45	45	60 (55)	Hot-rolled 23–25	
				Cold-rolled 22	
	50	50	65 (60)	Hot-rolled 20–22	—
				Cold-rolled 20	—
	55	55	70 (65)	Hot-rolled 18–20	—
				Cold-rolled 18	—
	60	60	75 (70)	Hot-rolled 16–18	—
				Cold-rolled 16	—
	65	65	80 (75)	Hot-rolled 14–16	—
				Cold-rolled 15	—
	70	70	85 (80)	Hot-rolled 12–14	—
				Cold-rolled 14	—

Mechanical Properties of Steels Referred to in the AISI 1996 Specification (continued)

Steel Designation	ASTM Designation	Yield Point, F_y (ksi)	Tensile Strength, F_u (ksi)	Elongation (%) In 2-in. Gage Length	Elongation (%) In 8-in. Gage Length
Cold-rolled carbon structural steel sheet	A611 Gr. A	25	42	26	—
	B	30	45	24	—
	C	33	48	22	—
	D	40	52	20	—
	E	80	82	—	—
Zinc-coated steel sheets of structural quality	A653 SQ Gr. 33	33	45	20	—
	37	37	52	18	—
	40	40	55	16	—
	50 (class 1)	50	65	12	—
	50 (class 3)	50	70	12	—
	80	80	82	—	—
	HSLA Gr. 50	50	60	20	—
	60	60	70	16	—
	70	70	80	12 (14)	—
	80	80	90	10 (12)	—
Hot-rolled high-strength low-alloy steel sheets and strip with improved formability	A715 Gr. 50	50	60	22–24	—
	60	60	70	20–22	—
	70	70	80	18	—
	80	80	90	14	—
Aluminum-zinc alloy-coated by the hot-dip process general requirements	A792 Gr. 33	33	45	20	—
	37	37	52	18	—
	40	40	55	16	—
	50	50	65	12	—
	80	80	82	—	—

Notes:
1. The tabulated values are based on ASTM Standards.
2. 1 in. = 25.4 mm; 1 ksi = 6.9 MPa.
3. A653 Structural Quality Grade 80, Grade E of A611, and Structural Quality Grade 80 of A792 are allowed in the AISI Specification under special conditions. For these grades, F_y = 80 ksi, F_u = 82 ksi, elongations are unspecified. See AISI Specification for reduction of yield point and tensile strength.
4. For A653 steel, HSLA Grades 70 and 80, the elongation in 2-in. gage length given in the parenthesis is for Type II. The other value is for Type I.
5. For A607 steel, the tensile strength given in the parenthesis is for Class 2. The other value is for Class I.

From Yu, W.-W., Cold-formed steel structures, in *Handbook of Structural Engineering*, Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, pp. **7**–8 to **7**–9.

Some Nominal Properties of Aluminum Alloys

Property	Value
Weight	0.1 lb/in.^{3}
Modulus of elasticity	
Tension and compression	10,000 ksi
Shear	3,750 ksi
Poisson's ratio	1/3
Coefficient of thermal expansion (68 to 212°F)	0.000013 per ˚F

From Fridley, M.J., Aluminum structures, in *Handbook of Structural Engineering*, Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, p. **8**–2. Originally from Gaylord and Gaylord, *Structural Engineering Handbook*, McGraw-Hill, New York, 1990.

Minimum Mechanical Properties

Alloy and Temper	Product	Thickness Range, in.	Tension		Compression YS	Shear		Bearing	
			TS	YS		US	YS	US	YS
3003-H14	Sheet and plate	0.009–1.000	20	17	14	12	10	40	25
5456-H116	Sheet and plate	0.188–1.250	46	33	27	27	19	87	56
6061–T6	Sheet and plate	0.010–4.000	42	35	35	27	20	88	58
6061-T6	Shapes	All	38	35	35	24	20	80	56
6063–T5	Shapes	to 0.500	22	16	16	13	9	46	26
6063-T6	Shapes	All	30	25	25	19	14	63	40

Note: All properties are in ksi. TS is tensile strength, YS is yield strength, and US is ultimate strength.

From Fridley, M.J., Aluminum structures, in *Handbook of Structural Engineering*, Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, p. **8**–3. Originally from The Aluminum Association, *Structural Design Manual*, 1994.

Steel Plate Materials

Group	Class	Specification	Specified Minimum Yield Stress (ksi)[a]	Specified Minimum Tensile Stress (ksi)[a]
I	C	ASTM A36 (to 2 in. thick)	36	58
		ASTM A131 Grade A (to ½ in. thick)	34	58
		ASTM A285 Grade C (to ¾ in. thick)	30	55
I	B	ASTM A131 Grades B, D	34	58
		ASTM A516 Grade 65	35	65
		ASTM A573 Grade 65	35	65
		ASTM A709 Grade 36T2	36	58
I	A	ASTM A131 Grades CS, E	34	58
II	C	ASTM A572 Grade 42 (to 2 in. thick)	42	60
		ASTM A591 required over ½ in. thick		
		ASTM A572 Grade 50 (to 2 in. thick)	50	65
		ASTM A591 required over ½ in. thick		
II	B	ASTM A709 Grades 50T2, 50T3	50	65
		ASTM A131 Grade AH32	45.5	68
		ASTM A131 Grade AH36	51	71
II	A	API Spec 2H Grade 42	42	65
		API Spec 2H Grade 50 (to 2½ in. thick)	50	70
		API Spec 2H Grade 50 (over 2½ in. thick)	47	70
		API Spec 2W Grade 42 (to 1 in. thick)	42	62
		API Spec 2W Grade 42 (over 1 in. thick)	42	62
		API Spec 2W Grade 50 (to 1 in. thick)	50	65
		API Spec 2W Grade 50 (over 1 in. thick)	50	65
		API Spec 2W Grade 50T (to 1 in. thick)	50	70
		API Spec 2W Grade 50T (over 1 in. thick)	50	70
		API Spec 2Y Grade 42 (to 1 in. thick)	42	62
		API Spec 2Y Grade 42 (over 1 in. thick)	42	62
		API Spec 2Y Grade 50 (to 1 in. thick)	50	65
		API Spec 2Y Grade 50 (over 1 in. thick)	50	65
		API Spec 2Y Grade 50T (to 1 in. thick)	50	70
		API Spec 2Y Grade 50T (over 1 in. thick)	50	70
		ASTM A131 Grades DH32, EH32	45.5	68
		ASTM A131 Grades DH36, EH36	51	71
		ASTM A537 Class I (to 2½ in. thick)	50	70
		ASTM A633 Grade A	42	63
		ASTM A633 Grades C, D	50	70
		ASTM A678 Grade A	50	70
III	A	ASTM A537 Class II (to 2½ in. thick)	60	80
		ASTM A678 Grade B	60	80
		API Spec 2W Grade 60 (to 1 in. thick)	60	75
		API Spec 2W Grade 60 (over 1 in. thick)	60	75
		ASTM A710 Grade A Class 3 (to 2 in. thick)	75	85
		ASTM A710 Grade A Class 3 (2 in. to 4 in. thick)	65	75
		ASTM A710 Grade A Class 3 (over 4 in. thick)	60	70

[a] 1 ksi = 6.895 MPa

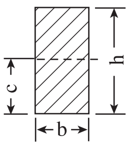
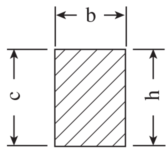
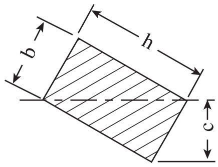
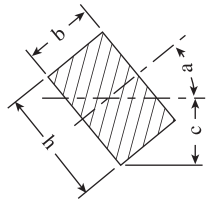
From Miller, C.D., Shell structures in *Handbook of Structural Engineering*, Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, p. **11**-4.

Mechanical Properties of Common Design Materials

Material	Yield Strength, σ_Y (ksi)	Ultimate Tensile Strength, σ_u (ksi)	Modulus of Elasticity, E (psi)	Percent Elongation (%)	Absorbed Elastic Energy, $\sigma_Y^2/2E$ (psi)
Mild steel	35	60	30×10^6	35	20.4
Medium carbon steel	45	85	30×10^6	25	33.7
High carbon steel	75	120	30×10^6	8	94.0
A514 Steel	100	115–135	30×10^6	18	166.7
Gray cast iron	6	20	15×10^6	5	1.2
Malleable cast iron	20	50	23×10^6	10	8.7
5056-H18 Aluminum alloy	59	63	10×10^6	10	174.1

From Blodgett, O.W. and Miller, D.K., Basic principles of shock loading, in *Handbook of Structural Engineering*, Chen, W.-F., Ed., CRC Press, Boca Raton, FL, 1998, p. **21**-7.

Properties of Sections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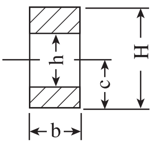
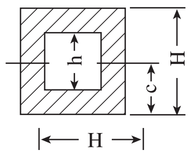
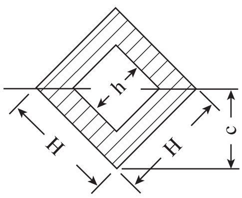
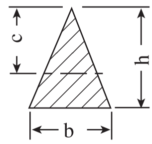
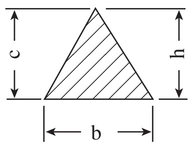
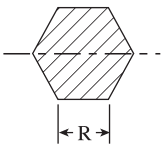
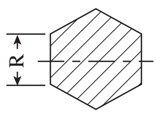
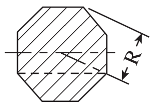
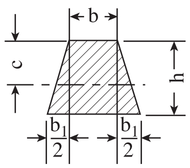
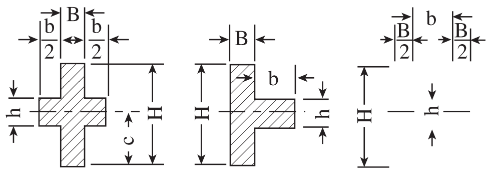
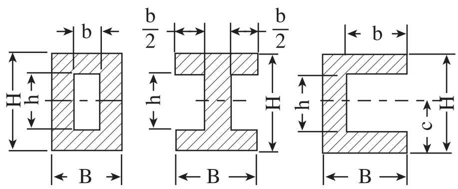
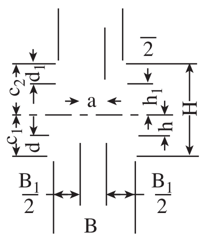
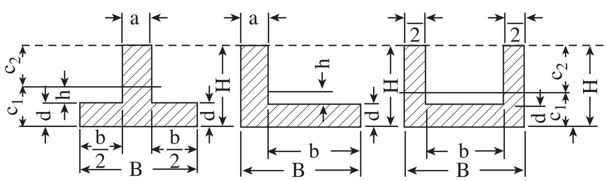
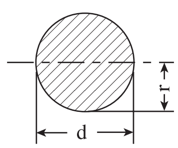
			
$I = \frac{b}{12}(H^3 - h^3)$ $\frac{I}{c} = \frac{b}{6}\frac{H^3-h^3}{H}$ $r = \sqrt{\frac{H^3-h^3}{12(H-h)}}$	$\frac{H^4-h^4}{12}$ $\frac{1}{6}\frac{H^4-h^4}{H}$ $\sqrt{\frac{H^2+h^2}{12}}$	$\frac{H^4-h^4}{12}$ $\frac{\sqrt{2}}{12}\frac{H^4-h^4}{H}$ $\sqrt{\frac{H^2+h^2}{12}}$	$\frac{bh^3}{36};\ c = \frac{2}{3}h$ $\frac{bh^2}{24}$ $\frac{h}{\sqrt{18}}$
			
$I = \frac{bh^3}{12}$ $\frac{I}{c} = \frac{bh^3}{12}$ $r = \frac{h}{\sqrt{6}}$	$\frac{5\sqrt{3}}{16}R^4$ $\frac{5}{8}R^3$ $\sqrt{\frac{5}{24}}R$	$\frac{5\sqrt{3}}{16}R^3$	$\frac{1+2\sqrt{2}}{6}R^4$ $0.6906R^3$ $0.475R$

Square, axis same as first rectangle, side = h; $I = h^4/12$; $I/c = h^3/6$; $r = 0.289h$.
Square, diagonal taken as axis: $I = h^4/12$; $I/c = 0.1179h^3$; $r = 0.289h$.

Properties of Sections (continued)

Equilateral Polygon A = area R = rad circumscribed circle r = rad inscribed circle n = no. sides a = length of side Axis as in preceding section of octagon	$I = \frac{A}{24}\left(6R^2 - a^2\right)$ $= \frac{A}{48}\left(12r^2 + a^2\right)$ $= \frac{AR^2}{4}$ (approx)	$\frac{I}{c} = \frac{I}{r}$ $= \frac{I}{R\cos\frac{180°}{n}}$ $= \frac{AR}{4}$ (approx)	$\sqrt{\frac{6R^2 - a^2}{24}} \approx \frac{R}{2}$ $\sqrt{\frac{12r^2 + a^2}{48}}$
	$I = \frac{6b^2 + 6bb_1 + b_1^2}{36(2b + b_1)}h^3$ $c = \frac{1}{3}\frac{3b + 2b_1}{2b + b_1}h$	$\frac{I}{c} = \frac{6b^2 + 6bb_1 + b_1^2}{12(3b + 2b_1)}h^2$	$\frac{h\sqrt{12b^2 + 12bb_1 + 2b_1^2}}{6(2b + b_1)}$
		$I = \frac{BH^3 + bh^3}{12}$ $\frac{I}{c} = \frac{BH^3 + bh^3}{6H}$	$\sqrt{\frac{BH^3 + bh^3}{12(BH + bh)}}$
		$I = \frac{BH^3 - bh^3}{12}$ $\frac{I}{c} = \frac{BH^3 + bh^3}{6H}$	$\sqrt{\frac{BH^3 - bh^3}{12(BH - bh)}}$
	$I = ⅓\left(Bc_1^3 - B_1h^3 + bc_2^3 - b_1h_1^3\right)$ $c_1 = \frac{1}{2}\frac{aH^2 + B_1d^2 + b_1d_1(2H - d_1)}{aH + B_1d + b_1d_1}$	$\sqrt{\frac{I}{(Bd + bd_1) + a(h + h_1)}}$	
		$I = ⅓\left(Bc_1^3 - bh^3 + ac_2^3\right)$ $c_1 = \frac{1}{2}\frac{aH^2 + bd^2}{aH + bd}$ $c_2 = H - c_1$ $r = \sqrt{\frac{I}{[Bd + a(H - d)]}}$	
	$I = \frac{\pi d^4}{64} = \frac{\pi r^4}{4} = \frac{A}{4}r^2$ $= 0.05d^4$ (approx)	$\frac{I}{c} = \frac{\pi d^3}{32} = \frac{\pi r^3}{4} = \frac{A}{4}r$ $= 0.1d^2$ (approx)	$\frac{r}{2} = \frac{d}{4}$

From Bolz, R.E. and Tuve, G.L., Structures and materials, in *CRC Handbook of Tables for Applied Engineering Science,* CRC Press, Boca Raton, FL, pp. 628–629.

Components of the Atmosphere*

Average Composition of Dry Air

For most engineering applications the following accepted values for the "average" composition of the atmosphere are adequate. These values are for sea level or any land elevation. Proportions remain essentially constant to 50,000 ft (15,240 m) altitude.

Gas	Molecular Weight	Percentage by Volume, mol fraction	Percentage by Weight
Nitrogen	N_2 = 28.016	78.09	75.55
Oxygen	O_2 = 32.000	20.95	23.13
Argon	Ar = 39.944	0.93	1.27
Carbon dioxide	CO_2 = 44.010	0.03	0.05
		100.00	100.00

For many engineering purposes the percentages 79% N_2–21% O_2 by volume and 77% N_2–23% O_2 by weight are sufficiently accurate, the argon being considered as nitrogen with an adjustment of molecular weight to 28.16.

Other gases in the atmosphere constitute less than 0.003% (actually 27.99 parts per million by volume), as given in the following table.

Minor Constituents of Dry Air

Gas	Molecular Weight	Parts per Million	
		By Volume	By Weight
Neon	Ne = 20.183	18.	12.9
Helium	He = 4.003	5.2	0.74
Methane	CH_4 = 16.04	2.2	1.3
Krypton	Kr = 83.8	1.	3.0
Nitrous oxide	N_2O = 44.01	1.	1.6
Hydrogen	H_2 = 2.0160	0.5	0.03
Xenon	Xe = 131.3	0.08	0.37
Ozone	O_3 = 48.000	0.01	0.02
Radon	Rn = 222.	(0.06×10^{-12})	

Minor constituents may also include dust, pollen, bacteria, spores, smoke particles, SO_2, H_2S, hydrocarbons, and larger amounts of CO_2 and ozone, depending on weather, volcanic activity, local industrial activity, and concentration of human, animal, and vehicle population. In certain enclosed spaces the minor constituents will vary considerably with industrial operations and with occupancy by humans, plants, or animals.

The above data do not include water vapor, which is an important constituent in all normal atmospheres.

* Compiled from several sources.

From Bolz, R.E. and Tuve, G.L., Atmosphere, earth, and ocean, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 649.

Sound Transmission Through Partition Walls*

Dry-Wall Construction

The following table presents typical results selected from approximately 100 tests in the National Research Council of Canada Building Research series. The tests were conducted in accordance with ASTM E90–66T, "Recommended Practice for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions." The gypsum board samples represented extremes of density and thickness (as allowed under CSA Standards); they included the fire-resistant and the vinyl-covered types, with no significant differences in performance.

			Transmission Loss, db, at Octave Frequencies of[a]					
Number	Description of Wall	Transmission Loss, Nominal Average	125	250	500	1000	2000	4000
	Single-Leaf or Board on One Side of Studs Only							
1	3/8-in. plasterboard[b]	26	12	17	23	28	33	23
2	1/2-in. plasterboard[b]	28	15	20	25	30	33	27
3	5/8-in. plasterboard[b]	29	16	21	27	31	29	30
4	22-gage galvanized iron	27	13	17	22	28	34	39
5	1/2-in. plasterboard + 3/16-in. plywood[c]	28	16	20	25	29	32	31
6	1/2-in. plasterboard + 1/2-in. fiberboard[d]	30	16	22	28	33	32	30
	Two-Leaf Walls—Wallboard Both Sides							
7	1/2-in. plasterboard, 3 5/8-in. space	35	15	28	32	41	46	38
8	1/2-in. plasterboard, 2-in. fill[e]	40	22	33	35	43	47	40
9	Staggered studs + 2-in. fill[f]	46	26	37	45	50	50	47
10	Plasterboard + plywood + fiberboard[g]	46	22	36	46	54	56	56
11	5/8-in. plasterboard, 3 5/8-in. space	36	21	25	34	41	36	42
12	5/8-in. plasterboard, 4-in. fill[h]	45	28	40	45	48	40	45
13	Staggered studs + no fill[j]	39	27	25	37	46	38	49
14	Staggered studs, 4-in. fill[k]	46	32	36	47	50	42	52
15	Multilayer, steel studs, glass fiber[m]	53	36	45	49	55	55	56

[a] The quoted report included test data on the following additional frequencies: 160, 200, 315, 400, 630, 1,250, 1,600, 2,500, 3,150, and 5,000 hz.
[b] Joints taped for plasterboard walls.
[c] Sheets joined by contact cement on faces.
[d] Plasterboard and wood fiberboard laminated with gypsum joint compound.
[e] Glass fiber batts, 2-in. thick, between studs; 1/2-in. plasterboard.
[f] Staggered wood studs, 2-in. × 4-in., 3 5/8-in. space, 2-in. thick glass fiber batts, 1/2-in. plasterboard, both faces.
[g] 1/2-in. plasterboard and 3/16-in. plywood on both faces; 2-in. × 4-in. wood studs on 16-in. wood fiberboard between studs.
[h] 4-in. low-density glasswool batts, compressed into stud space between 3 5/8-in. steel-channel studs.
[j] 2-in. × 4-in. wood studs, staggered, 3 5/8-in. space, 5/8-in. plasterboard, no fill.
[k] Same as No. 13 but 4-in. low-density glasswool batts in space between 2-in. × 4-in. wood studs.
[m] Three 1/2-in. layers, one 5/8-in. layer plasterboard; 3 5/8-in. steel channel studs, 24-in. centers; 2 1/2-in. glass fiber.

General Notes

With studs of low torsional rigidity, such as steel channels, sound transmission via the studs appears to be negligible. The simpler constructions have been tested by several laboratories, and results have been found to be reasonably reproducible.

The test specimens were mounted and caulked into an opening 10-ft wide by 8-ft high that separated two reverberation rooms. The test signal consisted of third-octave bands of "pink" noise.

The test results were not critically sensitive to normal variations in thickness, density, or techniques of erection.

Several of the additional tests included multi-layer constructions and the additions of resilient bars, horizontal or vertical. Highest sound attenuation was 53 db (test No. 15 in table).

From Bolz, R.E. and Tuve, G.L., Sound and acoustics, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 696. Originally from T.D. Northwood, "Transmission Loss of Plasterboard Walls," Building Research Note 66, Division of Building Research, National Research Council, revised July 1970.

Sound-Absorption Coefficients

Sound-absorption data on various materials are presented here in terms of the acoustic properties of rooms; these data are also valuable for other applications, such as the acoustic treatments for ducts and tunnels. Architectural applications include the control of noise level in offices, stores, restaurants, and other occupied spaces, and the control of reverberation time and elimination of echoes in concert and lecture halls.

Non-absorbent surfaces. Solid walls, floors, or ceilings finished with glazed tile, marble, terrazzo, very smooth concrete, or with linoleum, rubber, cork, or plastic tile cemented directly to concrete, are not sound absorbent. The absorption coefficient (in percentage of incident energy absorbed) is seldom more than 1 or 2 percent at all wavelengths from 125 hz to 4,000 hz.

Poor sound absorbers. Brick surfaces, painted concrete blocks, hardwood floors, gypsum board, or smooth nonporous plaster (lime or gypsum) are all poor absorbers. With solid structural backing these finishes seldom afford as much as 10 percent absorption at any wavelength from 125 hz to 4,000 hz. Ordinary window areas may absorb up to 25 percent of the low-frequency sounds (125 to 250 hz) but much less at the higher frequencies.

Sound-absorbing materials. Carpets, drapes, and upholstered seats are fair-to-good sound absorbers.

	Absorption Coefficients, % (Percentage of Incident Energy Absorbed)					
	Sound Frequency, hz					
Materials	125	250	500	1000	2000	4000
Heavy carpet on concrete or solid floor	2	6	14	37	60	65
Heavy carpet on heavy hairfelt or elastic pad	8	25	50	60	65	65
Heavy drapes (1 lb/sq yd) draped 2 to 1 area	10	30	50	75	70	65
Light hung fabric	3	4	11	17	24	35
Unoccupied wood or metal chairs[a]	15	20	25	40	40	30
Unoccupied upholstered seating[a]	45	55	65	70	70	60
Full audience, occupying upholstered seats[a]	70	75	85	95	90	85

[a] Equivalent values based on floor area.

Acoustic Treatments

The following data apply mainly to acoustic ceiling treatments, but other surfaces may be similarly treated. These data do not apply to through-transmission of sound. Low sound transmission accompanies high density or weight of material.

	Absorption Coefficients, % (Percentage of Incident Energy Absorbed)					
	Sound Frequency, hz					
Class Description[b]	125	250	500	1000	2000	4000
Porous, lightweight fiber board or tile ¾ in. thick; perforated or fissured; painted; on ¾ in. furring strips	20	58	61	80	80	68
Porous fireproof mineral tile, ⅝ in. thick; perforated or fissured; painted; direct solid application to structural surface	10	26	70	89	75	60
Porous fireproof mineral tile, ¾ in. thick, drop ceiling or large air space; metal supports	70	66	72	92	88	75
Bonded wood or mineral fibers; thickness about 1½ in.	41	59	88	85	76	65
Perforated metal pans or hardboard backed with 1½ in. loose pad	36	56	87	94	74	56

[b] Data on each class based on five or more commercial products.

From Bolz, R.E. and Tuve, G.L., Sound and acoustics, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 697.

3

Chemical Engineering, Chemistry, and Materials Science

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INTERNATIONAL SYSTEM OF UNITS (SI)

1 SI base units

Table 1 gives the seven base quantities, assumed to be mutually independent, on which the SI is founded; and the names and symbols of their respective units, called ``SI base units.'' Definitions of the SI base units are given in Appendix A. The kelvin and its symbol K are also used to express the value of a temperature interval or a temperature difference.

Table 1. SI base units

	SI base unit	
Base quantity	Name	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

2 SI derived units

Derived units are expressed algebraically in terms of base units or other derived units (including the radian and steradian which are the two supplementary units – see Sec. 3). The symbols for derived units are obtained by means of the mathematical operations of multiplication and division. For example, the derived unit for the derived quantity molar mass (mass divided by amount of substance) is the kilogram per mole, symbol kg/mol. Additional examples of derived units expressed in terms of SI base units are given in Table 2.

Table 2. Examples of SI derived units expressed in terms of SI base units

	SI derived unit	
Derived quantity	Name	Symbol
area	square meter	m^2
volume	cubic meter	m^3
speed, velocity	meter per second	m/s
acceleration	meter per second squared	m/s^2
wave number	reciprocal meter	m^{-1}
mass density (density)	kilogram per cubic meter	kg/m^3
specific volume	cubic meter per kilogram	m^3/kg
current density	ampere per square meter	A/m^2
magnetic field strength	ampere per meter	A/m
amount-of-substance concentration (concentration)	mole per cubic meter	mol/m^3
luminance	candela per square meter	cd/m^2

2.1 SI derived units with special names and symbols

Certain SI derived units have special names and symbols; these are given in Tables 3a and 3b. As discussed in Sec. 3, the radian and steradian, which are the two supplementary units, are included in Table 3a.

INTERNATIONAL SYSTEM OF UNITS (SI) (continued)

Table 3a. SI derived units with special names and symbols, including the radian and steradian

Derived quantity	SI derived unit			
	Special name	Special symbol	Expression in terms of other SI units	Expression in terms of SI base units
plane angle	radian	rad		$m \cdot m^{-1} = 1$
solid angle	steradian	sr		$m^2 \cdot m^{-2} = 1$
frequency	hertz	Hz		s^{-1}
force	newton	N		$m \cdot kg \cdot s^{-2}$
pressure, stress	pascal	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
energy, work, quantity of heat	joule	J	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
power, radiant flux	watt	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
electric charge, quantity of electricity	coulomb	C		$s \cdot A$
electric potential, potential difference, electromotive force	volt	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
capacitance	farad	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
electric resistance	ohm	Ω	V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
electric conductance	siemens	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
magnetic flux	weber	Wb	$V \cdot s$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
magnetic flux density	tesla	T	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
inductance	henry	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
Celsius temperature[(a)]	degree Celsius	°C		K
luminous flux	lumen	lm	$cd \cdot sr$	$cd \cdot sr$[(b)]
illuminance	lux	lx	lm/m^2	$m^{-2} \cdot cd \cdot sr$[(b)]

[(a)] See Sec. 2.1.1.
[(b)] The steradian (sr) is not an SI base unit. However, in photometry the steradian (sr) is maintained in expressions for units (see Sec. 3).

Table 3b. SI derived units with special names and symbols admitted for reasons of safeguarding human health[(a)]

Derived quantity	SI derived unit			
	Special name	Special symbol	Expression in terms of other SI units	Expression in terms of SI base units
activity (of a radionuclide)	becquerel	Bq		s^{-1}
absorbed dose, specific energy (imparted), kerma	gray	Gy	J/kg	$m^2 \cdot s^{-2}$
dose equivalent, ambient dose equivalent, directional dose equivalent, personal dose equivalent, equivalent dose	sievert	Sv	J/kg	$m^2 \cdot s^{-2}$

[(a)] The derived quantities to be expressed in the gray and the sievert have been revised in accordance with the recommendations of the International Commission on Radiation Units and Measurements (ICRU).

2.1.1 Degree Celsius In addition to the quantity thermodynamic temperature (symbol T), expressed in the unit kelvin, use is also made of the quantity Celsius temperature (symbol t) defined by the equation

$$t = T - T_0 \ ,$$

where $T_0 = 273.15$ K by definition. To express Celsius temperature, the unit degree Celsius, symbol °C, which is equal in magnitude to the unit kelvin, is used; in this case, ``degree Celsius'' is a special name used in place of ``kelvin.'' An interval or difference of Celsius temperature can, however, be expressed in the unit kelvin as well as in the unit degree Celsius. (Note that the thermodynamic temperature T_0 is exactly 0.01 K below the thermodynamic temperature of the triple point of water.)

INTERNATIONAL SYSTEM OF UNITS (SI) (continued)

2.2 Use of SI derived units with special names and symbols

Examples of SI derived units that can be expressed with the aid of SI derived units having special names and symbols (including the radian and steradian) are given in Table 4.

Table 4. Examples of SI derived units expressed with the aid of SI derived units having special names and symbols

Derived quantity	SI derived unit: Name	Symbol	Expression in terms of SI base units
angular velocity	radian per second	rad/s	$m \cdot m^{-1} \cdot s^{-1} = s^{-1}$
angular acceleration	radian per second squared	rad/s^2	$m \cdot m^{-1} \cdot s^{-2} = s^{-2}$
dynamic viscosity	pascal second	Pa · s	$m^{-1} \cdot kg \cdot s^{-1}$
moment of force	newton meter	N · m	$m^2 \cdot kg \cdot s^{-2}$
surface tension	newton per meter	N/m	$kg \cdot s^{-2}$
heat flux density, irradiance	watt per square meter	W/m^2	$kg \cdot s^{-3}$
radiant intensity	watt per steradian	W/sr	$m^2 \cdot kg \cdot s^{-3} \cdot sr^{-1}$ (a)
radiance	watt per square meter steradian	$W/(m^2 \cdot sr)$	$kg \cdot s^{-3} \cdot sr^{-1}$ (a)
heat capacity, entropy	joule per kelvin	J/K	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$
specific heat capacity, specific entropy	joule per kilogram kelvin	J/(kg · K)	$m^2 \cdot s^{-2} \cdot K^{-1}$
specific energy	joule per kilogram	J/kg	$m^2 \cdot s^{-2}$
thermal conductivity	watt per meter kelvin	W/(m · K)	$m \cdot kg \cdot s^{-3} \cdot K^{-1}$
energy density	joule per cubic meter	J/m^3	$m^{-1} \cdot kg \cdot s^{-2}$
electric field strength	volt per meter	V/m	$m \cdot kg \cdot s^{-3} \cdot A^{-1}$
electric charge density	coulomb per cubic meter	C/m^3	$m^{-3} \cdot s \cdot A$
electric flux density	coulomb per square meter	C/m^2	$m^{-2} \cdot s \cdot A$
permittivity	farad per meter	F/m	$m^{-3} \cdot kg^{-1} \cdot s^4 \cdot A^2$
permeability	henry per meter	H/m	$m \cdot kg \cdot s^{-2} \cdot A^{-2}$
molar energy	joule per mole	J/mol	$m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1}$
molar entropy, molar heat capacity	joule per mole kelvin	J/(mol · K)	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}$
exposure (x and γ rays)	coulomb per kilogram	C/kg	$kg^{-1} \cdot s \cdot A$
absorbed dose rate	gray per second	Gy/s	$m^2 \cdot s^{-3}$

(a) The steradian (sr) is not an SI base unit. However, in radiometry the steradian (sr) is maintained in expressions for units (see Sec. 3).

The advantages of using the special names and symbols of SI derived units are apparent in Table 4. Consider, for example, the quantity molar entropy: the unit J/(mol · K) is obviously more easily understood than its SI base-unit equivalent, $m^2 \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}$. Nevertheless, it should always be recognized that the special names and symbols exist for convenience; either the form in which special names or symbols are used for certain combinations of units or the form in which they are not used is correct. For example, because of the descriptive value implicit in the compound-unit form, communication is sometimes facilitated if magnetic flux (see Table 3a) is expressed in terms of the volt second (V · s) instead of the weber (Wb).

Tables 3a, 3b, and 4 also show that the values of several different quantities are expressed in the same SI unit. For example, the joule per kelvin (J/K) is the SI unit for heat capacity as well as for entropy. Thus the name of the unit is not sufficient to define the quantity measured.

A derived unit can often be expressed in several different ways through the use of base units and derived units with special names. In practice, with certain quantities, preference is given to using certain units with special names, or combinations of units, to facilitate the distinction between quantities whose values have identical expressions in terms of SI base units. For example, the SI unit of frequency is specified as the hertz (Hz) rather than the reciprocal second (s^{-1}), and the SI unit of moment of force is specified as the newton meter (N · m) rather than the joule (J).

INTERNATIONAL SYSTEM OF UNITS (SI) (continued)

Similarly, in the field of ionizing radiation, the SI unit of activity is designated as the becquerel (Bq) rather than the reciprocal second (s^{-1}), and the SI units of absorbed dose and dose equivalent are designated as the gray (Gy) and the sievert (Sv), respectively, rather than the joule per kilogram (J/kg).

3 SI supplementary units

As previously stated, there are two units in this class: the radian, symbol rad, the SI unit of the quantity plane angle; and the steradian, symbol sr, the SI unit of the quantity solid angle. Definitions of these units are given in Appendix A.

The SI supplementary units are now interpreted as so-called dimensionless derived units for which the CGPM allows the freedom of using or not using them in expressions for SI derived units.[3] Thus the radian and steradian are not given in a separate table but have been included in Table 3a together with other derived units with special names and symbols (seeSec.2.1). This interpretation of the supplementary units implies that plane angle and solid angle are considered derived quantities of dimension one (so-called dimensionless quantities), each of which has the which has the unit one, symbol 1, as its coherent SI unit. However, in practice, when one expresses the values of derived quantities involving plane angle or solid angle, it often aids understanding if the special names (or symbols) ``radian'' (rad) or ``steradian'' (sr) are used in place of the number 1. For example, although values of the derived quantity angular velocity (plane angle divided by time) may be expressed in the unit s^{-1}, such values are usually expressed in the unit rad/s.

Because the radian and steradian are now viewed as so-called dimensionless derived units, the Consultative Committee for Units (CCU, *Comité Consultatif des Unités*) of the CIPM as result of a 1993 request it received from ISO/TC12, recommended to the CIPM that it request the CGPM to abolish the class of supplementary units as a separate class in the SI. The CIPM accepted the CCU recommendation, and if the abolishment is approved by the CGPM as is likely (the question will be on the agenda of the 20th CGPM, October 1995), the SI will consist of only two classes of units: base units and derived units, with the radian and steradian subsumed into the class of derived units of the SI. (The option of using or not using them in expressions for SI derived units, as is convenient, would remain unchanged.)

4 Decimal multiples and submultiples of SI units: SI prefixes

Table 5 gives the SI prefixes that are used to form decimal multiples and submultiples of SI units. They allow very large or very small numerical values to be avoided. A prefix attaches directly to the name of a unit, and a prefix symbol attaches directly to the symbol for a unit. For example, one kilometer, symbol 1 km, is equal to one thousand meters, symbol 1000 m or 10^3 m. When prefixes are attached to SI units, the units so formed are called ``multiples and submultiples of SI units'' in order to distinguish them from the coherent system of SI units.

Note: Alternative definitions of the SI prefixes and their symbols are not permitted. For example, it is unacceptable to use kilo (k) to represent $2^{10} = 1024$, mega (M) to represent 2^{20} = 1 048 576, or giga (G) to represent 2^{30} = 1 073 741 824.

[3] This interpretation was given in 1980 by the CIPM . It was deemed necessary because Resolution 12 of the 11th CGPM, which established the SI in 1960 , did not specify the nature of the supplementary units. The interpretation is based on two principal considerations: that plane angle is generally expressed as the ratio of two lengths and solid angle as the ratio of an area and the square of a length, and are thus quantities of dimension one (so-called dimensionless quantities); and that treating the radian and steradian as SI base units – a possibility not disallowed by Resolution 12 – could compromise the internal coherence of the SI based on only seven base units. (See ISO 31-0 for a discussion of the concept of dimension.)

INTERNATIONAL SYSTEM OF UNITS (SI) (continued)

Table 5. SI prefixes

Factor	Prefix	Symbol	Factor	Prefix	Symbol
$10^{24} = (10^3)^8$	yotta	Y	10^{-1}	deci	d
$10^{21} = (10^3)^7$	zetta	Z	10^{-2}	centi	c
$10^{18} = (10^3)^6$	exa	E	$10^{-3} = (10^3)^{-1}$	milli	m
$10^{15} = (10^3)^5$	peta	P	$10^{-6} = (10^3)^{-2}$	micro	μ
$10^{12} = (10^3)^4$	tera	T	$10^{-9} = (10^3)^{-3}$	nano	n
$10^{9} = (10^3)^3$	giga	G	$10^{-12} = (10^3)^{-4}$	pico	p
$10^{6} = (10^3)^2$	mega	M	$10^{-15} = (10^3)^{-5}$	femto	f
$10^{3} = (10^3)^1$	kilo	k	$10^{-18} = (10^3)^{-6}$	atto	a
10^{2}	hecto	h	$10^{-21} = (10^3)^{-7}$	zepto	z
10^{1}	deka	da	$10^{-24} = (10^3)^{-8}$	yocto	y

5 Units Outside the SI

Units that are outside the SI may be divided into three categories:

– those units that are accepted for use with the SI;

– those units that are temporarily accepted for use with the SI; and

– those units that are not accepted for use with the SI and thus must strictly be avoided.

5.1 Units accepted for use with the SI

The following sections discuss in detail the units that are acceptable for use with the SI.

5.1.1 Hour, degree, liter, and the like

Certain units that are not part of the SI are essential and used so widely that they are accepted by the CIPM for use with the SI. These units are given in Table 6. The combination of units of this table with SI units to form derived units should be restricted to special cases in order not to lose the advantages of the coherence of SI units.

Additionally, it is recognized that it may be necessary on occasion to use time-related units other than those given in Table 6; in particular, circumstances may require that intervals of time be expressed in weeks, months, or years. In such cases, if a standardized symbol for the unit is not available, the name of the unit should be written out in full.

Table 6. Units accepted for use with the SI

Name		Symbol	Value in SI units
minute	time	min	1 min = 60 s
hour	time	h	1 h = 60 min = 3600 s
day	time	d	1 d = 24 h = 86 400 s
degree	plane angle	°	1° = (π/180) rad
minute	plane angle	'	1' = (1/60)°=(π/10 800) rad
second	plane angle	"	1" = (1/60)' =(π/648 000) rad
liter		l, L[(b)]	1 L = 1 dm^3 = 10^{-3} m^3
metric ton[(c)]		t	1 t = 10^3 kg

[(b)] The alternative symbol for the liter, L, was adopted by the CGPM in order to avoid the risk of confusion between the letter l and the number 1 . Thus, although both l and L are internationally accepted symbols for the liter, to avoid this risk the symbol to be used in the United States is L . The script letter ℓ is not an approved symbol for the liter.

[(c)] This is the name to be used for this unit in the United States; it is also used in some other English-speaking countries. However, ``tonne'' is used in many countries.

INTERNATIONAL SYSTEM OF UNITS (SI) (continued)

5.1.2 Neper, bel, shannon, and the like

There are a few highly specialized units not listed in Table 6 that are given by the International Organization for Standardization (ISO) or the International Electrotechnical Commission (IEC) and which are also acceptable for use with the SI. They include the neper (Np), bel (B), octave, phon, and sone, and units used in information technology, including the baud (Bd), bit (bit), erlang (E), hartley (Hart), and shannon (Sh).[4] It is the position of NIST that the only such additional units that may be used with the SI are those given in either the International Standards on quantities and units of ISO or of IEC .

5.1.3 Electronvolt and unified atomic mass unit

The CIPM also finds it necessary to accept for use with the SI the two units given in Table 7. These units are used in specialized fields; their values in SI units must be obtained from experiment and, therefore, are not known exactly.

Note: In some fields the unified atomic mass unit is called the dalton, symbol Da; however, this name and symbol are not accepted by the CGPM, CIPM, ISO, or IEC for use with the SI. Similarly, AMU is not an acceptable unit symbol for the unified atomic mass unit. The only allowed name is ``unified atomic mass unit'' and the only allowed symbol is u.

Table 7. Units accepted for use with the SI whose values in SI units are obtained experimentally

Name	Symbol	Definition
electronvolt	eV	(*a*)
unified atomic mass unit	u	(*b*)

(*a*) The electronvolt is the kinetic energy acquired by an electron in passing through a potential difference of 1 V in vacuum; 1 eV = 1.602 177 33$\times 10^{-19}$ J with a combined standard uncertainty of 0.000 000 49$\times 10^{-19}$ J .

(*b*) The unified atomic mass unit is equal to 1/12 of the mass of an atom of the nuclide ^{12}C; 1 u = 1.660 540 2$\times 10^{-27}$ kg with a combined standard uncertainty of 0.000 001 0$\times 10^{-27}$ kg .

5.1.4 Natural and atomic units

In some cases, particularly in basic science, the values of quantities are expressed in terms of fundamental constants of nature or so-called natural units.The use of these units with the SI is permissible when it is necessary for the most effective communication of information. In such cases, the specific natural units that are used must be identified. This requirement applies even to the system of units customarily called ``atomicunits'' used in theoretical atomic physics and chemistry, inasmuch as there are several different systems that have the appellation ``atomic units." Examples of physical quantities used as natural units are given in Table 8.

NIST also takes the position that while theoretical results intended primarily for other theorists may be left in natural units, if they are also intended for experimentalists, they must also be given in acceptable units.

[4] The symbol in parentheses following the name of the unit is its internationally accepted unit symbol, but the octave, phon, and sone have no such unit symbols. For additional information on the neper and bel, see Sec. 0.5 of ISO 31-2.
The question of the byte (B) is under international consideration.

INTERNATIONAL SYSTEM OF UNITS (SI) (continued)

Table 8. Examples of physical quantities sometimes used as natural units

Kind of quantity	Physical quantity used as a unit	Symbol
action	Planck constant divided by 2π	$\hbar$
electric charge	elementary charge	e
energy	Hartree energy	E_h
length	Bohr radius	a_0
length	Compton wavelength (electron)	λ_C
magnetic flux	magnetic flux quantum	Φ_0
magnetic moment	Bohr magneton	μ_B
magnetic moment	nuclear magneton	μ_N
mass	electron rest mass	m_e
mass	proton rest mass	m_p
speed	speed of electromagnetic waves in vacuum	c

5.2 Units temporarily accepted for use with the SI

Because of existing practice in certain fields or countries, in 1978 the CIPM considered that it was permissible for the units given in Table 9 to continue to be used with the SI until the CIPM considers that their use is no longer necessary. However, these units must not be introduced where they are not presently used. Further, NIST strongly discourages the continued use of these units except for the nautical mile, knot, are, and hectare; and except for the curie, roentgen, rad, and rem until the year 2000 (the cessation date suggested by the Committee for Ineragency Radiation Research and Policy Coordination or CIRRPC, a United States Government interagency group).[5]

Table 9. Units temporarily accepted for use with the SI[(a)]

Name	Symbol	Value in SI units
nautical mile		1 nautical mile = 1852 m
knot		1 nautical mile per hour = (1852/3600) m/s
ångström	Å	1 Å = 0.1 nm = 10^{-10}m
are[(b)]	a	1 a = 1 dam^2 = 10^2 m^2
hectare[(b)]	ha	1 ha = 1 hm^2 = 10^4 m^2
barn	b	1 b = 100 fm^2 = 10^{-28} m^2
bar	bar	1 bar=0.1 MPa=100 kPa=1000 hPa=10^5 Pa
gal	Gal	1 Gal = 1 cm/s^2 = 10^{-2} m/s^2
curie	Ci	1 Ci = 3.7×10^{10} Bq
roentgen	R	1 R = 2.58×10^{-4} C/kg
rad	rad[(c)]	1 rad = 1 cGy = 10^{-2} Gy
rem	rem	1 rem = 1 cSv = 10^{-2} Sv

(a) See Sec. 5.2 regarding the continued use of these units.
(b) This unit and its symbol are used to express agrarian areas.
(c) When there is risk of confusion with the symbol for the radian, rd may be used as the symbol for rad.

[5] In 1993 the CCU (see Sec. 3) was requested by ISO/TC 12 to consider asking the CIPM to deprecate the use of the units of Table 9 except for the nautical mile and knot, and possibly the are and hectare. The CCU discussed this request at its February 1995 meeting.

INTERNATIONAL SYSTEM OF UNITS (SI) (continued)

Appendix A. Definitions of the SI Base Units and the Radian and Steradian

A.1 Introduction

The following definitions of the SI base units are taken from NIST SP 330; the definitions of the SI supplementary units, the radian and steradian, which are now interpreted as SI derived units (see Sec. 3), are those generally accepted and are the same as those given in ANSI/IEEE Std 268-1992. SI derived units are uniquely defined only in terms of SI base units; for example, $1\ \mathrm{V} = 1\ \mathrm{m}^2 \cdot \mathrm{kg} \cdot \mathrm{s}^{-3} \cdot \mathrm{A}^{-1}$.

A.2 Meter (17th CGPM, 1983)

The meter is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 *of a second.*

A.3 Kilogram (3d CGPM, 1901)

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram.

A.4 Second (13th CGPM, 1967)

The second is the duration of 9 192 631 770 *periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-* 133 *atom.*

A.5 Ampere (9th CGPM, 1948)

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed 1 *meter apart in vacuum, would produce between these conductors a force equal to* 2×10^{-7} *newton per meter of length.*

A.6 Kelvin (13th CGPM, 1967)

The kelvin, unit of thermodynamic temperature, is the fraction 1/273.16 *of the thermodynamic temperature of the triple point of water.*

A.7 Mole (14th CGPM, 1971)

1. *The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in* 0.012 *kilogram of carbon* 12.

2. *When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.*

In the definition of the mole, it is understood that unbound atoms of carbon 12, at rest and in their ground state, are referred to.

Note that this definition specifies at the same time the nature of the quantity whose unit is the mole.

A.8 Candela (16th CGPM, 1979)

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} *hertz and that has a radiant intensity in that direction of (* 1/683*) watt per steradian.*

A.9 Radian

The radian is the plane angle between two radii of a circle that cut off on the circumference an arc equal in length to the radius.

A.10 Steradian

The steradian is the solid angle that, having its vertex in the center of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

From *CRC Handbook of Chemistry and Physics,* 83rd ed., Lide, D., Ed., CRC Press, Boca Raton, FL, 2002, pp. **1**-25 to **1**-32.

CONVERSION FACTORS

The following table gives conversion factors from various units of measure to SI units. It is reproduced from NIST Special Publication 811, *Guide for the Use of the International System of Units (SI)*. The table gives the factor by which a quantity expressed in a non-SI unit should be multiplied in order to calculate its value in the SI. The SI values are expressed in terms of the base, supplementary, and derived units of SI in order to provide a coherent presentation of the conversion factors and facilitate computations (see the table "International System of Units" in this Section). If desired, powers of ten can be avoided by using SI Prefixes and shifting the decimal point if necessary.

Conversion from a non-SI unit to a different non-SI unit may be carried out by using this table in two stages, e.g.,

$$1\ \text{cal}_{\text{th}} = 4.184\ \text{J}$$
$$1\ \text{Btu}_{\text{IT}} = 1.055056\ \text{E+03 J}$$

Thus,

$$1\ \text{Btu}_{\text{IT}} = (1.055056\ \text{E+03} \div 4.184)\ \text{cal}_{\text{th}} = 252.164\ \text{cal}_{\text{th}}$$

Conversion factors are presented for ready adaptation to computer readout and electronic data transmission. The factors are written as a number equal to or greater than one and less than ten with six or fewer decimal places. This number is followed by the letter E (for exponent), a plus or a minus sign, and two digits which indicate the power of 10 by which the number must be multiplied to obtain the correct value. For example:

$$3.523\,907\ \text{E-02 is } 3.523\,907 \times 10^{-2}$$

or

$$0.035\,239\,07$$

Similarly:

$$3.386\,389\ \text{E+03 is } 3.386\,389 \times 10^{3}$$

or

$$3\,386.389$$

A factor in boldface is exact; i.e., all subsequent digits are zero. All other conversion factors have been rounded to the figures given in accordance with accepted practice. Where less than six digits after the decimal point are shown, more precision is not warranted.

It is often desirable to round a number obtained from a conversion of units in order to retain information on the precision of the value. The following rounding rules may be followed:

(1) If the digits to be discarded begin with a digit less than 5, the digit preceding the first discarded digit is not changed.

Example: 6.974 951 5 rounded to 3 digits is 6.97

(2) If the digits to be discarded begin with a digit greater than 5, the digit preceding the first discarded digit is increased by one.

Example: 6.974 951 5 rounded to 4 digits is 6.975

(3) If the digits to be discarded begin with a 5 and at least one of the following digits is greater than 0, the digit preceding the 5 is increased by 1.

Example: 6.974 851 rounded to 5 digits is 6.974 9

(4) If the digits to be discarded begin with a 5 and all of the following digits are 0, the digit preceding the 5 is unchanged if it is even and increased by one if it is odd. (Note that this means that the final digit is always even.)

Examples: 6.974 951 5 rounded to 7 digits is 6.974 952
6.974 950 5 rounded to 7 digits is 6.974 950

REFERENCE

Taylor, B. N., *Guide for the Use of the International System of Units (SI)*, NIST Special Publication 811, 1995 Edition, Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402, 1995.

Factors in **boldface** are exact

To convert from	to	Multiply by	
abampere	ampere (A)	**1.0**	**E+01**
abcoulomb	coulomb (C)	**1.0**	**E+01**
abfarad	farad (F)	**1.0**	**E+09**
abhenry	henry (H)	**1.0**	**E−09**
abmho	siemens (S)	**1.0**	**E+09**
abohm	ohm (Ω)	**1.0**	**E−09**
abvolt	volt (V)	**1.0**	**E−08**
acceleration of free fall, standard (g_n)	meter per second squared (m/s^2)	**9.806 65**	**E+00**
acre (based on U.S. survey foot)[9]	square meter (m^2)	4.046 873	E+03
acre foot (based on U.S. survey foot)[9]	cubic meter (m^3)	1.233 489	E+03
ampere hour (A · h)	coulomb (C)	**3.6**	**E+03**
ångström (Å)	meter (m)	**1.0**	**E−10**
ångström (Å)	nanometer (nm)	**1.0**	**E−01**
are (a)	square meter (m^2)	**1.0**	**E+02**
astronomical unit (AU)	meter (m)	1.495 979	E+11
atmosphere, standard (atm)	pascal (Pa)	**1.013 25**	**E+05**
atmosphere, standard (atm)	kilopascal (kPa)	**1.013 25**	**E+02**
atmosphere, technical (at)[10]	pascal (Pa)	**9.806 65**	**E+04**
atmosphere, technical (at)[10]	kilopascal (kPa)	**9.806 65**	**E+01**
bar (bar)	pascal (Pa)	**1.0**	**E+05**
bar (bar)	kilopascal (kPa)	**1.0**	**E+02**
barn (b)	square meter (m^2)	**1.0**	**E−28**
barrel [for petroleum, 42 gallons (U.S.)](bbl)	cubic meter (m^3)	1.589 873	E−01
barrel [for petroleum, 42 gallons (U.S.)](bbl)	liter (L)	1.589 873	E+02
biot (Bi)	ampere (A)	**1.0**	**E+01**
British thermal unit$_{IT}$ (Btu_{IT})[11]	joule (J)	1.055 056	E+03
British thermal unit$_{th}$ (Btu_{th})[11]	joule (J)	1.054 350	E+03
British thermal unit (mean) (Btu)	joule (J)	1.055 87	E+03
British thermal unit (39 °F) (Btu)	joule (J)	1.059 67	E+03
British thermal unit (59 °F) (Btu)	joule (J)	1.054 80	E+03
British thermal unit (60 °F) (Btu)	joule (J)	1.054 68	E+03
British thermal unit$_{IT}$ foot per hour square foot degree Fahrenheit [$Btu_{IT} \cdot ft/(h \cdot ft^2 \cdot °F)$]	watt per meter kelvin [$W/(m \cdot K)$]	1.730 735	E+00
British thermal unit$_{th}$ foot per hour square foot degree Fahrenheit [$Btu_{th} \cdot ft/(h \cdot ft^2 \cdot °F)$]	watt per meter kelvin [$W/(m \cdot K)$]	1.729 577	E+00
British thermal unit$_{IT}$ inch per hour square foot degree Fahrenheit [$Btu_{IT} \cdot in/(h \cdot ft^2 \cdot °F)$]	watt per meter kelvin [$W/(m \cdot K)$]	1.442 279	E−01
British thermal unit$_{th}$ inch per hour square foot degree Fahrenheit [$Btu_{th} \cdot in/(h \cdot ft^2 \cdot °F)$]	watt per meter kelvin [$W/(m \cdot K)$]	1.441 314	E−01
British thermal unit$_{IT}$ inch per second square foot degree Fahrenheit [$Btu_{IT} \cdot in/(s \cdot ft^2 \cdot °F)$]	watt per meter kelvin [$W/(m \cdot K)$]	5.192 204	E+02

[9] The U.S. survey foot equals (1200/3937) m. 1 international foot = 0.999998 survey foot.

[10] One technical atmosphere equals one kilogram-force per square centimeter (1 at = 1 kgf/cm^2).

[11] The Fifth International Conference on the Properties of Steam (London, July 1956) defined the International Table calorie as 4.1868 J. Therefore the exact conversion factor for the International Table Btu is 1.055 055 852 62 kJ. Note that the notation for International Table used in this listing is subscript ''IT''. Similarily, the notation for thermochemical is subscript ''th.'' Further, the thermochemical Btu, Btu_{th}, is based on the thermochemical calorie, cal_{th}, where cal_{th} = 4.184 J exactly.

To convert from	to	Multiply by	
British thermal unit$_{th}$ inch per second square foot degree Fahrenheit [$Btu_{th} \cdot in/(s \cdot ft^2 \cdot °F)$]	watt per meter kelvin [$W/(m \cdot K)$]	5.188 732	E+02
British thermal unit$_{IT}$ per cubic foot (Btu_{IT}/ft^3)	joule per cubic meter (J/m^3)	3.725 895	E+04
British thermal unit$_{th}$ per cubic foot (Btu_{th}/ft^3)	joule per cubic meter (J/m^3)	3.723 403	E+04
British thermal unit$_{IT}$ per degree Fahrenheit ($Btu_{IT}/°F$)	joule per kelvin (J/k)	1.899 101	E+03
British thermal unit$_{th}$ per degree Fahrenheit ($Btu_{th}/°F$)	joule per kelvin (J/k)	1.897 830	E+03
British thermal unit$_{IT}$ per degree Rankine ($Btu_{IT}/°R$)	joule per kelvin (J/k)	1.899 101	E+03
British thermal unit$_{th}$ per degree Rankine ($Btu_{th}/°R$)	joule per kelvin (J/k)	1.897 830	E+03
British thermal unit$_{IT}$ per hour (Btu_{IT}/h)	watt (W)	2.930 711	E−01
British thermal unit$_{th}$ per hour (Btu_{th}/h)	watt (W)	2.928 751	E−01
British thermal unit$_{IT}$ per hour square foot degree Fahrenheit [$Btu_{IT}/(h \cdot ft^2 \cdot °F)$]	watt per square meter kelvin [$W/(m^2 \cdot K)$]	5.678 263	E+00
British thermal unit$_{th}$ per hour square foot degree Fahrenheit [$Btu_{th}/(h \cdot ft^2 \cdot °F)$]	watt per square meter kelvin [$W/(m^2 \cdot K)$]	5.674 466	E+00
British thermal unit$_{th}$ per minute (Btu_{th}/min)	watt (W)	1.757 250	E+01
British thermal unit$_{IT}$ per pound (Btu_{IT}/lb)	joule per kilogram (J/kg)	**2.326**	**E+03**
British thermal unit$_{th}$ per pound (Btu_{th}/lb)	joule per kilogram (J/kg)	2.324 444	E+03
British thermal unit$_{IT}$ per pound degree Fahrenheit [$Btu_{IT}/(lb \cdot °F)$]	joule per kilogram kelvin (J/(kg · K)]	**4.1868**	**E+03**
British thermal unit$_{th}$ per pound degree Fahrenheit [$Btu_{th}/(lb \cdot °F)$]	joule per kilogram kelvin [$J/(kg \cdot K)$]	**4.184**	**E+03**
British thermal unit$_{IT}$ per pound degree Rankine [$Btu_{IT}/(lb \cdot °R)$]	joule per kilogram kelvin [$J/(kg \cdot K)$]	**4.1868**	**E+03**
British thermal unit$_{th}$ per pound degree Rankine [$Btu_{th}/(lb \cdot °R)$]	joule per kilogram kelvin [$J/(kg \cdot K)$]	**4.184**	**E+03**
British thermal unit$_{IT}$ per second (Btu_{IT}/s)	watt (W)	1.055 056	E+03
British thermal unit$_{th}$ per second (Btu_{th}/s)	watt (W)	1.054 350	E+03
British thermal unit$_{IT}$ per second square foot degree Fahrenheit [$Btu_{IT}/(s \cdot ft^2 \cdot °F)$]	watt per square meter kelvin [$W/(m^2 \cdot K)$]	2.044 175	E+04
British thermal unit$_{th}$ per second square foot degree Fahrenheit [$Btu_{th}/(s \cdot ft^2 \cdot °F)$]	watt per square meter kelvin [$W/(m^2 \cdot K)$]	2.042 808	E+04
British thermal unit$_{IT}$ per square foot (Btu_{IT}/ft^2)	joule per square meter (J/m^2)	1.135 653	E+04
British thermal unit$_{th}$ per square foot (Btu_{th}/ft^2)	joule per square meter (J/m^2)	1.134 893	E+04
British thermal unit$_{IT}$ per square foot hour [($Btu_{IT}/(ft^2 \cdot h)$]	watt per square meter (W/m^2)	3.154 591	E+00
British thermal unit$_{th}$ per square foot hour [$Btu_{th}/(ft^2 \cdot h)$]	watt per square meter (W/m^2)	3.152 481	E+00
British thermal unit$_{th}$ per square foot minute [$Btu_{th}/(ft^2 \cdot min)$]	watt per square meter (W/m^2)	1.891 489	E+02
British thermal unit$_{IT}$ per square foot second [($Btu_{IT}/(ft^2 \cdot s)$]	watt per square meter (W/m^2)	1.135 653	E+04
British thermal unit$_{th}$ per square foot second [$Btu_{th}/(ft^2 \cdot s)$]	watt per square meter (W/m^2)	1.134 893	E+04
British thermal unit$_{th}$ per square inch second [$Btu_{th}/(in^2 \cdot s)$]	watt per square meter (W/m^2)	1.634 246	E+06

To convert from	to	Multiply by	
bushel (U.S.) (bu)	cubic meter (m^3)	3.523 907	E−02
bushel (U.S.) (bu)	liter (L)	3.523 907	E+01
calorie_{IT} (cal_{IT})[11]	joule (J)	**4.1868**	**E+00**
calorie_{th} (cal_{th})[11]	joule (J)	**4.184**	**E+00**
calorie (cal) (mean)	joule (J)	4.190 02	E+00
calorie (15 °C) (cal_{15})	joule (J)	4.185 80	E+00
calorie (20 °C) (cal_{20})	joule (J)	4.181 90	E+00
calorie_{IT}, kilogram (nutrition)[12]	joule (J)	**4.1868**	**E+03**
calorie_{th}, kilogram (nutrition)[12]	joule (J)	**4.184**	**E+03**
calorie (mean), kilogram (nutrition)[12]	joule (J)	4.190 02	E+03
calorie_{th} per centimeter second degree Celsius [cal_{th}/(cm · s · °C)]	watt per meter kelvin [W/(m · K)]	**4.184**	**E+02**
calorie_{IT} per gram (cal_{IT}/g)	joule per kilogram (J/kg)	**4.1868**	**E+03**
calorie_{th} per gram (cal_{th}/g)	joule per kilogram (J/kg)	**4.184**	**E+03**
calorie_{IT} per gram degree Celsius [cal_{IT}/(g · °C)]	joule per kilogram kelvin [J/(kg · K)]	**4.1868**	**E+03**
calorie_{th} per gram degree Celsius [cal_{th}/(g · °C)]	joule per kilogram kelvin [J/(kg · K)]	**4.184**	**E+03**
calorie_{IT} per gram kelvin [cal_{IT}/(g · K)]	joule per kilogram kelvin [J/(kg · K)]	**4.1868**	**E+03**
calorie_{th} per gram kelvin [cal_{th}/(g · K)]	joule per kilogram kelvin [J/(kg · K)]	**4.184**	**E+03**
calorie_{th} per minute (cal_{th}/min)	watt (W)	6.973 333	E−02
calorie_{th} per second (cal_{th}/s)	watt (W)	**4.184**	**E+00**
calorie_{th} per square centimeter ($\text{cal}_{th}/\text{cm}^2$)	joule per square meter (J/m^2)	**4.184**	**E+04**
calorie_{th} per square centimeter minute [$\text{cal}_{th}/(\text{cm}^2 \cdot \text{min})$]	watt per square meter (W/m^2)	6.973 333	E+02
calorie_{th} per square centimeter second [$\text{cal}_{th}/(\text{cm}^2 \cdot \text{s})$]	watt per square meter (W/m^2)	**4.184**	**E+04**
candela per square inch (cd/in^2)	candela per square meter (cd/m^2)	1.550 003	E+03
carat, metric	kilogram (kg)	**2.0**	**E−04**
carat, metric	gram (g)	**2.0**	**E−01**
centimeter of mercury (0 °C)[13]	pascal (Pa)	1.333 22	E+03
centimeter of mercury (0 °C)[13]	kilopascal (kPa)	1.333 22	E+00
centimeter of mercury, conventional (cmHg)[13]	pascal (Pa)	1.333 224	E+03
centimeter of mercury, conventional (cmHg)[13]	kilopascal (kPa)	1.333 224	E+00
centimeter of water (4 °C)[13]	pascal (Pa)	9.806 38	E+01
centimeter of water, conventional (cmH_2O)[13]	pascal (Pa)	**9.806 65**	**E+01**
centipoise (cP)	pascal second (Pa · s)	**1.0**	**E−03**
centistokes (cSt)	meter squared per second (m^2/s)	**1.0**	**E−06**
chain (based on U.S. survey foot) (ch)[9]	meter (m)	2.011 684	E+01
circular mil	square meter (m^2)	5.067 075	E−10
circular mil	square millimeter (mm^2)	5.067 075	E−04
clo	square meter kelvin per watt ($m^2 \cdot K/W$)	1.55	E−01
cord (128 ft^3)	cubic meter (m^3)	3.624 556	E+00
cubic foot (ft^3)	cubic meter (m^3)	2.831 685	E−02
cubic foot per minute (ft^3/min)	cubic meter per second (m^3/s)	4.719 474	E−04
cubic foot per minute (ft^3/min)	liter per second (L/s)	4.719 474	E−01
cubic foot per second (ft^3/s)	cubic meter per second (m^3/s)	2.831 685	E−02

[12] The kilogram calorie or ''large calorie'' is an obsolete term used for the kilocalorie, which is the calorie used to express the energy content of foods. However, in practice, the prefix ''kilo'' is usually omitted.

[13] Conversion factors for mercury manometer pressure units are calculated using the standard value for the acceleration of gravity and the density of mercury at the stated temperature. Additional digits are not justified because the definitions of the units do not take into account the compressibility of mercury or the change in density caused by the revised practical temperature scale, ITS-90. Similar comments also apply to water manometer pressure units. Conversion factors for conventional mercury and water manometer pressure units are based on ISO 31-3.

To convert from	to	Multiply by	
cubic inch (in^3)[14]	cubic meter (m^3)	1.638 706	E−05
cubic inch per minute (in^3/min)	cubic meter per second (m^3/s)	2.731 177	E−07
cubic mile (mi^3)	cubic meter (m^3)	4.168 182	E+09
cubic yard (yd^3)	cubic meter (m^3)	7.645 549	E−01
cubic yard per minute (yd^3/min)	cubic meter per second (m^3/s)	1.274 258	E−02
cup (U.S.)	cubic meter (m^3)	2.365 882	E−04
cup (U.S.)	liter (L)	2.365 882	E−01
cup (U.S.)	milliliter (mL)	2.365 882	E+02
curie (Ci)	becquerel (Bq)	**3.7**	**E+10**
darcy[15]	meter squared (m^2)	9.869 233	E−13
day (d)	second (s)	**8.64**	**E+04**
day (sidereal)	second (s)	8.616 409	E+04
debye (D)	coulomb meter (C · m)	3.335 641	E−30
degree (angle) (°)	radian (rad)	1.745 329	E−02
degree Celsius (temperature) (°C)	kelvin (K)	$T/\text{K} = t/°\text{C}$+**273.15**	
degree Celsius (temperature interval) (°C)	kelvin (K)	**1.0**	**E+00**
degree centigrade (temperature)[16]	degree Celsius (°C)	$t/°\text{C} \approx t/\text{deg. cent.}$	
degree centigrade (temperature interval)[16]	degree Celsius (°C)	1.0	E+00
degree Fahrenheit (temperature) (°F)	degree Celsius (°C)	$t/°\text{C} = (t/°\text{F} - \mathbf{32})/\mathbf{1.8}$	
degree Fahrenheit (temperature) (°F)	kelvin (K)	$T/\text{K} = (t/°\text{F} + \mathbf{459.67})/\mathbf{1.8}$	
degree Fahrenheit (temperature interval) (°F)	degree Celsius (°C)	5.555 556	E−01
degree Fahrenheit (temperature interval) (°F)	kelvin (K)	5.555 556	E−01
degree Fahrenheit hour per British thermal unit$_{IT}$ (°F · h/Btu_{IT})	kelvin per watt (K/W)	1.895 634	E+00
degree Fahrenheit hour per British thermal unit$_{th}$ (°F · h/Btu_{th})	kelvin per watt (K/W)	1.896 903	E+00
degree Fahrenheit hour square foot per British thermal unit$_{IT}$ (°F · h · ft^2/Btu_{IT})	square meter kelvin per watt (m^2 · K/W)	1.761 102	E−01
degree Fahrenheit hour square foot per British thermal unit$_{th}$ (°F · h · ft^2/Btu_{th})	square meter kelvin per watt (m^2 · K/W)	1.762 280	E−01
degree Fahrenheit hour square foot per British thermal unit$_{IT}$ inch [°F · h · $ft^2/(Btu_{IT}$ · in)]	meter kelvin per watt (m · K/W)	6.933 472	E+00
degree Fahrenheit hour square foot per British thermal unit$_{th}$ inch [°F · h · $ft^2/(Btu_{th}$ · in)]	meter kelvin per watt (m · K/W)	6.938 112	E+00
degree Fahrenheit second per British thermal unit$_{IT}$ (°F · s/Btu_{IT})	kelvin per watt (K/W)	5.265 651	E−04
degree Fahrenheit second per British thermal unit$_{th}$ (°F · s/Btu_{th})	kelvin per watt (K/W)	5.269 175	E−04
degree Rankine (°R)	kelvin (K)	$T/\text{K} = (T/°\text{R})/\mathbf{1.8}$	
degree Rankine (temperature interval) (°R)	kelvin (K)	5.555 556	E−01
denier	kilogram per meter (kg/m)	1.111 111	E−07
denier	gram per meter (g/m)	1.111 111	E−04
dyne (dyn)	newton (N)	**1.0**	**E−05**
dyne centimeter (dyn · cm)	newton meter (N · m)	**1.0**	**E−07**
dyne per square centimeter (dyn/cm^2)	pascal (Pa)	**1.0**	**E−01**
electronvolt (eV)	joule (J)	1.602 177	E−19
EMU of capacitance (abfarad)	farad (F)	**1.0**	**E+09**
EMU of current (abampere)	ampere (A)	**1.0**	**E+01**
EMU of electric potential (abvolt)	volt (V)	**1.0**	**E−08**
EMU of inductance (abhenry)	henry (H)	**1.0**	**E−09**

[14] The exact conversion factor is 1.638 706 4 E−05.
[15] The darcy is a unit for expressing the permeability of porous solids, not area.
[16] The centigrade temperature scale is obsolete; the degree centigrade is only approximately equal to the degree Celsius.

To convert from	to	Multiply by	
EMU of resistance (abohm)	ohm (Ω)	**1.0**	**E−09**
erg (erg)	joule (J)	**1.0**	**E−07**
erg per second (erg/s)	watt (W)	**1.0**	**E−07**
erg per square centimeter second |1obrkt&1ru|/(cm^2 · s)]	watt per square meter (W/m^2)	**1.0**	**E−03**
ESU of capacitance (statfarad)	farad (F)	1.112 650	E−12
ESU of current (statampere)	ampere (A)	3.335 641	E−10
ESU of electric potential (statvolt)	volt (V)	2.997 925	E+02
ESU of inductance (stathenry)	henry (H)	8.987 552	E+11
ESU of resistance (statohm)	ohm (Ω)	8.987 552	E+11
faraday (based on carbon 12)	coulomb (C)	9.648 531	E+04
fathom (based on U.S. survey foot)[9]	meter (m)	1.828 804	E+00
fermi	meter (m)	**1.0**	**E−15**
fermi	femtometer (fm)	**1.0**	**E+00**
fluid ounce (U.S.) (fl oz)	cubic meter (m^3)	2.957 353	E−05
fluid ounce (U.S.) (fl oz)	milliliter (mL)	2.957 353	E+01
foot (ft)	meter (m)	**3.048**	**E−01**
foot (U.S. survey) (ft)[9]	meter (m)	3.048 006	E−01
footcandle	lux (lx)	1.076 391	E+01
footlambert	candela per square meter (cd/m^2)	3.426 259	E+00
foot of mercury, conventional (ftHg)[13]	pascal (Pa)	4.063 666	E+04
foot of mercury, conventional (ftHg)[13]	kilopascal (kPa)	4.063 666	E+01
foot of water (39.2 °F)[13]	pascal (Pa)	2.988 98	E+03
foot of water (39.2 °F)[13]	kilopascal (kPa)	2.988 98	E+00
foot of water, conventional (ftH$_2$O)[13]	pascal (Pa)	2.989 067	E+03
foot of water, conventional (ftH$_2$O)[13]	kilopascal (kPa)	2.989 067	E+00
foot per hour (ft/h)	meter per second (m/s)	8.466 667	E−05
foot per minute (ft/min)	meter per second (m/s)	**5.08**	**E−03**
foot per second (ft/s)	meter per second (m/s)	**3.048**	**E−01**
foot per second squared (ft/s^2)	meter per second squared (m/s^2)	**3.048**	**E−01**
foot poundal	joule (J)	4.214 011	E−02
foot pound-force (ft · lbf)	joule (J)	1.355 818	E+00
foot pound-force per hour (ft · lbf/h)	watt (W)	3.766 161	E−04
foot pound-force per minute (ft · lbf/min)	watt (W)	2.259 697	E−02
foot pound-force per second (ft · lbf/s)	watt (W)	1.355 818	E+00
foot to the fourth power (ft^4)[17]	meter to the fourth power (m^4)	8.630 975	E−03
franklin (Fr)	coulomb (C)	3.335 641	E−10
gal (Gal)	meter per second squared (m/s^2)	**1.0**	**E−02**
gallon [Canadian and U.K. (Imperial)] (gal)	cubic meter (m^3)	**4.546 09**	**E−03**
gallon [Canadian and U.K. (Imperial)] (gal)	liter (L)	**4.546 09**	**E+00**
gallon (U.S.) (gal)	cubic meter (m^3)	3.785 412	E−03
gallon (U.S.) (gal)	liter (L)	3.785 412	E+00
gallon (U.S.) per day (gal/d)	cubic meter per second (m^3/s)	4.381 264	E−08
gallon (U.S.) per day (gal/d)	liter per second (L/s)	4.381 264	E−05
gallon (U.S.) per horsepower hour [gal/(hp · h)]	cubic meter per joule (m^3/J)	1.410 089	E−09
gallon (U.S.) per horsepower hour [gal/(hp · h)]	liter per joule (L/J)	1.410 089	E−06
gallon (U.S.) per minute (gpm)(gal/min)	cubic meter per second (m^3/s)	6.309 020	E−05
gallon (U.S.) per minute (gpm)(gal/min)	liter per second (L/s)	6.309 020	E−02

[17] This is a unit for the quantity second moment of area, which is sometimes called the ''moment of section'' or ''area moment of inertia'' of a plane section about a specified axis.

To convert from	to	Multiply by	
gamma (γ)	tesla (T)	**1.0**	**E−09**
gauss (Gs, G)	tesla (T)	**1.0**	**E−04**
gilbert (Gi)	ampere (A)	7.957 747	E−01
gill [Canadian and U.K. (Imperial)] (gi)	cubic meter (m^3)	1.420 653	E−04
gill [Canadian and U.K. (Imperial)] (gi)	liter (L)	1.420 653	E−01
gill (U.S.) (gi)	cubic meter (m^3)	1.182 941	E−04
gill (U.S.) (gi)	liter (L)	1.182 941	E−01
gon (also called grade) (gon)	radian (rad)	1.570 796	E−02
gon (also called grade) (gon)	degree (angle) (°)	**9.0**	**E−01**
grain (gr)	kilogram (kg)	**6.479 891**	**E−05**
grain (gr)	milligram (mg)	**6.479 891**	**E+01**
grain per gallon (U.S.) (gr/gal)	kilogram per cubic meter (kg/m^3)	1.711 806	E−02
grain per gallon (U.S.) (gr/gal)	milligram per liter (mg/L)	1.711 806	E+01
gram-force per square centimeter (gf/cm^2)	pascal (Pa)	**9.806 65**	**E+01**
gram per cubic centimeter (g/cm^3)	kilogram per cubic meter (kg/m^3)	**1.0**	**E+03**
hectare (ha)	square meter (m^2)	**1.0**	**E+04**
horsepower (550 ft · lbf/s) (hp)	watt (W)	7.456 999	E+02
horsepower (boiler)	watt (W)	9.809 50	E+03
horsepower (electric)	watt (W)	**7.46**	**E+02**
horsepower (metric)	watt (W)	7.354 988	E+02
horsepower (U.K.)	watt (W)	7.4570	E+02
horsepower (water)	watt (W)	7.460 43	E+02
hour (h)	second (s)	**3.6**	**E+03**
hour (sidereal)	second (s)	3.590 170	E+03
hundredweight (long, 112 lb)	kilogram (kg)	5.080 235	E+01
hundredweight (short, 100 lb)	kilogram (kg)	4.535 924	E+01
inch (in)	meter (m)	**2.54**	**E−02**
inch (in)	centimeter (cm)	**2.54**	**E+00**
inch of mercury (32 °F)[13]	pascal (Pa)	3.386 38	E+03
inch of mercury (32 °F)[13]	kilopascal (kPa)	3.386 38	E+00
inch of mercury (60 °F)[13]	pascal (Pa)	3.376 85	E+03
inch of mercury (60 °F)[13]	kilopascal (kPa)	3.376 85	E+00
inch of mercury, conventional (inHg)[13]	pascal (Pa)	3.386 389	E+03
inch of mercury, conventional (inHg)[13]	kilopascal (kPa)	3.386 389	E+00
inch of water (39.2 °F)[13]	pascal (Pa)	2.490 82	E+02
inch of water (60 °F)[13]	pascal (Pa)	2.4884	E+02
inch of water, conventional (inH_2O)[13]	pascal (Pa)	2.490 889	E+02
inch per second (in/s)	meter per second (m/s)	**2.54**	**E−02**
inch per second squared (in/s^2)	meter per second squared (m/s^2)	**2.54**	**E−02**
inch to the fourth power (in^4)[17]	meter to the fourth power (m^4)	4.162 314	E−07
kayser (K)	reciprocal meter (m^{-1})	**1.0**	**E+02**
kelvin (K)	degree Celsius (°C)	$t/°C = T/K -$ **273.15**	
kilocalorie$_{IT}$ ($kcal_{IT}$)	joule (J)	**4.1868**	**E+03**
kilocalorie$_{th}$ ($kcal_{th}$)	joule (J)	**4.184**	**E+03**
kilocalorie (mean) (kcal)	joule (J)	4.190 02	E+03
kilocalorie$_{th}$ per minute ($kcal_{th}/min$)	watt (W)	6.973 333	E+01
kilocalorie$_{th}$ per second ($kcal_{th}/s$)	watt (W)	**4.184**	**E+03**
kilogram-force (kgf)	newton (N)	**9.806 65**	**E+00**
kilogram-force meter (kgf · m)	newton meter (N · m)	**9.806 65**	**E+00**

To convert from	to	Multiply by	
kilogram-force per square centimeter (kgf/cm^2)	pascal (Pa)	**9.806 65**	**E+04**
kilogram-force per square centimeter (kgf/cm^2)	kilopascal (kPa)	**9.806 65**	**E+01**
kilogram-force per square meter (kgf/m^2)	pascal (Pa)	**9.806 65**	**E+00**
kilogram-force per square millimeter (kgf/mm^2)	pascal (Pa)	**9.806 65**	**E+06**
kilogram-force per square millimeter (kgf/mm^2)	megapascal (MPa)	**9.806 65**	**E+00**
kilogram-force second squared per meter ($kgf \cdot s^2/m$)	kilogram (kg)	**9.806 65**	**E+00**
kilometer per hour (km/h)	meter per second (m/s)	2.777 778	E−01
kilopond (kilogram-force) (kp)	newton (N)	**9.806 65**	**E+00**
kilowatt hour (kW · h)	joule (J)	**3.6**	**E+06**
kilowatt hour (kW · h)	megajoule (MJ)	**3.6**	**E+00**
kip (1 kip=1000 lbf)	newton (N)	4.448 222	E+03
kip (1 kip=1000 lbf)	kilonewton (kN)	4.448 222	E+00
kip per square inch (ksi) (kip/in^2)	pascal (Pa)	6.894 757	E+06
kip per square inch (ksi) (kip/in^2)	kilopascal (kPa)	6.894 757	E+03
knot (nautical mile per hour)	meter per second (m/s)	5.144 444	E−01
lambert[18]	candela per square meter (cd/m^2)	3.183 099	E+03
langley (cal_{th}/cm^2)	joule per square meter (J/m^2)	**4.184**	**E+04**
light year (l.y.)[19]	meter (m)	9.460 73	E+15
liter (L)[20]	cubic meter (m^3)	**1.0**	**E−03**
lumen per square foot (lm/ft^2)	lux (lx)	1.076 391	E+01
maxwell (Mx)	weber (Wb)	**1.0**	**E−08**
mho	siemens (S)	**1.0**	**E+00**
microinch	meter (m)	**2.54**	**E−08**
microinch	micrometer (μm)	**2.54**	**E−02**
micron (μ)	meter (m)	**1.0**	**E−06**
micron (μ)	micrometer (μm)	**1.0**	**E+00**
mil (0.001 in)	meter (m)	**2.54**	**E−05**
mil (0.001 in)	millimeter (mm)	**2.54**	**E−02**
mil (angle)	radian (rad)	9.817 477	E−04
mil (angle)	degree (°)	**5.625**	**E−02**
mile (mi)	meter (m)	**1.609 344**	**E+03**
mile (mi)	kilometer (km)	**1.609 344**	**E+00**
mile (based on U.S. survey foot) (mi)[9]	meter (m)	1.609 347	E+03
mile (based on U.S. survey foot) (mi)[9]	kilometer (km)	1.609 347	E+00
mile, nautical[21]	meter (m)	**1.852**	**E+03**
mile per gallon (U.S.) (mpg) (mi/gal)	meter per cubic meter (m/m^3)	4.251 437	E+05
mile per gallon (U.S.) (mpg) (mi/gal)	kilometer per liter (km/L)	4.251 437	E−01
mile per gallon (U.S.) (mpg) (mi/gal)[22]	liter per 100 kilometer (L/100 km)	divide 235.215 by number of miles per gallon	
mile per hour (mi/h)	meter per second (m/s)	**4.4704**	**E−01**
mile per hour (mi/h)	kilometer per hour (km/h)	**1.609 344**	**E+00**

[18] The exact conversion factor is $10^4/\pi$.

[19] This conversion factor is based on 1 d = 86 400 s; and 1 Julian century = 36 525 d. (See *The Astronomical Almanac for the Year 1995*, page K6, U.S. Government Printing Office, Washington, DC, 1994).

[20] In 1964 the General Conference on Weights and Measures reestablished the name ''liter'' as a special name for the cubic decimeter. Between 1901 and 1964 the liter was slightly larger (1.000 028 dm^3); when one uses high-accuracy volume data of that time, this fact must be kept in mind.

[21] The value of this unit, 1 nautical mile = 1852 m, was adopted by the First International Extraordinary Hydrographic Conference, Monaco, 1929, under the name ''International nautical mile.''

[22] For converting fuel economy, as used in the U.S., to fuel consumption.

To convert from	to	Multiply by	
mile per minute (mi/min)	meter per second (m/s)	**2.682 24**	**E+01**
mile per second (mi/s)	meter per second (m/s)	**1.609 344**	**E+03**
millibar (mbar)	pascal (Pa)	**1.0**	**E+02**
millibar (mbar)	kilopascal (kPa)	**1.0**	**E−01**
millimeter of mercury, conventional (mmHg)[13]	pascal (Pa)	1.333 224	E+02
millimeter of water, conventional (mmH_2O)[13]	pascal (Pa)	**9.806 65**	**E+00**
minute (angle) (')	radian (rad)	2.908 882	E−04
minute (min)	second (s)	**6.0**	**E+01**
minute (sidereal)	second (s)	5.983 617	E+01
oersted (Oe)	ampere per meter (A/m)	7.957 747	E+01
ohm centimeter (Ω · cm)	ohm meter (Ω · m)	**1.0**	**E−02**
ohm circular-mil per foot	ohm meter (Ω · m)	1.662 426	E−09
ohm circular-mil per foot	ohm square millimeter per meter (Ω · mm^2/m)	1.662 426	E−03
ounce (avoirdupois) (oz)	kilogram (kg)	2.834 952	E−02
ounce (avoirdupois) (oz)	gram (g)	2.834 952	E+01
ounce (troy or apothecary) (oz)	kilogram (kg)	3.110 348	E−02
ounce (troy or apothecary) (oz)	gram (g)	3.110 348	E+01
ounce [Canadian and U.K. fluid (Imperial)] (fl oz)	cubic meter (m^3)	2.841 306	E−05
ounce [Canadian and U.K. fluid (Imperial)] (fl oz)	milliliter (mL)	2.841 306	E+01
ounce (U.S. fluid) (fl oz)	cubic meter (m^3)	2.957 353	E−05
ounce (U.S. fluid) (fl oz)	millimeter (mL)	2.957 353	E+01
ounce (avoirdupois)-force (ozf)	newton (N)	2.780 139	E−01
ounce (avoirdupois)-force inch (ozf · in)	newton meter (N · m)	7.061 552	E−03
ounce (avoirdupois)-force inch (ozf · in)	millinewton meter (mN · m)	7.061 552	E+00
ounce (avoirdupois) per cubic inch (oz/in^3)	kilogram per cubic meter (kg/m^3)	1.729 994	E+03
ounce (avoirdupois) per gallon [Canadian and U.K. (Imperial)] (oz/gal)	kilogram per cubic meter (kg/m^3)	6.236 023	E+00
ounce (avoirdupois) per gallon [Canadian and U.K. (Imperial)] (oz/gal)	gram per liter (g/L)	6.236 023	E+00
ounce (avoirdupois) per gallon (U.S.) (oz/gal)	kilogram per cubic meter (kg/m^3)	7.489 152	E+00
ounce (avoirdupois) per gallon (U.S.) (oz/gal)	gram per liter (g/L)	7.489 152	E+00
ounce (avoirdupois) per square foot (oz/ft^2)	kilogram per square meter (kg/m^2)	3.051 517	E−01
ounce (avoirdupois) per square inch (oz/in^2)	kilogram per square meter (kg/m^2)	4.394 185	E+01
ounce (avoirdupois) per square yard (oz/yd^2)	kilogram per square meter (kg/m^2)	3.390 575	E−02
parsec (pc)	meter (m)	3.085 678	E+16
peck (U.S.) (pk)	cubic meter (m^3)	8.809 768	E−03
peck (U.S.) (pk)	liter (L)	8.809 768	E+00
pennyweight (dwt)	kilogram (kg)	1.555 174	E−03
pennyweight (dwt)	gram (g)	1.555 174	E+00
perm (0 °C)	kilogram per pascal second square meter [kg/(Pa · s · m^2)]	5.721 35	E−11
perm (23 °C)	kilogram per pascal second square meter [kg/(Pa · s · m^2)]	5.745 25	E−11
perm inch (0 °C)	kilogram per pascal second meter [kg/(Pa · s · m)]	1.453 22	E−12
perm inch (23 °C)	kilogram per pascal second meter [kg/(Pa · s · m)]	1.459 29	E−12

To convert from	to	Multiply by	
phot (ph)	lux (lx)	**1.0**	**E+04**
pica (computer) (1/6 in)	meter (m)	4.233 333	E−03
pica (computer) (1/6 in)	millimeter (mm)	4.233 333	E+00
pica (printer's)	meter (m)	4.217 518	E−03
pica (printer's)	millimeter (mm)	4.217 518	E+00
pint (U.S. dry) (dry pt)	cubic meter (m^3)	5.506 105	E−04
pint (U.S. dry) (dry pt)	liter (L)	5.506 105	E−01
pint (U.S. liquid) (liq pt)	cubic meter (m^3)	4.731 765	E−04
pint (U.S. liquid) (liq pt)	liter (L)	4.731 765	E−01
point (computer) (1/72 in)	meter (m)	3.527 778	E−04
point (computer) (1/72 in)	millimeter (mm)	3.527 778	E−01
point (printer's)	meter (m)	3.514 598	E−04
point (printer's)	millimeter (mm)	3.514 598	E−01
poise (P)	pascal second (Pa · s)	**1.0**	**E−01**
pound (avoirdupois) (lb)[23]	kilogram (kg)	4.535 924	E−01
pound (troy or apothecary) (lb)	kilogram (kg)	3.732 417	E−01
poundal	newton (N)	1.382 550	E−01
poundal per square foot	pascal (Pa)	1.488 164	E+00
poundal second per square foot	pascal second (Pa · s)	1.488 164	E+00
pound foot squared (lb · ft^2)	kilogram meter squared (kg · m^2)	4.214 011	E−02
pound-force (lbf)[24]	newton (N)	4.448 222	E+00
pound-force foot (lbf · ft)	newton meter (N · m)	1.355 818	E+00
pound-force foot per inch (lbf · ft/in)	newton meter per meter (N · m/m)	5.337 866	E+01
pound-force inch (lbf · in)	newton meter (N · m)	1.129 848	E−01
pound-force inch per inch (lbf · in/in)	newton meter per meter (N · m/m)	4.448 222	E+00
pound-force per foot (lbf/ft)	newton per meter (N/m)	1.459 390	E+01
pound-force per inch (lbf/in)	newton per meter (N/m)	1.751 268	E+02
pound-force per pound (lbf/lb) (thrust to mass ratio)	newton per kilogram (N/kg)	**9.806 65**	**E+00**
pound-force per square foot (lbf/ft^2)	pascal (Pa)	4.788 026	E+01
pound-force per square inch (psi) (lbf/in^2)	pascal (Pa)	6.894 757	E+03
pound-force per square inch (psi) (lbf/in^2)	kilopascal (kPa)	6.894 757	E+00
pound-force second per square foot (lbf · s/ft^2)	pascal second (Pa · s)	4.788 026	E+01
pound-force second per square inch (lbf · s/in^2)	pascal second (Pa · s)	6.894 757	E+03
pound inch squared (lb · in^2)	kilogram meter squared (kg · m^2)	2.926 397	E−04
pound per cubic foot (lb/ft^3)	kilogram per cubic meter (kg/m^3)	1.601 846	E+01
pound per cubic inch (lb/in^3)	kilogram per cubic meter (kg/m^3)	2.767 990	E+04
pound per cubic yard (lb/yd^3)	kilogram per cubic meter (kg/m^3)	5.932 764	E−01
pound per foot (lb/ft)	kilogram per meter (kg/m)	1.488 164	E+00
pound per foot hour [lb/(ft · h)]	pascal second (Pa · s)	4.133 789	E−04
pound per foot second [lb/(ft · s)]	pascal second (Pa · s)	1.488 164	E+00
pound per gallon [Canadian and U.K. (Imperial)] (lb/gal)	kilogram per cubic meter (kg/m^3)	9.977 637	E+01
pound per gallon [Canadian and U.K. (Imperial)] (lb/gal)	kilogram per liter (kg/L)	9.977 637	E−02
pound per gallon (U.S.) (lb/gal)	kilogram per cubic meter (kg/m^3)	1.198 264	E+02
pound per gallon (U.S.) (lb/gal)	kilogram per liter (kg/L)	1.198 264	E−01
pound per horsepower hour [lb/(hp · h)]	kilogram per joule (kg/J)	1.689 659	E−07
pound per hour (lb/h)	kilogram per second (kg/s)	1.259 979	E−04

[23] The exact conversion factor is 4.535 923 7 E−01. All units that contain the pound refer to the avoirdupois pound.

[24] If the local value of the acceleration of free fall is taken as $g_n = 9.806\ 65\ m/s^2$ (the standard value), the exact conversion factor is 4.448 221 615 260 5 E+00.

To convert from	to	Multiply by	
pound per inch (lb/in)	kilogram per meter (kg/m)	1.785 797	E+01
pound per minute (lb/min)	kilogram per second (kg/s)	7.559 873	E−03
pound per second (lb/s)	kilogram per second (kg/s)	4.535 924	E−01
pound per square foot (lb/ft^2)	kilogram per square meter (kg/m^2)	4.882 428	E+00
pound per square inch (*not* pound-force) (lb/in^2)	kilogram per square meter (kg/m^2)	7.030 696	E+02
pound per yard (lb/yd)	kilogram per meter (kg/m)	4.960 546	E−01
psi (pound-force per square inch) (lbf/in^2)	pascal (Pa)	6.894 757	E+03
psi (pound-force per square inch) (lbf/in^2)	kilopascal (kPa)	6.894 757	E+00
quad (10^{15} Btu_{IT})[11]	joule (J)	1.055 056	E+18
quart (U.S. dry) (dry qt)	cubic meter (m^3)	1.101 221	E−03
quart (U.S. dry) (dry qt)	liter (L)	1.101 221	E+00
quart (U.S. liquid) (liq qt)	cubic meter (m^3)	9.463 529	E−04
quart (U.S. liquid) (liq qt)	liter (L)	9.463 529	E−01
rad (absorbed dose) (rad)	gray (Gy)	**1.0**	**E−02**
rem (rem)	sievert (Sv)	**1.0**	**E−02**
revolution (r)	radian (rad)	6.283 185	E+00
revolution per minute (rpm) (r/min)	radian per second (rad/s)	1.047 198	E−01
rhe	reciprocal pascal second [$(Pa \cdot s)^{-1}$]	**1.0**	**E+01**
rod (based on U.S. survey foot) (rd)[9]	meter (m)	5.029 210	E+00
roentgen (R)	coulomb per kilogram (C/kg)	**2.58**	**E−04**
rpm (revolution per minute) (r/min)	radian per second (rad/s)	1.047 198	E−01
second (angle) (")	radian (rad)	4.848 137	E−06
second (sidereal)	second (s)	9.972 696	E−01
shake	second (s)	**1.0**	**E−08**
shake	nanosecond (ns)	**1.0**	**E+01**
slug (slug)	kilogram (kg)	1.459 390	E+01
slug per cubic foot ($slug/ft^3$)	kilogram per cubic meter (kg/m^3)	5.153 788	E+02
slug per foot second [$slug/(ft \cdot s)$]	pascal second ($Pa \cdot s$)	4.788 026	E+01
square foot (ft^2)	square meter (m^2)	**9.290 304**	**E−02**
square foot per hour (ft^2/h)	square meter per second (m^2/s)	**2.580 64**	**E−05**
square foot per second (ft^2/s)	square meter per second (m^2/s)	**9.290 304**	**E−02**
square inch (in^2)	square meter (m^2)	**6.4516**	**E−04**
square inch (in^2)	square centimeter (cm^2)	**6.4516**	**E+00**
square mile (mi^2)	square meter (m^2)	2.589 988	E+06
square mile (mi^2)	square kilometer (km^2)	2.589 988	E+00
square mile (based on U.S. survey foot) (mi^2)[9]	square meter (m^2)	2.589 998	E+06
square mile (based on U.S. survey foot) (mi^2)[9]	square kilometer (km^2)	2.589 998	E+00
square yard (yd^2)	square meter (m^2)	8.361 274	E−01
statampere	ampere (A)	3.335 641	E−10
statcoulomb	coulomb (C)	3.335 641	E−10
statfarad	farad (F)	1.112 650	E−12
stathenry	henry (H)	8.987 552	E+11
statmho	siemens (S)	1.112 650	E−12
statohm	ohm (Ω)	8.987 552	E+11
statvolt	volt (V)	2.997 925	E+02
stere (st)	cubic meter (m^3)	**1.0**	**E+00**
stilb (sb)	candela per square meter (cd/m^2)	**1.0**	**E+04**
stokes (St)	meter squared per second (m^2/s)	**1.0**	**E−04**

To convert from	to	Multiply by	
tablespoon	cubic meter (m^3)	1.478 676	E−05
tablespoon	milliliter (mL)	1.478 676	E+01
teaspoon	cubic meter (m^3)	4.928 922	E−06
teaspoon	milliliter (mL)	4.928 922	E+00
tex	kilogram per meter (kg/m)	**1.0**	**E−06**
therm (EC)[25]	joule (J)	**1.055 06**	**E+08**
therm (U.S.)[25]	joule (J)	**1.054 804**	**E+08**
ton, assay (AT)	kilogram (kg)	2.916 667	E−02
ton, assay (AT)	gram (g)	2.916 667	E+01
ton-force (2000 lbf)	newton (N)	8.896 443	E+03
ton-force (2000 lbf)	kilonewton (kN)	8.896 443	E+00
ton, long (2240 lb)	kilogram (kg)	1.016 047	E+03
ton, long, per cubic yard	kilogram per cubic meter (kg/m^3)	1.328 939	E+03
ton, metric (t)	kilogram (kg)	**1.0**	**E+03**
tonne (called ''metric ton'' in U.S.) (t)	kilogram (kg)	**1.0**	**E+03**
ton of refrigeration (12 000 Btu_{IT}/h)	watt (W)	3.516 853	E+03
ton of TNT (energy equivalent)[26]	joule (J)	**4.184**	**E+09**
ton, register	cubic meter (m^3)	2.831 685	E+00
ton, short (2000 lb)	kilogram (kg)	9.071 847	E+02
ton, short, per cubic yard	kilogram per cubic meter (kg/m^3)	1.186 553	E+03
ton, short, per hour	kilogram per second (kg/s)	2.519 958	E−01
torr (Torr)	pascal (Pa)	1.333 224	E+02
unit pole	weber (Wb)	1.256 637	E−07
watt hour (W · h)	joule (J)	**3.6**	**E+03**
watt per square centimeter (W/cm^2)	watt per square meter (W/m^2)	**1.0**	**E+04**
watt per square inch (W/in^2)	watt per square meter (W/m^2)	1.550 003	E+03
watt second (W · s)	joule (J)	**1.0**	**E+00**
yard (yd)	meter (m)	**9.144**	**E−01**
year (365 days)	second (s)	**3.1536**	**E+07**
year (sidereal)	second (s)	3.155 815	E+07
year (tropical)	second (s)	3.155 693	E+07

[25] The therm (EC) is legally defined in the Council Directive of 20 December 1979. Council of the European Communities (now the European Union, EU). The Therm (U.S.) is legally defined in the Federal Register of July 27, 1968. Although the therm (EC), which is based on the International Table Btu, is frequently used by engineers in the United States, the therm (U.S.) is the legal unit used by the U.S. natural gas industry.

[26] Defined (not measured) value.

From *CRC Handbook of Chemistry & Physics,* 83rd ed., Lide, D., Ed., CRC Press, Boca Raton, FL, 2002, pp. **1**-34 to **1**-45.

PERIODIC TABLE OF THE ELEMENTS

New Notation / Previous IUPAC Form / CAS Version

Key to Chart: Atomic Number (50), Symbol (Sn), 1995 Atomic Weight (118.710), Oxidation States (+2 +4), Electron Configuration (-18-18-4)

1 Group IA	2 IIA	3 IIIA IIIB	4 IVA IVB	5 VA VB	6 VIA VIB	7 VIIA VIIB	8 VIIIA	9 VIII	10	11 IB IB	12 IIB IIB	13 IIIB IIIA	14 IVB IVA	15 VB VA	16 VIB VIA	17 VIIB VIIA	18 VIIIA	Shell
1 H +1 -1 1.00794 1																	2 He 0 4.002602 2	K
3 Li +1 6.941 2-1	4 Be +2 9.012182 2-2											5 B +3 10.811 2-3	6 C +2 +4 -4 12.0107 2-4	7 N +1 +2 +3 +4 +5 -1 -2 -3 14.0067 2-5	8 O -2 15.9994 2-6	9 F -1 18.9984032 2-7	10 Ne 0 20.1797 2-8	K-L
11 Na +1 22.989770 2-8-1	12 Mg +2 24.3050 2-8-2											13 Al +3 26.981538 2-8-3	14 Si +2 +4 -4 28.0855 2-8-4	15 P +3 +5 -3 30.973761 2-8-5	16 S +4 +6 -2 32.065 2-8-6	17 Cl +1 +5 +7 -1 35.453 2-8-7	18 Ar 0 39.948 2-8-8	K-L-M
19 K +1 39.0983 -8-8-1	20 Ca +2 40.078 -8-8-2	21 Sc +3 44.955910 -8-9-2	22 Ti +2 +3 +4 47.867 -8-10-2	23 V +2 +3 +4 +5 50.9415 -8-11-2	24 Cr +2 +3 +6 51.9961 -8-13-1	25 Mn +2 +3 +4 +7 54.938049 -8-13-2	26 Fe +2 +3 55.845 -8-14-2	27 Co +2 +3 58.933200 -8-15-2	28 Ni +2 +3 58.6934 -8-16-2	29 Cu +1 +2 63.546 -8-18-1	30 Zn +2 65.409 -8-18-2	31 Ga +3 69.723 -8-18-3	32 Ge +2 +4 72.64 -8-18-4	33 As +3 +5 -3 74.92160 -8-18-5	34 Se +4 +6 -2 78.96 -8-18-6	35 Br +1 +5 -1 79.904 -8-18-7	36 Kr 0 83.798 -8-18-8	-L-M-N
37 Rb +1 85.4678 -18-8-1	38 Sr +2 87.62 -18-8-2	39 Y +3 88.90585 -18-9-2	40 Zr +4 91.224 -18-10-2	41 Nb +3 +5 92.90638 -18-12-1	42 Mo +6 95.94 -18-13-1	43 Tc +4 +6 +7 (98) -18-13-2	44 Ru +3 101.07 -18-15-1	45 Rh +3 102.90550 -18-16-1	46 Pd +2 +3 106.42 -18-18-0	47 Ag +1 107.8682 -18-18-1	48 Cd +2 112.411 -18-18-2	49 In +3 114.818 -18-18-3	50 Sn +2 +4 118.710 -18-18 -4	51 Sb +3 +5 -3 121.760 -18-18-5	52 Te +4 +6 -2 127.60 -18-18-6	53 I +1 +5 +7 -1 126.90447 -18-18-7	54 Xe 0 131.293 -18-18-8	-M-N-O
55 Cs +1 132.90545 -18-8-1	56 Ba +2 137.327 -18-8-2	57* La +3 138.9055 -18-9-2	72 Hf +4 178.49 -32-10-2	73 Ta +5 180.9479 -32-11-2	74 W +6 183.84 -32-12-2	75 Re +4 +6 +7 186.207 -32-13-2	76 Os +3 +4 190.23 -32-14-2	77 Ir +3 +4 192.217 -32-15-2	78 Pt +2 +4 195.078 -32-17-1	79 Au +1 +3 196.96655 -32-18-1	80 Hg +1 +2 200.59 -32-18-2	81 Tl +1 +3 204.3833 -32-18-3	82 Pb +2 +4 207.2 -32-18-4	83 Bi +3 +5 208.98038 -32-18-5	84 Po +2 +4 (209) -32-18-6	85 At (210) -32-18-7	86 Rn 0 (222) -32-18-8	-N-O-P
87 Fr +1 (223) -18-8-1	88 Ra +2 (226) -18-8-2	89** Ac +3 (227) -18-9-2	104 Rf +4 (261) -32-10-2	105 Db (262) -32-11-2	106 Sg (266) -32-12-2	107 Bh (264) -32-13-2	108 Hs (277) -32-14-2	109 Mt (268) -32-15-2	110 Uun (281) -32-16-2	111 Uuu (272)	112 Uub (285)		114 Uuq (289)		116 Uuh (289)			-O-P-Q

* Lanthanides	58 Ce +3 +4 140.116 -19-9-2	59 Pr +3 140.90765 -21-8-2	60 Nd +3 144.24 -22-8-2	61 Pm +3 (145) -23-8-2	62 Sm +2 +3 150.36 -24-8-2	63 Eu +2 +3 151.964 -25-8-2	64 Gd +3 157 .25 -25-9-2	65 Tb +3 158.92534 -27-8-2	66 Dy +3 162.500 -28-8-2	67 Ho +3 164.93032 -29-8-2	68 Er +3 167.259 -30-8-2	69 Tm +3 168.93421 -31-8-2	70 Yb +2 +3 173.04 -32-8-2	71 Lu +3 174.967 -32-9-2	-N-O-P
** Actinides	90 Th +4 232.0381 -18-10-2	91 Pa +5 +4 231.03588 -20-9-2	92 U +3 +4 +5 +6 238.02891 -21-9-2	93 Np +3 +4 +5 +6 (237) -22-9-2	94 Pu +3 +4 +5 +6 (244) -24-8-2	95 Am +3 +4 +5 +6 (243) -25-8-2	96 Cm +3 (247) -25-9-2	97 Bk +3 +4 (247) -27-8-2	98 Cf +3 (251) -28-8-2	99 Es +3 (252) -29-8-2	100 Fm +3 (257) -30-8-2	101 Md +2 +3 (258) -31-8-2	102 No +2 +3 (259) -32-8-2	103 Lr +3 (262) -32-8-3	-O-P-Q

The new IUPAC format numbers the groups from 1 to 18. The previous IUPAC numbering system and the system used by Chemical Abstracts Service (CAS) are als o shown. For radioactive elements that do not occur in nature, the mass number of the most stable isotope is given in parentheses.

References

1. G. J. Leigh, Editor, *Nomenclature of Inorganic Chemistry*, Blackwell Scientific Publications, Oxford, 1990.
2. *Chemical and Engineering News*, 63(5), 27, 1985.
3. Atomic Weights of the Elements, 1999, *Pure & Appl. Chem.*, 73, 667, 2001.

From *CRC Handbook of Chemistry and Physics,* 83rd ed., Lide, O., Ed., CRC Press, Boca Raton, FL, 2002.

Properties of Semiconductors

The term *semiconductor* is applied to a material in which electric current is carried by electrons or holes and whose electrical conductivity, when extremely pure, rises exponentially with temperature and may be increased from its low "intrinsic" value by many orders of magnitude by "doping" with electrically active impurities.

Semiconductors are characterized by an energy gap in the allowed energies of electrons in the material which separates the normally filled energy levels of the *valence band* (where "missing" electrons behave like positively charged current carriers "holes") and the *conduction band* (where electrons behave rather like a gas of free negatively charged carriers with an effective mass dependent on the material and the direction of the electrons' motion). This energy gap depends on the nature of the material and varies with direction in anisotropic crystals. It is slightly dependent on temperature and pressure, and this dependence is usually almost linear at normal temperatures and pressures.

Data are presented in three tables. Table I "General Properties of Semiconductors" lists the main crystallographic and semiconducting properties of a large number of semiconducting materials in three main categories: "Tetrahedral Semiconductors" in which every atom is tetrahedrally co-ordinated to four nearest neighbor atoms (or atomic sites) as for example in the diamond structure; "Octahedral Semiconductors: in which every atom is octahedrally co-ordinated to six nearest neighbor atoms—as for examples the halite structure; and "Other Semiconductors."

Table II gives more detailed information about some better known semiconductors, while Table III gives some information about the electronic energy band structure parameters of the best known materials.

Table I.
PHYSICO-CHEMICAL PROPERTIES OF SEMICONDUCTORS (LISTED BY CRYSTAL STRUCTURE)

Substance	Molecular Mass	Average Atomic Mass	Lattice Parameters (Å, Room Temp.)	Density (g/cm^3)	Melting Point (K)	Microhardness, N/mm^2 (M-Mohs Scale)	Specific Heat, J/kg·K (300 K)	Debye Temp. (K)	Coefficient of Thermal Linear Expansion [10^{-6} K^{-1} (300K)]	Thermal Conductivity [mW/cm·K (300K)]
Part A. Adamantine Semiconductors										
§A1. Diamond Structure Elements (Strukturbericht symbol A4, Space Group Fd3m-O_h^7)										
C		12.01	3.56683	3.51	≈3850 Transition to graphite > 980	10 (M)	471.5	2340	1.18	9900(I) 23200(IIA) 13600(IIB)
Si		28.09	5.43072	2.3283	1685 ± 2	11270	702	645	2.49	1240
Ge		72.59	5.65754	5.3234	1231	7644	321.9	374	6.1	640
α-Sn		118.69	6.4912	5.765 (281 K)	505.2 (Tr. 286.4)		213	230	5.4 (220 K)	

§A2. Sphalerite (Zinc Blende) Structure Compounds (Strukturbericht symbo1 B3 Space Group F $\bar{4}$ 3m-T_d^2)

I VII Compounds										
CuF	82.54	41.27	4.255		1181					
CuCl	98.99	49.49	5.4057	3.53	695	2.3 (M)	490	240	12.1	8.4
CuBr	143.36	71.73	5.6905	4.98	770	2.5 (M)	381	207	15.4	12.5
Cul	190.46	95.23	6.60427	5.63	878	192	276	181	19.2	16.8
AgBr	187.78	93.89		6.473	>1570 (Tr. 410)	2.5 (M)	270			
AgI	234.77	117.39	6.502	5.67	831	2.5 (M)	232	134	–2.5	4.2
II VI Compounds										
BeS	41.08	20.54	4.865	2.36						
BeSe	87.97	43.99	5.139	4.315						
BeTe	136.61	68.31	5.626	5.090						
BePo	(2318)	(109)	5.838	7.3						
ZnO	81.37	40.69	4.63	5.675	2248	5.0 (M)	494	416	2.9	234
ZnS	97.43	48.72	5.4093	4.079	2100 (Tr. 1295)	1780	472	530	6.36	251
ZnSe	144.34	72.17	5.6676	5.42	1790	1350	339	400	7.2	140
ZnTe	192.99	96.5	6.101	6.34	1568	900	264	223	8.19	108
ZnPo	(274)	(137)	6.309							
CdS	144.46	72.23	5.832	4.826	1750	1250	330	219	4.7	200
CdSe	191.36	95.68	6.05	5.674	1512	1300	255	181	3.8	90
CdTe	240.00	120.00	6.477	5.86	1365	600	205	200	4.9	58.5
CdPo	(321)	(161)	6.665							
HgS	232.65	116.33	5.8517	7.73	1820	3 (M)	210			
HgSe	279.55	139.78	6.084	8.25	1070	2.5 (M)	178	151	5.46	10
HgTe	328.19	164.10	6.4623	8.17	943	300	164	242	4.6	20
III V Compounds										
BN	24.82	12.41	3.615	3.49	≈3300	10 (M)	793	≈1900		200
BP(L.T.)	41.78	20.87	4.538	2.9	≈2800	37000		≈980		
BAs	85.73	42.87	4.777		≈2300	19000		≈625		
AIP	57.95	28.98	5.451	2.42	≈2100	5.5 (M)		588		920
AIAs	101.90	50.95	5.6622	3.81	2013	5000		417	3.5	840
AISb	148.73	74.37	6.1355	4.218	1330	4000		292	4.2	600
GaP	100.69	50.35	5.4905	4.13	1750	9450		446	5.3	752
GaAs	144.64	72.32	5.65315	5.316	1510	7500		344	5.4	560
GaSb	191.47	95.74	6.0954	5.619	980	4480	320	265	6.1	270
InP	145.79	72.90	5.86875	4.787	1330	4100		321	4.6	800
InAs	189.74	94.87	6.05838	5.66	1215	3300	268	249	4.7	290
InSb	236.57	118.29	6.47877	5.775	798	2200	144	202	4.7	160

Table I.
PHYSICO-CHEMICAL PROPERTIES OF SEMICONDUCTORS (LISTED BY CRYSTAL STRUCTURE) (continued)

Substance	Molecular Mass	Average Atomic Mass	Lattice Parameters (Å, Room Temp.)		Density (g/cm³)	Melting Point (K)	Microhardness, N/mm² (M-Mohs Scale)	Specific Heat, J/kg·K (300 K)	Debye Temp. (K)	Coefficient of Thermal Linear Expansion [10^{-6} K^{-1} (300K)]	Thermal Conductivity [mW/cm·K (300K)]
Other sphalerite structure compounds											
MnS	87.0	43.5	5.011								
MnSe	133.9	66.95	5.82								
β-SiC	40.1	20.1	4.348		3.21	3070					
Ga_2Se_3	376.32	75.26	5.429		4.92	1020	3160			8.9	50
Ga_2Te_3	522.24	104.45	5.899		5.75	1063	2370				47
In_2Te_3(H.T.)	608.44	121.7	61.50		5.8	940	1660				69
$MgGeP_2$	158.84	39.71	5.652								
$ZnSnP_2$	246.00	61.5	5.65			1200					
$ZnSnAs_2$(H.T.)	333.90	82.38	5.851		5.53	1050					76
$ZnSnSb_2$	427.56	106.89	6.281		5.67	870	2500				76
§A3. Wurtzite (Zincite) Structure Compounds (Strukturbericht symbol B4, Space Group P 6_3mc-C^4_{6v})											
I VII Compounds											
CuCl	99.0	49.5	3.91	6.42		T_c680K					
CuBr	143.46	71.73	4.06	6.66		T_c658K					
Cul	190.46	95.23	4.31	7.09							
Agl	234.80	117.40	4.580	7.494							
II VI Compounds											
BeO	25.01	12.51	2.698	4.380		2800					
MgTe	151.9	76.0	4.54	7.39	3.85	≈2800					
Zno	81.37	40.69	3.24950	5.2069	5.66	2250					600
ZnS	97.43	48.72	3.8140	6.2576	4.1	2100					460
ZnTe	192.99	46.50	4.27	6.99		1568					
Cds	144.46	72.23	4.1348	6.7490	4.82	1748					401
CdSe	191.36	95.68	4.299	7.010	5.66	1512					316
CdTe	240.00	120.00	4.57	7.47							
III V Compounds											
BP(H.T.)	41.79	20.90	3.562	5.900							
AIN	40.99	20.50	3.111	4.978	3.26	≈2500					823
GaN	83.73	41.87	3.190	5.189	6.10	1500					656
InN	128.83	64.42	3.533	5.693	6.88	1200					556

Other wurtzite structure compounds										
MnS	87.0	43.5	3.985	6.45	3.248					
MnSe	133.9	66.95	4.12	6.72						
SiC	40.1	20.1	3.076	5.048						
MnTe	182.54	91.27	4.078	6.701						
Al_2S_3	150.14	30.03	3.579	5.829	2.55	1400				
Al_2Se_3	290.84	58.17	3.890	6.30	3.91	1250				

§A4. Chalcopyrite Structure Compounds (Strukturbericht symbol $E1_1$, Space Group $I\bar{4}2d$-D_{24}^{12})

I III VI_2 Compounds										
$CuAlS_2$	154.65	38.66	5.323	10.44	3.47	2500				
$CuAlSe_2$	248.45	62.11	5.617	10.92	4.70	2260				
$CuAlTe_2$	345.73	86.43	5.976	11.80	5.50	2550				
$CuGaS_2$	197.39	49.53	5.360	10.49	4.35	2300				
$CuGaSe_2$	291.19	72.80	5.618	11.01	5.56	1970	4200	275	5.4	42
$CuGaTe_2$	388.47	97.12	6.013	11.93	5.99	2400	3500		6.9	27
$CuInS_2$	242.49	60.62	5.528	11.08	4.75	1400	2550			
$CuInSe_2$	336.29	84.07	5.785	11.56	5.77	1600	2050		6.6	37
$CuInTe_2$	433.57	108.39	6.179	12.365	6.10	1660	400	195	7.1	49
$CuTlS_2$	322.05	83.01	5.580	11.17	6.32					
$CuTlSe_2$(L.T.)	425.85	106.46	5.844	11.65	7.11	900				
$CuFeS_2$	183.51	45.88	5.25	10.32	4.088					
$CuFeSe_2$	277.31	69.33				850				
$CuLaS_2$	266.58	66.65	5.65	10.86						
$AgAlS_2$	198.97	49.74	5.707	10.28	3.94					
$AgAlSe_2$	292.77	73.19	5.968	10.77	5.07	1220				
$AgAlTe_2$	390.05	97.51	6.309	11.85	6.18	1000				
$AgGaS_2$	241.71	60.43	5.755	10.28	4.72					
$AgGaSe_2$	335.51	83.88	5.985	10.90	5.84	1120	4400			
$AgGaTe_2$	432.79	108.2	6.301	11.96	6.05	990	1800	212		10
$AgInS_2$(L.T.)	286.87	71.70	5.828	11.19	5.00		2250			
$AgInSe_2$	380.61	95.15	6.102	11.69	5.81	1053	1850			30
$AgInTe_2$	477.89	119.47	6.42	12.59	6.12	965			9.49, 0.69	
$AgFeS_2$	227.83	56.96	5.66	10.30	4.53					
II IV V_2 Compounds										
$ZnSiP_2$	155.40	38.85	5.400	10.441	3.39	1640	1100			
$ZnGeP_2$	199.90	49.98	5.465	10.771	4.17	1295	8100			180
$ZnSnP_2$	246.00	61.5					6500			
$CdSiP_2$	202.43	50.61	5.678	10.431	4.00	≈1470	10500	282		
$CdGeP_2$	246.94	61.74	5.741	10.775	4.48	1049	5650			110

Table I.
PHYSICO-CHEMICAL PROPERTIES OF SEMICONDUCTORS (LISTED BY CRYSTAL STRUCTURE) (continued)

Substance	Molecular Mass	Average Atomic Mass	Lattice Parameters (Å, Room Temp.)		Density (g/cm^3)	Melting Point (K)	Microhardness, N/mm^2 (M-Mohs Scale)	Specific Heat, J/kg·K (300 K)	Debye Temp. (K)	Coefficient of Thermal Linear Expansion [10^{-6} K^{-1} (300K)]	Thermal Conductivity [mW/cm·K (300K)]
$CdSnP_2$	243.03	73.26	5.900	11.518			5000		195		140
$ZnSiAs_2$	242.20	60.55	5.61	10.88	4.70	1311	9200				
$ZnGeAs_2$	287.80	71.95	5.672	11.153	5.32	1150	6800		263		110
$ZnSnAs_2$	333.90	83.48	5.8515	11.704	5.53	1048	4550		271		150
$CdSiAs_2$	290.34	72.58	5.884	10.882			6850				
$CdGeAs_2$	334.83	83.71	5.9427	11.2172	5.60	938	4700				48
$CdSnAs_2$	380.93	95.23	6.0944	11.9182	5.72	880	3450				40
§A5. Other Ternary Semiconductors with Tetrahedral Coordination											
I_2 IV VI_3 Compounds											
Cu_2SiS_3(H.T.)	251.36	41.89	3.684	6.004	3.81	1200					23
Cu_2SiS_3(L.T.)			5.290	10.156	3.63						
Cu_2SiTe_3	537.98	89.66	5.93		5.47						
Cu_2GeS_3(H.T.)	295.88	49.31	5.317		4.45	1210	4550	510	254	7.2	12
Cu_2GeS_3(L.T.)			5.327	5.215	4.46						
Cu_2GeSe_3	436.56	72.76	5.589	5.485	5.57	1030	3840	340	168	8.4	24
Cu_2GeTe_3	582.51	97.09	5.958	5.935	5.92		2890				130
Cu_2SnS_3	341.98	57.00	5.436		5.02	1110	2770	440	214	7.8	28
$CuSnSe_3$	482.66	80.44	5.687		5.94	960	2510	310	148	8.9	35
Cu_2SnTe_3	628.61	104.77	6.048		6.51	680	1970				144
Ag_2GeSe_3	525.21	87.54									
Ag_2SnSe_3	571.31	95.22									
Ag_2GeTe_3	671.13	111.86									
Ag_2SnTe_3	717.23	119.54									
I_3 V VI_4 Compounds											
Cu_3PS_4	349.85	40.73	7.44	6.19							
Cu_3AsS_4	393.79	49.22	6.43	6.14	4.37					3.2	30.2
Cu_3AsSe_4	581.37	72.67	5.570	10.957	5.61				169	9.5	19
Cu_3SbS_4	440.64	55.08	5.38	16.76	4.90						
Cu_3SbSe_4	628.22	78.53	5.654	11.256	6.0				131	12.4	14.6
I IV_2 V_3 Compounds											
$CuSi_2P_3$	212.64	35.44	5.25								
$CuGe_2P_3$	301.65	50.28	5.375		4.318	1113	8500	429	8.21	37.6	
$AgGe_2P_3$	345.97	57.66				1015	6150				

§A6. "Defect Chalcopyrite" Structure Compounds (Strukturbericht symbol E3, Space Group I $\bar{4}$-S_4^2)

$ZnAl_2Se_4$	435.18	62.17	5.503	10.90	4.37		
$ZnAl_2Te_4$(?)	629.74	84.96	5.904	12.05	4.95		
$ZnGa_2S_4$(?)	333.06	47.58	5.274	10.44	3.80		
$ZnGa_2Se_4$(?)	520.66	74.38	5.496	10.99	5.21		
$ZnGa_2Te_4$(?)	715.22	102.17	5.937	11.87	5.67		
$ZnIn_2Se_4$	610.86	87.27	5.711	11.42	5.44	1250	
$ZnIn_2Te_4$	805.42	115.06	6.122	12.24	5.83	1075	
$CdAl_2S_4$	294.61	42.09	5.564	10.32	3.06		
$CdAl_2Se_4$	482.21	68.89	5.747	10.68	4.54		
$CdAl_2Te_4$(?)	676.77	97.68	6.011	12.21	5.10		
$CdGa_2S_4$	380.09	54.30	5.577	10.08	4.03		
$CdGa_2Se_4$	567.69	81.10	5.743	10.73	5.32		
$CdGa_2Te_4$	762.25	108.89	6.093	11.81	5.77		
$CdIn_2Te_4$	852.45	121.78	6.205	12.41	5.9	1060	
$HgAl_2S_4$	382.79	54.68	5.488	10.26	4.11		
$HgAl_2Se_4$	570.39	82.48	5.708	10.74	5.05		
$HgAl_2Te_4$(?)	764.48	109.28	6.004	12.11	5.81		
$HgGa_2S_4$	468.27	66.90	5.507	10.23	5.00		
$HgGa_2Se_4$	655.87	93.70	5.715	10.78	6.18		
$HgIn_2Se_4$	746.07	106.58	5.764	11.80	6.3	1100	
$HgIn_2Te_4$(?)	940.63	134.38	6.186	12.37	6.3	980	

§A7. Other Adamantine Compounds

αSiC	40.1	20.1	3.0817		3.21	3070	
			15.1183				
$Hg_5Ga_2Te_8$	2163.19	144.21	6.235				
$Hg_5In_2Te_8$	2253.39	150.23	6.328				
$CdIn_2Se_4$	657.89	93.98	a = c = 5.823				

Part B. Octahedral Semiconductors

§B1. Halite Structure Semiconductors (Strukturbericht symbol B1, Space Group Fm3m-O_h^5)

GeTe	200.19	100.1	5.98		6.14		
SnSe	197.65	98.83	6.020			1133	
SnTe	246.29	123.15	6.313		6.45	1080 (max)	91
Pbs	239.26	119.63	5.9362		7.61	1390	23
PbSe	286.16	143.08	6.1243		8.15	1340	17
PbTe	334.8	167.4	6.454		8.16	1180	23

Table I.
PHYSICO-CHEMICAL PROPERTIES OF SEMICONDUCTORS (LISTED BY CRYSTAL STRUCTURE) (continued)

Substance	Molecular Mass	Average Atomic Mass	Lattice Parameters (Å, Room Temp.)		Density (g/cm³)	Melting Point (K)	Microhardness, N/mm² (M-Mohs Scale)	Specific Heat, J/kg·K (300 K)	Debye Temp. (K)	Coefficient of Thermal Linear Expansion [10^{-6} K^{-1} (300K)]	Thermal Conductivity [mW/cm·K (300K)]
Selected Other Binary Halites											
BiSe	287.94	143.97	5.99		7.98	880					
BiTe	336.58	168.29	6.47								
EuSe	230.92	115.46	6.191			2300					2.4
GdSe	236.21	118.11	5.771			2400					
NiD	60.71	30.35	4.1684		6.6	2260					
CdO	128.41	64.21	4.6953			1700					7
SrS	119.68	59.84	6.0199		3.643	3000					
Part C. Other Semiconductors											
§C1. Antifluorite Structure Compounds ($Fm3m–O_h^5$)											
Mg_2Si	76.70	25.57	6.338		1.88	1375				11.5	
Mg_2Ge	121.20	40.4	6.380		3.08	1388				15.0	
Mg_2Sn	167.3	55.77	6.765		3.53	1051				9.9	92
Mg_2Pb	225.81	85.27	6.836		5.1	823				10.0	
§C2. Tetradymite Structure Compounds ($\bar{R}3m–D_{3d}^5$)											
Sb_2Te_3	626.3	125.26	4.25	30.3	6.44	895					
Bi_2Se_3	654.84	130.97	4.14	28.7	7.51	979	167				24
Bi_2Te_3	800.76	160.15	4.38	30.45	7.73	858	155	16			30
§C3. Skutterudite Structure Compounds ($Im3–T_h^5$)											
CoP_3	151.85	37.96	7.7073			>1270					
$CoAs_3$	286.70	71.65	8.2060		6.73	1230					
$CoSb_3$	424.18	106.05	9.0385			1123			307		50
$NiAs_3$	283.45	70.86	8.330		6.43						
RhP_3	195.83	48.96	7.9951			>1470					
$RhAs_3$	327.67	81.92	8.4427			>1270					100

$RhSb_3$	468.16	117.04	9.2322		1170					
IrP_3	285.14	71.29	8.0151	7.36	>1470					
$IrAs_3$	416.98	104.25	8.4673	9.12	>1470					90
$IrSb_3$	557.47	139.37	9.2533	9.35	1170			303		
§C4. Selected Multinary Compounds										
$AgSbSe_2$	387.54	96.88	5.786	6.60	910					10.5
$AgSbTe_2$ (or $Ag_{19}Sb_{29}Te_{52}$)	484.82	121.2	6.078	7.12	830					86, 0.3
$AgBiS_2$(H.T.)	380.97	95.24	5.648							
$AgBiSe_2$(H.T.)	474.77	118.69	5.82							
$AgBiTe_2$(H.T.)	572.05	143.01	6.155							
Cu_2CdSnS_4	486.43	60.80	5.586	10.83						
§C5. Some Elemental Semiconductors										
β	10.81	4.91	12.6	2.34	2348	9.5 (M)	1277	1370	8.3	600
Se(gray)	78.96	4.36	4.95	4.81	493	350	292.6		(‖C) 17.89 (⊥C) 74.09	(‖C) 45.2 (⊥C) 13.1
Te	127.6	4.45	5.91	6.23	723		196.5		16.8	(‖C) 33.8 (⊥C) 19.7

Table II
Basic Thermodynamic, Electrical, and Magnetic Properties of Semiconductors (Listed by Crystal Structure)

Substance	Heat of Formation [kJ/mole (300K)]	Volume Compressibility ($10^{-10}m^2/N$)	Static Dielectric Constant	Atomic Magnetic Susceptibility (10^{-6} CGS)	Index of Refraction	Miniumum Room Temperature Energy Gap (eV)	Mobility (Room Temp.) ($cm^2/V·s$): Electrons	Mobility (Room Temp.) ($cm^2/V·s$): Holes	Optical Transition	Remarks
Part A. Adamantine Semiconductors										
§Al. Diamond Structure Elements (Strukturbericht symbol A4, Space Group Fd 3m–O_h^7)										
C	714.4	18	5.7	–5.88	2.419 (589 nm)	5.4	1800	1400	i*	
Si	324	0.306	11.8	–3.9	3.49 (589 nm)	1.107	1900	500	i	
Ge	291	0.768	16	–012	3.99 (589 nm)	0.67	3800	1820	i	
α-Sn	267.5		24		2.75 (589 nm)	0.0; 0.8	2500	2400		

Table II
Basic Thermodynamic, Electrical, and Magnetic Properties of Semiconductors (Listed by Crystal Structure)

Substance	Heat of Formation [kJ/mole (300K)]	Volume Compressibility ($10^{-10}m^2/N$)	Static Dielectric Constant	Atomic Magnetic Susceptibility (10^{-6} CGS)	Index of Refraction	Miniumum Room Temperature Energy Gap (eV)	Mobility (Room Temp.) ($cm^2/V\cdot s$) Electrons	Holes	Optical Transition	Remarks
§A2. Sphalerite (Zinc Blende) Structure Compounds (Strukturbericht symbol B3 Space Group F $\bar{4}$ 3m–T_d^2)										
I VII Compounds										
CuF										
CuCl	481	0.26	7.9		1.93	3.17			d	Nantokite
CuBr	481	0.26	7.9		2.12	2.91			d	
Cul	439	0.27	6.5		2.346	2.95			d	Marshite
AgBr	486		12.4		2.253	2.50	4000		i	Bromirite
Agl	389	0.41	10		2.22	2.22	30		d	Miersite
II VI Compounds										
BeS					4.17				i	
BeSe					3.61				i	
BeTe					1.45		20		d	
BePo										
ZnO										See A3
ZnS	477		8.9	–9.9	2.356	3.54	180	5(400˚C)	d	See also A3
ZnSe	422		9.2		2.89	2.58	540	28	d	
ZnTe	376		10.4		3.56	2.26	340	100	d	
ZnP										
Cds										See A3
CdSe										See A3
CdTe	339		7.2		2.50	1.44	1200	50	d	
CdPo										
HgS					2.85		250		d	Metacinnabarite
HgSe	247					2.10 (α)	2000	≈1.5	s	Tiemannite
HgTe	242					–0.06	25000	350	s	Coloradoite
III V Compounds										
BN	815					4.6				Borazone
BP(L.T.)						≈2.1	500	70		Ignites 470K

BAs						≈1.5				
AlP						2.45	80		i	
AlAs	627		10.9			2.16	1200	420	i	
AlSb	585	0.571	11		3.2	1.60	200–400	550	i	
GaP	635	0.110	11.1	–13.8	3.2	2.24	300	150	i	
GaAs	535	0.771	13.2	–16.2	3.30	1.35	8800	400	d	
GaSb	493	0.457	15.7	–14.2	3.8	0.67	4000	1400	d	
InP	560	0.735	12.4	–22.8	3.1	1.27	4600	150	d	
InAs	477	0.549	14.6	–27.7	3.5	0.36	33000	460	d	
InSb	447	0.442	17.7	–32.9	3.96	0.163	78000	750	d	

* i = indirect, d = direct, s = semimetal.

Other sphalerite structure compounds										
MnS										See also §A3
MnSe										See also §A3
β-SiC					2.697	2.3	4000			
Ga_2Te_3	271			–13.5		1.35	50			
In_2Te_3(H.T.)	198			–13.6		1.04	50			
$MgGeP_2$										El–T^{d12}
$ZnSnP_2$						2.1				Same
$ZnSnAs_2$(H.T.)						≈0.7				Same
$ZnSnSb_2$						0.4				Same

§A3. Wurtzite (Zincite) Structure Compounds (Strukturbericht symbol B4, Space Group P 6_3 mc-C^4_{6v})

I VII Compounds										
CuCl										
CuBr										
CuI										
AgI						2.63				Iodargirite
II VI Compounds										
BeO										
MgTe										
ZnO	–350					3.2	180			
ZnS	–206					3.67				
ZnTe	–163									
CdS			8.45; 9.12		2.32	2.42	350	40	d	Greenockide
CdSe						1.74	900	50	d	Cadmoselite
CdTe						1.50	650			

Table II
Basic Thermodynamic, Electrical, and Magnetic Properties of Semiconductors (Listed by Crystal Structure)

Substance	Heat of Formation [kJ/mole (300K)]	Volume Compressibility ($10^{-10}m^2/N$)	Static Dielectric Constant	Atomic Magnetic Susceptibility (10^{-6} CGS)	Index of Refraction	Miniumum Room Temperature Energy Gap (eV)	Mobility (Room Temp.) ($cm^2/V{\cdot}s$)		Optical Transition	Remarks
							Electrons	Holes		
III V Compounds										
BP(H.T.)										
AlN						6.02				
GaN						3.34				
lnN						2.0				
Other wurtzite structure compounds										
MnS										
MnSe										
SiC					2.654					
MnTe						≈1.0				
Al_2S_3	426					4.1				
Al_2Se_3	367					3.1				

§A4. Chalcopyrite Structure Compounds (Strukturbericht symbol $E1_1$, Space Group I $\bar{4}$ 2d-D^{12}_{2d})

Substance	Heat of Formation [kJ/mole (300K)]	Volume Compressibility ($10^{-10}m^2/N$)	Static Dielectric Constant	Atomic Magnetic Susceptibility (10^{-6} CGS)	Index of Refraction	Miniumum Room Temperature Energy Gap (eV)	Electrons	Holes	Optical Transition	Remarks
I III VI_2 Compounds										
$CuAlS_2$		0.106				2.5				
$CuAlSe_2$						1.1				
$CuAlTe_2$						0.88				
$CuCaS_2$		0.106				2.38				
$CuGaSe_2$		0.141				0.96, 1.63				
$CuGaTe_2$		0.227				0.82, 1.0				
$CulnS_2$		0.141				1.2				
$CulnSe_2$		0.187				0.86, 0.92				
$CulnTe_2$		0.278				0.95				
$CuTlS_2$										
$CuTlSe_2$(L.T.)						1.07				
$CuFeS_2$						0.53				Chalcopyrite
$CuFeSe_2$						0.16				
$CuLaS_2$										
$AgAlS_2$										

$AgAlSe_2$					0.7			
$AgAlTe_2$					0.56			
$AgGaS_2$		0.150			1.66			
$AgGaSe_2$		0.182			1.1			
$AgGaTe_2$		0.280			1.9			
$AgInS_2$(L.T.)		0.185			1.18			
$AgInSe_2$		0.238			0.96, 0.52			
$AgInTe_2$		0.338						
$AgFeS_2$								
V V_2 Compounds								
$ZnSiP_2$	312				2.3	1000		
$ZnGeP_2$	293				2.2			
$ZnSnP_2$	275				1.45			
$CdSiP_2$		0.103			2.2	1000		
$CdGeP_2$	289				1.8			
$CdSnP_2$	270				1.5			
$ZnSiAs_2$	290				1.7		50	
$ZnGeAs_2$	271			–14.4	0.85			
$ZnSnAs_2$	252			–18.4	0.65		300	Disorders at 910K
$CdSiAs_2$		0.143			1.6			
$CdGeAs_2$	266			–23.4	0.53	70	25	Disorders at 903
$CdSnAs_2$	247		13.7	–21.5	0.26	22000	250	

§A5. Other Ternary Semiconductors with Tetrahedral Coordination

IV VI_3 Compounds								
Cu_2SiS_3(H.T.)								Wurtzite
Cu_2SiS_3(L.T.)								Tetragonal
Cu_2SiTe_3								Cubic
Cu_2GeS_3(H.T.)				–18.7				Cubic
Cu_2GeS_3(L.T.)						360		Tetragonal
Cu_2GeSe_3	211.5			–21.3	0.94	238		Same
Cu_2GeTe_3	190.2			–23.4				Same
Cu_2SnS_3				–18.2	0.91	405		Cubic
$CuSnSe_3$				–21.0	0.66	870		Cubic
Cu_2SnTe_3				–28.4				Cubic
Ag_2GeSe_3				–29.6	0.91 (77K)			
Ag_2SnSe_3				–29.5	0.81			
Ag_2GeTe_3				–31.4	0.25			
Ag_2SnTe_3				–31.10	0.08			

Table II
Basic Thermodynamic, Electrical, and Magnetic Properties of Semiconductors (Listed by Crystal Structure)

Substance	Heat of Formation [kJ/mole (300K)]	Volume Compressibility ($10^{-10}m^2/N$)	Static Dielectric Constant	Atomic Magnetic Susceptibility (10^{-6} CGS)	Index of Refraction	Miniumum Room Temperature Energy Gap (eV)	Mobility (Room Temp.) ($cm^2/V\cdot s$) Electrons	Holes	Optical Transition	Remarks
V VI_4 Compounds										
Cu_3PS_4										Enargite
Cu_3AsS_4	269.6			–15.8		1.24				
Cu_3AsSe_4	161.3			–13.1		0.88				Famatinite
Cu_3SbS_4				–8.3		0.74				Famatinite
Cu_3SbSe_4	127.1			–20.5		0.31				
V_2 V_3 Compounds										
$CuSi_2P_3$										El
$CuGe_2P_3$		0.12				0.90				El
$AgGe_2P_3$										
§A6. "Defect Chalcopyrite" Structure Compounds (Strukturbericht symbol E3, Space Group I $\bar{4}$-S_4^2)										
$ZnAl_2Se_4$										
$ZnAl_2Te_4$(?)										
$ZnGa_2S_4$(?)						≈3.4				
$ZnGa_2Se_4$(?)						≈2.2				
$ZnGa_2Te_4$(?)						1.35				
$Znln_2Se_4$	206					1.82	35			
$Znln_2Te_4$	198					1.2				
$CdAl_2S_4$										
$CdAl_2Se_4$										
$CdAl_2Te_4$(?)										
$CdGa_2S_4$	256					3.44	60			
$CdGa_2Se_4$	216					2.43	33			
$CdGa_2Te_4$										
$Cdln_2Te_4$	195					(1.26 or 0.9)	4000			
$HgAl_2S_4$										
$HgAl_2Se_4$										

$HgAl_2Te_4$(?)									
$HgGa_2S_4$	249					2.84			
$HgGa_2Se_4$	204					1.95	400		
$HgIn_2Se_4$	196					0.6	290		
$HgIn_2Te_4$(?)	188					0.86	200		
§A7. Other Adamantine Compounds									
αSiC		10.2	–6.4	2.67	2.86	400			6H structure
$Hg_5Ga_2Te_8$									B3 with superlattice
$Hg_5In_2Te_8$					0.7	2000			B3 with superlattice
$CdIn_2Se_4$					1.55				
Part B. Octahedral Semiconductors									
§B1. Halite Structure Semiconductors (Strukturbericht symbol B1, Space Group Fm3m-O_h^5)									
GeTe									
SnSe									
SnTe									
PbS	435					0.5	600	600	
PbSe	393		161			0.37	1000	900	
PbTe	393		280			0.26	1600	600	Altaite
			360			0.25			
Selected Other Binary Halites									
BiSe									
BiTe						0.4			
EuSe									
GdSe						1.8	4		
NiD						2.0 or 3.7	100		
CdO	531					2.5			
SrSW						4.1			
Part C. Other Semiconductors									
§C1. Antifluorite Structure Compounds (Fm3m-O_h^5)									
Mg_2Si	79.08					0.77	405	70	
Mg_2Ge						0.74	520	110	
Mg_2Sn	76.57					0.36	320	260	
Mg_2Pb	52.72					0.1			

Table II
Basic Thermodynamic, Electrical, and Magnetic Properties of Semiconductors (Listed by Crystal Structure)

Substance	Heat of Formation [kJ/mole (300K)]	Volume Compressibility ($10^{-10}m^2/N$)	Static Dielectric Constant	Atomic Magnetic Susceptibility (10^{-6} CGS)	Index of Refraction	Miniumum Room Temperature Energy Gap (eV)	Mobility (Room Temp.) ($cm^2/V{\cdot}s$)		Optical Transition	Remarks
							Electrons	Holes		
§C2. Tetradymite Structure Compounds ($R\bar{3}m\text{-}D^5_{3d}$)										
Sb_2Te_3						0.3		360		
Bi_2Se_3						0.35	600			
Bi_2Te_3						0.21	1140	680		R3m (166)
§C3. Skutterudite Structure Compounds ($Im3\text{-}T^5_h$)										
CoP_3						0.43				
$CoAs_3$						0.69		–4000		
$CoSb_3$						0.63	70	–3000		
RhP_3								700		
$RhAs_3$						0.85		–3000		
$RhSb_3$						0.80		–7000		
$IrSb_3$						1.18		1500		
§C4. Selected Multinary Compounds										
$AgSbSe_2$						0.58				
$AgSbTe_2$ (or $Ag_{19}Sb_{29}Te_{52}$)						0.7, 0.27				
$AgBiS_2$(H.T.)										
$AgBiSe_2$(H.T.)										
$AgBiTe_2$(H.T.)										
Cu_2CdSnS_4						1.16	<2			
§C5. Some Elemental Semiconductors										
B	397.1			–6.7	3.4	1.55	10			
Se(gray)			6.6 (0.1 GHz)	–22.1	2.5	1.5		5		$P3_121(152)$
Te				–39.5	3.3	0.33	1700	1200		Same

Table III
Semiconducting Properties of Selected Materials

Substance	Minimum Energy Gap (eV) R.T.	Minimum Energy Gap (eV) 0 K	$dE_g/dT \times 10^4$ cV/°C	$dE_g/dP \times 10^6$ cV·cm²/kg	Density of States Electron Effective Mass m_{da} (m_o)	Electron Mobility and Temperature Dependence μ_n cm²/V·s	Electron Mobility and Temperature Dependence –x	Density of States Hole Effective Mass m_{dp} (m_n)	Role Mobility and Temperature Dependence μ_p cm²/V·s	Role Mobility and Temperature Dependence –x
Si	1.107	1.153	–2.3	–2.0	1.1	1900	2.6	0.56	500	2.3
Ge	0.67	0.744	–3.7	+7.3	0.55	3800	1.66	0.3	1820	2.33
αSn	0.08	0.094	–0.5		0.02	2500	1.65	0.3	2400	2.0
Te	0.33				0.08	1100		0.19	560	
III-V Compounds										
AlAs	2.2	2.3				1200			420	
AlSb	1.6	1.7	–3.5	–1.6	0.09	200	1.5	0.4	500	1.8
GaP	2.24	2.40	–5.4	–1.17	0.35	300	1.5	0.5	150	1.5
GaAs	1.35	1.53	–5.0	+9.4	0.068	9000	1.0	0.5	500	2.1
GaSb	0.67	0.78	–3.5	+12	0.050	5000	2.0	0.23	1400	0.9
InP	1.27	1.41	–4.6	+4.6	0.067	5000	2.0		200	2.4
InAs	0.36	0.43	2.8	+8	0.022	33,000	1.2	0.41	460	2.3
InSb	0.165	0.23	–2.8	+15	0.014	78,000	1.6	0.4	750	2.1
II-VI Compounds										
Zn()	3.2		–0.5	+0.6	0.38	180	1.5			
ZnS	3.54		–5.3	+5.7		180			5(400°C)	
ZnSe	2.58	2.80	–7.2	+6		540			28	
ZnTe	2.26			+6		340			100	
CdO	2.5 ± .1		–6		0.1	120				
CdS	2.4		–5	+3.3	0.165	400		0.8		
CdSe	1.74	1.85	–4.6		0.13	650	1.0	0.6		
GdTe	1.44	1.56	–4.1	+8	0.14	1200		0.35	50	
HgSe	0.30				0.030	20,000	2.0			
HgTe	0.15		–1		0.017	25,000		0.5	350	
Halite Structure Compounds										
PbS	0.37	0.28	+4		0.16	800		0.1	1000	2.2
PbSe	0.26	0.16	+4		0.3	1500		0.34	1500	2.2
PbTe	0.25	0.19	+4	–7	0.21	1600		0.14	750	2.2

Properties of Semiconductors (continued)

Table III
Semiconducting Properties of Selected Materials

Substance	Minimum Energy Gap (eV) R.T.	Minimum Energy Gap (eV) 0 K	$dE_g/dT \times 10^4$ cV/°C	$dE_g/dP \times 10^6$ cV·cm²/kg	Density of States Electron Effective Mass m_{da} (m_o)	Electron Mobility and Temperature Dependence μ_n cm²/V·s	Electron Mobility and Temperature Dependence –x	Density of States Hole Effective Mass m_{dp} (m_n)	Role Mobility and Temperature Dependence μ_p cm²/V·s	Role Mobility and Temperature Dependence –x
Others										
ZnSb	0.50	0.56			0.15	10				1.5
CdSb	0.45	0.57	–5.4		0.15	300			2000	1.5
Bi_2S_3	1.3					200			1100	
Bi_2Se_3	0.27					600			675	
Bi_2Te_3	0.13		–0.05		0.58	1200	1.68	1.07	510	1.95
Mg_2Si		0.77	–6.4		0.46	400	2.5		70	
Mg_2Ge		0.74	–9			280	2		110	
Mg_2Sn	0.21	0.33	–3.5		0.37	320			260	
Mg_3Sb_2		0.32				20			82	
Zn_3As_2	0.93					10	1.1		10	
Cd_3As_2	0.55				0.046	100,000	0.88			
GaSe	2.05		3.8						20	
GaTe	1.66	1.80	–3.6			14	–5			
InSe	1.8					900				
TlSe	0.57		–3.9		0.3	30		0.6	20	1.5
$CdSnAs_2$	0.23				0.05	25,000	1.7			
Ga_2Te_2	1.1	1.55	–4.8							
α-ln_2Te_2	1.1	1.2			0.7				50	1.1
β-ln_2Te_2	1.0								5	
$Hg_5ln_2Te_8$	0.5								11,000	
SnO_2									78	

Table IV
Band Properties of Semiconductors

Part A. Data on Valence Bands of Semiconductors (Room Temperatures)

Substance	Band Curvature Effective Mass (Expressed as Fraction of Free Electron Mass)			Energy Separation of "Split-Off" Band (eV)	Measured (Light) Hole Mobility $cm^2/V \cdot s$
	Heavy Holes	Light Holes	"Split-Off" Band Boles		
Semiconductors with Valence Band Maximum at the Center of the Brillouin Zone ("F")					
Si	0.52	0.16	0.25	0.044	500
Ge	0.34	0.043	0.08	0.3	1820
Sn	0.3				2400
AlAs					
AlSb	0.4			0.7	550
GaP				0.13	100
GaAs	0.8	0.12	0.20	0.34	400
GaSb	0.23	0.06		0.7	1400
InP				0.21	150
InAs	0.41	0.025	0.083	0.43	460
InSb	0.4	0.015		0.85	750
CdTe	0.35				50
HgTe	0.5				350

Semiconductors with Multiple Band Maxima

Substance	Number of Equivalent Valleys and Direction	Band Curvature Effective Masses		Anistrophy	Measured (Light) Hole Mobility $cm^2/V \cdot s$
		Longitudinal m_L	Transverse m_T	$K = m_L/m_T$	
PbSe	4 "L" [111]	0.095	0.047	2.0	1500
PbTe	4 "L" [111]	0.27	0.02	10	750
Bi_2Te_3	6	0.207	~0.045	4.5	515

Properties of Semiconductors (continued)

Table IV
Band Properties of Semiconductors

Part B. Data on Conduction Bands of Semiconductors (Room temperature Data)

Single Valley Semiconductors

Substance	Energy Gap (eV)	Effective Mass (m_o)	Mobility ($cm^2/V \cdot s$)	Comments
GaAs	1.35	0.067	8500	3(or 6?) equivalent [100] valleys 0.36 eV above this maximum with a mobility of ~50
InP	1.27	0.067	5000	3(or 6?) equivalent [100] valleys 0.4 eV above this minimum.
InAs	0.36	0.022	33,000	Equivalent valleys ~1.0 eV above this minimum.
InSb	0.165	0.014	78,000	
CdTe	1.44	0.11	1000	4(or 8?) equivalent [111] valleys 0.51 eV above this minimum.

Multivalley Semiconductors

Substance	Energy Gap	Number of Equivalent Valleys and Direction	Band Curvature Effective Mass		Anisotropy $K = m_L/m_T$	Comments
			Longitudinal m_L	Transverse m_T		
Si	1.107	6 in [100] "Δ"	0.00	0.192	4.7	
Ge	0.6	4 in [111] at "L"	1.588	0.0815	19.5	
GaSb	0.67	as Ge (?)	~1.0	~0.2	~5	
PbSe	0.26	4 in [111] at "L"	0.085	0.05	1.7	
PbTe	0.25	4 in [111] at "L"	0.21	0.029	5.5	
Bi_2Te_2	0.13	6			~0.05	

Table V
Resistivity of Semiconducting Minerals

Mineral	ρ (ohm · m)	Mineral	ρ (ohm · m)
Diamond (C)	2.7	Gersdorfite, NiAsS	1 to 160 × 10^{-6}
Sulfides		Glaucodote, (Co, Fe)AsS	5 to 100 × 10^{-6}
Argentite, Ag_2S	1.5 to 2.0 × 10^{-3}	Antimonide	
Bismuthinite, Bi_2S_3	3 to 570	Dyscrasite, Ag_3Sb	0.12 to 1.2 × 10^{-6}
Bornite, $Fe_2S_3 \cdot nCu_3S$	1.6 to 6000 × 10^{-4}	Arsenides	
Chalcocite, Cu_2S	80 to 100 × 10^{-6}	Allemonite, $SbAs_1$	70 to 60,000
Chalcopyrite, $Fe_2S_1 \cdot Cu_1S$	150 to 9000 × 10^{-6}	Lollingite, $FeAs_2$	2 to 270 × 10^{-6}
Covellite, CuS	0.30 to 83 × 10^{-6}	Nicollite, NiAs	0.1 to 2 × 10^{-6}
Galena, PbS	6.8 × 10^{-6} to 9.0 × 10^{-2}	Skutterudite, $CoAs_3$	1 to 400 × 10^{-6}
Haverite, MnS_2	10 to 20	Smaltite, $CoAs_2$	1 to 12 × 10^{-6}
Marcasite, FeS_2	1 to 150 × 10^{-2}	Tellurides	
Metacinnabarite, 4HgS	2 × 10^{-6} to 1 × 10^{-3}	Altaite, PbTe	20 to 200 × 10^{-6}
Millerite, NiS	2 to 4 × 10^{-7}	Calavarite, $AuTe_2$	6 to 12 × 10^{-6}
Molybdenite, MoS_2	0.12 to 7.5	Coloradoite, HgTe	4 to 100 × 10^{-6}
Pentlandite, $(Fe, Ni)_4S_4$	1 to 11 × 10^{-6}	Hessite, Ag_2Te	4 to 100 × 10^{-6}
Pyrrhotite, Fe_7S_4	2 to 160 × 10^{-6}	Nagyagite, $Pb_6Au(S,Te)_{14}$	20 to 80 × 10^{-6}
Pyrite, FeS_2	1.2 to 600 × 10^{-3}	Sylvanite, $AgAuTe_4$	4 to 20 × 10^{-6}
Sphalerite, ZnS	2.7 × 10^{-2} to 1.2 × 10^{4}	Oxides	
Antimony-sulfur compounds		Braunite, Mn_2O_1	0.16 to 1.0
Berthierite, $FeSb_2S_4$	0.0083 to 2.0	Cassiterite, SnO_3	4.5 × 10^{-4} to 10,000
Boulangerite, $Pb_5Sb_3S_{11}$	2 × 10^{3} to 4 × 10^{4}	Cuprite, Cu_2O	10 to 50
Cylindrite, $Pb_3Sn_4Sb_2S_{14}$	2.5 to 60	Hollandite, (Ba, Na, K) Mn_8O_{16}	2 to 100 × 10^{-3}
Franckeite, $Pb_5Sn_1Sb_2S_{14}$	1.2 to 4	Ilmenite, $FeTiO_1$	0.001 to 4
Hauchecornite, $Ni_4(Bi, Sb)_2S_4$	1 to 83 × 10^{-6}	Magnetite, Fe_1O_4	52 × 10^{-6}
Jamesonite, $Pb_4FeSb_6S_{14}$	0.020 to 0.15	Manganite, MnO · OH	0.018 to 0.5
Tetrahedrite, Cu_3SbS_3	0.30 to 30,000	Melaconite, CuO	6000
Arsenic-sulfur compounds		Psilomelane, $KMnO \cdot MnO_1 \cdot nH_2O$	0.04 to 6000
Arsenopyrite, FeAsS	20 to 300 × 10^{-6}	Pyrolusite, MnO_2	0.007 to 30
Cobaltite, CoAsS	6.5 to 130 × 10^{-3}	Rutile, TiO_2	29 to 910
Enargite, Cu_3AsS_4	0.2 to 40 × 10^{-3}	Uraninite, UO	1.5 to 200

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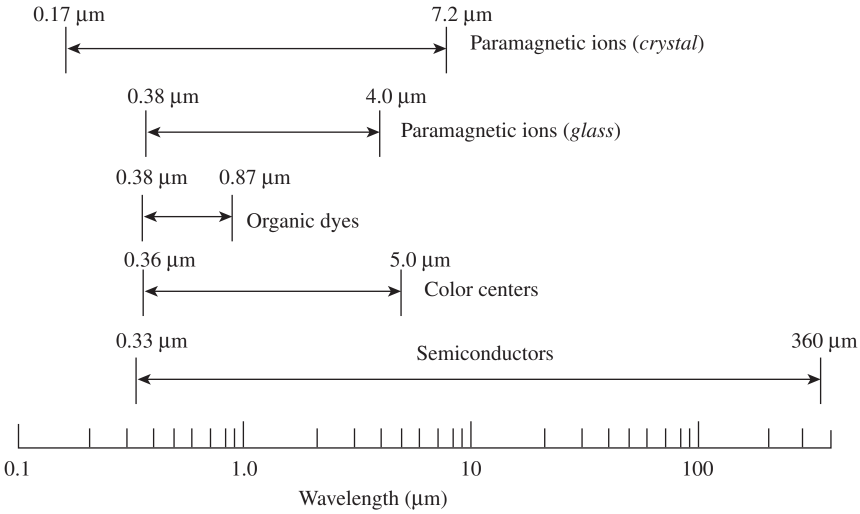
From Berger, L.I. and Pamplin, B.R., Properties of semiconductors, in *CRC Handbook of Chemistry and Physics*, 83rd ed., Lide, D., Ed., CRC Press, Boca Raton, FL, 2002, pp. **12**-97 to **12**-107. Originally from Carmichael, R.S., ed., *Handbook of Physical Properties of Rocks,* Vol. I, CRC Press, 1982.

Solid State Lasers

Solid state lasers include lasers based on paramagnetic ions, organic dye molecules, and color centers in crystalline or amorphous hosts. Semiconductor lasers are included in this section because they are a solid-state device, although the nature of the active center—recombination of electrons and holes—is different from the dopants or defect centers used in other lasers in this category. Conjugated polymer lasers, solid-state excimer lasers, and fiber raman, Brillouin, and soliton lasers are also covered in this section.

Reported ranges of output wavelengths for the various types of solid state lasers are shown in the figure. The differences in the ranges of spectral coverage arise in part from the dependence on host properties, in particular the range of transparency and the rate of nonradiative decay due to multiphonon processes.



Reported ranges of output wavelengths for various types of solid state lasers.

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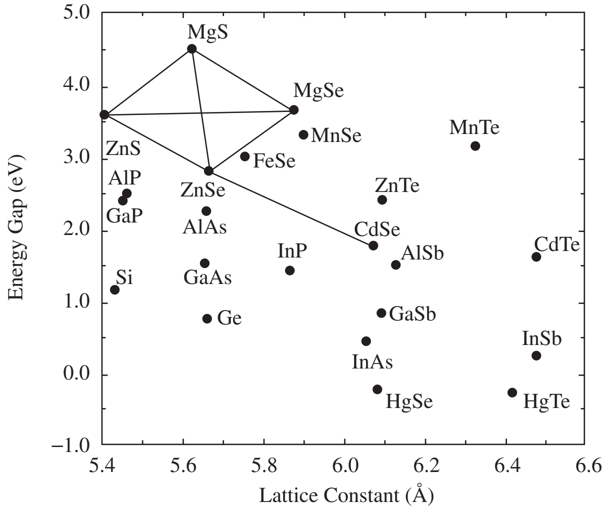
III-V Material Systems with Important Optoelectronic Applications

Material System	Substrate	Lattice-Matched Members	Important Strained Members	Main Optoelectronic Applications
AlGaAs	GaAs	GaAs $Al_xGa_{1-x}As$ $0 \le x \le 1$ AlAs	$Ga_{1-x}In_xAs$ $0 \le x \le 0.25$	Emitters and modulators: $0.75\ \mu m \le \lambda \le 1.1\ \mu m$, Detectors: $0.4\ \mu m \le \lambda \le 1.1\ \mu m$ Saturable absorbers: $\lambda \sim 0.8–0.9\ \mu m$
GaInAsP/InP	InP	$Ga_{0.47}In_{0.53}As$ $Ga_xIn_{1-x}AsyP_{1-y}$ $x = 0.47\ y;\ 0 \le y \le 1$ InP	$Ga_{1-x}In_xAs$ $0.4 \le x \le 0.6$ $InAs_xP_{1-x}$ $0 \le x \le 0.2$	Optoelectronic devices at $\lambda = 1.3\ \mu m$ and $1.55\ \mu m$
AlGaInAs/InP	InP	$Ga_{0.47}In_{0.53}As$ $(Al_xGa_{1-x})_{0.47}In_{0.53}As$ $0 \le x \le 1$ $Al_{0.48}In_{0.52}As$	$Ga_{1-x}In_xAs$ $0.4 \le x \le 0.6$	Optoelectronic devices at $\lambda = 1.3\ \mu m$ and $1.55\ \mu m$
AlGaInP	GaAs	GaAs $Ga_{0.5}In_{0.5}P$ $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ $0 \le x \le 1$ $Al_{0.5}In_{0.5}P$	$Ga_{1-x}In_xAs$ $0 \le x \le 0.25$ $Ga_{1-x}In_xP$ $0.4 \le x \le 0.6$	Red emitters
AlGaAsSb/ GaInAsSb/ GaSb	GaSb	GaSb $Al_xGa_{1-x}As_ysb_{1-y}$ $x = 12\ y;\ 0 \le x \le 1$ $Ga_{1-x}In_xAs_{1-y}Sb_y$ $x = 1.1\ y;\ 0 \le x \le 1$		Emitters and detectors: $\lambda \sim 2\text{-}3\ \mu m$
GaAsP	GaAs or GaP	GaAs (on GaAs substrates); GaP (on GaP substrates)	GaAsP	Visible LED's

From Wicks, G.W., III-V Semiconductor materials, in *Handbook of Photonics*, Gupta, M.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 6.



Energy Gap and lattice parameters for cubic group IV, III-V and II-VI semiconductors. (From Luo, H. and Petrou, A., Optical properties and optoelectronic applications of II-VI semiconductor heterostructures, in *Handbook of Photonics*, Gupta, M.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 26.)

Important Parameters of Semiconductors of Interest for Conventional Electronics and Emerging High Temperature Electronics

Property	Si	GaAs	GaP	3C SiC (6H SiC)	Diamond	GaN
Bandgap (eV) at 300K	1.1	1.4	2.3	2.2 (2.9)	5.5	3.39
Maximum operating temperature (K)	600?	760?	1250?	1200 (1580) sublimes	1400(?) phase change	
Melting point (K)	1690	1510	1740	>2100		
Physical stability	Good	Fair	Fair	Excellent	Very good	Good
Electron mobility R.T., cm^2/V-s	1400	8500	350	1000 (600)	2200	900
Hole mobility R.T., cm^2/V-s	600	400	100	40	1600	50?
Breakdown voltage E_b, 10^6/V/cm	0.3	0.4	—	4	10	5?
Thermal conductivity K, W/cm-C	1.5	0.5	0.8	5	20	1.3
Sat. elec. drift vel. v(sat), 10^7 cm/s	1	2	—	2	2.7	2.7
Dielectric const, K	11.8	12.8	11.1	9.7	3.5	9

From Morkoc, H., GaN and silicon carbide as optoelectronic materials, in *Handbook of Photonics*, Gupta, M.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 52.

Properties of GaN(a), AIN(b), and InN(c)

Wurtzite Polytype		
Bandgap energy	E_g (300K) = 3.39 eV	E_g (1.6K) = 3.50 eV
Temperature coefficient	$\frac{dE_g}{dT} = 6.0 \times 10^{-4}$ eV/K	
Pressure coefficient	$\frac{dE_g}{dP} = 4.2 \times 10^{-3}$ eV/kbar	
Lattice constants	a = 3.189 ≈ Å	
Thermal expansion	$\frac{\Delta a}{a} = 5.59 \times 10^{-6}/\text{K}$	$\frac{\Delta c}{c} = 3.17 \times 10^{-6}/\text{K}$
Thermal conductivity	κ = 1.3 W/cmK	
Index of refraction	n(1 eV) = 2.33	n(3.38 eV) = 2.67
Dielectric constants	$\in_r \approx 9$	$\in_\infty = 5.35$
Zincblende Polytype		
Bandgap energy	E_g (300K) = 3.2–3.3 eV	
Lattice constant	a = 4.52 Å	
Index of refraction	n(3 eV) = 2.5	
Bandgap energy	E_g (300K) = 6.2 eV	E_g (5K) = 6.28 eV
Lattice constants	a = 3.112 Å, c = 4.982 Å	
Thermal expansion	$\frac{\Delta a}{a} = 4.2 \times 10^{-6}/\text{K}$	$\frac{\Delta c}{c} = 5.3 \times 10^{-6}/\text{K}$
Thermal conductivity	κ = 2\W/cmK	
Index of refraction	n(3eV) = 2.15 ± 0.05	
Dielectric constants	$\in_r \approx 8.5 \pm 0.2$	$\in_\infty$ = 4.68–4.84
Zincblende Polytype		
Bandgap energy	E_g (300K) = 5.11 eV, theory	
Lattice constant	a = 4.38 Å	
Bandgap energy	E_g (300K) = 1.89 eV	
Temperature coefficient	$\frac{dE_g}{dT} = 1.8 \times 10^{-4}$ eV/K	
Lattice constants	a = 3.5438 Å	c = 5.760 Å
Index of refraction	n = 2.80–3.05	
Dielectric constants	$\in_r \approx$	
Zincblende Polytype		
Bandgap energy	E_g (300K) = 2.2 eV, theory	
Lattice constant	a = 4.98 Å	

From Morkoc, H., GaN and silicon carbide as optoelectronic materials, in *Handbook of Photonics*, Gupta, M.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 65.

List of Ferroelectric Materials and Their Crystal Growth Methods

Family	Ferroelectric Material	Chemical Formula	Abbrev.	Growth Method
Perovskite type	Barium titanate	$BaTiO_3$	—	Remeika method Top seed pulling method
	Potassium niobate	$KNbO_3$	—	Spontaneous nucleation and slow cooling Top seed solution growth Kyropoulos pulling
	Potassium tantalate	$KTaO_3$	—	The same as $KNbO_3$
	Potassium tantalate niobate	$KTa_{1-x}Nb_xO_3$	KTN	Kyropoulos technique Top seed solution growth
	Lead Ianthanum zirconate titanate (in the form of ceramics)	$Pb_{1-x}(Zr_yTi_{1-y})_{1-0.25x} V^B_{0.25x}O_3$	PLZT	Chemical coprecipitation of powder and subsequent hot-pressing in oxygen environment
Lithium niobate family	Lithium niobate	$LiNbO_3$	—	Czochralski's technique
	Lithium tantalate	$LiTaO_3$	—	Czochralski's technique
Tungsten-bronzetype	Barium strontium niobate	$Ba_{5x}Sr_{5(1-x)}Nb_{10}O_{30}$	SBN	Czochralski's method
	Barium sodium niobate	$Ba_{5x}Na_{5(1-x)}Nb_{10}O_{30}$	BNN	Czochralski's method
	Potassium lithium niobate	$K_3Li_2Nb_5O_{15}$	KLN	Kyropoulos method
	Potassium sodium strontium niobate	$(K_xNa_{1-x})_{0.4}(Sr_yBa_{1-y})_{0.8} Nb_2O_6$	KNSBN	Czochralski's technique
KDP family	Potassium dihydrogen phosphate	KH_2PO_4	KDP	Water solution temperature reduction method
	Potassium dihydrogen arsenate	KH_2AsO_4	KDA	The same as KDP
	Rubidium dihydrogen phosphate	RbH_2PO_4	RDP	The same as KDP
TGS type	Triglycine sulphate	$(NH_2CH_2COOH)_3 \cdot H_2SO_4$	TGS	Temperature reduction method
	Triglycine selenate	$(NH_2CH_2COOH)_3 \cdot H_2S_eO_4$	TGSe	The same as TGS
KTP family	Potassium titanyl phosphate	$KTiOPO_4$	KTP	Top seed flux growth
Bismuth titanate	Bismuth titanate	$Bi_4Ti_3O_{12}$	—	Flux-growth method
Rare earth molybdate	Gadolinium molybdate	β-$Gd_2(MoO)_3$	GMO	Pulling from melt
Lead germanium oxide	Lead germanium oxide	$5PbO \cdot 3GeO_2$, or $Pb_5Ge_3O_{11}$	—	Czochralski's technique Bridgman's technique
Antimony sulphoiodide	Antimony sulphoiodide	SbSI		Vapor phase growth

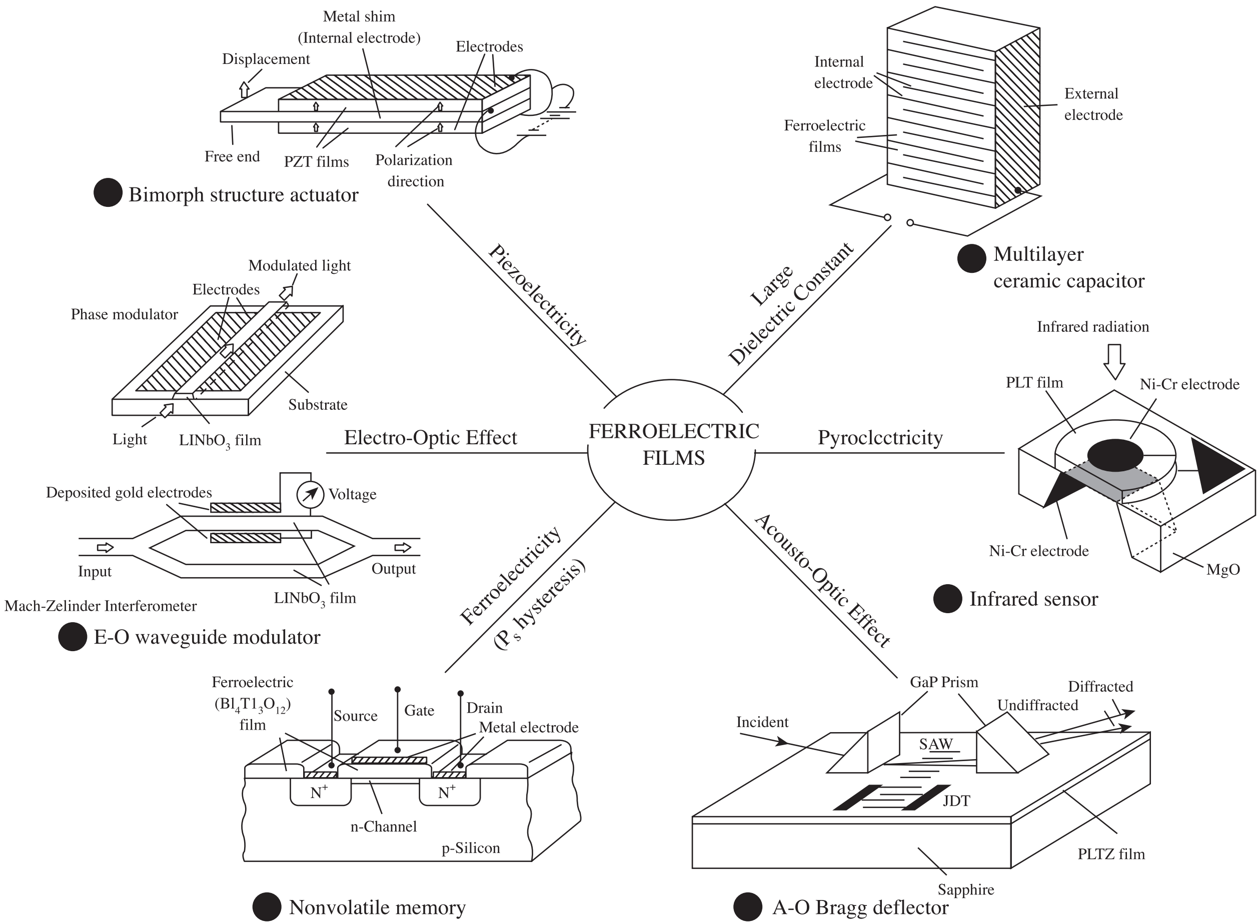
From Li, C.-Y. and Xu, Y., Ferroelectric materials, in *Handbook of Photonics*, Gupta, M.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 93. Originally from Xu, Y., *Ferroelectric Materials and Their Applications*, Elsevier Science Publishers B.V., Amsterdam, The Netherlands, 1991. With permission.

General Physical Properties of Ferroelectric Materials

Chemical Formula	Point Group*	Phase Transition Temperature (°C)	Spontaneous Polarization (μC/cm²)	Density (g/cm³)	Melting Point (°C)
$BaTiO_3$	*m*3*m* → **4*mm*** → *mm*2 → 3*m*	120, 5, –90	26	6.02	1618
$KNbO_3$	*m*3*m* → 4*mm* → ***mm*2** → 3*m*	435, 225, –10	30		1050
$KTaO_3$	*m*3*m* → 4*mm* → ***mm*2** → 3*m*				
$KTa_{1-x}Nb_xO_3$	*m*3*m* → 4*mm* → ***mm*2** → 3*m*				
$Pb_{1-x}La_x(Zr_yTi_{1-y})_{1-.0.25x}V^B_{0.25x}O_3$				7.80	
$LiNbO_3$	$\bar{3}m$ → **3*m***	1210	71	4.64	1240
$LiTaO_3$	$\bar{3}m$ → **3*m***	665	50	7.45	1650
$Ba_{0.4}Sr_{0.6}Nb_2O_6$	(4/*m*)*mm* → **4*mm*** → *m*	75, –213	32	~5.4	~1480
$Ba_2NaNb_5O_{15}$	(4/*m*)*mm* → 4*mm* → ***mm*2**	560, 300	40	5.40	~1450
$K_3Li_2Nb_5O_{15}$	(4/*m*)*mm* → **4*mm***	430	~40		1250
$(K_xNa_{1-x})_{0.4}(Sr_yBa_{1-y})_{0.8}Nb_2O_6$	(4/*m*)*mm* → **4*mm***		~30	5.16	
KH_2PO_4(KDP)	$\bar{\mathbf{4}}\mathbf{2}\boldsymbol{m}$ → *mm*2	–150	–4.8	2.34	Decomposes at 180°C
KH_2AsO_4	$\bar{\mathbf{4}}\mathbf{2}\boldsymbol{m}$ → *mm*2	–176			
RbH_2PO_4	$\bar{\mathbf{4}}\mathbf{2}\boldsymbol{m}$ → *mm*2	–126			
$(NH_2CH_2COOH)_3 \cdot H_2SO_4$ (TGS)	2/*m* → 2	49	2.8	1.69	
$(NH_2CH_2COOH)_3 \cdot H_2SeO_4$	2/*m* → 2	26			
$KTiOPO_4$	*mmm* → ***mm*2**	943	~17		
$Bi_4Ti_3O_{12}$	(4/*m*)*mm* → ***m***	675	50, *a*-axis 4, *c*-axis	6.1	
β-$Gd_2(MoO)_3$	$\bar{4}2m$ → ***mm*2**	159	0.17		1175
5PbO · $3GeO_2$, or $Pb_5Ge_3O_{11}$	$\bar{6}$ → 3	177	4.8	7.33	738
SbSI	*mmm* → ***mm*2**	22	25 (0°C)	5.25	

* Point groups in bold are point groups at room temperature.

From Li, C.-Y. and Xu, Y., Ferroelectric materials, in *Handbook of Photonics*, Gupta, M.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 94. Originally from Xu, Y., *Ferroelectric Materials and Their Applications*, Elsevier Science Publishers B.V., Amsterdam, The Netherlands, 1991. With permission.



Applications of the ferroelectric thin films. (From Li, C.-Y. and Xu, Y., Ferroelectric materials, in *Handbook of Photonics*, Gupta, M.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 100.)

The Principal Photometric Units

Quantity	Defining Equation	SI Unit	US Unit	Conversion[1] Factor
Luminous flux	$F = Km \int_0^\infty V(\lambda)\, P(\lambda)\, d\lambda$	lumens	lumens	1
Intensity	$I = dF/d\Omega$	candela (lumens/steradian)	candela	1
Luminance	$L = dI/dA_e$	candela/m² (A_e is emitting area)	ft-lamberts (1 cd/π ft²)	0.2919
Illuminance	$E = dF/dA_i$	lux (lum/m²) (A_i is illumin'd area)	Foot-candle (1 lum/ft²)	0.09294

[1] From metric into U.S. units.

From Infante, C., Electronic displays, in *Handbook of Photonics*, Gupta, M.C., ed., CRC Press, Boca Raton, FL, 1997, p. 770.

Dielectric Constants of Common Materials

Material	Dielectric Constant (k)
Vacuum	1
Air	1.00054
Water	78
Paper	3.5
Porcelain	6.5
Fused quartz	3.8
Pyrex glass	4.5
Polyethylene	2.3
Amber	2.7
Polystyrene	2.6
Teflon	2.1
Transformer oil	4.5
Titanium dioxide	100

From Morgan, D., Applications, standards, and products for grounding and shielding, in *Instrument Engineers' Handbook: Process Software and Digital Networks,* 3rd ed., Liptak, B., Ed., CRC Press, Boca Raton, FL, 2002.

Characteristics of Coaxial Cables

Cable Type	Characteristic Impedance	Common Usage
RG-6	75	Broadband, Carrier Band Drop
RG-8	50	Thick Ethernet
RG-11	75	Broadband, Carrier Band Trunk
RG-58	50	Thin Ethernet
RG-59	75	Broadband Drop
RG-62	93	ARCnet

Note: Some references include the dash in RG-X, others do not.

From Barton, C.C., PLC proprietary and open networks, in *Instrument Engineers' Handbook: Process Software and Digital Networks,* 3rd ed., Liptak, B., Ed., CRC Press, Boca Raton, FL, 2002.

Dry Saturated Steam: Temperature Table

		Specific Volume, ft³/lbm†			Enthalpy, Btu/lbm†			Entropy, Btu/lbm R†		
Temp., °F/°C	Abs. Press., PSIA P†	Sat. Liquid v_f	Evap. v_{fg}	Sat. Vapor v_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Evap. s_{fg}	Sat. Vapor s_g
32/0	0.08854	0.01602	3306	3306	0.00	1075.8	1075.8	0.0000	2.1877	2.1877
35/1.7	0.09995	0.01602	2947	2947	3.02	1074.1	1077.1	0.0061	2.1709	2.1770
40/4.4	0.12170	0.01602	2444	2444	8.05	1071.3	1079.3	0.0162	2.1435	2.1597
45/7.2	0.14752	0.01602	2036.4	2036.4	13.06	1068.4	1081.5	0.0262	2.1167	2.1429
50/10	0.17811	0.01603	1703.2	1703.2	18.07	1065.6	1083.7	0.0361	2.0903	2.1264
60/15.6	0.2563	0.01604	1206.6	1206.7	28.06	1059.9	1088.0	0.0555	2.0393	2.0948
70/21.1	0.3631	0.01606	867.8	867.9	38.04	1054.3	1092.3	0.0745	1.9902	2.0647
80/26.7	0.5069	0.01608	633.1	633.1	48.02	1048.6	1096.6	0.0932	1.9428	2.0360
90/32.2	0.6982	0.01610	468.0	468.0	57.99	1042.9	1100.9	0.1115	1.8972	2.0087
100/37.8	0.9492	0.01613	350.3	350.4	67.97	1037.2	1105.2	0.1295	1.8531	1.9826
110/43	1.2748	0.01617	265.3	265.4	77.94	1031.6	1109.5	0.1471	1.8106	1.9577
120/49	1.6924	0.01620	203.25	203.27	87.92	1025.8	1113.7	0.1645	1.7694	1.9339
130/54	2.2225	0.01625	157.32	157.34	97.90	1020.0	1117.9	0.1816	1.7296	1.9112
140/60	2.8886	0.01629	122.99	123.01	107.89	1014.1	1122.0	0.1984	1.6910	1.8894
150/66	3.718	0.01634	97.06	97.07	117.89	1008.2	1126.1	0.2149	1.6537	1.8685
160/71	4.741	0.01639	77.27	77.29	127.89	1002.3	1130.2	0.2311	1.6174	1.8485
170/77	5.992	0.01645	62.04	62.06	137.90	996.3	1134.2	0.2472	1.5822	1.8293
180/82	7.510	0.01651	50.21	50.23	147.92	990.2	1138.1	0.2630	1.5480	1.8109
190/88	9.339	0.01657	40.94	40.96	157.95	984.1	1142.0	0.2785	1.5147	1.7932
200/93	11.526	0.01663	33.62	33.64	167.99	977.9	1145.9	0.2938	1.4824	1.7762
210/90	14.123	0.01670	27.80	27.82	178.05	971.6	1149.7	0.3090	1.4508	1.7598
212/100	14.696	0.01672	26.78	26.80	180.07	970.3	1150.4	0.3120	1.4446	1.7566
220/104	17.186	0.01677	23.13	23.15	188.13	965.2	1153.4	0.3239	1.4201	1.7440
230/110	20.780	0.01684	19.365	19.382	198.23	958.8	1157.0	0.3387	1.3901	1.7288
240/116	24.969	0.01692	16.306	16.323	208.34	952.2	1160.5	0.3531	1.3609	1.7140
250/121	29.825	0.01700	13.804	13.821	218.48	945.5	1164.0	0.3675	1.3323	1.6998
260/127	35.429	0.01709	11.746	11.763	228.64	938.7	1167.3	0.3817	1.3043	1.6860
270/132	41.858	0.01717	10.044	10.061	238.84	931.8	1170.6	0.3958	1.2769	1.6727
280/138	49.203	0.01726	8.628	8.645	249.06	924.7	1173.8	0.4096	1.2501	1.6597
290/143	57.556	0.01735	7.444	7.461	259.31	917.5	1176.8	0.4234	1.2238	1.6472
300/149	67.013	0.01745	6.449	6.466	269.59	910.1	1179.7	0.4369	1.1980	1.6350
310/154	77.68	0.01755	5.609	5.626	279.92	902.6	1182.5	0.4504	1.1727	1.6231
320/160	89.66	0.01765	4.896	4.914	290.28	894.9	1185.2	0.4637	1.1478	1.6115
330/166	103.06	0.01776	4.289	4.307	300.68	887.0	1187.7	0.4769	1.1233	1.6002
340/171	118.01	0.01787	3.770	3.788	311.13	879.0	1190.1	0.4900	1.0992	1.5891
350/177	134.63	0.01799	3.324	3.342	321.63	870.7	1192.3	0.5029	1.0754	1.5783
360/182	153.04	0.01811	2.939	2.957	332.18	862.2	1194.4	0.5158	1.0519	1.5677
370/188	173.37	0.01823	2.606	2.625	342.79	853.5	1196.3	0.5286	1.0287	1.5573
380/193	195.77	0.01836	2.317	2.335	353.45	844.6	1198.1	0.5413	1.0059	1.5471
390/199	220.37	0.01850	2.0651	2.0836	364.17	835.4	1199.6	0.5539	0.9832	1.5371
400/204	247.31	0.01864	1.8447	1.8633	374.97	826.0	1201.0	0.5664	0.9608	1.5272
410/210	276.75	0.01878	1.6512	1.6700	385.83	816.3	1202.1	0.5788	0.9386	1.5174
420/216	308.83	0.01894	1.4811	1.5000	396.77	806.3	1203.1	0.5912	0.9166	1.5078
430/221	343.72	0.01910	1.3308	1.3499	407.79	796.0	1203.8	0.6035	0.8947	1.4982
440/227	381.59	0.01926	1.1979	1.2171	418.90	785.4	1204.3	0.6158	0.8730	1.4887
450/232	422.6	0.0194	1.0799	1.0993	430.1	774.5	1204.6	0.6280	0.8513	1.4793
460/238	466.9	0.0196	0.9748	0.9944	441.4	763.2	1204.6	0.6402	0.8298	1.4700
470/243	514.7	0.0198	0.8811	0.9009	452.8	751.5	1204.3	0.6523	0.8083	1.4606

Dry Saturated Steam: Temperature Table (continued)

Temp., °F/°C t	Abs. Press., PSIA P†	Specific Volume, ft³/lbm† Sat. Liquid υ_f	Evap. υ_{fg}	Sat. Vapor υ_g	Enthalpy, Btu/lbm† Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Entropy, Btu/lbm R† Sat. Liquid s_f	Evap. s_{fg}	Sat. Vapor s_g
480/249	566.1	0.0200	0.7972	0.8172	464.4	739.4	1203.7	0.6645	0.7868	1.4513
490/254	621.4	0.0202	0.7221	0.7423	476.0	726.8	1202.8	0.6766	0.7653	1.4419
500/260	680.8	0.0204	0.6545	0.6749	487.8	713.9	1201.7	0.6887	0.7438	1.4325
520/271	812.4	0.0209	0.5385	0.5594	511.9	686.4	1198.2	0.7130	0.7006	1.4136
540/282	962.5	0.0215	0.4434	0.4649	536.6	656.6	1193.2	0.7374	0.6568	1.3942
560/293	1133.1	0.0221	0.3647	0.3868	562.2	624.2	1186.4	0.7621	0.6121	1.3742
580/304	1325.8	0.0228	0.2989	0.3217	588.9	588.4	1177.3	0.7872	0.5659	1.3532
600/316	1542.9	0.0236	0.2432	0.2668	617.0	548.5	1165.5	0.8131	0.5176	1.3307
620/327	1786.6	0.0247	0.1955	0.2201	646.7	503.6	1150.3	0.8398	0.4664	1.3062
640/338	2059.7	0.0260	0.1538	0.1798	678.6	452.0	1130.5	0.8679	0.4110	1.2789
660/349	2365.4	0.0278	0.1165	0.1442	714.2	390.2	1104.4	0.8987	0.3485	1.2472
680/360	2708.1	0.0305	0.0810	0.1115	757.3	309.9	1067.2	0.9351	0.2719	1.2071
700/371	3093.7	0.0369	0.0392	0.0761	823.3	172.1	995.4	0.9905	0.1484	1.1389
705.4/374.1	3206.2	0.0503	0	0.0503	902.7	0	902.7	1.0580	0	1.0580

† PSIA = 0.069 bar (abs); ft³/lbm = 62.4 l/kg; Btu/lbm = 0.556 Kcal/kg

From Liptak, B.G., Ed., *Instrument Engineers' Handbook: Process Software and Digital Networks,* 3rd ed., CRC Press, Boca Raton, FL, 2002, pp. 817–818. Originally abridged from *Thermodynamic Properties of Steam,* by Joseph H. Keenan and Fredrick G. Keyes. © 1936, by Joseph H. Keenan and Frederick G. Keyes. Published by John Wiley & Sons, Inc., New York.

Abs. Press., PSIA (Sat. Temp. °F)	Temperature, °F/°C 200/93	220/104	300/149	350/177	400/204	450/232	500/260	550/288	600/316	700/371	800/427	900/482	1000/538
υ	392.6	404.5	452.3	482.2	512.0	541.8	571.6	601.4	631.2	690.8	750.4	809.9	869.5
1 *h*	1150.4	1159.5	1195.8	1218.7	1241.7	1264.9	1288.3	1312.0	1335.7	1383.8	1432.8	1482.7	1533.5
(101.74) *s*	2.0512	2.0647	2.1153	2.1444	2.1720	2.1983	2.2233	2.2468	2.2702	2.3137	2.3542	2.3923	2.4283
υ	78.16	80.59	90.25	96.26	102.26	108.24	114.22	120.19	126.16	138.10	150.03	161.95	173.87
5 *h*	1148.8	1158.1	1195.0	1218.1	1241.2	1264.5	1288.0	1311.7	1335.4	1383.6	1432.7	1482.6	1533.4
(162.24) *s*	1.8718	1.8857	1.9370	1.9664	1.9942	2.0205	2.0456	2.0692	2.0927	2.1361	2.1767	2.2148	2.2509
υ	38.85	40.09	45.00	48.03	51.04	54.05	57.05	60.04	63.03	69.01	74.98	80.95	86.92
10 *h*	1146.6	1156.2	1193.9	1217.2	1240.6	1264.0	1287.5	1311.3	1335.1	1383.4	1432.5	1482.4	1533.1
(193.21) *s*	1.7927	1.8071	1.8595	1.8892	1.9172	1.9436	1.9689	1.9924	2.0160	2.0596	2.1002	2.1383	2.1744
υ		27.15	30.53	32.62	34.68	36.73	38.78	40.82	42.86	46.94	51.00	55.07	59.13
14.696 *h*		1154.4	1192.8	1216.4	1239.9	1263.5	1287.1	1310.9	1335.8	1383.2	1432.3	1482.3	1533.1
(212.00) *s*		1.7624	1.8160	1.8460	1.8743	1.9008	1.9261	1.9498	1.9734	2.0170	2.0576	2.0958	2.1319
υ			22.36	23.91	25.43	26.95	28.46	29.97	31.47	34.47	37.46	40.45	43.44
20 *h*			1191.6	1215.6	1239.2	1262.9	1286.6	1310.5	1334.4	1382.9	1432.1	1482.1	1533.0
(227.96) *s*			1.7808	1.8112	1.8396	1.8664	1.8918	1.9160	1.9392	1.9829	2.0235	2.0618	2.0978
υ			11.040	11.843	12.628	13.401	14.168	14.93	15.688	17.198	18.702	20.20	21.70
40 *h*			1186.8	1211.9	1236.5	1260.7	1284.8	1308.9	1333.1	1381.9	1431.3	1481.4	1532.4
(267.25) *s*			1.6994	1.7314	1.7608	1.7881	1.8140	1.8384	1.8619	1.9058	1.9467	1.9850	2.0214
υ			7.259	7.818	8.357	8.884	9.403	9.916	10.427	11.441	12.449	13.452	14.454
60 *h*			1181.6	1208.2	1233.6	1258.5	1283.0	1307.4	1331.8	1380.9	1430.5	1480.8	1531.9
(292.71) *s*			1.6492	1.6830	1.7135	1.7416	1.7678	1.7926	1.8162	1.8605	1.9015	1.9400	1.9762
υ				5.803	6.220	6.624	7.020	7.410	7.797	8.562	9.322	10.077	10.830
80 *h*				1204.3	1230.7	1256.1	1281.1	1305.8	1330.5	1379.9	1429.7	1480.1	1531.3
(312.03) *s*				1.6475	1.6791	1.7078	1.7346	1.7598	1.7836	1.8281	1.8694	1.9079	1.9442
υ				4.592	4.937	5.268	5.589	5.905	6.218	6.835	7.446	8.052	8.656
100 *h*				1200.1	1227.6	1253.7	1279.1	1304.2	1329.1	1378.9	1428.9	1479.5	1530.8
(327.81) *s*				1.6188	1.6518	1.6813	1.7085	1.7339	1.7581	1.8029	1.8443	1.8829	1.9193
υ				3.783	4.081	4.363	4.636	4.902	5.165	5.683	6.195	6.702	7.207
120 *h*				1195.7	1224.4	1251.3	1277.2	1302.5	1327.7	1377.8	1428.1	1478.8	1530.2
(341.25) *s*				1.5944	1.6287	1.6591	1.6869	1.7127	1.7370	1.7822	1.8237	1.8625	1.8990
υ					3.468	3.715	3.954	4.186	4.413	4.861	5.301	5.738	6.172
140 *h*					1221.1	1248.7	1275.2	1300.9	1326.4	1376.8	1427.3	1478.2	1529.7
(353.02) *s*					1.6087	1.6399	1.6683	1.6945	1.7190	1.7645	1.8063	1.8451	1.8817

Properties of Superheated Steam (continued)

Abs. Press., PSIA (Sat. Temp. °F)	Temperature, °F/°C												
	200/93	220/104	300/149	350/177	400/204	450/232	500/260	550/288	600/316	700/371	800/427	900/482	1000/538
υ					3.008	3.230	3.443	3.648	3.849	4.244	4.631	5.015	5.396
160 *h*					1217.6	1246.1	1273.1	1299.3	1325.0	1375.7	1426.4	1477.5	1529.1
(363.53) *s*					1.5908	1.6230	1.6519	1.6785	1.7033	1.7491	1.7911	1.8301	1.8667
υ					2.649	2.852	3.044	3.229	3.411	3.764	4.110	4.452	4.792
180 *h*					1214.0	1243.5	1271.0	1297.6	1323.5	1374.7	1425.6	1476.8	1528.6
(373.06) *s*					1.5745	1.6077	1.6373	1.6642	1.6894	1.7355	1.7776	1.8167	1.8534
υ					2.361	2.549	2.726	2.895	3.060	3.380	3.693	4.002	4.309
200 *h*					1210.3	1240.7	1268.9	1295.8	1322.1	1373.6	1424.8	1476.2	1528.0
(381.79) *s*					1.5594	1.5937	1.6240	1.6513	1.6767	1.7232	1.7655	1.8048	1.8415
υ					2.125	2.301	2.465	2.621	2.772	3.066	3.352	3.634	3.913
220 *h*					1206.5	1237.9	1266.7	1294.1	1320.7	1372.6	1424.0	1475.5	1527.5
(389.86) *s*					1.5453	1.5808	1.6117	1.6395	1.6652	1.7120	1.7545	1.7939	1.8308
υ					1.9276	2.094	2.247	2.393	2.533	2.804	3.068	3.327	3.584
240 *h*					1202.5	1234.9	1264.5	1292.4	1319.2	1371.5	1423.2	1474.8	1526.9
(397.37) *s*					1.5319	1.5686	1.6003	1.6286	1.6546	1.7017	1.7444	1.7839	1.8209
υ						1.9183	2.063	2.199	2.330	2.582	2.827	3.067	3.305
260 *h*						1232.0	1262.3	1290.5	1317.7	1370.4	1422.3	1474.2	1526.3
(404.42) *s*						1.5573	1.5897	1.6184	1.6447	1.6922	1.7352	1.7748	1.8118
υ						1.7674	1.9047	2.033	2.156	2.392	2.621	2.845	3.066
280 *h*						1228.9	1260.0	1288.7	1316.2	1369.4	1421.5	1473.5	1525.8
(411.05) *s*						1.5464	1.5796	1.6087	1.6354	1.6834	1.7265	1.7662	1.8033
υ						1.6364	1.7675	1.8891	2.005	2.227	2.442	2.652	2.859
300 *h*						1225.8	1257.6	1286.8	1314.7	1368.3	1420.6	1427.8	1525.2
(417.33) *s*						1.5360	1.5701	1.5998	1.6268	1.6751	1.7184	1.7582	1.7954
υ						1.3734	1.4923	1.6010	1.7036	1.8980	2.084	2.266	2.445
350 *h*						1217.7	1251.5	1282.1	1310.9	1365.5	1418.5	1471.1	1523.8
(431.72) *s*						1.5119	1.5481	1.5792	1.6070	1.6563	1.7002	1.7403	1.7777
υ						1.1744	1.2851	1.3843	1.4770	1.6508	1.8161	1.9767	2.134
400 *h*						1208.8	1245.1	1277.2	1306.9	1362.7	1416.4	1469.4	1522.4
(444.59) *s*						1.4892	1.5281	1.5607	1.5894	1.6398	1.6842	1.7247	1.7623

Abs. Press., PSIA (Sat. Temp. °F)	Temperature, °F/°C													
	500/260	550/288	600/316	620/327	640/338	660/349	680/360	700/371	800/427	900/482	1000/538	1200/649	1400/760	1600/871
υ	1.1231	1.2155	1.3005	1.3332	1.3652	1.3967	1.4278	1.4584	1.6074	1.7516	1.8928	2.170	2.443	2.714
450 *h*	1238.4	1272.0	1302.8	1314.6	1326.2	1337.5	1348.8	1359.9	1414.3	1467.7	1521.0	1628.6	1738.7	1851.9
(456.28) *s*	1.5095	1.5437	1.5735	1.5845	1.5951	1.6054	1.6153	1.6250	1.6699	1.7108	1.7486	1.8177	1.8803	1.9381
υ	0.9927	1.0800	1.1591	1.1893	1.2188	1.2478	1.2763	1.3044	1.4405	1.5715	1.6996	1.9504	2.197	2.442
500 *h*	1231.3	1266.8	1298.6	1310.7	1322.6	1334.2	1345.7	1357.0	1412.1	1466.0	1519.6	1627.6	1737.9	1851.3
(467.01) *s*	1.4919	1.5280	1.5588	1.5701	1.5810	1.5915	1.6016	1.6115	1.6571	1.6982	1.7363	1.8056	1.8683	1.9262
υ	0.8852	0.9686	1.0431	1.0714	1.0989	1.1259	1.1523	1.1783	1.3038	1.4241	1.5414	1.7706	1.9957	2.219
550 *h*	1223.7	1261.2	1294.3	1306.8	1318.9	1330.8	1342.5	1354.0	1409.9	1464.3	1518.2	1626.6	1737.1	1850.6
(476.94) *s*	1.4751	1.5131	1.5451	1.5568	1.5680	1.5787	1.5890	1.5991	1.6452	1.6868	1.7250	1.7946	1.8575	1.9155
υ	0.7947	0.8753	0.9463	0.9729	0.9988	1.0241	1.0489	1.0732	1.1899	1.3013	1.4096	1.6208	1.8279	2.033
600 *h*	1215.7	1255.5	1289.9	1302.7	1315.2	1327.4	1339.3	1351.1	1407.7	1462.5	1516.7	1625.5	1736.3	1850.0
(486.21) *s*	1.4586	1.4990	1.5323	1.5443	1.5558	1.5667	1.5773	1.5875	1.6343	1.6762	1.7147	1.7846	1.8476	1.9056
υ		0.7277	0.7934	0.8177	0.8411	0.8639	0.8860	0.9077	1.0108	1.1082	1.2024	1.3853	1.5641	1.7405
700 *h*		1243.2	1280.6	1294.3	1307.5	1320.3	1332.8	1345.0	1403.2	1459.0	1513.9	1623.5	1734.8	1848.8
(503.10) *s*		1.4722	1.5084	1.5212	1.5333	1.5449	1.5559	1.5665	1.6147	1.6573	1.6963	1.7666	1.8299	1.8881
υ		0.6154	0.6779	0.7006	0.7223	0.7433	0.7635	0.7833	0.8763	0.9633	1.0470	1.2088	1.3662	1.5214
800 *h*		1229.8	1270.7	1285.4	1299.4	1312.9	1325.9	1338.6	1398.6	1455.4	1511.0	1621.4	1733.2	1847.5
(518.23) *s*		1.4467	1.4863	1.5000	1.5129	1.5250	1.5366	1.5476	1.5972	1.6407	1.6801	1.7510	1.8146	1.8729
υ		0.5264	0.5873	0.6089	0.6294	0.6491	0.6680	0.6863	0.7716	0.8506	0.9262	1.0714	1.2124	1.3509
900 *h*		1215.0	1260.1	1275.9	1290.9	1305.1	1318.8	1332.1	1393.9	1451.8	1508.1	1619.3	1731.6	1846.3
(531.98) *s*		1.4216	1.4653	1.4800	1.4938	1.5066	1.5187	1.5303	1.5814	1.6257	1.6656	1.7371	1.8009	1.8595
υ		0.4533	0.5140	0.5350	0.5546	0.5733	0.5912	0.6084	0.6878	0.7604	0.8294	0.9615	1.0893	1.2146
1000 *h*		1198.3	1248.8	1265.9	1281.9	1297.0	1311.4	1325.3	1389.2	1448.2	1505.1	1617.3	1730.0	1845.0
(544.61) *s*		1.3961	1.4450	1.4610	1.4757	1.4893	1.5021	1.5141	1.5670	1.6121	1.6525	1.7245	1.7886	1.8474
υ			0.4532	0.4738	0.4929	0.5110	0.5281	0.5445	0.6191	0.6866	0.7503	0.8716	0.9885	1.1031
1100 *h*			1236.7	1255.3	1272.4	1288.5	1303.7	1318.3	1384.3	1444.5	1502.2	1615.2	1728.4	1843.8
(556.31) *s*			1.4251	1.4425	1.4583	1.4728	1.4862	1.4989	1.5535	1.5995	1.6405	1.7130	1.7775	1.8363
υ			0.4016	0.4222	0.4410	0.4586	0.4752	0.4909	0.5617	0.6250	0.6843	0.7967	0.9046	1.0101
1200 *h*			1223.5	1243.9	1262.4	1279.6	1295.7	1311.0	1379.3	1440.7	1499.2	1613.1	1726.9	1842.5
(567.22) *s*			1.4052	1.4243	1.4413	1.4568	1.4710	1.4843	1.5409	1.5879	1.6293	1.7025	1.7672	1.8263
υ			0.3174	0.3390	0.3580	0.3753	0.3912	0.4062	0.4714	0.5281	0.5805	0.6789	0.7727	0.8640
1400 *h*			1193.0	1218.4	1240.4	1260.3	1278.5	1295.5	1369.1	1433.1	1493.2	1608.9	1723.7	1840.0
(587.10) *s*			1.3639	1.3877	1.4079	1.4258	1.4419	1.4567	1.5177	1.5666	1.6093	1.6836	1.7489	1.8083

Abs. Press., PSIA (Sat. Temp. °F)	Temperature, °F/°C													
	500/260	550/288	600/316	620/327	640/338	660/349	680/360	700/371	800/427	900/482	1000/538	1200/649	1400/760	1600/871
υ				0.2733	0.2936	0.3112	0.3271	0.3417	0.4034	0.4553	0.5027	0.5906	0.6738	0.7545
1600 *h*				1187.8	1215.2	1238.7	1259.6	1278.7	1358.4	1425.3	1487.0	1604.6	1720.5	1837.5
(604.90) *s*				1.3489	1.3741	1.3952	1.4137	1.4303	1.4964	1.5476	1.5914	1.6669	1.7328	1.7926
υ					0.2407	0.2597	0.2760	0.2907	0.3502	0.3986	0.4421	0.5218	0.5968	0.6693
1800 *h*					1185.1	1214.0	1238.5	1260.3	1347.2	1417.4	1480.8	1600.4	1717.3	1835.0
(621.03) *s*					1.3377	1.3638	1.3855	1.4044	1.4765	1.5301	1.5752	1.6520	1.7185	1.7786
υ					0.1936	0.2161	0.2337	0.2489	0.3074	0.3532	0.3935	0.4668	0.5352	0.6011
2000 *h*					1145.6	1184.9	1214.8	1240.0	1335.5	1409.2	1474.5	1596.1	1714.1	1832.5
(635.82) *s*					1.2945	1.3300	1.3564	1.3783	1.4576	1.5139	1.5603	1.6384	1.7055	1.7660
υ							0.1484	0.1686	0.2294	0.2710	0.3061	0.3678	0.4244	0.4784
2500 *h*							1132.3	1176.8	1303.6	1387.8	1458.4	1585.3	1706.1	1826.2
(668.13) *s*							1.2687	1.3073	1.4127	1.4772	1.5273	1.6088	1.6775	1.7389
υ								0.0984	0.1760	0.2159	0.2476	0.3018	0.3505	0.3966
3000 *h*								1060.7	1267.2	1365.0	1441.8	1574.3	1698.0	1819.9
(695.36) *s*								1.1966	1.3690	1.4439	1.4984	1.5837	1.6540	1.7163
υ									0.1583	0.1981	0.2288	0.2806	0.3267	0.3703
3206.2 *h*									1250.5	1355.2	1434.7	1569.8	1694.6	1817.2
(705.40) *s*									1.3508	1.4309	1.4874	1.5742	1.6452	1.7080
υ								0.0306	0.1364	0.1762	0.2058	0.2546	0.2977	0.3381
3500 *h*								780.5	1224.9	1340.7	1424.5	1563.3	1689.8	1813.6
S								0.9515	1.3241	1.4127	1.4723	1.5615	1.6336	1.6968
υ								0.0287	0.1052	0.1462	0.1743	0.2192	0.2581	0.2943
4000 *h*								763.8	1174.8	1314.4	1406.8	1552.1	1681.7	1807.2
S								0.9347	1.2757	1.3827	1.4482	1.5417	1.6154	1.6795
υ								0.0276	0.0798	0.1226	0.1500	0.1917	0.2273	0.2602
4500 *h*								753.5	1113.9	1286.5	1388.4	1540.8	1673.5	1800.9
S								0.9235	1.2204	1.3529	1.4253	1.5235	1.5990	1.6640
υ								0.0268	0.0593	0.1036	0.1303	0.1696	0.2027	0.2329
5000 *h*								746.4	1047.1	1256.5	1369.5	1529.5	1665.3	1794.5
S								0.9152	1.1622	1.3231	1.4034	1.5066	1.5839	1.6499
υ								0.0262	0.0463	0.0880	0.1143	0.1516	0.1825	0.2106
5500 *h*								741.3	985.0	1224.1	1349.3	1518.2	1657.0	1788.1
S								0.9090	1.1093	1.2930	1.3821	1.4908	1.5699	1.6369

From Liptak, B.G., Ed., *Instrument Engineers' Handbook: Process Software and Digital Networks,* 3rd ed., CRC Press, Boca Raton, FL, 2002, pp. 819–822. Originally abridged from *Thermodynamic Properties of Steam,* by Joseph H. Keenan and Fredrick G. Keyes. © 1936, by Joseph H. Keenan and Frederick G. Keyes. Published by John Wiley & Sons, Inc., New York.

Properties of Water at Various Temperatures from 40 to 540°F (4.4 to 282.2°C)

Temp. °F	Temp. °C	Specific Volume* ft^3/lb	Specific Gravity	Weight* (lb/ft^3)	Vapor Pressure* PSIA
40	4.4	.01602	1.0013	62.42	0.1217
50	10.0	.01603	1.0006	62.38	0.1781
60	15.6	.01604	1.0000	62.34	0.2563
70	21.1	.01606	0.9987	62.27	0.3631
80	26.7	.01608	0.9975	62.19	0.5069
90	32.2	.01610	0.9963	62.11	0.6982
100	37.8	.01613	0.9944	62.00	0.9492
120	48.9	.01620	0.9901	61.73	1.692
140	60.0	.01629	0.9846	61.39	2.889
160	71.1	.01639	0.9786	61.01	4.741
180	82.2	.01651	0.9715	60.57	7.510
200	93.3	.01663	0.9645	60.13	11.526
212	100.0	.01672	0.9593	59.81	14.696
220	104.4	.01677	0.9565	59.63	17.186
240	115.6	.01692	0.9480	59.10	24.97
260	126.7	.01709	0.9386	58.51	35.43
280	137.8	.01726	0.9293	58.00	49.20
300	148.9	.01745	0.9192	57.31	67.01
320	160.0	.01765	0.9088	56.66	89.66
340	171.1	.01787	0.8976	55.96	118.01
360	182.2	.01811	0.8857	55.22	153.04
380	193.3	.01836	0.8736	54.47	195.77
400	204.4	.01864	0.8605	53.65	247.31
420	215.6	.01894	0.8469	52.80	308.83
440	226.7	.01926	0.8328	51.92	381.59
460	237.8	.0196	0.8183	51.02	466.9
480	248.9	.0200	0.8020	50.00	566.1
500	260.0	.0204	0.7863	49.02	680.8
520	271.1	.0209	0.7674	47.85	812.4
540	282.2	.0215	0.7460	46.51	962.5

*ft^3/lb = 62.4 l/Kg; lb/ft^3 = 0.016 Kg/l; PSIA = 0.069 bar (abs). Computed from Keenan & Keyes Steam Table.

From Liptak, B.G., Ed., *Instrument Engineers' Handbook: Process Software and Digital Networks,* CRC Press, Boca Raton, FL, 2002, p. 823.

Atomic Mass of Selected Elements

Atomic Number	Element	Symbol	Atomic Mass	Atomic Number	Element	Symbol	Atomic Mass
1	Hydrogen	H	1.008	48	Cadmium	Cd	112.4
2	Helium	He	4.003	49	Indium	In	114.82
3	Lithium	Li	6.941	50	Tin	Sn	118.69
4	Beryllium	Be	9.012	51	Antimony	Sb	121.75
5	Boron	B	10.81	52	Tellurium	Te	127.6
6	Carbon	C	12.01	53	Iodine	I	126.9
7	Nitrogen	N	14.01	54	Xenon	Xe	131.3
8	Oxygen	O	16.00	55	Cesium (–10°)	Ce	132.91
9	Fluorine	F	19.00	56	Barium	Ba	137.33
10	Neon	N	20.18	57	Lantium	La	138.91
11	Sodium	Na	22.99	58	Cerium	Ce	140.12
12	Magnesium	Mg	24.31	59	Praseodymium	Pr	140.91
13	Aluminum	Al	26.98	60	Neodymium	Nd	144.24
14	Silicon	Si	28.09	61	Promethium	Pm	(145)
15	Phosphorus (White)	P	30.97	62	Samarium	Sm	150.4
				63	Europium	Eu	151.96
16	Sulfur	S	32.06	64	Gadolinium	Gd	157.25
17	Chlorine	Cl	35.45	65	Terbium	Tb	158.93
18	Argon	Ar	39.95	66	Dysprosium	Dy	162.5
19	Potassium	K	39.1	67	Holmium	Ho	164.93
20	Calcium	Ca	40.08	68	Erbium	Er	167.26
21	Scandium	Sc	44.96	69	Thulium	Tm	168.93
22	Titanium	Ti	47.9	70	Ytterbium	Yb	173.04
23	Vanadium	V	50.94	71	Lutetium	Lu	174.97
24	Chromium	Cr	52.00	72	Hafnium	Hf	178.49
25	Manganese	Mn	54.94	73	Tantalum	Ta	180.95
26	Iron	Fe	55.85	74	Tungsten	W	183.85
27	Cobalt	Co	58.93	75	Rhenium	Re	186.2
28	Nichel	Ni	58.71	76	Osmium	Os	190.2
29	Copper	Cu	63.55	77	Iridium	Ir	192.22
30	Zinc	Zn	65.38	78	Platinum	Pt	195.09
31	Gallium	Ga	69.72	79	Gold	Au	196.97
32	Germanium	Ge	72.59	80	Mercury	Hg	200.59
33	Arsenic	As	74.92	81	Thallium	Tl	204.37
34	Selenium	Se	78.96	82	Lead	Pb	207.2
35	Bromine	Br	79.9	83	Bismuth	Bi	208.98
36	Krypton	Kr	83.8	84	Polonium	Po	(~210)
37	Rubidium	Rb	85.47	85	Asatine	At	(210)
38	Strontium	Sr	87.62	86	Radon	Rn	(222)
39	Yttrium	Y	88.91	87	Francium	Fr	(223)
40	Zirconium	Zr	91.22	88	Radium	Ra	226.03
41	Niobium	Nb	92.91	89	Actinium	Ac	(227)
42	Molybdenum	Mo	95.94	90	Thorium	Th	232.04
43	Technetium	Tc	98.91	91	Protoactinium	Pa	231.04
44	Ruthenium	Ru	101.07	92	Uranium	U	238.03
45	Rhodium	Rh	102.91	93	Neptunium	Np	237.05
46	Palladium	Pd	106.4	94	Plutonium	Pu	(244)
47	Silver	Ag	107.87	95	Americium	Am	(243)

Atomic Mass of Selected Elements (continued)

Atomic Number	Element	Symbol	Atomic Mass	Atomic Number	Element	Symbol	Atomic Mass
96	Curium	Cm	(247)	100	Fermium	Fm	(257)
97	Berkelium	Bk	(247)	101	Mendelevium	Md	(258)
98	Californium	Cf	(251)	102	Nobelium	No	(259)
99	Einsteinium	Es	(254)	103	Lawrencium	Lw	(260)

From Shackelford, J.F. and Alexander, W., *CRC Handbook of Materials Science & Engineering*, CRC Press, Boca Raton, FL, 2001, pp. 51–54. Data from James F. Shackelford, *Introduction to Materials Science for Engineers*, Second Edition, Macmillian Publishing Company, New York, pp. 686–688, (1988).

Solid Density of Selected Elements

Atomic Number	Element	Symbol	Solid Density (Mg/m3)	Atomic Number	Element	Symbol	Solid Density (Mg/m3)
3	Lithium	Li	0.533	51	Antimony	Sb	6.69
4	Beryllium	Be	1.85	52	Tellurium	Te	6.25
5	Boron	B	2.47	53	Iodine	I	4.95
6	Carbon	C	2.27	55	Cesium (–10°)	Ce	1.91
11	Sodium	Na	0.966	56	Barium	Ba	3.59
12	Magnesium	Mg	1.74	57	Lantium	La	6.17
13	Aluminum	Al	2.7	58	Cerium	Ce	6.77
14	Silicon	Si	2.33	59	Praseodymium	Pr	6.78
15	Phosphorus (White)	P	1.82	60	Neodymium	Nd	7.00
16	Sulfur	S	2.09	62	Samarium	Sm	7.54
19	Potassium	K	0.862	63	Europium	Eu	5.25
20	Calcium	Ca	1.53	64	Gadolinium	Gd	7.87
21	Scandium	Sc	2.99	65	Terbium	Tb	8.27
22	Titanium	Ti	4.51	66	Dysprosium	Dy	8.53
23	Vanadium	V	6.09	67	Holmium	Ho	8.80
24	Chromium	Cr	7.19	68	Erbium	Er	9.04
25	Manganese	Mn	7.47	69	Thulium	Tm	9.33
26	Iron	Fe	7.87	70	Ytterbium	Yb	6.97
27	Cobalt	Co	8.8	71	Lutertium	Lu	9.84
28	Nickel	Ni	8.91	72	Hafnium	Hf	13.28
29	Copper	Cu	8.93	73	Tantalum	Ta	16.67
30	Zinc	Zn	7.13	74	Tungsten	W	19.25
31	Gallium	Ga	5.91	75	Rhenium	Re	21.02
32	Germanium	Ge	5.32	76	Osmium	Os	22.58
33	Arsenic	As	5.78	77	Iridium	Ir	22.55
34	Selenium	Se	4.81	78	Platinum	Pt	21.44
37	Rubidium	Rb	1.53	79	Gold	Au	19.28
38	Strontium	Sr	2.58	81	Thallium	Tl	11.87
39	Yttrium	Y	4.48	82	Lead	Pb	11.34
40	Zirconium	Zr	6.51	83	Bismuth	Bi	9.80
41	Niobium	Nb	8.58	84	Polonium	Po	9.2
42	Molybdenum	Mo	10.22	90	Thorium	Th	11.72
43	Technetium	Tc	11.5	92	Uranium	U	19.05
44	Ruthenium	Ru	12.36	94	Plutonium	Pu	19.81
45	Rhodium	Rh	12.42				
46	Palladium	Pd	12.00				
47	Silver	Ag	10.50				
48	Cadmium	Cd	8.65				
49	Indium	In	7.29				
50	Tin	Sn	7.29				

From Shackelford, J.F. and Alexander, W., *CRC Handbook of Materials Science & Engineering*, CRC Press, Boca Raton, FL, 2001, pp. 55–57. Data from James F. Shackelford, *Introduction to Materials Science for Engineers*, Second Edition, Macmillian Publishing Company, New York, pp. 686–688, (1988).

Thermal Conductivity of Metals (Part 1)

T (K)	Aluminum	Cadmium	Chromium	Copper	Gold
1	7.8	48.7	0.401	28.7	4.4
2	15.5	89.3	0.802	57.3	8.9
3	23.2	104	1.20	85.5	13.1
4	30.8	92.0	1.60	113	17.1
5	38.1	69.0	1.99	138	20.7
6	45.1	44.2	2.38	159	23.7
7	51.5	28.0	2.77	177	26.0
8	57.3	18.0	3.14	189	27.5
9	62.2	12.2	3.50	195	28.2
10	66.1	8.87	3.85	196	28.2
11	69.0	6.91	4.18	193	27.7
12	70.8	5.56	4.49	185	26.7
13	71.5	4.67	4.78	176	25.5
14	71.3	4.01	5.04	166	24.1
15	70.2	3.55	5.27	156	22.6
16	68.4	3.16	5.48	145	20.9
18	63.5	2.62	5.81	124	17.7
20	56.5	2.26	6.01	105	15.0
25	40.0	1.79	6.07	68	10.2
30	28.5	1.56	5.58	43	7.6
35	21.0	1.41	5.03	29	6.1
40	16.0	1.32	4.30	20.5	5.2
45	12.5	1.25	3.67	15.3	4.6
50	10.0	1.20	3.17	12.2	4.2
60	6.7	1.13	2.48	8.5	3.8
70	5.0	1.08	2.08	6.7	3.58
80	4.0	1.06	1.82	5.7	3.52
90	3.4	1.04	1.68	5.14	3.48
100	3.0	1.03	1.58	4.83	3.45
200	2.37	0.993	1.11	4.13	3.27
273	2.36	0.975	0.948	4.01	3.18
300	2.37	0.968	0.903	3.98	3.15
400	2.4	0.947	0.873	3.92	3.12
500	2.37	0.92	0.848	3.88	3.09
600	2.32	(0.42)	0.805	3.83	3.04
700	2.26	(0.49)	0.757	3.77	2.98
800	2.2	(0.559)	0.713	3.71	2.92
900	2.13		0.678	3.64	2.85
1000	(0.93)		0.653	3.57	2.78
1100	(0.96)		0.636	3.5	2.71
1200	(0.99)		0.624	3.42	2.62
1400			0.611		

Values are in watt · cm^{-1} · K^{-1}.

Note: Values in parentheses are for liquid state.

These data apply only to metals of purity of at least 99.9%.

The third significant figure may not be accurate.

From Shackelford, J.F. and Alexander, W., *CRC Handbook of Materials Science and Engineering*, CRC Press, Boca Raton, FL, 2001, pp. 384–385. Data from Ho, C.Y., Powell, R.W., and Liley, P.E., Thermal Conductivity of Selected Materials, NSRDS–NBS–8 and NSRD–NBS–16, Part 2, National Standard Reference Data System–National Bureau of Standards, Part 1, 1966; Part 2, 1968.

Thermal Conductivity of Metals (Part 2)

T (K)	Iron	Lead	Magnesium	Mercury	Molybdenum
1	0.75	27.7	1.30		0.146
2	1.49	42.4	2.59		0.292
3	2.24	34.0	3.88		0.438
4	2.97	22.4	5.15		0.584
5	3.71	13.8	6.39		0.730
6	4.42	8.2	7.60		0.876
7	5.13	4.9	8.75		1.02
8	5.80	3.2	9.83		1.17
9	6.45	2.3	10.8		1.31
10	7.05	1.78	11.7		1.45
11	7.62	1.46	12.5		1.60
12	8.13	1.23	13.1		1.74
13	8.58	1.07	13.6		1.88
14	8.97	0.94	14.0		2.01
15	9.30	0.84	14.3		2.15
16	9.56	0.77	14.4		2.28
18	9.88	0.66	14.3		2.53
20	9.97	0.59	13.9		2.77
25	9.36	0.507	12.0		3.25
30	8.14	0.477	9.5		3.55
35	6.81	0.462	7.4		3.62
40	5.55	0.451	5.7		3.51
45	4.50	0.442	4.57		3.26
50	3.72	0.435	3.75		3.00
60	2.65	0.424	2.74		2.60
70	2.04	0.415	2.23		2.30
80	1.68	0.407	1.95		2.09
90	1.46	0.401	1.78		1.92
100	1.32	0.396	1.69		1.79
200	0.94	0.366	1.59		1.43
273	0.835	0.355	1.57	(0.078)	1.39
300	0.803	0.352	1.56	(0.084)	1.38
400	0.694	0.338	1.53	(0.098)	1.34
500	0.613	0.325	1.51	(0.109)	1.3
600	0.547	0.312	1.49	(0.12)	1.26
700	0.487	(0.174)	1.47	(0.127)	1.22
800	0.433	(0.19)	1.46	(0.13)	1.18
900	0.38	(0.203)	1.45		1.15
1000	0.326	(0.215)	(0.84)		1.12
1100	0.297		(0.91)		1.08
1200	0.282		(0.98)		1.05
1400	0.309				0.996
1600	0.327				0.946
1800					0.907
2000					0.88
2200					0.858
2600					0.825

Thermal Conductivity of Metals (Part 2) (continued)

Values are in watt · cm^{-1} · K^{-1}.
Note: Values in parentheses are for liquid state.
These data apply only to metals of purity of at least 99.9%.
The third significant figure may not be accurate.
From Shackelford, J.F. and Alexander, W., *CRC Handbook of Materials Science and Engineering*, CRC Press, Boca Raton, FL, 2001, pp. 386–387.

Thermal Conductivity of Metals (Part 3)

T (K)	Nickel	Niobium	Platinum	Silver	Tantalum
1	0.64	0.251	2.31	39.4	0.115
2	1.27	0.501	4.60	78.3	0.230
3	1.91	0.749	6.79	115	0.345
4	2.54	0.993	8.8	147	0.459
5	3.16	1.23	10.5	172	0.571
6	3.77	1.46	11.8	187	0.681
7	4.36	1.67	12.6	193	0.788
8	4.94	1.86	12.9	190	0.891
9	5.49	2.04	12.8	181	0.989
10	6.00	2.18	12.3	168	1.08
11	6.48	2.30	11.7	154	1.16
12	6.91	2.39	10.9	139	1.24
13	7.30	2.46	10.1	124	1.30
14	7.64	2.49	9.3	109	1.36
15	7.92	2.50	8.4	96	1.40
16	8.15	2.49	7.6	85	1.44
18	8.45	2.42	6.1	66	1.47
20	8.56	2.29	4.9	51	1.47
25	8.15	1.87	3.15	29.5	1.36
30	6.95	1.45	2.28	19.3	1.16
35	5.62	1.16	1.80	13.7	0.99
40	4.63	0.97	1.51	10.5	0.87
45	3.91	0.84	1.32	8.4	0.78
50	3.36	0.76	1.18	7.0	0.72
60	2.63	0.66	1.01	5.5	0.651
70	2.21	0.61	0.90	4.97	0.616
80	1.93	0.58	0.84	4.71	0.603
90	1.72	0.563	0.81	4.60	0.596
100	1.58	0.552	0.79	4.50	0.592
200	1.06	0.526	0.748	4.3	0.575
273	0.94	0.533	0.734	4.28	0.574
300	0.905	0.537	0.73	4.27	0.575
400	0.801	0.552	0.722	4.2	0.578
500	0.721	0.567	0.719	4.13	0.582
600	0.655	0.582	0.72	4.05	0.586
700	0.653	0.598	0.723	3.97	0.59
800	0.674	0.613	0.729	3.89	0.594

Thermal Conductivity of Metals (Part 3) (continued)

T (K)	Nickel	Niobium	Platinum	Silver	Tantalum
900	0.696	0.629	0.737	3.82	0.598
1000	0.718	0.644	0.748	3.74	0.602
1100	0.739	0.659	0.76	3.66	0.606
1200	0.761	0.675	0.775	3.58	0.610
1400	0.804	0.705	0.807		0.618
1600		0.735	0.842		0.626
1800		0.764	0.877		0.634
2000		0.791	0.913		0.640
2200		0.815			0.647
2600					0.658
3000					0.665

From Shackelford, J.F. and Alexander, W., *CRC Handbook of Materials Science and Engineering*, CRC Press, Boca Raton, FL, 2001, pp. 388–389.

Thermal Conductivity of Metals (Part 4)

T (K)	Tin	Titanium	Tungsten	Zinc	Zirconium
1		0.0144	14.4	19.0	0.111
2		0.0288	28.7	37.9	0.223
3	297	0.0432	42.6	55.5	0.333
4	181	0.0576	55.6	69.7	0.442
5	117	0.0719	67.1	77.8	0.549
6	76	0.0863	76.2	78.0	0.652
7	52	0.101	82.4	71.7	0.748
8	36	0.115	85.3	61.8	0.837
9	26	0.129	85.1	51.9	0.916
10	19.3	0.144	82.4	43.2	0.984
11	14.8	0.158	77.9	36.4	1.04
12	11.6	0.172	72.4	30.8	1.08
13	9.3	0.186	66.4	26.1	1.11
14	7.6	0.200	60.4	22.4	1.13
15	6.3	0.214	54.8	19.4	1.13
16	5.3	0.227	49.3	16.9	1.12
18	4.0	0.254	40.0	13.3	1.08
20	3.2	0.279	32.6	10.7	1.01
25	2.22	0.337	20.4	6.9	0.85
30	1.76	0.382	13.1	4.9	0.74
35	1.50	0.411	8.9	3.72	0.65
40	1.35	0.422	6.5	2.97	0.58
45	1.23	0.416	5.07	2.48	0.535
50	1.15	0.401	4.17	2.13	0.497
60	1.04	0.377	3.18	1.71	0.442
70	0.96	0.356	2.76	1.48	0.403
80	0.91	0.339	2.56	1.38	0.373
90	0.88	0.324	2.44	1.34	0.350
100	0.85	0.312	2.35	1.32	0.332

Thermal Conductivity of Metals (Part 4) (continued)

T (K)	Tin	Titanium	Tungsten	Zinc	Zirconium
200	0.733	0.245	1.97	1.26	0.252
273	0.682	0.224	1.82	1.22	0.232
300	0.666	0.219	1.78	1.21	0.227
400	0.622	0.204	1.62	1.16	0.216
500	0.596	0.197	1.49	1.11	0.210
600	(0.323)	0.194	1.39	1.05	0.207
700	(0.343)	0.194	1.33	(0.499)	0.209
800	(0.364)	0.197	1.28	(0.557)	0.216
900	(0.384)	0.202	1.24	(0.615)	0.226
1000	(0.405)	0.207	1.21	(0.673)	0.237
1100	(0.425)	0.213	1.18	(0.73)	0.248
1200	(0.446)	0.220	1.15		0.257
1400	(0.487)	0.236	1.11		0.275
1600		0.253	1.07		0.290
1800		0.271	1.03		0.302
2000			1.00		0.313
2200			0.98		
2600			0.94		
3000			0.915		

Values are in watt · cm^{-1} · K^{-1}.

Note: Values in parentheses are for liquid state.

These data apply only to metals of purity of at least 99.9%.

The third significant figure may not be accurate.

From Shackelford, J.F. and Alexander, W., *CRC Handbook of Materials Science and Engineering*, CRC Press, Boca Raton, FL, 2001, pp. 390–391.

	R-11	R-12	R-13	R-22	R-113	R-114	R-500	R-502	R-717
Chemical formula	CCl_3F	CCl_2F_3	$CCIF_3$	$CHClF_2$	$CCl_2F\text{-}CCIF_2$	$C_2Cl_2F_4$	‡	**	NH_3
Molecular weight	137.38	120.93	104.47	86.48	187.39	170.94	99.31	111.6	17.03
Boiling temperature at 14.7 psia, ˚F	74.9	–21.6	–114.6	–41.4	117.6	38.8	–28.3	–50.1	–28.0
Freezing temperature at 14.7 psia, ˚F	–168	–252	–294	–256	–31	–137	–254	—	–108
Critical temperature, ˚F	388.4	233.6	83.9	204.8	417.4	294.3	221.9	194	271.4
Critical pressure, psia	640	597	561	721.9	498.9	473	641.9	619	1 657
Critical pressure, MN/m^2	4.41	4.12	3.87	4.98	3.44	3.26	4.43	4.27	11.4
Critical density, lb/cu ft	34.6	34.84	36.1	32.8	36.0	36.3	31.0	34.91	14.6
Critical density, kg/m^3	554	558	578	525	577	581	496	559	234
Density of liquid, 86˚F, lb/cu ft	91.39	80.67	81.05[–22]	73.28	96.96	89.95	71.06	76.13	37.16
Density of liquid, 303.15 K, kg/m^3	1 464	1 292	1 298[–22]	1 174	1 553	1 441	1 138	1 219	595.2
Sp vol of sat bvapor, 5˚F, cu ft/lb	12.205	1.458	0.304	1.243	27.04	4.226	1.501	0.825	8.150
Sp vol of sat vapor, 258.15 K, m^3/kg	0.7619	0.091 02	0.018 98	0.077 60	1.688	0.263 8	0.093 7	0.051 50	0.508 8
Sp heat of liquid, 86˚F, Btu/lb ˚F	0.21	0.235	0.247	0.305	0.218	0.246	0.290	0.305	1.14
Sp heat of liquid, 303.15 K, kJ/kg·K	0.878	0.983	1.03	1.28	0.912	1.03	1.21	1.28	4.77
Sp heat ratio (c_p/c_v); vapor at 86˚F and 14.7 psia	1.13	1.139	1.17	1.18	1.12	1.09	1.14	1.135	1.29
Thermal conductivity									
Sat liquid, 5˚F	0.058	0.052	0.06[–95]	0.069	0.044	0.041		0.052	0.29
Sat liquid, 258.15 K	100	90	100[–95]	120	76	71		90	500
Sat liquid, 86˚F	0.049	0.040		0.050	0.037	0.033		0.037	0.29
Sat liquid, 303.15 K	85	69		86	64	57		64	500
Vapor at sat press, 5˚F	0.003 4	0.004 7		0.005 1	0.003 5	0.004 7		0.005 4	0.012
Vapor at sat press, 258.15 K	5.9	8.1		8.8	6.0	8.1		9.3	21
Vapor at 14.7 psia, 86˚F	0.004 5	0.005 9		0.006 5	0.004 5	0.0065 2		0.006 9	0.014
Vapor at 0.101 3 MN/m^2, 303.15 K	7.8	10		11	7.8	11		12	24
Viscosity, $N{\cdot}s/m^2$									
Sat liquid, 5˚F	0.630	0.335	.037[–95]	0.298	1.28	0.614	0.292	0.334	0.250
Sat liquid, 258.15 K	0.000 630	0.000 335	0.000 037[–95]	0.000 298	0.001 28	0.000 614	0.000 292	0.000 334	0.000 2
Sat liquid, 86˚F	0.404	0.254		0.230	0.638	0.356	0.220	0.240	0.207
Sat liquid, 303.15 K	0.000 404	0.000 254		0.000 230	0.000 638	0.000 356	0.000 220	0.000 240	0.000 2
Vapor at sat press, 5˚F	0.008 7	0.010 8		0.011 2	0.007 9	0.009 6		0.011 2	0.008 5
Vapor at sat press, 258.15 K	0.000 008 7	0.000 010 8		0.000 011 2	0.000 007 9	0.000 009 6		0.000 011 2	0.000 000
Vapor at 14.7 psia, 86˚F	0.010 8	0.012 7		0.013 2	0.009 6	0.011 4		0.013 1	0.010 2
Vapor at 0.101 3 MN/m^2, 303.15 K	0.000 010 8	0.000 012 7		0.000 012 3	0.000 009 6	0.000 011 4		0.000 013 1	0.000 00
Relative dielectric strength of vapor at 73˚F and 14.7 psia (nitrogen = 1)	3.1	2.4	1.4	1.3	3.9				0.82 (84˚F)

Toxicity Underwriters' Laboratories Classification†	Group 5a	Group 6	Group 6+	Group 5a	Group 4 1/2	Group 6	Group 5a	Group 5a

† See explanation at end of table.
‡ R-500 is azeotrope 73.8% (by wt) CCl_2F_2 and 26.2% (by wt) CH_3-CHF_2.
** R-502 is azeotrope $CHClF_2$ = 48.8% and $CClF_2CF_3$ = 51.2%.

Property	Fluorocarbons R-13B1	Fluorocarbons R-14	R-40, Methyl Chloride	R-50, Methane	R-170, Ethane	R-290, Propane	R-600, n-Butane	R-744, Carbon Dioxide
Chemical formula	$CBrF_3$	CF_4	CH_3Cl	CH_4	C_2H_6	C_3H_8	C_4H_{10}	CO_2
Molecular weight	148.9	88.01	50.48	16.03	30.04	44.09	58.12	44.01
Boiling point at 14.7 psia, °F	–72.0	–198.4	–10.8	–258.9	–127.5	–44.2	31.3	–109.3 subl.
Freezing point at 14.7 psia, °F	–270	–299	–144	–297	–278	–309.8	–217	–69.9[a]
Critical temperature, °F	152.6	–50	289.4	–115.8	90.1	206	306	87.8
Critical pressure, psia	575	543	968.7	673.1	708.3	617.4	550.1	1057.4
Critical pressure, MN/m^2	3.96	3.74	6.68	4.64	4.88	4.26	3.79	7.29
Critical density, lb/cu ft	46.5	39	23.3	10.1	13.2	13.7	14.2	28.6
Critical density, kg/m^3	745	625	373	162	211	219	227	458
Density of liquid, 86°F, lb/cu ft	93.58	82.2[b]	56.24		16.57	36.2	35.62	
Density of liquid, 303.15 K, kg/m^3	1 499	1 317[b]	900.9		265.4	579.9	570.6	
Sp vol of sat vapor, 5°F, cu ft/lb	0.379 6		4.471		0.531 3	2.509	9.98	0.266 1
Sp vol of sat vapor, 258.15 K, m^3/kg	0.023 70		0.279 1		0.033 17	0.156 6	0.623 0	0.016 61
Toxicity (Underwriters' Laboratories Classification)[d]	Group 6	Group 6[c]	Group 4	Group 5[a]	Group 5[a]	Group 5[a]	Group 5	Group 5

[a] At 76.4 psia.
[b] At –112°F (317.59 K).
[c] Unofficial.
[d] The Underwriters' Laboratories Classification of toxicity is as follows:

Group 1: Lethal concentration 0.5 to 1.0 percent for durations of 5 minutes.
Group 2: Lethal concentration 0.5 to 1.0 percent for durations of 30 minutes.
Group 3: Lethal concentration 2.0 to 2.5 percent for durations of 1 hour.
Group 4: Lethal concentration 2.0 to 2.5 percent for durations of 2 hours.
Group 5a: Less toxic than group 4, more toxic than group 6.
Group 5b: Available data would classify these as 5a or 6.
Group 6: Concentrations up to about 20 percent for 2 hours do not appear to produce injury.

* Based largely on: "ASHRAE Handbook of Fundamentals," American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1972.

Reference

"Properties of Commonly-Used Refrigerants," Air-Conditioning Refrigeration Institute, 1967.

From Bolz, R.E. and Tuve, G.L., Gases and vapors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 68–69.

Thermodynamic Properties of Saturated Mercury

Enthalpy and Entropy Measured from 32°F

For pressures in MN/m², multiply value in lbf/in.² by 0.006 894 8. For temperature in K, add 459.67 to value in deg F and multiply he result by 5/9. For enthalpy in J/kg, multiplying value in Btu/lb by 2 324.4. For entropy in J/kg·K, multiply value in Btu/lb·deg F by 4 186.8. For specific volume in m³/kg. Multiply value in ft³/lb$_m$ by 0.062 420.

		Enthalpy, Btu/lb$_m$			Entropy, Btu/lb$_m$°R			Specific Volume,
Pressure lb$_f$/in.²	Temperature, °F	Saturated Liquid	Evaporation	Saturated Vapor	Saturated Liquid	Evaporation	Saturated Vapor	Sat Vapor, ft³/lb$_m$
0.020	259.9	7.532	127.614	135.146	0.01259	0.17735	0.18994	1893
0.040	288.3	8.463	127.486	135.949	0.01386	0.17044	0.18430	986
0.075	316.2	9.373	127.361	136.734	0.01504	0.16415	0.17919	545
0.100	329.7	9.814	127.300	137.114	0.01561	0.16126	0.17687	416
0.200	364.3	10.936	127.144	138.080	0.01699	0.15432	0.17131	217.3
0.400	402.0	12.159	126.975	139.134	0.01844	0.14736	0.16580	113.7
0.600	425.8	12.929	126.868	139.797	0.01932	0.14328	0.16260	77.84
0.800	443.5	13.500	126.788	140.288	0.01994	0.14038	0.16032	59.58
1.00	457.7	13.959	126.724	140.683	0.02045	0.13814	0.15859	48.42
2.00	504.9	15.476	126.512	141.988	0.02205	0.13116	0.15321	25.39
4.00	557.9	17.161	126.275	143.436	0.02373	0.12434	0.14787	13.38
6.00	591.2	18.233	126.124	144.357	0.02477	0.12002	0.14479	9.26
8.00	616.5	19.035	126.011	145.046	0.02551	0.11712	0.14264	7.12
10	637.0	19.685	125.919	145.604	0.02610	0.11483	0.14093	5.81
20	706.0	21.864	125.609	147.473	0.02800	0.10779	0.13579	3.09
40	784.4	24.345	125.255	149.600	0.03004	0.10068	0.13072	1.648
60	835.7	25.940	125.024	150.964	0.03127	0.19652	0.12779	1.144
80	874.8	27.159	124.849	152.008	0.03218	0.09356	0.12574	0.885
100	906.8	28.152	124.706	152.858	0.03290	0.09127	0.12417	0.725
120	934.3	29.005	124.582	153.587	0.03350	0.08938	0.12288	0.617
140	958.3	29.748	124.474	154.222	0.03401	0.08778	0.12179	0.538
160	979.9	30.415	124.376	154.791	0.03447	0.08640	0.12087	0.478
180	999.5	31.018	124.288	155.306	0.03488	0.08518	0.12006	0.431
200	1017.2	31.560	124.209	155.769	0.03523	0.08411	0.11934	0.392
225	1038.0	32.204	124.115	156.319	0.03565	0.08287	0.11852	0.354
250	1057.2	32.784	124.029	156.813	0.03603	0.08178	0.11871	0.322
275	1074.8	33.322	123.950	157.272	0.03637	0.08079	0.11716	0.297
300	1091.2	33.824	123.876	157.700	0.03669	0.07989	0.11658	0.276
350	1121.4	34.747	123.740	158.487	0.03725	0.07828	0.11553	0.241
400	1148.4	35.565	123.620	159.185	0.03775	0.07688	0.11463	0.215
500	1196.0	37.006	123.406	160.412	0.03861	0.07455	0.11316	0.177
600	1236.8	38.245	123.221	161.466	0.03932	0.07264	0.11196	0.151
800	1306.1	40.324	122.910	163.234	0.04047	0.06961	0.11008	0.118
1000	1364.0	42.056	122.649	164.705	0.04139	0.06726	0.10865	0.098
1100	1390.0	42.828	122.533	165.361	0.04179	0.06625	0.10804	0.090

From Bolz, R.E. and Tuve, G.L., Gases and vapors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 87. Originally abridged from "Thermodynamic Properties of Mercury Vapor," by L.A. Sheldon. Courtesy of General Electric Company.

Properties of Rare-Earth Metals

To convert density from g/cm³ to kg/m³, multiply by 1000. To convert Young's modulus from kg/cm² to N/m², multiply by 98,067. Values in parentheses are estimates.

Element	Melting Point, °C	Boiling Point, °C	Heat of Sublimation, kcal/mole ΔH 298°K	Density, g/cm³ 298°K	Atomic Volume, cm³/mole	Metallic Radius, Å	Electrical Restivity at 298°K, microhm-cm	Residual Resistivity at 4.2°K, microhm-cm	Compresibility, cm²/kg†	Young's Modulus kg/cm², Millions	Poisson's Ratio
Scandium	1539	2832	91.0	2.989	15.04	1.641	50.9	3.7	2.26	0.809	(0.269)
Yttrium	1523	3337	99.6	4.457	19.95	1.803	59.6	3.2	2.68	0.663	0.265
Lanthanum	920	3454	103.0	6.166	22.53	1.877	79.8	S.C.‡	4.04	0.384	0.288
Cerium	798	3257	111.60	6.771	20.69	1.824	75.3		4.10	0.306	0.248
Praseodymium	931	3212	89.09	6.772	20.81	1.828	68.0	0.7	3.21	0.332	0.305
Neodymium	1010	3127	77.3	7.003	20.60	1.822	64.3	6.8	3.0	0.387	0.306
Promethium	1080	(2460)	(64)	—	—	—	—	—	(2.8)	(0.430)	(0.278)
Samarium	1072	1778	49.3	7.537	19.95	1.802	105.0	6.2	3.34	0.348	0.352
Europium	822	1597	42.5	5.253	28.93	1.983	91.0	0.6	8.29	0.150	(0.286)
Gradolinium	1311	3233	95.75	7.898	19.91	1.801	131.0	4.4	2.56	0.573	0.259
Terbium	1360	3041	93.96	8.234	19.30	1.783	114.5	3.5	2.45	0.586	0.261
Dysprosium	1409	2335	71.2	8.540	19.03	1.775	92.6	2.4	2.55	0.644	0.243
Holmium	1470	2720	71.7	8.781	18.78	1.767	81.4	7.0	2.47	0.684	0.255
Erbium	1522	2510	74.5	9.045	18.49	1.758	86.0	4.7	2.39	0.748	0.238
Thulium	1545	1727	58.3	9.314	18.14	1.747	67.6	5.6	2.47	(0.770)	(0.235)
Ytterbium	824	1193	38.2	6.972	24.82	1.939	25.1	0.29	7.39	0.182	0.284
Lutertium	1656	3315	102.16	9.835	17.79	1.735	58.2	4.5	2.38	(0.860)	(0.233)

† All values in this column should be divided by 10^6.
‡ S.C.–Superconductor.
From Spedding, F.H., Solids — Metals, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 129.

Products of Powder Metallurgy

Powder metallurgy refers to the production of parts by a process of molding metal powders and agglomerating the form by heat. The powder mixture is often hot-molded under pressure (10,000–10,000 psi) and is sintered in an inert or a reducing atmosphere, at a temperature between 400–2,000 deg F, depending on the metal mixture. For the refractory metals higher temperatures are necessary. The methods of powder metallurgy provide a close control of the composition and allow use of mixtures that could not be fabricated by any other process. As dimensions are determined by the mold, finish machining or grinding is often eliminated, thereby reducing cost and handling, especially for large lots. Special properties of the finished product, such as porosity, friction coefficient, and electrical conductivity, can be varied somewhat by changing the proportions of the powder components.

Class	Composition or Constituents	Applications and Uses	Desirable Properties and Advantages
Small, finished parts	Various ferrous, copper, and nickel alloys	Complex shapes; small parts not requiring high strength or ductility; plain bearings	Control of dimensions and finish; two-phase bearing metals; low cost in large production lots
Refractory metals	Pure W, Mo, Ta, Nb, Re, Ti alloys	Production of high-purity tungsten, molybdenum, tantalum, niobium, etc.; beryllium; cobalt alloys	Metals used in high-temperature service; electrical, electronic, and nuclear applications
Porous metals	Copper; copper-lead; bronze; stainless steel	Porous bearings, oil-impregnated, or with graphite or plastic; friction materials; metal filters; porous electrodes; catalysts; throttle plates	Interconnected pores in the size range 5–50 microns; porosity about 20–30%
Composite metals	Al, Cu, etc. with W, Mo, Co, or stainless steel reinforcing; reactor fuel elements	Services requiring high strength with lightness, high electrical and thermal conductivities; nuclear reactor components	High-strength materials from common metals; durability of nuclear materials
Metal–nonmetal composites	Filament-reinforced ceramics; dispersion strengthening by oxides	Ceramics with good structural properties; lightweight materials for high temperature (e.g., SAP)	Strengthened ceramics; heat-resistant aluminum
Magnetic materials	Nickel-iron; cobalt mixtures; ferrites	High-permeability materials; permanent magnets; ferrite cores; magnetic storage	Very high magnetic properties and close control of magnetic properties
Cermets, oxide	Al_2O_3-Cr; Al_2O_3-Cr-W; Al_2O_3-Cr-Mo; ThO_2-W	Combustion and rocket nozzles; furnace muffler, tubes, seals, extrusion dies; power-tube cathodes	High-temperature strength (2,000 deg F and above); resistance to thermal shock; high thermal conductivity; corrosion resistance
Cermets, carbide	TiC-Ni; TiC-Fe-Cr; TiC-Co-Cr-W; Cr_3C_2-Ni-W	High-temperature bearings, seals, and dies; gage blocks	Strength toughness, and corrosion resistance at high temperatures (to 1,700 deg F); hardness
Cemented carbides	WC-Co; WC-TaC-Co; TiC-Ni; Cr_3C_2-WC-Ni	Tips for cutting tools, lathe centers, gages; wire-drawing dies; rock drills; crushers; blast nozzles	Very high hardness, compressive strength, and elastic modulus; war and corrosion resistance; high conductivity; high-temperature strength

From Bolz, R.E. and Tuve, G.L., Solids — Metals, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 133.

Fiber-Reinforced Metals

Ductile and low-strength metals have been reinforced with various fibers. Fiber bundles or mats in molten metals, powder mixtures pressed or extruded, and electroplating are some of the fabrication methods. Copper, aluminum, silver, nickel and titanium are among the matrix materials, with reinforcement by steel, tungsten, boron, molybdenum, silica, glass, oxides, and carbides. The ratio of fiber-strength/matrix-strength determines a certain minimum fiber volume for effective reinforcement, but the fiber–matrix bond and fiber-to-stress alignment are also critical. Increase of strength is almost linear with fiber volume. Short fibers are not fully effective so that the strength is increased much less for a given fiber-volume fraction. Typical test results for fiber-reinforced metals are included in the following table.

Test Results on Composite Metals*

Matrix Metals	Strengthener: Component	Strengthener: % vol	Stress, kpsi: Matrix Only, No Reinforcement	Stress, kpsi: Composite Material
		Metals Strengthened by Fibers		
Copper	W fibers	60	20	200[a]
Silver	Al_2O_3 whiskers	35	10[b]	75[b]
Aluminum	Glass fibers	50	(23%)[c]	(94%)[c]
Aluminum	Al_2O_3	35	25[d]	161[d]
Aluminum	Steel	25	25[d]	173[d]
Nickel	B	8	70[d]	384[d]
Iron	Al_2O_3	36	40[d]	237[d]
Titanium	Mo	20	80[d]	96[d]
		Metals Strengthened by Sintered Carbides		
Cobalt	WC	90	(E = 30)[e]	(E = 85)[e]
Nickel	TiC	75	(E = 31)[f]	(E = 55)[f]

[a] Tensile strength with continuous fibers.
[b] Tensile strength at 350 deg C; modulus of elasticity: Cu = 17, composite 42 (millions of psi).
[c] Percentage of tensile strength at room temperature retained when tested at 300 deg C.
[d] Tensile strength, room temperature.
[e] Modulus of elasticity, *E*, measured in compression; hardness, 90 R-A; compressive strength, about 600,000 psi.
[f] Modulus of elasticity, *E*, measured in compression; hardness about 85 R-A.
* Compiled from various sources.

References

"Metals Handbook: Properties and Selection," Vol. 1, American Society for Metals, 1961.

"Modern Composite Materials," L.J. Broutman and R.H. Krock, Addison-Wesley Publishing Company, 1967.

From Bolz, R.E. and Tuve, G.L., Solids — Metals, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 135.

Properties of Commercial Plastics

Of the many plastics commercially available in each chemical class, only one or a very few examples have been selected for this table as typical of the class. In some cases the range or properties have been expanded to include several grades or types. It is impractical to include a comprehensive list of materials or known properties of these materials in a table of convenient size. Properties vary widely with amount and kind of modifier, such as filler and plasticizer. Within any type of thermoplastic resins, molecular weight is an important variable. This property is controlled to afford the best physical properties available consistent with economical processing properties.

The information shown refers in all cases, except for "Forms available" and "Fabrication," to material in the fabricated form, which in the case of thermosetting materials means commercially cured. Physical and electrical properties will vary, to a greater or lesser degree, with different materials, with humidity conditioning environment and with orientation. Strength values are quoted on the basis of short-time tests at normal room temperature and are not suitable for engineering design purposes for load-bearing applications. Maximum continuous service temperature refers to unloaded structures. The user of this table is referred to the specifications and test procedures of the American Society for Testing Materials.

To convert psi to N/m^2, multiply by 6,895. For specific heat in J/kg·K, multiply by 4,184.

	Chemical Class	Cellulose Acetate	Cellulose Acetate	Cellulose Acetate Butyrate
	Resin Type	Thermoplastic	Thermoplastic	Thermoplastic
Properties	Subclass or Modification	Soft	Hard	Soft
Electrical Properties				
D.C. resistivity, ohm-cm		10^{10}–10^{13}	10^{10}–10^{13}	10^{10}–10^{12}
Dielectric constant, 60 cps		3.5–7.5	3.5–7.5	3.5–6.4
Dielectric constant, 10^6 cps		3.2–7.0	3.2–7.0	3.2–6.2
Dissipation factor, 60 cps		0.01–0.06	0.01–0.06	0.01–0.04
Dissipation factor, 10^6 cps		0.01–0.10	0.01–0.10	0.01–0.04
Mechanical Properties				
Modulus of elasticity, 10^3 psi		86–250	190–400	74–126
Tensile strength, psi		1,900–4,700	4,600–8,500	1,900–3,800
Ultimate elongation, %		32–50	6–40	60–74
Yield stress, psi		2,200–4,200	4,100–7,600	1,200–2,600
Yield strain, %				
Rockwell hardness		R 49–R 103	R 101–R 123	R 59–R 95
Notched Izod impact strength, ft lb/in.		2.0–5.2	0.4–2.7	2.5–5.4
Specific gravity		1.27–1.34	1.27–1.34	1.15–1.22
Thermal Properties				
Burning rate		Medium	Medium	Medium
Heat distortion, 264 psi, °C		44–57	60–113	49–58
Specific heat, cal/g		0.3–0.42	0.3–0.42	0.3–0.4
Linear thermal expansion coefficient, 10^{-5}, °C		8–16	8–16	11–17
Maximum continuous service temperature, °C				
Chemical Resistance				
Mineral acids, weak		Fair to good	Fair to good	Good
Mineral acids, strong		Poor	Poor	Fair to good
Oxidizing acids, concentrated		Very poor	Very poor	
Alkalies, weak		Poor	Poor	Good
Alkalies, strong		Very poor	Very poor	Poor
Alcohols		Poor	Poor	Poor
Ketones		Poor	Poor	Poor
Esters		Poor	Poor	Poor
Hydrocarbons, aliphatic		Fair to good	Fair to good	Fair to good
Hydrocarbons, aromatic		Poor to fair	Poor to fair	Poor
Oils: vegetable, animal, mineral		Fair to good	Fair to good	Good
Miscellaneous Properties				
Clarity		Excellent	Excellent	Good to excellent
Color		Pale to colorless	Pale to colorless	Pale to colorless
Refractive index, n_D		1.46–1.50	1.46–1.50	1.46–1.49
Application ASTM specifications and test methods		D786, D706, D257, D150, D638, D785, D256, D792, D648, D696, D543, D542	D786, D706, D257, D150, D638, D785, D256, D792, D648, D696, D543, D542	D707, D257, D150, D638, D785, D256, D792, D648, D696

Properties of Commercial Plastics (continued)

Forms Available Cs—castings, F—film, Fb—fibers, I—impregnants, L—laminations, Lq—lacquers, Mf—monofilaments, P—powder, pellet, or granules, R—rods, tubes, or other extruded forms, S—sheets.	F, Lq, P, R, S	F, Lq, P, R, S	F, Lq, P, R, S
Fabrication Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MB—blow molding, MC—compression molding, MI—injection molding, S—spreading.	Cs, E, F, MB, MC, MI, S	Cs, E, F, MB, MC, MI, S	Cs, E, F, MB, MC, MI, S

Properties	Chemical Class	Cellulose Acetate Butyrate	Nylon	Polycarbonates
	Resin Type	Thermoplastic	Thermoplastic	Thermoplastic
	Subclass or Modification	Hard	6/6	Unfilled
Electrical Properties				
D.C. resistivity, ohm-cm		10^{10}–10^{12}		2×10^{16}
Dielectric constant, 60 cps		3.5–6.4	4.0–4.6	3.17
Dielectric constant, 10^6 cps		3.2–6.2	3.4–3.6	2.96
Dissipation factor, 60 cps		0.01–0.04	0.014–.04	0.0009
Dissipation factor, 10^6 cps		0.01–0.04	0.04	0.001
Mechanical Properties				
Modulus of elasticity, 10^3 psi		150–200		290–325
Tensile strength, psi		5,000–6,800	9,000–12,000	8,000–-9,500
Ultimate elongation, %		38–54	60–300	20–100
Yield stress, psi		3,600–6,100		8,000–10,000
Yield strain, %				
Rockwell hardness		R 108–R 117	R 108–R 120	M 70–M 180
Notched Izod impact strength, ft lb/in.		0.7–2.4	1.0–2.0	8–16
Specific gravity		1.19–1.25	1.13–1.15	1.2
Thermal Properties				
Burning rate		Medium	Self-extinguishing	Self-extinguishing
Heat distortion, 264 psi, ˚C		70–99		135–145
Specific heat, cal/g		0.3–0.4	0.4	0.3
Linear thermal expansion coefficient, 10^{-5}, ˚C		11–17	8.0	6.6
Maximum continuous service temperature, ˚C			80–150	138–143
Chemical Resistance				
Mineral acids, weak		Good	Very good	Excellent
Mineral acids, strong		Fair to good	Poor	Fair
Oxidizing acids, concentrated			Poor	
Alkalies, weak		Good	No effect	Poor
Alkalies, strong		Poor	No effect	Poor
Alcohols		Poor	Good	Poor
Ketones		Poor	Good	Poor
Esters		Poor	Good	Poor
Hydrocarbons, aliphatic		Fair to good	Very good	Poor
Hydrocarbons, aromatic		Poor	Fair to good	Poor
Oils: vegetable, animal, mineral		Good	Good	Poor
Miscellaneous Properties				
Clarity		Good to excellent	Clear	Clear
Color		Pale to colorless	Pale amber to colorless	Colorless
Refractive index, n_D		1.46–1.49	1.53	1.60
Application ASTM specifications and test methods		D707, D257, D150, D256, D792, D648, D542, D638, D785, D696, D543	D257, D150, D638, D792, D648, D696, D785, D256, D542, D543	D257, D150, D638, D792, D648, D696, D785, D256, D542, D543

Properties of Commercial Plastics (continued)

Forms Available Cs—castings, F—film, Fb—fibers, I—impregnants, L—laminations, Lq—lacquers, Mf—monofilaments, P—powder, pellet, or granules, R—rods, tubes, or other extruded forms, S—sheets.	F, Lq, P, R, S	F, Fb, Mf, P, R, S	F, Fb, Mf, P, R, S
Fabrication Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MB—blow molding, MC—compression molding, MI—injection molding, S—spreading.	Cs, E, F, MB, MC, MI, S	E, F, MB, MC, MI	Cs, E, F, MB, MC, MI

To convert psi to N/m², multiply by 6,895. For specific heat in J/kg·K, multiply by 4,184.

Properties	Chemical Class / Resin Type / Subclass or Modification	Polyethylene / Thermoplastic / Low Density	Polyethylene / Thermoplastic / Medium Density	Polyethylene / Thermoplastic / High Density
Electrical Properties				
D.C. resistivity, ohm-cm		$>10^{15}$	$>10^{15}$	$>10^{15}$
Dielectric constant, 60 cps		2.3–2.35	2.3	2.3–2.35
Dielectric constant, 10^6 cps		2.3–2.35	2.3	2.3–2.35
Dissipation factor, 60 cps		<0.0005	<0.0005	<0.0005
Dissipation factor, 10^6 cps		<0.0005	<0.0005	<0.0005
Mechanical Properties				
Modulus of elasticity, 10^3 psi		14–38	35–90	85–160
Tensile strength, psi		1,000–1,400	1,200–3,500	3,100–5,500
Ultimate elongation, %		400–700	50–600	15–100
Yield stress, psi		1,100–1,700	1,500–2,600	2,400–5,000
Yield strain, %		20–40	10–20	5–10
Rockwell hardness				R 30–R 50
Notched Izod impact strength, ft lb/in.		No break	0.5–>16	1.5–20
Specific gravity		0.91–0.925	0.926–0.941	0.941–0.965
Thermal Properties				
Burning rate		Very slow	Slow	Slow
Heat distortion, 264 psi, °C				
Specific heat, cal/g		0.55	0.55	0.55
Linear thermal expansion coefficient, 10^{-5}, °C		10–20	14.16	11.13
Maximum continuous service temperature, °C		60–77	71–93	92–200
Chemical Resistance				
Mineral acids, weak		Good	Excellent	Excellent
Mineral acids, strong		Good	Excellent	Excellent
Oxidizing acids, concentrated		Good to poor	Good to poor	Good to poor
Alkalies, weak		Good	Excellent	Excellent
Alkalies, strong		Good	Excellent	Excellent
Alcohols		Excellent to poor	Excellent to poor	Excellent to poor
Ketones		Excellent to poor	Excellent to poor	Excellent to poor
Esters		Excellent to poor	Excellent to poor	Excellent to poor
Hydrocarbons, aliphatic		Fair	Fair	Fair
Hydrocarbons, aromatic		Fair	Good	Fair
Oils: vegetable, animal, mineral		Good	Excellent	Good
Miscellaneous Properties				
Clarity		Translucent	Translucent	Translucent
Color		Colorless	Colorless	Colorless
Refractive index, n_D		1.50–1.54	1.52–1.54	1.54
Application ASTM specifications and test methods		D702, D788, D257, D638, D696, D543, D150, D412, D1248, D542	D257, D150, D412, D256, D696, D543, D638, D785, D1248, D542	D257, D150, D412, D256, D696, D543, D638, D785, D1248, D542

Properties of Commercial Plastics (continued)

Forms Available Cs—castings, F—film, Fb—fibers, I—impregnants, L—laminations, Lq—lacquers, Mf—monofilaments, P—powder, pellet, or granules, R—rods, tubes, or other extruded forms, S—sheets.	F, Mf, P, R, S	F, Mf, P, R, S	F, Fb, Mf, P, R, S
Fabrication Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MB—blow molding, MC—compression molding, MI—injection molding, S—spreading.	Cl, E, F, MB, MC, MI	Cl, E, F, MB, MC, MI	Cl, E, F, MB, MC, MI

Properties	Chemical Class	Methylmethacrylate	Polypropylene	Polypropylene
	Resin Type	Thermoplastic	Thermoplastic	Thermoplastic
	Subclass or Modification	Unmodified	Unmodified	Unmodified
Electrical Properties				
D.C. resistivity, ohm-cm		$>10^{14}$	$>10^{15}$	$>10^{17}$
Dielectric constant, 60 cps		3.5–4.5	2.2–2.6	2.3
Dielectric constant, 10^6 cps		3.0–3.5	2.2–2.6	2.3
Dissipation factor, 60 cps		0.04–0.06	<0.0005	0.0001–0.0005
Dissipation factor, 10^6 cps		0.02–0.03	0.0005–0.002	0.0001–0.002
Mechanical Properties				
Modulus of elasticity, 10^3 psi		350–500	1.4–1.7	
Tensile strength, psi		7,000–11,000	4,300–5,500	2,900–4,500
Ultimate elongation, %		2.0–1.0	>220	200–700
Yield stress, psi			4,900	
Yield strain, %			15	
Rockwell hardness		M 80–M 105	93	R 30–R 96
Notched Izod impact strength, ft lb/in.		0.3–0.6	1.0	1.1–12
Specific gravity		1.18–1.20	0.90	0.90
Thermal Properties				
Burning rate		Slow	Medium	Medium
Heat distortion, 264 psi, ˚C		66–99		
Specific heat, cal/g		0.35	0.5	0.5
Linear thermal expansion coefficient, 10^{-5}, ˚C		5.0–9.0	5.8–10	8–10
Maximum continuous service temperature, ˚C		60–93		190–240
Chemical Resistance				
Mineral acids, weak		Good	Excellent	Excellent
Mineral acids, strong		Fair to poor	Excellent	Excellent
Oxidizing acids, concentrated		Attacked	Good to poor	Poor
Alkalies, weak		Good	Excellent to good	Excellent
Alkalies, strong		Poor	Excellent to good	Good
Alcohols			Excellent to good	Good below 80˚C
Ketones		Dissolves	Excellent to good	Good below 80˚C
Esters		Dissolves	Excellent to good	Good below 80˚C
Hydrocarbons, aliphatic		Good	Good to fair	Good below 80˚C
Hydrocarbons, aromatic		Softens	Good to fair	Good below 80˚C
Oils: vegetable, animal, mineral		Good	Good	
Miscellaneous Properties				
Clarity		Excellent	Transparent	Transparent
Color		Colorless	Colorless to sl. yellow	Colorless to sl. yellow
Refractive index, n_D		1.48–1.50	1.49	
Application ASTM specifications and test methods		D257, D150, D638, D792, D648, D696, D785, D256, D543, D542	D257, D150, D412, D256, D648, D543, D638, D785, D542	D257, D150, D412, D256, D648, D543, D638, D785, D542

Properties of Commercial Plastics (continued)

Forms Available Cs—castings, F—film, Fb—fibers, I—impregnants, L—laminations, Lq—lacquers, Mf—monofilaments, P—powder, pellet, or granules, R—rods, tubes, or other extruded forms, S—sheets.	Cs, P, R, S	F, Fb, Mf, P, R, S	F, Fb, Mf, P, R, S
Fabrication Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MB—blow molding, MC—compression molding, MI—injection molding, S—spreading.	Cs, E, F, Lq, MB, MC, MI	Cl, E, F, MB, MC, MI	Cl, E, F, MB, MC, MI

To convert psi to N/m^2, multiply by 6,895. For specific heat in J/kg·K, multiply by 4,184.

Properties	Chemical Class	Methylmethacrylate	Polypropylene	Polypropylene
	Resin Type	Thermoplastic	Thermoplastic	Thermoplastic
	Subclass or Modification	Unmodified	Unmodified	Unmodified
Electrical Properties				
D.C. resistivity, ohm-cm		>10^{16}	>10^{13}–10^{17}	>10^{18}
Dielectric constant, 60 cps		2.5–2.65	2.6–3.4	2.
Dielectric constant, 10^6 cps		2.5–2.65	2.5–3.1	2.
Dissipation factor, 60 cps		0.0001–0.0003	0.0006–0.008	0.0002
Dissipation factor, 10^6 cps		0.0001–0.0004	0.007–0.01	0.0002
Mechanical Properties				
Modulus of elasticity, 10^3 psi		400–600	>10^{16}	33–65
Tensile strength, psi		5,000–10,000	9,000–12,000	2,000–4,500
Ultimate elongation, %		1.0–2.5	1.0–2.5	200–400
Yield stress, psi				1,600–2,000
Yield strain, %				50–75
Rockwell hardness		M 65–M 85	M 75–M 90	D 50–D 65
Notched Izod impact strength, ft lb/in.		0.25–0.60	0.3–0.6	2.5–4.0
Specific gravity		1.04–1.08	1.05–1.1	2.1–2.3
Thermal Properties				
Burning rate		Medium to slow	Slow	Self-extinguishing
Heat distortion, 264 psi, ˚C			91–104	60
Specific heat, cal/g		0.32–0.35	0.32–0.35	0.25
Linear thermal expansion coefficient, 10^{-5}, ˚C		6.0–8.0	3.6–3.8	10
Maximum continuous service temperature, ˚C		66–82	77–88	260
Chemical Resistance				
Mineral acids, weak		Excellent	Excellent	Excellent
Mineral acids, strong		Excellent	Good to excellent	Excellent
Oxidizing acids, concentrated		Poor	Poor	Excellent
Alkalies, weak		Excellent	Excellent	Excellent
Alkalies, strong		Excellent	Good to excellent	Excellent
Alcohols		Excellent	Good to excellent	Excellent
Ketones		Dissolves	Dissolves	Excellent
Esters		Poor	Dissolves	Excellent
Hydrocarbons, aliphatic		Poor	Good	Excellent
Hydrocarbons, aromatic		Dissolves	Fair to good	Excellent
Oils: vegetable, animal, mineral		Fair to poor	Good to excellent	Excellent
Miscellaneous Properties				
Clarity		Transparent	Transparent	Translucent
Color		Colorless	Colorless to amber	Colorless to gray
Refractive index, n_D		1.59–1.60	1.56–1.57	1.30–1.40
Application ASTM specifications and test methods		D257, D150, D638, D792, D648, D696, D785, D256, D543, D542	D257, D150, D638, D792, D648, D696, D785, D256, D543, D542	

Properties of Commercial Plastics (continued)

Forms Available Cs—castings, F—film, Fb—fibers, I—impregnants, L—laminations, Lq—lacquers, Mf—monofilaments, P—powder, pellet, or granules, R—rods, tubes, or other extruded forms, S—sheets.	F, Fb, Mf, P, R, S	F, Mf, P, R, S	F, L, P, R, S
Fabrication Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MB—blow molding, MC—compression molding, MI—injection molding, S—spreading.	E, F, MB, MC, MI	Cl, E, F, MB, MC, MI	E, F, MC, MI

Properties	Chemical Class	Polytrifluoro-chloroethylene	Polyvinylchloride and Vinylchloride Acetate	Polyvinylchloride and Vinylchloride Acetate
	Resin Type	Thermoplastic	Thermoplastic	Thermoplastic
	Subclass or Modification	Unmodified	Unmodified, Rigid	Plasticized, Non-Rigid
Electrical Properties				
D.C. resistivity, ohm-cm		10^{18}	10^{12}–10^{16}	10^{11}–10^{14}
Dielectric constant, 60 cps		2.2–2.8	3.2–4.0	5.0–9.0
Dielectric constant, 10^6 cps		2.3–2.5	3.0–4.0	3.0–4.0
Dissipation factor, 60 cps		0.001	0.01–0.02	0.03–0.05
Dissipation factor, 10^6 cps		0.005	0.006–0.02	0.06–0.1
Mechanical Properties				
Modulus of elasticity, 10^3 psi		150	200–600	
Tensile strength, psi		4,500–6,000	5,000–9,000	1,500–3,000
Ultimate elongation, %		250	2.0–40	200–400
Yield stress, psi		4,200		
Yield strain, %		10	1.0–5.0	
Rockwell hardness		J 75–J 95	R 110–R 120	
Notched Izod impact strength, ft lb/in.		2.5–4.0	0.4–2.0	
Specific gravity		2.1–2.3	1.36–1.4	1.15–1.35
Thermal Properties				
Burning rate		Self-extinguishing	Self-extinguishing	Slow to self-extinguishing
Heat distortion, 264 psi, °C			60–80	
Specific heat, cal/g		0.22	0.2–0.28	0.36–0.5
Linear thermal expansion coefficient, 10^{-5}, °C		7.0	5.0–18	7.0–25
Maximum continuous service temperature, °C		200	70–74	80–105
Chemical Resistance				
Mineral acids, weak		Excellent	Excellent	Fair to good
Mineral acids, strong		Excellent	Good to excellent	Fair to good
Oxidizing acids, concentrated		Excellent	Fair to good	Poor to fair
Alkalies, weak		Excellent	Excellent	Fair to good
Alkalies, strong		Excellent	Good	Fair to good
Alcohols		Excellent	Excellent	Fair
Ketones		Excellent	Poor	Poor
Esters		Excellent	Poor	Poor
Hydrocarbons, aliphatic		Excellent	Excellent	Poor
Hydrocarbons, aromatic		Excellent	Poor	Poor
Oils: vegetable, animal, mineral		Excellent	Excellent	Poor
Miscellaneous Properties				
Clarity		Transparent	Transparent	Transparent
Color		Colorless to pale	Colorless to amber	Colorless to amber
Refractive index, n_D		1.43	1.54	1.50–1.55
Application ASTM specifications and test methods		D1430, D257, D150, D256, D792, D648, D542, D638, D785, D696, D543	D708, D728, D257, D256, D792, D648, D542, D150, D638, D696, D543	D1432, D257, D150, D543, D542

Properties of Commercial Plastics (continued)

Forms Available Cs—castings, F—film, Fb—fibers, I—impregnants, L—laminations, Lq—lacquers, Mf—monofilaments, P—powder, pellet, or granules, R—rods, tubes, or other extruded forms, S—sheets.	F, Mf, P, R, S	F, Fb, I, Lq, Mf, P, R, S	F, L, P, R, S
Fabrication Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MB—blow molding, MC—compression molding, MI—injection molding, S—spreading.	Cs, E, F, I, MC, MI, S	Cl, Cs, E, F, I, MB, MC, MI, S	Cl, Cs, E, MB, MC, MI, S

To convert psi to N/m², multiply by 6,895. For specific heat in J/kg·K, multiply by 4,184.

Properties	Chemical Class	Epoxy	Melamine-Formaldehyde	Melamine-Formaldehyde
	Resin Type	Thermosetting	Thermosetting	Thermosetting
	Subclass or Modification	Unfilled	α-Cellulose Filled	Mineral-Filled (Electrical)
Electrical Properties				
D.C. resistivity, ohm-cm		10^{12}–10^{14}	10^{12}–10^{14}	10^{13}–10^{14}
Dielectric constant, 60 cps		3.5–5.0	7.9–9.4	10.2
Dielectric constant, 10^6 cps		3.4–4.4	7.2–8.4	6.1
Dissipation factor, 60 cps		0.001–0.005	0.03–0.08	0.10
Dissipation factor, 10^6 cps		0.03–0.05	0.03–0.043	0.051
Mechanical Properties				
Modulus of elasticity, 10^3 psi		>300	1,300	1,950
Tensile strength, psi		4,000–13,000	7,000–13,000	5,500–6,500
Ultimate elongation, %		2.0–6.0	0.6–0.9	
Yield stress, psi				
Yield strain, %				
Rockwell hardness		M 75–M 110	M 110–M 124	E 90
Notched Izod impact strength, ft lb/in.		0.2–1.0	0.24–0.35	0.3–0.4
Specific gravity		1.115	1.47–1.52	1.78
Thermal Properties				
Burning rate		Slow	Self-extinguishing	Self-extinguishing
Heat distortion, 264 psi, °C		Up to 120	204	130
Specific heat, cal/g		0.25–0.4	0.4	
Linear thermal expansion coefficient, 10^{-5}, °C		4.5–9.0	2.0–5.7	2.1–4.3
Maximum continuous service temperature, °C		80	99.0	149
Chemical Resistance				
Mineral acids, weak		Excellent	Good	Fair
Mineral acids, strong		Fair to good	Poor	Poor
Oxidizing acids, concentrated		Poor	Poor	Poor
Alkalies, weak		Excellent	Good	Fair
Alkalies, strong		Excellent	Poor	Poor
Alcohols		Excellent	Good	Good
Ketones		Poor	Good	Good
Esters			Good	Good
Hydrocarbons, aliphatic		Excellent	Good	Good
Hydrocarbons, aromatic		Excellent	Good	Good
Oils: vegetable, animal, mineral		Excellent	Good	Good
Miscellaneous Properties				
Clarity		Transparent	Transparent	Opaque
Color		Colorless	Colorless	Dark
Refractive index, n_D		1.58		
Application ASTM specifications and test methods		D257, D150, D651, D792, D648, D696, D785, D256, D5432	D704, D257, D150, D256, D792, D648, D638, D785, D543, D696	D704, D257, D150, D256, D792, D648, D638, D785, D543, D696

Properties of Commercial Plastics (continued)

Forms Available Cs—castings, F—film, Fb—fibers, I—impregnants, L—laminations, Lq—lacquers, Mf—monofilaments, P—powder, pellet, or granules, R—rods, tubes, or other extruded forms, S—sheets.	Cs, Lq	P, R, S	P, R, S
Fabrication Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MB—blow molding, MC—compression molding, MI—injection molding, S—spreading.	Cs, I, S	MC	MC

Properties / Chemical Class / Resin Type / Subclass or Modification	Phenol-Formaldehyde / Thermosetting / Cord Filled	Phenol-Formaldehyde / Thermosetting / Cellulose Filled	Phenol-Formaldehyde / Thermosetting / Unfilled Cast Phenolic, Mechanical and Chemical Grade
Electrical Properties			
D.C. resistivity, ohm-cm	10^{11}–10^{12}	10^{11}–10^{13}	1.0–7.0 × 10^{12}
Dielectric constant, 60 cps	7.0–10.0	5.0–9.0	6.5–7.5
Dielectric constant, 10^6 cps	5.0–6.0	4.0–7.0	4.0–5.5
Dissipation factor, 60 cps	0.1–0.3	0.0–0.3	0.10–0.15
Dissipation factor, 10^6 cps	0.04–0.09	0.03–0.07	0.04–0.05
Mechanical Properties			
Modulus of elasticity, 10^3 psi	900–1,300	800–1,200	4.0–5.0
Tensile strength, psi	6,000–9,000	6,500–8,500	6,000–9,000
Ultimate elongation, %	0.5–1.0	0.6–1.0	1.5–2.0
Yield stress, psi			
Yield strain, %			
Rockwell hardness		M 110–M 120	M 93–M 120
Notched Izod impact strength, ft lb/in.	4.0–8.0	0.24–0.34	0.25–0.4
Specific gravity	1.36–1.43	1.32–1.55	1.307–1.318
Thermal Properties			
Burning rate	Self-extinguishing	Self-extinguishing	Self-extinguishing
Heat distortion, 264 psi, ˚C	121–127	143–171	74–80
Specific heat, cal/g		0.35–0.40	
Linear thermal expansion coefficient, 10^{-5}, ˚C		3.0–4.5	6.0–8.0
Maximum continuous service temperature, ˚C	121	149–177	
Chemical Resistance			
Mineral acids, weak	Variable	Variable	Fair to good
Mineral acids, strong	Poor	Poor	Poor to good
Oxidizing acids, concentrated	Poor	Poor	Poor
Alkalies, weak	Variable	Variable	Poor to good
Alkalies, strong	Poor	Poor	Poor
Alcohols	Good	Good to excellent	Good to excellent
Ketones	Poor to fair	Fair	Fair
Esters	Fair to good	Fair to good	Fair to good
Hydrocarbons, aliphatic	Fair to good	Excellent	Good to excellent
Hydrocarbons, aromatic	Fair to good	Excellent	Good
Oils: vegetable, animal, mineral	Good	Excellent	Excellent
Miscellaneous Properties			
Clarity	Opaque	Opaque	Clear
Color			Colorless to amber
Refractive index, n_D			
Application ASTM specifications and test methods	D700, D257, D150, D785, D256, D792, D638, D651, D543, D648	D700, D257, D150, D785, D256, D792, D543, D638, D651, D648, D696	D257, D150, D638, D792, D648, D696, D785, D256, D543

Properties of Commercial Plastics (continued)

Forms Available Cs—castings, F—film, Fb—fibers, I—impregnants, L—laminations, Lq—lacquers, Mf—monofilaments, P—powder, pellet, or granules, R—rods, tubes, or other extruded forms, S—sheets.	L, P, S	L, P, S	Cs, R, S
Fabrication Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MB—blow molding, MC—compression molding, MI—injection molding, S—spreading.	MC	MC	Cs, F

To convert psi to N/m^2, multiply by 6,895. For specific heat in J/kg·K, multiply by 4,184.

Properties	Chemical Class / Resin Type / Subclass or Modification	Polyester (Styrene-Alkyd) / Thermosetting / Glassfiber Mat Reinforced	Silicones / Thermosetting / Mineral Filled	Urea Formaldehyde / Thermosetting / α-Cellulose Filled
Electrical Properties				
D.C. resistivity, ohm-cm		10^{11}	$>10^{12}$	0.5–5.0
Dielectric constant, 60 cps		4.0–5.5	3.5–3.6	7.7–9.5
Dielectric constant, 10^6 cps		4.0–5.5	3.4–3.6	6.7–8.0
Dissipation factor, 60 cps		001–0.04	0.004	0.036–0.043
Dissipation factor, 10^6 cps		0.01–0.06	0.005–0.007	0.025–0.035
Mechanical Properties				
Modulus of elasticity, 10^3 psi		500–1,500		1,300–1,400
Tensile strength, psi		30,000–50,000	3,000–4,000	5,500–13,000
Ultimate elongation, %		0.5–1.5		0.6
Yield stress, psi				
Yield strain, %				
Rockwell hardness		M 80–M 120	M 85–M 95	E 94–E 97
Notched Izod impact strength, ft lb/in.		7.0–30	0.25–0.35	0.24–0.40
Specific gravity		1.5–2.1	1.8–2.8	1.47–1.52
Thermal Properties				
Burning rate		Self-extinguishing	Self-extinguishing	Self-extinguishing
Heat distortion, 264 psi, °C		93–288	>260	130
Specific heat, cal/g		0.2–0.4	0.2–0.3	0.6
Linear thermal expansion coefficient, 10^{-5}, °C		1.8–3.0	2.0–4.0	2.2–3.6
Maximum continuous service temperature, °C		121–204	288	77
Chemical Resistance				
Mineral acids, weak		Good	Fair to good	Poor
Mineral acids, strong		Poor	Poor to good	Poor
Oxidizing acids, concentrated		Poor		Poor
Alkalies, weak		Good	Fair	Fair
Alkalies, strong		Poor	Poor	Poor
Alcohols		Good	Poor	Good
Ketones		Poor	Poor	Good
Esters		Good		Good
Hydrocarbons, aliphatic		Good	Fair to good	Good
Hydrocarbons, aromatic		Poor to fair	Poor	Good
Oils: vegetable, animal, mineral		Good	Good	
Miscellaneous Properties				
Clarity		Translucent	Opaque	Translucent
Color		Colorless	Pale to dark	Colorless
Refractive index, n_D				1.54–1.56
Application ASTM specifications and test methods		D257, D150, D638, D792, D648, D696, D785, D256, D543	D257, D150, D785, D648, D696, D543, D256, D792	D705, D257, D150, D256, D792, D648, D638, D785

Properties of Commercial Plastics (continued)

Forms Available Cs—castings, F—film, Fb—fibers, I—impregnants, L—laminations, Lq—lacquers, Mf—monofilaments, P—powder, pellet, or granules, R—rods, tubes, or other extruded forms, S—sheets.	L, S	P	P, R, S
Fabrication Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MB—blow molding, MC—compression molding, MI—injection molding, S—spreading.	I	MC	MC

Chemical Class	Acrylonitrile-Butadiene-Styrene (ABS)	Acetal	Alkyd Resins
Resin Type	Thermoplastic	Thermoplastic	Thermosetting
Properties / Subclass or Modification	High-Heat Resistant	Homopolymer	Synthetic-Fiber Filled
Electrical Properties			
D.C. resistivity, ohm-cm			
Dielectric constant, 60 cps	2.4–5.0		3.8–5.0
Dielectric constant, 10^6 cps	2.4–3.8	3.7	3.6–4.7
Dissipation factor, 60 cps	0.003–0.008		0.012–0.026
Dissipation factor, 10^6 cps	0.007–0.015	0.004	0.01–0.016
Mechanical Properties			
Modulus of elasticity, 10^3 psi			
Tensile strength, psi	7,000–8,000	10,000–12,000	4,500–6,500
Ultimate elongation, %	1.0–20	15–75	
Yield stress, psi	4,000–9,000		10,000–13,000
Yield strain, %			
Rockwell hardness	R 110–R 115	M 94, R 120	E 76
Notched Izod impact strength, ft lb/in.	2.0–4.0	1.4–2.3	0.50–4.5
Specific gravity	1.06–1.08	1.43	1.24–2.6
Thermal Properties			
Burning rate	Slow	Slow	Self-extinguishing
Heat distortion, 264 psi, °C	115–118		
Specific heat, cal/g	0.3–0.4	0.35	
Linear thermal expansion coefficient, 10^{-5}, °C	6.0–6.5	8.1	4.0–5.5
Maximum continuous service temperature, °C	88–110	84	149–220
Chemical Resistance			
Mineral acids, weak	Good	Fair	Good
Mineral acids, strong	Good	Poor	Fair
Oxidizing acids, concentrated	Poor	Poor	
Alkalies, weak	Good	Poor	Good
Alkalies, strong	Good	Poor	Fair
Alcohols	Good	Good	Fair to good
Ketones	Poor	Good	Fair to good
Esters	Poor	Good	Fair to good
Hydrocarbons, aliphatic	Fair	Good	Fair to good
Hydrocarbons, aromatic	Fair	Good	Fair to good
Oils: vegetable, animal, mineral	Good	Good	
Miscellaneous Properties			
Clarity	Translucent to opaque	Translucent to opaque	Opaque
Color	Colorless	Colorless	Colorless
Refractive index, n_D		1.48	
Application ASTM specifications and test methods	D638, D150, D792, D256, D758, D696, D651, D648, D543	D638, D150, D792, D256, D758, D696, D651, D648, D543	D638, D150, D792, D256, D758, D543, D651, D648

Properties of Commercial Plastics (continued)

Forms Available Cs—castings, F—film, Fb—fibers, I—impregnants, L—laminations, Lq—lacquers, Mf—monofilaments, P—powder, pellet, or granules, R—rods, tubes, or other extruded forms, S—sheets.	P, S, L, R	C, R	P
Fabrication Cl—calendering, Cs—casting, E—extrusion, F—hot forming or drawing, I—impregnation, MB—blow molding, MC—compression molding, MI—injection molding, S—spreading.	Cl, E, MB, MI	MI, E	Cs, MC, MI

References

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"Modern Plastics Encyclopedia," Vol. 44, No. 1A, McGraw-Hill, Inc., 1967.

From Bolz, R.E. and Tuve, G.L., Solids — Non-metals, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 137–147.

Rubbers and Elastomers

Elastomers cannot be classified in any brief and simple manner, nor are they well characterized by the usual mechanical tests. The terms *rubber* and *synthetic rubber* are loosely applied to a great variety of elastic materials, from pure gum natural rubber and pure synthetics to cured, compounded, filled, and even reinforced products.

ASTM designations (D418) by chemical polymer description are used in the following table; yet within each class the properties can vary widely, depending on the exact composition, heat treatment, service temperature, and application. Typical uses, such as rubber springs and cushioning, permit an almost unlimited number of combinations of design variables.

Mechanically, rubbers may be expected to lose strength rapidly with increase in temperature, to show a large hysteresis in stress-strain behavior, to exhibit marked creep and set, and to be greatly affected by rates of load application or frequency of repeated stress. "Heat build-up," i.e., increase in temperature in service, as well as deterioration from environment (sunlight, oils, ozone, etc.) will reduce the valuable properties of many rubbers, both natural and synthetic.

The following data apply to typical samples of commercial elastomers for common uses.

Key:

A — Acetone
B — Benzene
C — Carbon tetrachloride
D — Carbon disulfide
E — Phenol
F — Sulfur compounds
G — Glycerol or glycol
H — Hexane
I — Acids
J — Alkalies
K — Ketones
L — Alcohols
M — Ammonia
N — Turpentine
O — Coal derivatives; bitumens
P — Petroleum products
R — Aromatics
S — Salts
T — Heat of high temperature
U — Ultraviolet
V — Vegetable oils
W — Weathering
X — Oxidation
Y — Aging
Z — Ozone

Chemical Name	Polyisoprene	Butadiene	Styrene-Butadiene	Acrylonitrile Butadiene
Other Names	Natural (or Synthetic) Rubber NR (IR)	BR Cis 4	Buna S Styrene SBR, GR-S	Nitrile, Buna N Hycar NBR, GR-A
Chemical and Physical				
Specific gravity	0.93	1.0	1.0	1.0
Specific heat	0.40	0.45	0.40	0.47
Thermal conductivity				
W/cm·K	0.001 7	0.002 5	0.002 6	0.002 5
Btu/hr·ft·deg F	0.10	0.14	0.15	0.14
Service temperature, deg C				
min	–25	–40	–20	–20
max	90	90	75	110
Solvents, softeners	D,K,P,V	D,H,N,P	K,P,R,V	C,K,O.R
Resistant to	A,I,J,L	G,I,J,W,Y	G,I.L,S,X	G,I,K,L,P,S,T,V,W
Swelled by	D,P,V	A,P,V	P,V	A,E.N
Mechanical and Electrical				
Tensile strength				
kg/cm^2 (max)	300.	210.	210.	295.
kpsi (max)	4.3	3.0	3.0	4.2
Elongation at break, %	600.	700.	600.	600.
Vol. resistivity, ohm-cm	10^{15}	10^{15}	10^{14}	10^{10}
Dielectric strength				
kV/cm	235		235	185
V/mil	600.		600.	475.
Dielectric constant	3.0	2.3	2.8	3.0
Power factor (50–100 Hz)	0.003	0.005	0.005	0.007
Rebound	Good	Good	Fair	Good
Comparative Ratings — Resistance to				
Abrasion	Good	Excellent	Good	Excellent
Cold flow (set)	Excellent		Good	Good
Tearing	Good		Poor	Fair

Rubbers and Elastomers

Chemical Name	Polyisoprene	Butadiene	Styrene-Butadiene	Acrylonitrile Butadiene
Other Names	Natural (or Synthetic) Rubber NR (IR)	BR Cis 4	Buna S Styrene SBR, GR-S	Nitrile, Buna N Hycar NBR, GR-A
Air permeability	Fair	Good	Fair	Excellent
Oxidation	Fair	Fair	Fair	Fair
Flame	Poor		Poor	Poor

Chemical Name	Polychloroprene	Isobutylene-Isoprene	Polysulfide	Polymethane
Other Names	Neoprene[a], CR, GR-M	Butyl, IIR, GR-I	Thiokol[a], PS, GR-P	Adiprene[a], PU
Chemical and Physical				
Specific gravity	1.25	0.95	1.4	1.2
Specific heat	0.5	0.45	0.31	0.45
Thermal conductivity				
W/cm·K	0.002 1	0.001 3	0.003	0.001 3
Btu/hr·ft·deg F	0.12	0.075	0.17	0.075
Service temperature, deg C				
min	–20	–40	–15	–35
max	100	120	90	120
Solvents, softeners	A,B,C,D,I,N,R	D,P	C	
Resistant to	G,L,P,S,T,U,V,W,Y,Z	E,G,J,S,U,V,W,X,Y,Z	L,P,U,Z	P,V,X,Z
Swelled by	C,D,N,R	D.H.P	C,R	B,C,K,R
Mechanical and Electrical				
Tensile strength				
kg/cm^2 (max)	240.	175.	90.	350.
kpsi (max)	3,5	2.5	1.3	5.0
Elongation at break, %	800.	700.	500.	550.
Vol. resistivity, ohm-cm	10^{11}	10^{17}	10^{8}	10^{11}
Dielectric strength				
kV/cm	195	295	125	195
V/mil	500	750	325	500
Dielectric constant	7.	2.4	8.	7.
Power factor (50–100 Hz)	.04	0.004	0.02	0.04
Rebound	Good	Poor	Poor	
Comparative Ratings—Resistance to				
Abrasion	Excellent	Fair	Poor	Excellent
Cold flow (set)	Excellent	Fair	Poor	Poor
Tearing	Good	Good	Poor	Excellent
Air permeability	Good	Excellent	Good	Excellent
Oxidation	Good	Good	Good	Good
Flame	Excellent	Poor	Poor	Poor

[a] Proprietary.

From Bolz, R.E. and Tuve, G.L., Solids — Non-metals, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 156–157.

Electrical Properties of Various Kinds of Glass

Values are for room temperature. In general the volume resistivity is reduced at the higher temperatures, but the dissipation factor increases rapidly above 100–200°C.

Types of Glass	Volume Resistivity, ohm-cm	Dielectric Constant, 1 Mhz	Dissipation Factor, 1 Mhz
Fused silica	10^{12}	3.8	0.0002
96% silica (7900, 7910–11–12)†	10^{10}	3.8	0.0005
Soda lime			
General-purpose	10^{6}–10^{7}	7.0–7.6	0.004–0.011
Lamp bulb (0080)	10^{7}	7.2	0.009
Lead alkali silicate			
Electrical (0010)	10^{9}	6.6	0.0016
High lead (8870)	10^{12}	9.5	0.009
Alumino borosilicate			
(Kimble N51a)	10^{7}	5.6	0.010
Borosilicate			
Low expansion (7740)	10^{8}	4.6	0.0046
Low electrical loss (7070)	10^{11}	4.0	0.0006
Tungsten sealing (7050)	10^{9}	4.9	0.0033
Aluminosilicate (1710–20)	10^{11}	6.3	0.0037

† Numbers in parentheses indicate equivalent Corning glass code numbers.

From Bolz, R.E. and Tuve, G.L., Solids — Non-metals, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 166. Originally from "Electrical Insulating Materials," *Machine Design*, 39:161, Sept. 28, 1967.

Properties of the Chemical Elements

Name	Symbol	Atomic Number	International at. wt.[a]	Specific Gravity (or density)	Melting Point, °C	Boiling Point, °C	Specific Heat at 25°C	Thermal Conductivity, watt/cm°C
Actinium	Ac	89	(227)	(10.02)	1050.	3200.	—	—
Aluminum	Al	13	26.9815	2.70	660.	2441.	0.215	2.37
Americium	Am	95	(243)	11.7	994.	2607.	—	—
Antimony (Stibium)	Sb	51	121.75	6.69	630.	1750.	0.050	0.185
Argon	Ar	18	39.948	1.78 g/l	–189.	–186.	0.125	175×10^{-4}
Arsenic	As	33	74.9216	5.73 (gray)	815.[b]	613. (subl.)	0.079	—
Astatine	At	85	(210)	—	729.	2125.	—	—
Barium	Ba	56	137.34	3.5	725.	1630.	0.046	—
Berkelium	Bk	97	(247)	—	—	—	—	—
Beryllium	Be	4	9.0122	1.85	1285.	2475.	0.436	2.18
Bismuth	Bi	83	208.980	9.75	271.4	1560.	0.030	0.084
Boron	B	5	10.811	2.35	2300.	2550.	0.245	—
Bromine	Br	35	79.904	3.12 (liq.)	–7.2	56.8	0.11	0.45×10^{-4}
Cadmium	Cd	48	112.40	8.65	321.	767.	0.055	0.92
Calcium	Ca	20	40.08	1.55	840.	1485.	—	1.3
Californium	Cf	98	(251)	—	—	—	—	—
Carbon	C	6	12.01115					
Diamond				3.5	>3800.	4827.	0.124	1.5 (0°)
Graphite				2.1	>3500.	4200.	0.170	0.24
Cerium	Ce	58	140.12	6.77	798.	3257.	0.047	0.11
Cesium	Cs	55	132.905	1.87	28.6	678.	0.057	—
Chlorine	Cl	17	35.453	3.21 g/l	–101.	–34.6	0.114	0.86×10^{-4}
Chromium	Cr	24	51.996	7.2	1860.	2670.	0.110	0.91
Cobalt	Co	27	58.9332	8.9	1495.	2870.	0.10	0.69
Copper	Cu	29	63.546	8.96	1084.	2575.	0.092	3.98
Curium	Cm	96	(247)	—	—	—	—	—
Dysprosium	Dy	66	162.50	8.54	1409.	2335.	0.0414	0.10
Einsteinium	Es	99	(254)	—	—	—	—	—
Erbium	Er	68	167.26	9.05	1522.	2510.	0.04	0.096
Europium	Eu	63	151.96	5.25	822.	1597.	0.042	—
Fermium	Fm	100	(257)	—		—	—	—
Fluorine	F	9	18.9984	1.11 (liq.)	–219.6	–188.	0.197	2.63×10^{-4}
Francium	Fr	87	(223)	—	27.	677.	—	—
Gadolinium	Gd	64	157.25	7.90	1311.	3233.	0.055	0.088
Gallium	Ga	31	69.72	5.91	29.8	2300.	0.089	0.29–0.38
Germanium	Ge	32	72.59	5.32	937.	2380.	0.077	0.59
Gold (Aurum)	Au	79	196.967	19.32	1063.	2857.	0.031	3.15
Hafnium	Hf	72	178.49	13.29	2220.	4700.	0.035	0.220
Helium	He	2	4.0026	0.177 g/l	—	–269.	1.24	14.8×10^{-4}
Holmium	Ho	67	164.930	8.78	1470.	2720.	0.039	—
Hydrogen	H	1	1.00797	0.0899 g/l	–259.	–253.	3.41	18.4×10^{-4}
Indium	In	49	114.82	7.31	156.	2050.	0.056	0.24
Iodine	I	53	126.9044	4.93	113.5	184.4	0.102	43.5×10^{-4}
Iridium	Ir	77	192.2	22.42	2450.	4390.	0.031	1.47
Iron (Ferrum)	Fe	26	55.847	7.87	1536.	2870.	0.108	0.803
Krypton	Kr	36	83.80	3.73 g/l	–157.	–152.	0.059	0.94×10^{-4}
Lanthanum	La	57	138.91	6.17	920.	3454.	0.047	0.14
Lawrencium	Lr	103	(257)	—	—	—	—	—
Lead (Plumbum)	Pb	82	207.19	11.35	327.5	1750.	0.031	0.352
Lithium	Li	3	6.939	0.53	180.	1342.	0.84	0.71
Lutetium	Lu	71	174.97	9.84	1656.	3315.	0.037	—
Magnesium	Mg	12	24.312	1.74	650.	1090.	0.243	1.56
Manganese	Mn	25	54.930	7.21–7.44	1244.	2060.	0.114	—
Mendelevium	Md	101	(256)	—	—	—	—	—
Mercury (Hydragyrum)	Hg	80	200.59	13.546	–38.86	356.55	0.033	0.0839

Properties of the Chemical Elements (continued)

Name	Symbol	Atomic Number	International at. wt.[a]	Specific Gravity (or density)	Melting Point, °C	Boiling Point, °C	Specific Heat at 25°C	Thermal Conductivity, watt/cm°C
Molybdenum	Mo	42	95.94	10.22	2620.	4651.	0.060	1.38
Neodymium	Nd	60	144.24	7.00	1010.	3127.	0.049	0.13
Neon	Ne	10	20.183	0.90 g/l	–249.	–246.	0.246	4.77×10^{-4}
Neptunium	Np	93	(237)	18.0–20.45	640.	3902.	0.296	—
Nickel	Ni	28	58.71	8.90	1453.	2914.	0.106	0.905
Niobium (Columbium)	Nb	41	92.906	8.57	2467.	4740.	0.064	0.53
Nitrogen	N	7	14.0067	1.251 g/l	–210.	–196.	0.249	2.55×10^{-4}
Nobelium	No	102	(254)	—	—	—	—	—
Osmium	Os	76	190.2	22.57	3025.	4225.	0.031	0.61
Oxygen	O	8	15.9994	1.43 g/l	–218.4	–183.	0.220	2.61×10^{-4}
Palladium	Pd	46	106.4	12.02	1550.	2927.	0.058	0.71
Phosphorus, white	P	15	30.9738	1.82	44.1	280.	0.18	—
Platinum	Pt	78	195.09	21.45	1770.	3825.	0.032	0.73
Plutonium	Pu	94	(244)	19.84	640.	3230.	0.032	0.08
Polonium	Po	84	(209)	9.32	254.	962.	0.030	—
Potassium (Kalium)	K	19	39.102	0.86	63.3	760.	0.180	0.99
Praseodymium	Pr	59	140.907	6.77	931.	3212.	0.046	0.12
Promethium	Pm	61	(145)	—	1080.	2460.	0.044	—
Protactnium	Pa	91	(231)	(15.37)	—	—	0.029	—
Radium	Ra	88	(226)	—	700.	1700.	0.029	—
Radon	Rn	86	(222)	9.73 g/l	–71.	–62.	0.0224	—
Rhenium	Re	75	186.2	21.0	3180.	5650.	0.033	0.71
Rhodium	Rh	45	102.905	12.41	1965.	3700.	0.058	1.50
Rubidium	Rb	37	85.47	1.532	39.	700.	0.086	—
Ruthenium	Ru	44	101.07	12.4	2400.	4100.	0.057	—
Samarium	Sm	62	150.35	7.54	1072.	1778.	0.047	—
Scandium	Sc	21	44.956	2.99	1539.	2832.	0.135	—
Selenium	Se	34	78.96	4.8	217.	700.	0.077	0.005
Silicon	Si	14	28.086	2.33	1411.	3280.	0.17	0.835
Silver (Argentum)	Ag	47	107.868	10.50	961.	2212.	0.057	4.27
Sodium (Natrium)	Na	11	22.9898	0.97	97.83	884.	0.293	1.34
Strontium	Sr	38	87.62	2.55	770.	1375.	0.072	—
Sulfur	S	16	32.064	1.96–2.07	113.	445.	0.175	26.4×10^{-4}
Tantalum	Ta	73	180.948	16.6	2980.	5365.	0.034	0.575
Technetium	Tc	43	(97)	(11.50)	2172.	4877.	0.058	—
Tellurium	Te	52	127.60	6.24	450.	990.	0.05	0.059
Terbium	Tb	65	158.924	8.23	1360.	3041.	0.0435	—
Thallium	Tl	81	204.37	11.85	304.	1480.	0.031	0.39
Thorium	Th	90	232.038	11.7	1750.	4800.	0.03	0.41
Thulium	Tm	69	168.934	9.31	1545.	1727.	0.0385	—
Tin (Stannum)	Sn	50	118.69	7.31	232.	2600.	0.054	0.67
Titanium	Ti	22	47.90	4.54	1670.	3290.	0.125	0.22
Tungsten (Wolfram)	W	74	183.85	19.3	3400.	5550.	0.032	1.78
Uranium	U	92	238.03	18.8	1132.	4140.	0.028	0.25
Vanadium	V	23	50.942	6.1	1900.	3400.	0.116	0.60
Xenon	Xe	54	131.30	5.89 g/l	–112	–107.	0.038	5.2×10^{-4}
Ytterbium	Yb	70	173.04	6.97	824.	1193.	0.071	—
Yttrium	Y	39	88.905	4.46	1523.	3337.	0.0925	0.15
Zinc	Zn	30	65.37	7.	419.5	910.	0.093	1.21
Zirconium	Zr	40	91.22	6.53	1852.	4400.	0.067	0.227

[a] Value in parentheses is the mass number of the most stable isotope of the element.
[b] At 28 atm.
From Bolz, R.E. and Tuve, G.L., Basic chemical data, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 329–330.

Additional Properties of the Chemical Elements

Name	Atomic Number	Latent Heat of Fusion, cal/g	Coef. of Linear Thermal Expansion × 106, K^{-1} 100	300	500	Elasticity Modulus, psi × 10^{-6}	First Ionization Potential, eV	Thermal Neutron Absorption Cross Section, Barns[a]
Actinium (227)	89	11	—	—	—	—	6.9	510.
Aluminum	13	95	12.5	24	27	10.0	5.984	0.24
American (243)	95	10	—	—	—	—	—	—
Antimony	51	38.5	9	9.5	10.5	11.3	8.639	5.7
Argon	18	6.7	—	—	—	—	15.755	0.66
Arsenic	33	88.5	—	4.7	—	—	9.81	4.3
Astatine	85	—	—	—	—	—	9.5	—
Barium	56	13.4	—	16	24	—	5.21	1.2
Berkelium	97	—	—	—	—	—	—	—
Beryllium	4	324	—	12	15	40–44	9.32	0.01
Bismuth	83	12.4	12	13	13.5	4.6	7.287	0.034
Boron	5	400	—	2	—	64	8.296	755
Bromine	35	16.2	—	—	—	—	11.84	6.7
Cadmium	48	13.2	26	30	38	8	8.991	2450.
Calcium	20	52	17.5	23	26	3.2–3.8	6.111	0.44
Californium (251)	98	—	—	—	—	—	—	—
Carbon (Graphite)	6	—	—	—	—	0.7	11.256	0.004
Cerium	58	9	—	8	—	4.4	5.6	0.73
Cesium	55	3.8	—	97	—	—	3.893	30.0
Chlorine	17	2.16	—	—	—	—	13.01	34.
Chromium	24	79	3.5	6	9.5	36	6.764	3.1
Cobalt	27	66	—	12	13	30	7.86	38.
Columbium See Niobium								
Copper	29	49	10.5	16.5	18	17	7.724	3.8
Curium (247)	96	—	—	—	—	—	—	—
Dysprosium	66	26.4	—	9.0	—	9.2	6.8	950.
Einsteinium (254)	99	—	—	—	—	—	—	—
Erbium	68	24.6	—	9.0	—	10.6	6.08	170.
Europium	63	16.9	—	26	—	2.1	5.67	4300.
Fermium	—	—	—	—	—	—	—	—
Fluorine	9	10.1	—	—	—	—	17 418	0.01
Francium	87	—	—	—	—	—	4	—
Gadolinium	64	16.4	—	4	—	8.1	6.16	46,000
Gallium	31	19.2	—	18	—	—	6	2.8
Germanium	32	114	2.5	5.6	6.5	—	7.88	2.45
Gold	79	15	11.5	14	15	10.8	9.22	98.8
Hafnium	72	34	—	6	—	20	7	105.
Helium	2	1.2	—	—	—	—	24.481	0.007
Holmium	67	—	—	—	—	9.7	—	65.
Hydrogen	1	15.0	—	—	—	—	13.595	0.33
Indium	49	6.8	25	33	—	—	5.785	191.
Iodine	53	15	—	93	—	—	10.454	7.0
Iridium	77	33	4	6.5	7.5	75	9	425.
Iron	26	65	6	12	14.5	28.5	7.87	2.6
Krypton	36	4.7	—	—	—	—	13.996	31.
Lanthanum	57	10	—	5	6.5	5.5	5.61	8.9
Lawrencium	103	—	—	—	—	—	—	—

Additional Properties of the Chemical Elements (continued)

Name	Atomic Number	Latent Heat of Fusion, cal/g	Coef. of Linear Thermal Expansion × 106, K^{-1} 100	300	500	Elasticity Modulus, psi × 10^{-6}	First Ionization Potential, eV	Thermal Neutron Absorption Cross Section, Barns[a]
Lead	82	5.5	25	29	32	2.0	7.415	0.18
Lithium	3	103	23	50	—	—	5.39	71.
Lutetium	71	26.4	—	—	—	12.2	—	112.
Magnesium	12	88.0	15	25	29	6.4	7.644	0.07
Manganese	25	64	11.5	23	28	23	7.432	13.3
Mendelevium	101	—	—	—	—	—	—	—
Mercury	80	2.7	—	—	—	—	10.43	375.
Molybdenum	42	69	3	5	5.5	40	7.10	2.7
Neodymium	60	13	—	7	7.5	5.5	5.51	46.
Neon	10	4.0	—	—	—	—	21.559	<2.8
Neptunium (237)	93	9.7	—	—	—	—	—	(170)
Nickel	28	71	6.5	13	15.5	31	7.633	4.6
Niobium	41	68	5	7	7.5	15	6.88	1.15
Nitrogen	7	6.2	—	—	—	—	14.53	1.9
Nobelium	102	—	—	—	—	—	—	—
Osmium	76	34	—	5	5.5	80	8.5	15.3
Oxygen	8	3.3	—	—	—	—	13.614	<0.000 2
Palladium	46	38	8.5	12	13	17	8.33	8.
Phosphorus	15	4.8	—	125	—	—	10.484	0.2
Platinum	78	24	6.8	8.9	9.5	21.3	9.0	8.8
Plutonium (244)	94	3	—	54	—	14	5.1	—
Polonium	84	11	—	—	—	—	8.43	—
Potassium	19	14.5	—	83	—	—	4.339	2.1
Praseodymium	59	17	—	5.	5.3	4.7	5.46	11.3
Promethium	61	—	—	—	—	6.1	—	—
Protactinium (231)	91	17	—	—	—	—	—	(200)
Radium (226)	88	10	—	—	—	—	5.277	(20)
Rodon (222)	86	3.1	—	—	—	—	10.746	(0.7)
Rhenium	75	42	—	7	—	66.7	7.87	85.
Rhodium	45	50	5.0	8.3	9.3	42	7.46	150.
Rubidium	37	6.3	—	90	—	—	4.176	0.7
Ruthenium	44	60	—	9	—	60	7.364	2.6
Samarium	62	24.7	—	—	—	4.9	5.6	5600.
Scandium	21	87	—	—	—	11.5	6.54	24.
Selenium	34	16	—	35	—	8.4	9.75	12.3
Silicon	14	430	—	2.5	3.5	16	8.149	0.160
Silver	47	26.5	14.3	19.0	20.6	10.5	7.574	63.
Sodium	11	27	45.7	70.0	—	—	5.138	.53
Strontium	38	25	—	—	—	—	5.692	1.21
Sulfur	16	9.2	42	63	—	—	10.357	0.52
Tantalum	73	41	5.2	6.6	6.9	27	7.88	21.
Technetium	43	56.7	—	—	—	—	7.28	22.
Tellurium	52	33	—	17	—	17	9.01	4.7
Terbium	65	23.6	—	7.0	—	8.3	5.98	46.
Thallium	81	5.0	24	29	32	—	6.106	3.4
Thorium	90	17	8.7	11.4	12.5	8.5	6.95	7.5
Thulium	69	26.0	—	—	—	11.0	5.81	127.
Tin	50	14.1	15.5	21	27.5	6	7.342	0.63

Additional Properties of the Chemical Elements (continued)

Name	Atomic Number	Latent Heat of Fusion, cal/g	Coef. of Linear Thermal Expansion × 106, K^{-1} 100	300	500	Elasticity Modulus, psi × 10^{-6}	First Ionization Potential, eV	Thermal Neutron Absorption Cross Section, Barns[a]
Titanium	22	100	4.4	8.6	9.8	16	6.82	5.8
Tungsten	74	46	2.7	4.4	4.6	50	7.98	19.
Uranium	92	12	10.6	13.5	17	24	6.08	7.7
Vanadium	23	98	4	8	—	19	6.74	5.
Xenon	54	4.2	—	—	—	—	12.127	35.
Ytterbium	70	12.7	—	25	26.3	2.6	6.2	37.
Yttrium	39	45	—	—	—	9.4	6.38	1.3
Zinc	30	27	23	30	32	12	9.391	1.10
Zirconium	40	54	3.9	5.5	6.2	13.7	6.84	0.18

[a] Values in parentheses apply only to that isotope for which the mass number is given following the name of the element. All other values of neutron cross section apply to the naturally occurring mixture of isotopes.

From Bolz, R.E. and Tuve, G.L., Basic chemical data, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 331–332.

Available Stable Isotopes of the Elements

Element and Mass No.	Natural Abundance, Percent
Hydrogen	
1	99.985
2	0.015
Helium	
3	0.00013
4	~100.0
Lithium	
6	7.42
7	92.58
Beryllium	
9	100.0
Boron	
10	19.78
11	80.22
Carbon	
12	98.99
13	1.11
Nitrogen	
14	99.63
15	0.37
Oxygen	
16	99.76
17	0.04
18	0.20
Fluorine	
19	100.0
Neon	
20	90.92
21	0.26
22	8.82
Sodium	
23	100.0
Magnesium	
24	78.70
25	10.13
26	11.17
Aluminum	
27	100.0
Silicon	
28	92.21
29	4.70
30	3.09
Phosphorus	
31	100.0
Sulfur	
32	95.0
33	0.76
34	4.22
36	0.014
Chlorine	
35	75.53
37	24.47
Argon	
36	0.34
38	0.06
40	99.60
Potassium	
39	93.1
40[a]	0.01
41	6.9
Calcium	
40	96.97
42	0.64
43	0.14
44	2.06
46	0.003
48	0.18
Scandium	
45	100.0
Titanium	
46	7.93
47	7.28
48	73.94
49	5.51
50	5.34
Vanadium	
50[b]	0.24
51	99.76
Chromium	
50	4.31
52	83.76
53	9.55
54	2.38
Manganese	
55	100.0
Iron	
54	5.82
56	91.66
57	2.19
58	0.33
Cobalt	
59	100.0
Nickel	
58	67.84
60	26.33
61	1.19
62	3.66
64	1.08
Copper	
63	69.09
65	30.91
Zinc	
64	48.89
66	27.81
67	4.11
68	18.57
70	0.62
Gallium	
69	60.4
71	39.6
Germanium	
70	20.52
72	27.43
73	7.76
74	36.54
76	7.76
Arsenic	
75	100.0
Selenium	
74	0.87
76	9.02
77	7.58
78	23.52
80	49.82
82	9.19
Bromine	
79	50.54
81	49.46
Krypton	
78	0.35
80	2.27
82	11.56
83	11.55
84	56.90
86	17.37
Rubidium	
85	72.15
87	27.85

Available Stable Isotopes of the Elements (continued)

Element and Mass No.	Natural Abundance, Percent	Element and Mass No.	Natural Abundance, Percent	Element and Mass No.	Natural Abundance, Percent
Strontium		Cadmium (cont.)		Barium (cont.)	
84	0.56	113	12.26	136	7.81
86	9.86	114	28.86	137	11.30
87	7.02	116	7.58	138	71.66
88	82.56				
		Indium		Lanthanum	
Yttrium		113	4.28	138	0.09
89	100.0	115[c]	95.72	139	99.91
Zirconium		Tin		Cerium	
90	51.46	112	0.96	136	0.193
91	11.23	114	0.66	138	0.250
92	17.11	115	0.35	140	88.48
94	17.40	116	14.30	142[d]	11.07
96	2.80	117	7.61		
		118	24.03	Praseodymium	
Niobium		119	8.58	141	100.0
93	100.0	120	32.85		
		122	4.72	Neodymium	
Molybdenum		124	5.94	142	27.11
92	15.84			143	12.17
94	9.04	Antimony		144	23.85
95	15.72	121	57.25	145	8.30
96	16.53	123	42.75	146	17.22
97	9.46			148	5.73
98	23.78	Tellurium		150	5.62
100	9.63	120	0.09	Samarium	
		122	2.46	144	3.09
Ruthenium		123	0.87	147[e]	14.97
96	5.51	124	4.61	148[f]	11.24
98	1.87	125	6.99	149[g]	13.83
99	12.72	126	18.71	150	7.44
100	12.62	128	31.79	152	26.72
101	17.07	130	34.48	154	22.71
102	31.61				
104	18.60	Iodine		Europium	
		127	100.0	151	47.82
Rhodium				153	52.18
103	100.0	Xenon			
		124	0.096	Gadolinium	
Palladium		126	0.090	152[h]	0.20
102	0.96	128	1.92	154	2.15
104	10.97	129	26.44	155	14.73
105	22.23	130	4.08	156	20.47
106	27.33	131	21.18	157	15.68
108	26.71	132	26.89	158	24.87
110	11.81	134	10.44	160	21.90
Silver		136	8.87		
107	51.82			Terbium	
109	48.18	Cesium		159	100.0
		133	100.0		
Cadmium				Dysprosium	
106	1.22	Barium		156[i]	0.052
108	0.88	130	0.101	158	0.090
110	12.39	132	0.097	160	2.29
111	12.75	134	2.42	161	18.88
112	24.07	135	6.59	162	25.53

Available Stable Isotopes of the Elements (continued)

Element and Mass No.	Natural Abundance, Percent	Element and Mass No.	Natural Abundance, Percent	Element and Mass No.	Natural Abundance, Percent
Dysprosium (cont.)		Hafnium (cont.)		Platinum (cont.)	
163	24.97	179	13.75	195	33.8
164	28.18	180	35.24	196	25.3
				198	7.2
Holmium					
165	100.0	Tantalum		Gold	
		180	0.012	197	100.0
		181	99.988		
Erbium				Mercury	
162	0.136			196	0.146
164	1.56	Tungsten		198	10.02
166	33.41	180	0.14	199	16.84
167	22.94	182	26.41	200	23.13
168	27.07	183	14.40	201	13.22
170	14.88	184	30.64	202	29.80
		186	28.41	204	6.85
Thulium		Rhenium			
169	100.0	185	37.07	Thallium	
		187[l]	62.93	203	29.50
Ytterbium				205	70.50
168	0.135	Osmium			
170	3.03	184	0.018	Lead	
171	14.31	186	1.59	204	1.48
172	21.82	187	1.64	206	23.6
173	16.13	188	13.3	207	22.6
174	31.84	189	16.1	208	52.3
176	12.73	190	26.4		
		192	41.0	Bismuth	
Lutetium				209	100.0
175	97.40	Iridium			
176[j]	2.60	191	37.3	Thorium	
		193	62.7	232[n]†	100.0
Hafnium					
174[k]	0.18	Platinum		Uranium	
176	5.20	190[m]	0.013	234[o]†	0.0006
177	18.50	192	0.78	235[p]†	0.72
178	27.14	194	32.9	238[q]†	99.27

[a] Half-life = 1.3×10^{9}y.
[b] Half-life > 10^{15}y.
[c] Half-life = 5×10^{14}y.
[d] Half-life = 5×10^{15}y.
[e] Half-life = 1.06×10^{11}y.
[f] Half-life = 1.2×10^{13}y.
[g] Half-life = 4×10^{14}y.
[h] Half-life = 1.1×10^{14}y.
[i] Half-life = 2×10^{14}y.
[j] Half-life = 2.2×10^{10}y.
[k] Half-life = 4.3×10^{15}y.
[l] Half-life = 4×10^{10}y.
[m] Half-life = 6×10^{11}y.
[n] Half-life = 1.4×10^{10}y.
[o] Half-life = 2.5×10^{5}y.
[p] Half-life = 7.1×10^{8}y.
[q] Half-life = 4.5×10^{9}y.
† Naturally occurring.

Reference

CRC Handbook of Radioactive Nuclides, Y. Wang, Ed., The Chemical Rubber Co., 1969, pp. 25–63.

From Bolz, R.E. and Tuve, G.L., Basic chemical data, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 334–336.

Energy Absorption Mass Attenuation Coefficient In cm^2/g

Only a fraction of the events represented by the total attenuation cross section actually removes the gamma-ray. In particular, Compton scattering can cause a change in the direction and the energy of a photon without absorbing it. The energy absorption mass attenuation coefficient (μ_e/ρ) is a measure of the fraction of the gamma-ray energy that is converted from radiant energy into heat. The product of these coefficients and of the density of the material gives the energy absorption cross section.

	Gamma-Ray Energy, Mev						
Material	0.1	0.2	0.5	1.0	2	5	10.0
H	.0411	.0531	.0591	.0557	.0467	.0318	.0255
Be	.0183	.0237	.0264	.0248	.0210	.0151	.0118
C	.0215	.0267	.0297	.0280	.0237	.0177	.0145
N	.0224	.0267	.0297	.0280	.0236	.0180	.0151
O	.0233	.0271	.0297	.0280	.0238	.0183	.0157
Na	.0289	.0266	.0284	.0268	.0229	.0185	.0168
Mg	.0335	.0278	.0293	.0276	.0237	.0194	.0180
Al	.0373	.0275	.0286	.0270	.0232	.0192	.0182
Si	.0435	.0286	.0290	.0274	.0236	.0198	.0189
P	.0501	.0292	.0290	.0271	.0234	.0200	.0195
S	.0601	.0310	.0300	.0279	.0242	.0209	.0206
A	.0729	.0302	.0272	.0252	.0220	.0195	.0197
K	.0909	.0340	.0295	.0272	.0237	.0214	.0219
Ca	.111	.0367	.0304	.0279	.0244	.0222	.0231
Fe	.225	.0489	.0294	.0261	.0231	.0227	.0250
Cu	.310	.0594	.0296	.0260	.0229	.0231	.0261
Mo	.922	.141	.0348	.0263	.0233	.0262	.0316
Sn	1.469	.222	.0403	.0268	.0233	.0276	.0339
I	1.726	.260	.0433	.0274	.0236	.0283	.0353
W	4.112	.631	.0786	.0353	.0271	.0335	.0426
Pt	4.645	.719	.0892	.0375	.0280	.0343	.0438
Tl	5.057	.791	.0972	.0393	.0288	.0349	.0446
Pb	5.193	.821	.0994	.0402	.0293	.0352	.0450
U	9.63	1.096	.132	.0482	.0324	.0374	.0474
Air	.0233	.0268	.0297	.0280	.0238	.0181	.0153
NaI	1.466	.224	.0410	.0273	.0235	.0268	.0325
H_2O	.0253	.0300	.0330	.0311	.0264	.0198	.0165
Concrete	.0416	.0289	.0296	.0278	.0239	.0194	.0177
Tissue	.0271	.0293	.0320	.0300	.0256	.0192	.0160

From Bolz, R.E. and Tuve, G.L., Reactors and materials, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 466. Originally from *Reactor Physics Constants*, 2nd ed., Argonne National Laboratory, ANL-5800, U.S. Atomic Energy Commission, July 1963.

Gamma-Ray Absorption Cross Section In cm^{-1}

Material	Density, g/cm^3	Gamma-Ray Energy, Mev						
		0.1	0.2	0.5	1.0	2	5	10.0
Be	1.85	.0339	.0438	.0488	.0459	.0389	.0279	.0218
C	2.25	.0484	.0601	.0668	.0630	.0533	.0398	.0326
Na	.9712	.0281	.0258	.0276	.0260	.0222	.0180	.0163
Mg	1.741	.0583	.0484	.0510	.0481	.0413	.0338	.0313
Al	2.70	.1007	.0743	.0772	.0729	.0626	.0518	.0491
Si	2.42	.1053	.0692	.0702	.0663	.0571	.0479	.0457
P	1.83	.0917	.0534	.0531	.0496	.0428	.0366	.0357
S	2.07	.1244	.0642	.0621	.0578	.0501	.0433	.0426
K	0.87	.0791	.0296	.0257	.0237	.0206	.0186	.0191
Ca	1.55	.172	.0569	.0471	.0432	.0378	.0344	.0358
Fe	7.86	1.769	.3844	.2311	.2051	.1816	.1784	.1965
Cu	8.933	2.769	.5306	.2644	.2323	.2046	.2064	.2332
Mo	9.01	8.307	1.270	.3155	.2370	.2099	.2361	.2847
Sn	7.298	10.721	1.620	.2941	.1956	.1700	.2014	.2474
I	4.94	8.704	1.284	.2139	.1354	.1166	.1398	.1744
W	19.3	79.362	12.178	1.517	.6813	.5320	.6466	.8222
Pt	21.37	99.264	15.365	1.906	.8014	.5984	.7330	.9360
Tl	11.86	59.976	9.381	1.153	.4661	.3416	.4139	.5290
Pb	11.34	58.889	9.310	1.127	.4559	.3323	.3992	.5103
U	18.7	180.08	20.495	2.468	.9013	.6059	.6994	.8864
NaI	3.667	5.376	.8214	.1503	.1001	.0862	.0983	.1192
H_2O	1.00	.0253	.0300	.0330	.0311	.0264	.0198	.0165
Concrete	2.35	.0978	.0679	.0697	.0653	.0562	.0456	.0416

From Bolz, R.E. and Tuve, G.L., Reactors and materials, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 467. Originally from *Reactor Physics Constants*, 2nd ed., Argonne National Laboratory, ANL-5800, U.S. Atomic Energy Commission, July 1963.

Removal Cross Sections for Various Materials

The removal cross section is a measure of the ability of a material to remove fast neutrons for shielding attenuation. It is most often applied to a wall of solid material between the fission source and a layer of water or hydrogenous material. The solid wall reduces the neutron energy to such an extent that it will be thermalized and captued in the water.

Symbols: σ_R = microscopic removal cross section, barns/atom
Σ_R = macroscopic removal cross section per cm

Material	σ_R, Barn	N_0 at 20°C, atom/cm^3	Σ_R, cm^{-1}	Material	σ_R, Barn	N_0 at 20°C, atom/cm^3	Σ_R, cm^{-1}
Hydrogen	1.00 ± 0.05	—	—	Lead	3.53 ± 0.30	0.0330	0.116
Deuterium	0.92 ± 0.10[a]	—	—	Bismuth	3.49 ± 0.35	0.0282	0.098
Lithium	1.01 ± 0.04	0.0460 × 10^{24}	0.146	Uranium	3.6 ± 0.4	0.0473	0.17
Beryllium	1.07 ± 0.06	0.120	0.128	Boric Acid (B_2O_3)	4.30 ± 0.41	—	—
Boron	0.97 ± 0.10	0.139	0.135	Boron carbide (B_4C)	5.1 ± 0.4	—	—
Carbon (graphite)	0.72 ± 0.05	0.113	0.081	Fluorothene (C_2F_3Cl)	6.66 ± 0.8	—	—
Oxygen	0.92 ± 0.05	—	—	Heavy water (D_2O)	2.76 ± 0.11	—	—
Fluorine	1.29 ± 0.06	—	—	Lithium fluoride (LiF)	2.43 ± 0.34	—	—
Aluminum	1.31 ± 0.05	0.0603	0.079	Oil (CH_2)	2.84 ± 0.11	—	—
Chlorine	1.2 ± 0.8	—	—	Paraffin ($C_{30}H_{62}$)	80.5 ± 5.2	—	—
Iron	1.98 ± 0.08	0.0848	0.168	Perfluoroheptane (C_7F_{16})	26.3 ± 0.8	—	—
Nickel	1.89 ± 0.10	0.0913	0.173				
Copper	2.04 ± 0.11	0.,0846	0.173				
Zirconium	2.36 ± 0.12	0.0423	0.10				
Tungsten	3.13 ± 0.25	0.0631	0.198				

[a] Calculated: $\sigma_R(D_2O)$ = 2.76 b.

Reference

"Effective Neutron Removal Cross Sections for Shielding," G.T. Chapman and C.L. Storrs, AECD-3978 (ORNL-1843), September 19, 1955.

From Bolz, R.E. and Tuve, G.L., Reactors and materials, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 467. Originally from *Reactor Physics Constants*, 2nd ed., Argonne National Laboratory, ANL-5800, U.S. Atomic Energy Commission, July 1963.

Diffusion of Gases and Vapors into Air

Values of Diffusion Constant and Schmidt Number at 1 atm Pressure

Substance	Diffusion Constant, D, sq ft/hr 0°C	Diffusion Constant, D, sq ft/hr 25°C	Diffusion Constant, D, sq cm/sec 0°C	Diffusion Constant, D, sq cm/sec 25°C	(μ/ρD)† 0°C	(μ/ρD)† 25°C
H_2	2.37	2.76	0.611	0.712	0.217	0.216
NH_3	0.766	0.886	0.198	0.229	0.669	0.673
N_2	0.691		0.178		0.744	
O_2	0.689	0.80	0.178	0.206	0.744	0.748
CO_2	0.550	0.635	0.142	0.164	0.933	0.940
CS_2	0.36	0.414	0.094	0.107	1.41	1.44
Methyl alcohol	0.513	0.615	0.132	0.159	1.00	0.969
Formic acid	0.509	0.615	0.131	0.159	1.01	0.969
Acetic acid	0.411	0.515	0.106	0.133	1.25	1.16
Ethyl alcohol	0.394	0.461	0.102	0.119	1.30	1.29
Chloroform	0.352		0.091		1.46	
Diethylamine	0.342	0.406	0.0884	0.105	1.50	1.47
n-Propyl alcohol	0.329	0.387	0.085	0.100	1.56	1.54
Propionic acid	0.328	0.383	0.0846	0.099	1.57	1.56
Methyl acetate	0.325	0.387	0.0840	0.100	1.58	1.54
Butylamine	0.318	0.391	0.0821	0.101	1.61	1.53
Ethyl ether	0.304	0.360	0.0786	0.093	1.69	1.66
Benzene	0.291	0.341	0.0751	0.088	1.76	1.75
Ethyl acetate	0.277	0.330	0.0715	0.085	1.85	1.81
Toluene	0.274	0.325	0.0709	0.084	1.87	1.83
n-Butyl alcohol	0.272	0.348	0.0703	0.090	1.88	1.71
i-Butyric acid	0.263	0.313	0.0679	0.081	1.95	1.90
Chlorobenzene		0.283		0.073		2.11
Aniline	0.236	0.279	0.0610	0.072	2.17	2.14
Xylene	0.228	0.275	0.059	0.071	2.25	2.17
Amyl alcohol	0.228	0.271	0.0589	0.070	2.25	2.20
n-Octane	0.195	0.232	0.0505	0.060	2.62	2.57
Naphthalene	0.199	0.20	0.0513	0.052	2.58	2.96

† Based on μ/ρ = 0.1325 sq cm/sec for air at 0°C and 0.1541 sq cm/sec for air at 25°C; applies only when the diffusing gas or vapor is very dilute.

From Bolz, R.E. and Tuve, G.L., Heat and mass transfer, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 546.

Speed of Sound in Water and Steam (m·s^{-1})

	Pressure (MPa)													
t (°C)	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
Sat. Liq.	1540.0	1553.8	1556.6	1545.5	1520.7	1462.0	1391.6	1290.6	1088.4	847.7	422.2			
Sat. Vap.	440.5	449.5	462.2	472.1	481.9	493.8	500.9	504.7	498.2	472.4	384.5			
0	1402.3	1402.3	1402.4	1402.4	1402.6	1403.1	1403.8	1405.4	1410.2	1418.2	1434.5	1485.9	1530.6	1575.5
10	1447.4	1447.4	1447.5	1447.6	1447.7	1448.2	1449.0	1450.6	1455.3	1463.3	1479.6	1530.0	1573.3	1616.8
20	1483.3	1483.3	1483.3	1483.4	1483.6	1484.0	1484.8	1486.4	1491.2	1499.2	1515.3	1564.9	1607.2	1649.6
25	1498.0	1498.0	1498.1	1498.2	1498.3	1498.8	1499.6	1501.2	1506.0	1514.0	1530.1	1579.5	1621.4	1663.4
30	1510.8	1510.9	1510.9	1511.0	1511.1	1511.6	1512.4	1514.0	1518.8	1526.8	1543.0	1592.3	1634.1	1675.8
40	1531.2	1531.2	1531.2	1531.3	1531.5	1531.9	1532.8	1534.4	1539.2	1547.4	1563.7	1613.3	1655.0	1696.4
50	443.7	1545.2	1545.2	1545.3	1545.5	1546.0	1546.8	1548.5	1553.5	1561.8	1578.4	1628.7	1670.8	1712.2
60	450.7	1553.7	1553.8	1553.9	1554.0	1554.5	1555.4	1557.1	1562.3	1570.8	1587.9	1639.3	1682.0	1723.7
70	457.5	456.7	1557.5	1557.6	1557.8	1558.3	1559.2	1561.0	1566.3	1575.2	1592.9	1645.6	1689.1	1731.3
80	464.1	463.4	1557.0	1557.1	1557.2	1557.8	1558.7	1560.6	1566.2	1575.4	1593.7	1648.1	1692.6	1735.4
90	470.5	470.0	468.3	1552.8	1553.0	1553.5	1554.5	1556.5	1562.3	1571.9	1591.0	1647.2	1692.8	1736.3
100	476.9	476.4	475.0	472.3	1545.3	1545.9	1546.9	1549.0	1555.1	1565.1	1585.0	1643.2	1690.1	1734.4
110	483.1	482.7	481.4	479.3	1534.6	1535.2	1536.3	1538.4	1544.8	1555.4	1576.2	1636.5	1684.8	1730.0
120	489.2	488.9	487.8	485.9	1521.0	1521.7	1522.8	1525.1	1531.8	1543.0	1564.7	1627.4	1677.1	1723.4
130	495.3	495.0	494.0	492.3	488.8	1505.6	1506.8	1509.2	1516.3	1528.0	1550.8	1616.0	1667.4	1714.7
140	501.2	500.9	500.1	498.6	495.5	1487.0	1488.3	1490.8	1498.4	1510.7	1534.7	1602.5	1655.6	1704.3
150	507.1	506.8	506.0	504.7	502.0	1466.0	1467.4	1470.1	1478.1	1491.2	1516.5	1587.2	1642.2	1692.1
160	512.8	512.6	511.9	510.7	508.3	500.2	1444.3	1447.2	1455.7	1469.6	1496.2	1570.1	1627.1	1678.5
170	518.5	518.3	517.7	516.6	514.4	507.3	1418.9	1422.0	1431.1	1445.8	1474.0	1551.4	1610.4	1663.6
180	524.1	523.9	523.4	522.4	520.4	514.1	501.0	1394.6	1404.3	1420.1	1450.0	1531.0	1592.4	1647.3
190	529.7	529.5	529.0	528.1	526.3	520.6	509.7	1365.0	1375.4	1392.2	1424.0	1509.1	1572.9	1629.8
200	535.1	535.0	534.5	533.7	532.0	526.8	517.3	1333.2	1344.3	1362.3	1396.2	1485.8	1552.2	1611.2
220	545.8	545.7	545.3	544.6	543.2	538.9	531.2	512.6	1275.4	1296.1	1334.8	1434.7	1506.9	1570.7
240	556.3	556.2	555.9	555.3	554.1	550.4	544.0	529.5	1197.1	1221.1	1265.7	1378.0	1457.1	1526.2
260	566.0	566.5	566.2	565.6	564.6	561.5	556.1	544.1	1107.7	1136.3	1188.5	1316.0	1402.9	1478.1
280	576.6	576.5	576.2	575.8	574.9	572.2	567.5	557.4	518.9	1038.9	1102.1	1249.0	1345.1	1426.9
300	586.4	586.3	586.1	585.7	584.9	582.6	578.5	569.9	538.8	922.8	1004.3	1177.3	1284.3	1373.4
320	596.0	595.9	595.7	595.4	594.7	592.6	589.1	581.7	555.8	491.7	890.3	1101.5	1221.3	1318.5
340	605.4	605.3	605.1	604.8	604.2	602.4	599.3	592.9	570.9	522.2	751.1	1021.7	1157.0	1263.0
360	614.6	614.5	614.4	614.1	613.6	612.0	609.2	603.6	584.8	545.5	542.7	936.0	1091.6	1207.4
380	623.7	623.6	623.5	623.2	622.8	621.3	618.9	613.9	597.6	565.0	461.3	846.8	1023.5	1150.7
400	632.6	632.5	632.4	632.2	631.8	630.5	628.3	623.9	609.6	582.0	507.3	755.1	955.9	1093.3
420	641.3	641.3	641.2	641.0	640.6	639.4	637.5	633.5	620.9	597.3	538.7	666.1	890.2	1037.2
440	649.9	649.9	649.8	649.6	649.2	648.2	646.5	642.9	631.7	611.3	563.4	593.6	828.7	983.7
460	658.4	658.3	658.2	658.1	657.8	656.8	655.3	652.1	642.1	624.2	584.1	556.7	774.3	934.4
480	666.7	666.6	666.6	666.4	666.1	665.3	663.9	661.0	652.1	636.4	602.3	554.8	730.1	890.4
500	674.9	674.8	674.8	674.6	674.4	673.6	672.3	669.8	661.8	647.9	618.6	568.9	698.6	852.7
520	682.9	682.9	682.8	682.7	682.5	681.8	680.7	678.3	671.2	658.8	633.5	588.1	680.3	821.9
540	690.9	690.9	690.8	690.7	690.5	689.9	688.8	686.7	680.3	669.3	647.2	607.7	673.0	798.0
560	698.7	698.7	698.6	698.6	698.4	697.8	696.9	694.9	689.2	679.4	660.1	626.2	674.1	781.0
580	706.4	706.4	706.4	706.3	706.1	705.6	704.8	703.0	697.8	689.1	672.2	643.4	679.5	770.0
600	714.1	714.1	714.0	713.9	713.8	713.3	712.5	711.0	706.3	698.5	683.7	659.2	687.4	766.5
620	721.6	721.6	721.5	721.5	721.3	720.9	720.2	718.8	714.6	707.7	694.7	673.9	697.2	762.8
640	729.0	729.0	729.0	728.9	728.8	728.4	727.8	726.5	722.8	716.6	705.2	687.7	707.9	764.7
660	736.4	736.3	736.3	736.3	736.1	735.8	735.2	734.1	730.7	725.3	715.3	700.7	718.9	770.5
680	743.6	743.6	743.6	743.5	743.4	743.1	742.6	741.6	738.6	733.7	725.0	713.1	730.0	777.3
700	750.8	750.7	750.7	750.7	750.6	750.3	749.9	749.0	746.3	742.0	734.5	725.0	741.0	784.1

Speed of Sound in Water and Steam ($m \cdot s^{-1}$) (continued)

	Pressure (MPa)													
t (°C)	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
720	757.8	757.8	757.8	757.8	757.7	757.4	757.0	756.2	753.9	750.1	743.6	736.3	751.9	790.9
740	764.8	764.8	764.8	764.8	764.7	764.5	764.1	763.4	761.3	758.1	752.6	747.2	762.5	797.9
760	771.8	771.8	771.7	771.7	771.6	771.4	771.1	770.5	768.7	765.9	761.2	757.7	772.8	805.2
780	778.6	778.6	778.6	778.6	778.5	778.3	778.1	777.5	776.0	773.6	769.7	767.7	782.6	812.8
800	785.3	785.3	785.3	785.3	785.2	785.1	784.9	784.4	783.2	781.3	778.0	777.4	791.8	821.0

From ASME International Steam Tables for Industrial Use.

Dynamic Viscosity of Water and Steam ($mPa \cdot s$)

	Pressure (MPa)													
t (°C)	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
Sat. Liq.	587.6	466.0	348.6	282.9	231.6	180.1	150.2	126.1	100.0	81.8	56.2			
Sat. Vap.	10.5	10.9	11.6	12.3	13.0	14.1	15.0	16.1	18.0	20.3	27.5			
0	1791.8	1791.7	1791.7	1791.5	1791.3	1790.5	1789.3	1786.8	1779.5	1767.9	1746.6	1696.5	1668.8	1652.0
10	1306.0	1306.0	1305.9	1305.9	1305.8	1305.4	1304.9	1303.8	1300.7	1295.7	1286.6	1266.4	1256.7	1252.7
20	1001.6	1001.6	1001.6	1001.6	1001.6	1001.4	1001.2	1000.8	999.6	997.7	994.4	988.4	987.2	989.3
25	890.1	890.1	890.1	890.1	890.1	890.0	889.9	889.6	889.0	888.0	886.4	884.5	885.9	889.7
30	797.4	797.4	797.4	797.3	797.3	797.3	797.3	797.2	796.9	796.6	796.2	797.2	800.4	805.4
40	653.0	653.0	653.0	653.0	653.0	653.0	653.1	653.1	653.4	653.9	655.0	659.7	665.0	671.4
50	10.6	546.8	546.8	546.9	546.9	546.9	547.0	547.2	547.7	548.6	550.6	557.2	563.5	570.6
60	10.9	466.4	466.4	466.4	466.4	466.5	466.6	466.8	467.5	468.6	471.0	478.6	485.4	492.6
70	11.3	11.3	403.9	403.9	403.9	404.0	404.1	404.4	405.1	406.4	409.0	417.0	423.9	431.1
80	11.6	11.6	354.3	354.4	354.4	354.5	354.6	354.9	355.6	357.0	359.6	367.8	374.7	381.7
90	12.0	12.0	11.9	314.4	314.4	314.5	314.7	314.9	315.7	317.1	319.7	327.9	334.7	341.5
100	12.3	12.3	12.3	12.3	281.8	281.9	282.0	282.3	283.1	284.4	287.1	295.1	301.7	308.4
110	12.7	12.7	12.7	12.6	254.7	254.8	254.9	255.2	256.0	257.3	260.0	267.8	274.3	280.7
120	13.1	13.1	13.1	13.0	232.1	232.1	232.3	232.5	233.3	234.6	237.2	244.9	251.2	257.4
130	13.5	13.5	13.4	13.4	13.3	213.0	213.1	213.3	214.1	215.4	218.0	225.5	231.6	237.6
140	13.8	13.8	13.8	13.8	13.7	196.6	196.7	197.0	197.7	199.0	201.5	208.9	214.8	220.6
150	14.2	14.2	14.2	14.2	14.1	182.5	182.6	182.8	183.6	184.9	187.3	194.6	200.4	206.0
160	14.6	14.6	14.6	14.6	14.5	14.4	170.3	170.6	171.3	172.6	175.0	182.1	187.8	193.3
170	15.0	15.0	15.0	15.0	14.9	14.8	159.6	159.9	160.6	161.8	164.2	171.2	176.8	182.1
180	15.4	15.4	15.4	15.4	15.3	15.2	15.0	150.4	151.1	152.4	154.8	161.7	167.1	172.3
190	15.8	15.8	15.8	15.8	15.7	15.6	15.5	142.0	142.7	143.9	146.3	153.2	158.5	163.7
200	16.2	16.2	16.2	16.2	16.1	16.1	15.9	134.4	135.2	136.4	138.8	145.6	150.9	155.9
220	17.0	17.0	17.0	17.0	17.0	16.9	16.8	16.5	122.2	123.5	125.9	132.7	137.9	142.8
240	17.8	17.8	17.8	17.8	17.8	17.7	17.6	17.4	111.3	112.6	115.2	122.1	127.3	132.1
260	18.6	18.6	18.6	18.6	18.6	18.6	18.5	18.3	101.8	103.2	105.9	113.1	118.4	123.2
280	19.5	19.5	19.5	19.5	19.4	19.4	19.3	19.2	18.8	94.7	97.7	105.4	110.8	115.6
300	20.3	20.3	20.3	20.3	20.3	20.2	20.2	20.1	19.8	86.5	90.1	98.5	104.1	109.1
320	21.1	21.1	21.1	21.1	21.1	21.1	21.0	21.0	20.7	20.7	82.5	92.2	98.2	103.3
340	22.0	22.0	22.0	22.0	21.9	21.9	21.9	21.8	21.7	21.7	74.2	86.2	92.8	98.2
360	22.8	22.8	22.8	22.8	22.8	22.8	22.7	22.7	22.6	22.6	62.8	80.3	87.7	93.4
380	23.6	23.6	23.6	23.6	23.6	23.6	23.6	23.5	23.5	23.6	25.8	74.3	82.8	89.0
400	24.5	24.5	24.5	24.5	24.4	24.4	24.4	24.4	24.4	24.5	26.0	68.0	78.0	84.8

Dynamic Viscosity of Water and Steam (mPa·s) (continued)

	Pressure (MPa)													
t (˚C)	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
420	25.3	25.3	25.3	25.3	25.3	25.3	25.3	25.3	25.2	25.4	26.7	61.2	73.2	80.7
440	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.1	26.3	27.4	53.9	68.5	76.8
460	26.9	26.9	26.9	26.9	26.9	26.9	26.9	26.9	27.0	27.2	28.2	47.4	64.0	73.0
480	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	27.8	28.0	29.0	43.0	59.6	69.4
500	28.6	28.6	28.6	28.6	28.6	28.6	28.6	28.6	28.7	28.9	29.8	40.5	55.8	66.1
520	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.5	29.8	30.7	39.3	52.6	63.0
540	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.2	30.4	30.6	31.5	38.8	50.2	60.3
560	31.0	31.0	31.0	31.0	31.0	31.0	31.0	31.1	31.2	31.4	32.3	38.7	48.5	58.0
580	31.8	31.8	31.8	31.8	31.8	31.8	31.8	31.9	32.0	32.3	33.1	38.8	47.3	56.2
600	32.6	32.6	32.6	32.6	32.6	32.6	32.6	32.7	32.8	33.1	33.9	39.1	46.6	54.7
620	33.4	33.4	33.4	33.4	33.4	33.4	33.4	33.5	33.6	33.9	34.7	39.5	46.1	53.6
640	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.3	34.4	34.7	35.5	40.0	46.0	52.7
660	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.1	35.2	35.5	36.3	40.5	45.9	52.2
680	35.8	35.8	35.8	35.8	35.8	35.8	35.8	35.9	36.0	36.3	37.1	41.1	46.1	51.8
700	36.6	36.6	36.6	36.6	36.6	36.6	36.6	36.6	36.8	37.1	37.8	41.6	46.3	51.6
720	37.3	37.3	37.3	37.3	37.3	37.3	37.4	37.4	37.6	37.8	38.6	42.2	46.6	51.5
740	38.1	38.1	38.1	38.1	38.1	38.1	38.1	38.2	38.3	38.6	39.4	42.9	46.9	51.5
760	38.9	38.9	38.9	38.9	38.9	38.9	38.9	38.9	39.1	39.4	40.1	43.5	47.3	51.7
780	39.6	39.6	39.6	39.6	39.6	39.6	39.7	39.7	39.9	40.1	40.9	44.1	47.8	51.9
800	40.4	40.4	40.4	40.4	40.4	40.4	40.4	40.5	40.6	40.9	41.6	44.7	48.2	52.1

From ASME International Steam Tables for Industrial Use.

4

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Basic Mechanical Properties

Symbol	Definition	Remarks
E	Modulus of elasticity; Young's modulus; $E = \sigma/\varepsilon_e$	Hooke's law; T and ε_p effects small
G	Shear modulus of elasticity; $G = \frac{\tau}{\gamma_e} = E/2(1+v)$	T and ε_p effects small
v	Poisson's ratio; $v = \frac{\varepsilon_{lateral}}{\varepsilon_{longit.}}$	T and ε_p effects small
σ_{PL}	Proportional limit; at onset of noticeable yielding (or at onset of nonlinear elastic behavior)	Flow property; inaccurate; T and ε_p effects large
σ_y	0.2% offset yield strength (but yielding can occur at $\sigma < \sigma_y$ if $\sigma_{PL} < \sigma_y$)	Flow property; accurate; T and ε_p effects large
σ_f	True fracture strength; $\sigma_f = \frac{P_f}{A_f}$	Fracture property; T and ε_p effects medium
ε_f	True fracture ductility; $\varepsilon_f = \ln\frac{A_O}{A_f} = \ln\frac{100}{100 - \%RA}$	Max. ε_p; fracture property; T and ε_p effects medium
% RA	Percent reduction of area; $\%RA = \frac{A_O - A_f}{A_O} \times 100$	Fracture property; T and ε_p effects medium
n	Strain hardening exponent; $\sigma = K\varepsilon_p^n$	Flow property; T and ε_p effects small to large
Toughness	Area under σ vs. ε_p curve	True toughness or intrinsic toughness; T and ε_p effects large
σ_u	Ultimate strength; $\frac{P_{max}}{A_O}$	Fracture property; T and ε_p effects medium
M_r	Modulus of resilience; $M_r = \frac{\sigma_{PL}^2}{2E}$	Area under original elastic portion of $\sigma - \varepsilon$ curve

Notes: T is temperature; ε_p refers to prior plastic strain, especially cyclic plastic strain (fatigue) (these are qualitative indicators here; exceptions are possible)

$$\underset{\text{total}}{\varepsilon_t} = \underset{\text{elastic}}{\varepsilon_e} + \underset{\text{plastic}}{\varepsilon_p} = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{1/n} = \frac{\sigma}{E} + \varepsilon_f\left(\frac{\sigma}{\sigma_f}\right)^{1/n}$$

From Sandor, B.I., Mechanics of solids, in *The CRC Handbook of Mechanical Engineering*, Kreith, F., Ed., CRC Press, Boca Raton, FL, 1998, p. 1-75.

Symbols and Definitions for Selected Properties

Property	Symbol	Definition	Property	Symbol	Definition
Pressure	p		Specific heat, constant volume	c_v	$(\partial u/\partial T)_v$
Temperature	T		Specific heat, constant pressure	c_p	$(\partial h/\partial T)_p$
Specific volume	v		Volume expansivity	β	$\frac{1}{v}(\partial v/\partial T)_p$
Specific internal energy	u		Isothermal compressivity	κ	$-\frac{1}{v}(\partial v/\partial p)_T$
Specific entropy	s		Isentropic compressibility	α	$-\frac{1}{v}(\partial v/\partial p)_s$
Specific enthalpy	h	$u + pv$	Isothermal bulk modulus	B	$-v(\partial p/\partial v)_T$
Specific Helmholtz function	ψ	$u - Ts$	Isentropic bulk modulus	B_s	$-v(\partial p/\partial v)_s$
Specific Gibbs function	g	$h - Ts$	Joule-Thomson coefficient	μ_J	$(\partial T/\partial p)_h$
Compressibility factor	Z	pv/RT	Joule coefficient	η	$(\partial T/\partial v)_u$
Specific heat ratio	k	c_p/c_v	Velocity of sound	c	$\sqrt{-v^2(\partial p/\partial v)_s}$

From Moran, M.J., Property relations and data, in *The CRC Handbook of Mechanical Engineering*, Kreith, F., CRC Press, Boca Raton, FL, 1998, p. 2-25.

Heating Values in kJ/kg of Selected Hydrocarbons at 25°C

		Higher Value[a]		Lower Value[b]	
Hydrocarbon	Formula	Liquid Fuel	Gas. Fuel	Liquid Fuel	Gas. Fuel
Methane	CH_4	—	55,496	—	50,010
Ethane	C_2H_6	—	51,875	—	47,484
Propane	C_3H_8	49,973	50,343	45,982	46,352
n-Butane	C_4H_{10}	49,130	49,500	45,344	45,714
n-Octane	C_8H_{18}	47,893	48,256	44,425	44,788
n-Dodecane	$C_{12}H_{26}$	47,470	47,828	44,109	44,467
Methanol	CH_3OH	22,657	23,840	19,910	21,093
Ethanol	C_3H_5OH	29,676	30,596	26,811	27,731

[a] H_2O liquid in the products.
[b] H_2O vapor in the products.
From Moran, M. J., Combustion, in *The CRC Handbook of Mechanical Engineering*, Kreith, F., CRC Press, Boca Raton, FL, 1998, p. 2-62.

Some Fuel Properties of Four Different Biomass Types

Property	Pine Shavings	Switchgrass	Rice Hull	Rice Straw
Ash %	1.43	10.10	18.34	15.90
Carbon	48.54	47.79	40.96	41.78
Hydrogen	5.85	5.76	4.30	4.63
Nitrogen	0.47	1.17	0.40	0.70
Sulfur	0.01	0.10	0.02	0.08
Oxygen	43.69	35.07	35.86	36.57
Btu/lb	8337	7741	6944	7004
GJ/t	19.38	17.99	16.14	16.28

From Reed, M.C., Wright, L.L., Overend, R.P., and Carlton, W., Biomass energy, in *The CRC Handbook of Mechanical Engineering,* Kreith, F., CRC Press, Boca Raton, FL, 1998, p. 7-26.

Physical Properties of Selected Ceramics

Material	Porcelain	Cordierite Refractory	Alumina, Alumina Silicate Refractories	Magnesium Silicate
Specific gravity	2.2–2.4	1.6–2.1	2.2–2.4	2.3–2.8
Coefficient of linear thermal expansion, ppm/°C, 20–700°	5.0–6.5 × 10^6	2.5–3.0 × 10^6	5.0–7.0 × 10^6	11.5 × 10^6
Safe operating temperature, °C	~400	1,250	1,300–1,700	1,200
Thermal conductivity (cal/cm²/cm/sec/°C)	0.004–0.005	0.003–0.004	0.004–0.005	0.003–0.005
Tensile strength (psi)	1,500–2,500	1,000–3,500	700–3,000	2,500
Compressive strength (psi)	25,000–50,000	20,000–45,000	13,000–60,000	20,000–30,000
Flexural strength (psi)	3,500–6,000	1,500–7,000	1,500–6,000	7,000–9,000
Impact strength (ft-lb; $^1/_2$″ rod)	0.2–0.3	0.2–0.25	0.17–0.25	0.2–0.3
Modulus of elasticity (psi)	7–10 × 10^6	2–5 × 10^6	2–5 × 10^6	4–5 × 10^6
Thermal shock resistance	Moderate	Excellent	Excellent	Good
Dielectric strength, (V/mil; 0.25″ specimen)	40–100	40–100	40–100	80–100
Resistivity (Ω/cm², 22°C)	10^2–10^4	10^2–10^4	10^2–10^4	10^2–10^5
Power factor at 10^6 Hz	0.010–0.020	0.004–0.010	0.002–0.010	0.008–0.010
Dielectric constant	6.0–7.0	4.5–5.5	4.5–6.5	5.0–6.0

From Lehman, R.L., Strange, D.J., and Fischer, III, W.F., Ceramics and glass, in *The CRC Handbook of Mechanical Engineering,* Kreith, F., CRC Press, Boca Raton, FL, 1998, p. 12-85.

Steel Pipe Sizes

Nominal Pipe Size, in.	Outside Diameter, in.	Schedule Number or Weight	Wall Thickness, in.	Inside Diameter, in.	Surface Area: Outside, ft²/ft	Surface Area: Inside, ft²/ft	Areas and Weights Cross-sectional: Metal Area, in.²	Areas and Weights Cross-sectional: Flow Area, in.²	Weight: Pipe lb/ft
¾	1.05	40	0.113	0.824	0.275	0.216	0.333	0.533	1.131
		80	0.154	0.742	0.275	0.194	0.434	0.432	1.474
1	1.315	40	0.133	1.049	0.344	0.275	0.494	0.864	1.679
		80	0.179	0.957	0.344	0.250	0.639	0.719	2.172
1¼	1.660	40	0.140	1.38	0.434	0.361	0.668	1.496	2.273
		80	0.191	1.278	0.434	0.334	0.881	1.283	2.997
1½	1.900	40	0.145	1.61	0.497	0.421	0.799	2.036	2.718
		80	0.200	1.50	0.497	0.393	1.068	1.767	3.632
2	2.375	40	0.154	2.067	0.622	0.541	1.074	3.356	3.653
		80	0.218	1.939	0.622	0.508	1.477	2.953	5.022
2½	2.875	40	0.203	2.469	0.753	0.646	1.704	4.79	5.794
		80	0.276	2.323	0.753	0.608	2.254	4.24	7.662
3	3.5	40	0.216	3.068	0.916	0.803	2.228	7.30	7.58
		80	0.300	2.900	0.916	0.759	3.016	6.60	10.25
3½	4.0	40	0.226	3.548	1.047	0.929	2.680	9.89	9.11
		80	0.318	3.364	1.047	0.881	3.678	8.89	12.51
4	4.5	40	0.237	4.026	1.178	1.054	3.17	12.73	10.79
		80	0.337	3.826	1.178	1.002	4.41	11.50	14.99
5	5.563	10 S	0.134	5.295	1.456	1.386	2.29	22.02	7.77
		40	0.258	5.047	1.456	1.321	4.30	20.01	14.62
		80	0.375	4.813	1.456	1.260	6.11	18.19	20.78
6	6.625	10 S	0.134	6.357	1.734	1.664	2.73	31.7	9.29
		40	0.280	6.065	1.734	1.588	5.58	28.9	18.98
		80	0.432	5.761	1.734	1.508	8.40	26.1	28.58
8	8.625	10 S	0.148	8.329	2.258	2.180	3.94	54.5	13.40
		30	0.277	8.071	2.258	2.113	7.26	51.2	24.7
		80	0.500	7.625	2.258	1.996	12.76	45.7	43.4
10	10.75	10 S	0.165	10.420	2.81	2.73	5.49	85.3	18.7
		30	0.279	10.192	2.81	2.67	9.18	81.6	31.2
		Extra heavy	0.500	9.750	2.81	2.55	16.10	74.7	54.7
12	12.75	10 S	0.180	12.390	3.34	3.24	7.11	120.6	24.2
		30	0.330	12.09	3.34	3.17	12.88	114.8	43.8
		Extra heavy	0.500	11.75	3.34	3.08	19.24	108.4	65.4
14	14.0	10	0.250	13.5	3.67	3.53	10.80	143.1	36.7
		Standard	0.375	13.25	3.67	3.47	16.05	137.9	54.6
		extra heavy	0.500	13.00	3.67	3.40	21.21	132.7	72.1
16	16.0	10	0.250	15.50	4.19	4.06	12.37	188.7	42.1
		Standard	0.375	15.25	4.19	3.99	18.41	182.7	62.6
		extra heavy	0.500	15.00	4.19	3.93	24.35	176.7	82.8
18	18.0	10 S	0.188	17.624	4.71	4.61	10.52	243.9	35.8
		Standard	0.375	17.25	4.71	4.52	20.76	233.7	70.6
		extra heavy	0.500	17.00	4.71	4.45	27.49	227.0	93.5
20	20.0	10 S	0.218	19.564	5.24	5.12	13.55	300.6	46.1
		Standard	0.375	19.25	5.24	5.04	23.12	291	78.6
		extra heavy	0.500	19.00	5.24	4.97	30.6	283.5	104.1
22	22.0	10	0.250	21.50	5.76	5.63	17.1	363	58.1
		Standard	0.375	21.25	5.76	5.56	25.5	355	86.6
		extra heavy	0.500	21.00	5.76	5.50	33.8	346	114.8
24	24.0	10	0.250	23.50	6.28	6.15	18.7	434	63.4
		Standard	0.375	23.25	6.28	6.09	27.8	425	94.6
		extra heavy	0.500	23.00	6.28	6.02	36.9	415	125.5
26	26.0	Standard	0.375	25.25	6.81	6.61	30.2	501	102.6
		extra heavy	0.500	25.00	6.81	6.54	40.1	491	136.2
30	30.0	10	0.312	29.376	7.85	7.69	29.1	678	98.9
		Standard	0.375	29.250	7.85	7.66	34.9	672	118.7
		extra heavy	0.500	29.00	7.85	7.59	46.3	661	157.6
34	34.0	Standard	0.375	33.250	8.90	8.70	39.6	868	134.7
		extra heavy	0.500	33.00	8.90	8.64	52.6	855	178.9
36	36.0	Standard	0.375	35.25	9.42	9.23	42.0	976	142.7
		extra heavy	0.500	35.00	9.42	9.16	55.8	962	189.6
42	42.0	Standard	0.375	41.25	11.0	10.8	49.0	1336	166.7
		extra heavy	0.500	41.00	11.0	10.73	65.2	1320	221.6

From Kreith, F., Ed., *The CRC Handbook of Mechanical Engineering,* CRC Press, Boca Raton, FL, 1998, p. **E**-81. Originally from *Design Properties of Pipe,* Chemetron Corporation, 1958.

Commercial Copper Tubing*

The following table gives dimensional data and weights of copper tubing used for automotive, plumbing, refrigeration, and heat exchanger services. For additional data see the standards handbooks of the Copper Development Association, Inc., the ASTM standards, and the "SAE Handbook."

Dimensions in this table are actual specified measurements, subject to accepted tolerances. Trade size designations are usually by actual OD, except for water and drainage tube (plumbing), which measures 1/8-in. larger OD. A 1/2-in. plumbing tube, for example, measures 5/8-in. OD, and 2-in. plumbing tube measures 2 1/8-in. OD.

KEY TO GAGE SIZES

Standard-gage wall thicknesses are listed by numerical designation (14 to 21), BWG or Stubs gage. These gage sizes are standard for tubular heat exchangers. The letter *A* designates SAE tubing sizes for automotive service. Letter designations *K* and *L* are the common sizes for plumbing services, soft or hard temper.

OTHER MATERIALS

These same dimensional sizes are also common for much of the commercial tubing available in aluminum, mild steel, brass, bronze, and other alloys. Tube weights in this table are based on copper at 0.323 lb/in^3. For other materials the weights should be multiplied by the following approximate factors:

aluminum	0.30	monel	0.96
mild steel	0.87	stainless steel	0.89
brass	0.95		

Size, OD		*Wall Thickness*			*Flow Area*		*Metal Area,*	*Surface Area*		
in.	*mm*	*in.*	*mm*	*gage*	*in.*^{2}	*mm*^{2}	*in.*^{2}	*Inside,* *ft*^{2}*/ft*	*Outside,* *ft*^{2}*/ft*	*Weight,* *lb/ft*
1/8	3.2	.030	0.76	A	0.003	1.9	0.012	0.017	0.033	0.035
3/16	4.76	.030	0.76	A	0.013	8.4	0.017	0.034	0.049	0.058
1/4	6.4	.030	0.76	A	0.028	18.1	0.021	0.050	0.066	0.080
1/4	6.4	.049	1.24	18	0.018	11.6	0.031	0.038	0.066	0.120
5/16	7.94	.032	0.81	21A	0.048	31.0	0.028	0.065	0.082	0.109
3/8	9.53	.032	0.81	21A	0.076	49.0	0.033	0.081	0.098	0.134
3/8	9.53	.049	1.24	18	0.060	38.7	0.050	0.072	0.098	0.195
1/2	12.7	.032	0.81	21A	0.149	96.1	0.047	0.114	0.131	0.182
1/2	12.7	.035	0.89	20L	0.145	93.6	0.051	0.113	0.131	0.198
1/2	12.7	.049	1.24	18K	0.127	81.9	0.069	0.105	0.131	0.269
1/2	12.7	.065	1.65	16	0.108	69.7	0.089	0.97	0.131	0.344
5/8	15.9	.035	0.89	20A	0.242	156	0.065	0.145	0.164	0.251
5/8	15.9	.040	1.02	L	0.233	150	0.074	0.143	0.164	0.285
5/8	15.9	.049	1.24	18K	0.215	139	0.089	0.138	0.164	0.344
3/4	19.1	.035	0.89	20A	0.363	234	0.079	0.178	0.196	0.305
3/4	19.1	.042	1.07	L	0.348	224	0.103	0.174	0.196	0.362
3/4	19.1	.049	1.24	18K	0.334	215	0.108	0.171	0.196	0.418
3/4	19.1	.065	1.65	16	0.302	195	0.140	0.162	0.196	0.542
3/4	19.1	.083	2.11	14	0.268	173	0.174	0.151	0.196	0.674
7/8	22.2	.045	1.14	L	0.484	312	0.117	0.206	0.229	0.455
7/8	22.2	.065	1.65	16K	0.436	281	0.165	0.195	0.229	0.641
7/8	22.2	.083	2.11	14	0.395	255	0.206	0.186	0.229	0.800
1	25.4	.065	1.65	16	0.594	383	0.181	0.228	0.262	0.740
1	25.4	.083	2.11	14	0.546	352	0.239	0.218	0.262	0.927
1 1/8	28.6	.050	1.27	L	0.825	532	0.176	0.268	0.294	0.655

*Compiled and computed.

Commercial Copper Tubing* (continued)

Size, OD		*Wall Thickness*			*Flow Area*		*Metal Area,*	*Surface Area*		*Weight,*
in.	*mm*	*in.*	*mm*	*gage*	*in.*^{2}	*mm*^{2}	*in.*^{2}	*Inside,* *ft*^{2}*/ft*	*Outside,* *ft*^{2}*/ft*	*lb/ft*
1 1/8	28.6	.065	1.65	16K	0.778	502	0.216	0.261	0.294	0.839
1 1/4	31.8	.065	1.65	16	0.985	636	0.242	0.293	0.327	0.938
1 1/4	31.8	.083	2.11	14	0.923	596	0.304	0.284	0.327	1.18
1 3/8	34.9	.055	1.40	L	1.257	811	0.228	0.331	0.360	0.884
1 3/8	34.9	.065	1.65	16K	1.217	785	0.267	0.326	0.360	1.04
1 1/2	38.1	.065	1.65	16	1.474	951	0.294	0.359	0.393	1.14
1 1/2	38.1	.083	2.11	14	1.398	902	0.370	0.349	0.393	1.43
1 5/8	41.3	.060	1.52	L	1.779	1148	0.295	0.394	0.425	1.14
1 5/8	41.3	.072	1.83	K	1.722	1111	0.351	0.388	0.425	1.36
2	50.8	.083	2.11	14	2.642	1705	0.500	0.480	0.628	1.94
2	50.8	.109	2.76	12	2.494	1609	0.620	0.466	0.628	2.51
2 1/8	54.0	.070	1.78	L	3.095	1997	0.449	0.520	0.556	1.75
2 1/8	54.0	.083	2.11	14K	3.016	1946	0.529	0.513	0.556	2.06
2 5/8	66.7	.080	2.03	L	4.77	3078	0.645	0.645	0.687	2.48
2 5/8	66.7	.095	2.41	13K	4.66	3007	0.760	0.637	0.687	2.93
3 1/8	79.4	.090	2.29	L	6.81	4394	0.950	0.771	0.818	3.33
3 1/8	79.4	.109	2.77	12K	6.64	4284	1.034	0.761	0.818	4.00
3 5/8	92.1	.100	2.54	L	9.21	5942	1.154	0.897	0.949	4.29
3 5/8	92.1	.120	3.05	11K	9.00	5807	1.341	0.886	0.949	5.12
4 1/8	104.8	.110	2.79	L	11.92	7691	1.387	1.022	1.080	5.38
4 1/8	104.8	.134	3.40	10K	11.61	7491	1.682	1.009	1.080	6.51

From Kreith, F., Ed., *The CRC Handbook of Mechanical Engineering,* CRC Press, Boca Raton, FL, 1998, p. **E**-82 to **E**-83.

Summary of Definitions

Systems (Machining/Manufacturing)	Definitions
Machining System	One or more machine tools and tooling, and auxiliary equipment (e.g., material handling, control, communications) that operate in a coordinated manner to produce parts at the required volumes and quality.
Dedicated Machining System (DMS)	A machining system designed for production of a specific part, and uses transfer line technology with fixed tooling and automation.
Flexible Manufacturing System (FMS)	A machining system configuration with fixed hardware and fixed, but programmable, software to handle changes in work orders, production schedules, part programs, and tooling for several types of parts.
Reconfigurable Manufacturing System (RMS)	A machining system that can be created by incorporating basic process modules, both hardware and software, that can be rearranged or replaced quickly and reliably. Reconfiguration will allow adding, removing, or modifying specific process capabilities, controls, software, or machine structure to adjust production capacity in response to changing market demands or technologies. This type of system will provide customized flexibility for a particular part family, and will be open-ended, so that it can be improved, upgraded, and reconfigured, rather than replaced.

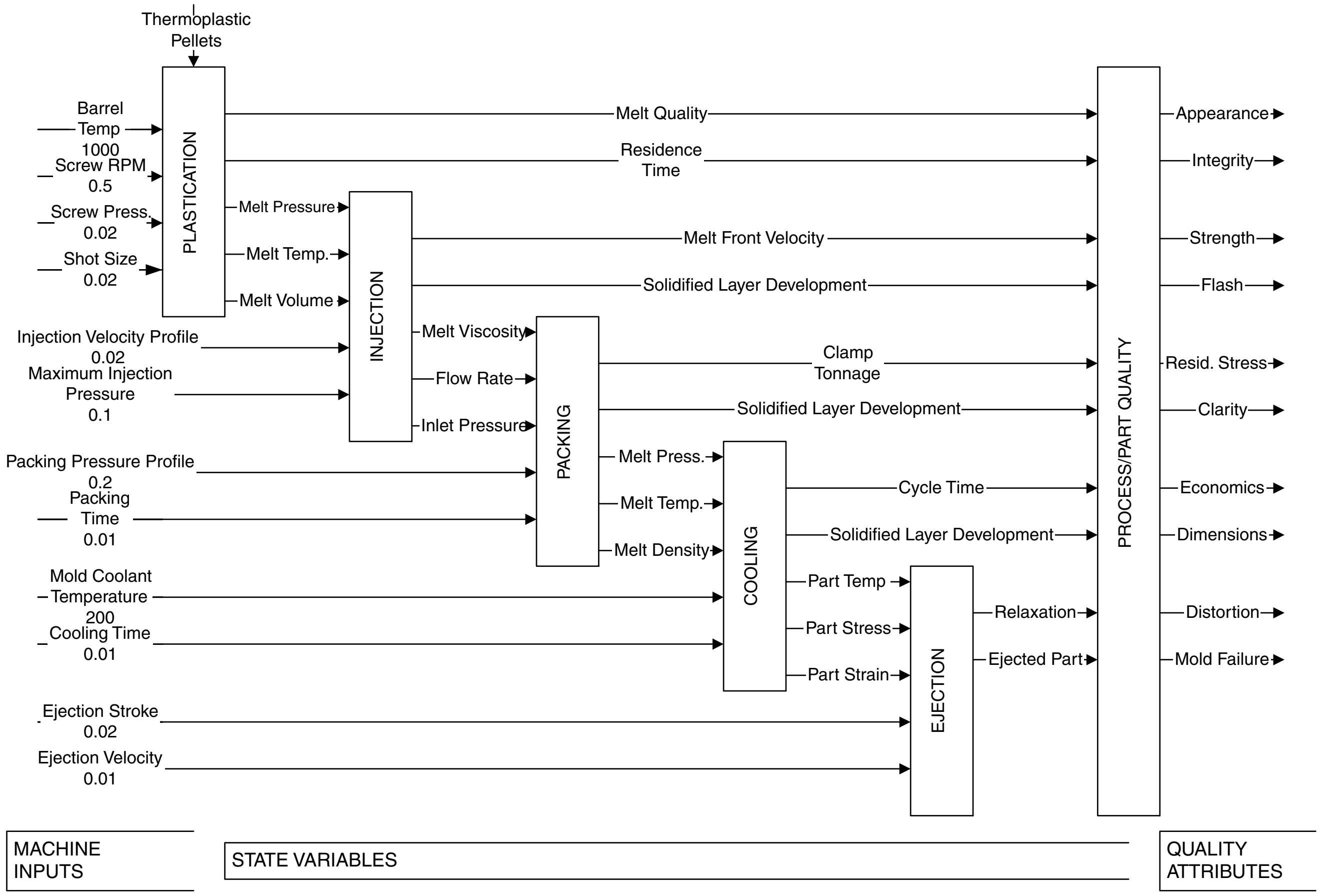
Note: A part family is defined as one or more part types with similar dimensions, geometric features, and tolerances, such that they can be produced on the same, or similar, production equipment.

From Mehrabi, M.G., Ulsoy, A.G., and Koren, Y., Manufacturing systems and their design principles, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 4.

CAPP System Characteristics and Their Effects

Characteristic	Effects
Complete	• Provides a complete manufacturing solution for the part in question. • Meets all the end-user's requirements. • Facilitates the generation of multiple solutions.
Extendable	• New technologies can be merged into the system. • The system can be extended by the end-user or a third-party software developer.
Adaptable	• The system can be used by many different types of end-users.
User Inclusive	• Utilizes human expertise and computer efficiency in correct proportions. • Promotes synthesis and analysis in addition to automation and simulation.
User Friendly	• Easy to implement and maintain. • Easy to use.
Teachable	• Allows the expertise of the end-user to be incorporated into the system. • The system can act as an archiving tool for the end-user's expertise. • The system can be used to train new process planners.
Customizable	• The system (and its cost) can be tailored to the end-user's requirements.
Modular	• Facilitates extendability, adaptability, customizability, and cost effectiveness.
Robust	• Provides consistently "correct" (by the end-user's standard) solutions. • Reduces human error.
Efficient	• Solutions are generated in a more timely fashion than by conventional planning. • The work load for a process planner generating a solution is reduced.
Integratable	• Implementation is not computer hardware or software specific.
Cost Effective	• The system in a customized form suits the budget of a wide range of end-users.

From Yip-Hoi, D., Computer-aided process planning for machining, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 24.

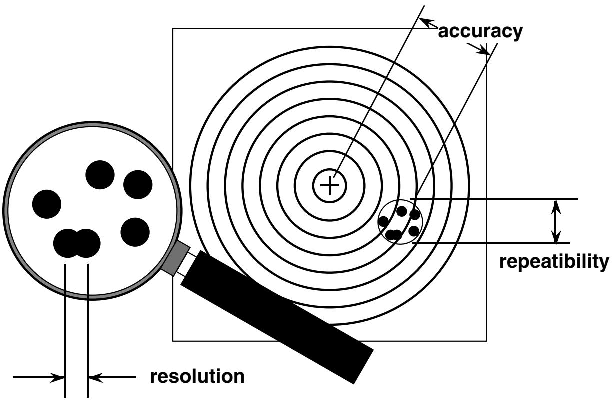


System's view of the injection molding process. (From Kazmer, D. and Danai, K., Control of polymer processing, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 141.)

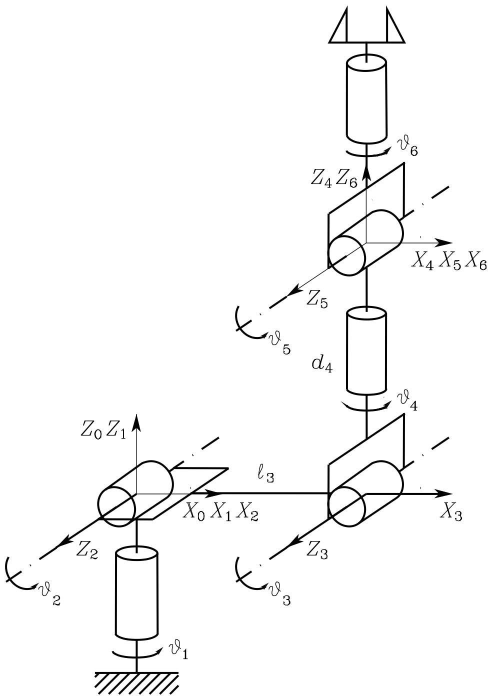
Magnitude of Process Variation by Machine Input

Control Quality	Low (Class 9)	High (Class 1)
Melt temperature (C)	5	1
Mold temperature (C)	8	2
Injection time (sec)	0.17	0.04
Pack pressure (Mpa)	0.5	0.1
Pack time (sec)	0.02	0.09
Cooling time (sec)	0.86	0.20

From Kazmer, D. and Danai, K., Control of polymer processing, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 143.



Visualization of accuracy, repeatability, and resolution. (From Kurfess, T.R., Precision manufacturing, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 153. Originally from Dorf, R. and Kusiak, A., *Handbook of Design, Manufacturing, and Automation*, John Wiley, New York, 1994. With permission.)

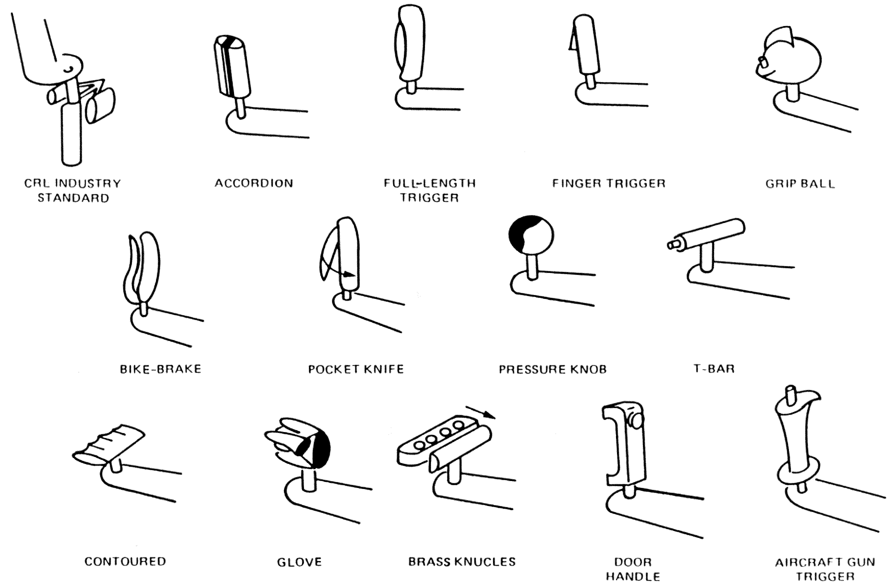


Anthropomorphic robot with frame assignment. (From Siciliano, B., Robot kinematics, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 460.)

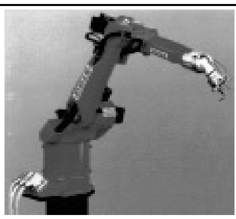
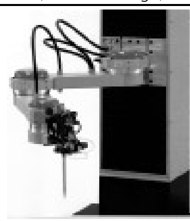
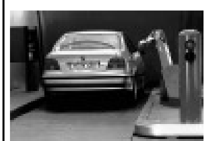
Denavit-Hartenberg Parameters of the Anthropomorphic Robot

i	α_i	ℓ_i	ϑ_i	d_i
1	0	0	q_1	0
2	$\pi/2$	0	q_2	0
3	0	ℓ_3	q_3	0
4	$-\pi/2$	0	q_4	d_4
5	$\pi/2$	0	q_5	0
6	$-\pi/2$	0	q_6	0

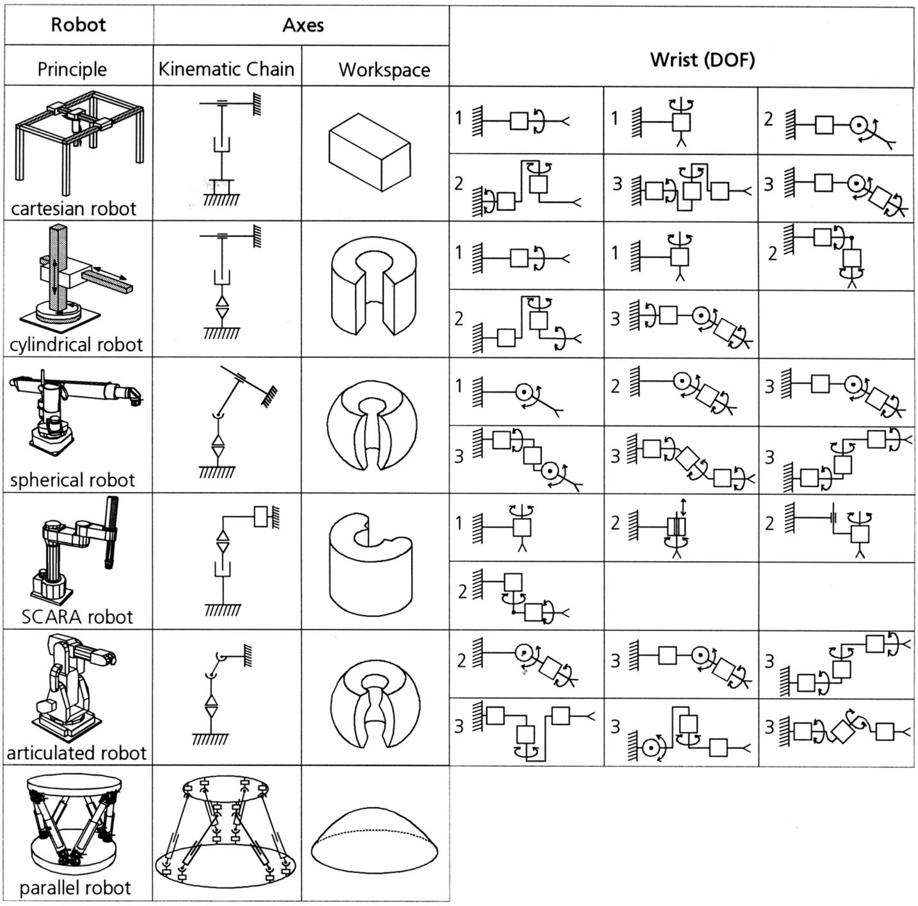
From Siciliano, B., Robot kinematics, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 460.



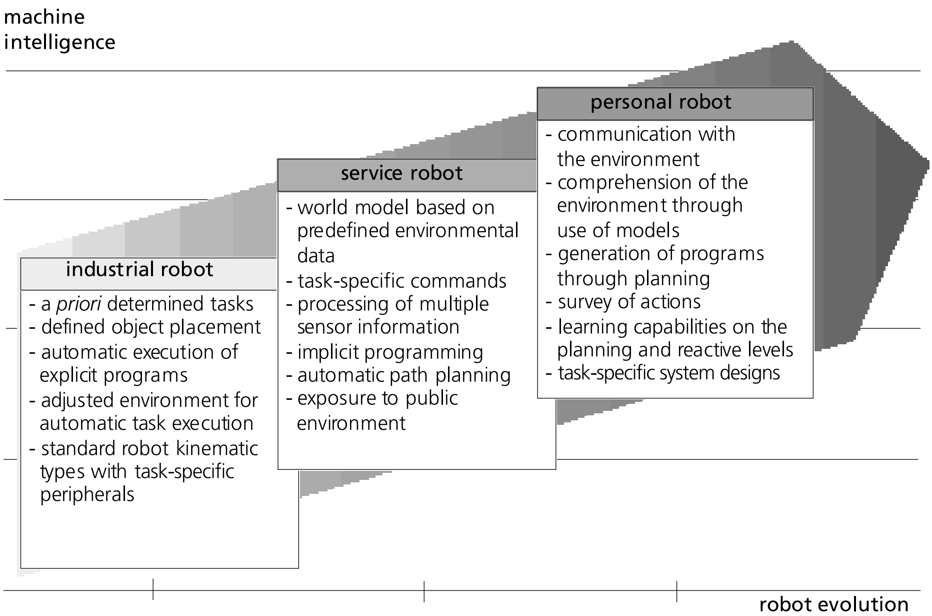
Basic grip and trigger concepts. (From Bejczy, A.K., Teleoperation and telerobotics, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 687.)

Specialization of robots			
universal robot	application specific	specialist (modular design)	specialist (customized design)
			
Examples: Reis RV6	ABB Flex Palettizer	CMB Modular Robot	IPA Robot Refuelling
• design fits standard applications • product variants according to payload, dexterity, working envelope • use of customized components • high manufacturing quantities	• application-oriented designs • integrated process-control functions • preconfigured workcells available • medium manufacturing quantities	• task specific design • integration of standard modules (axis, control, sensors) • preferred applications: material handling • small manufacturing quantities	• task specific designs • primary applications: nonmanufacturing fields (service robots) • task based kinematic structure • small to large manufacturing quantities

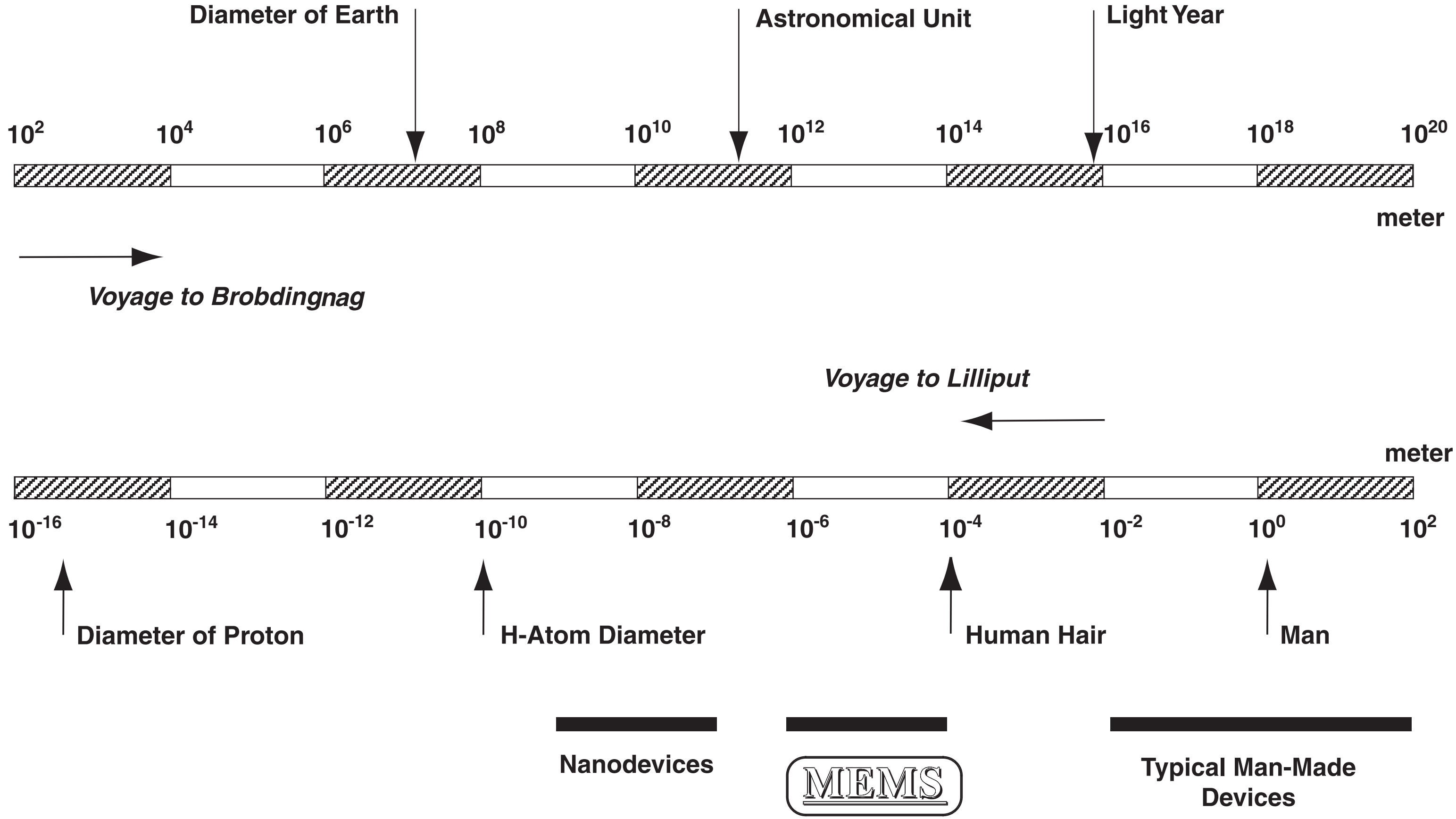
Examples of specialization of robot designs. (From Hagele, M. and Schraft, R.D., Present state and furture trends in mechanical systems design for robot application, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 781. Originally courtesy of Reis Robotics, ABB Flexible Automation, and CMB Automation. From Warnecke, H.-J. et al., in *Handbook of Industrial Robotics,* 1999, p. 42. Reprinted with permission of John Wiley & Sons.)



Typical arm and wrist configurations of industrial robots. (From Hagele, M. and Schraft, R.D., Present state and furture trends in mechanical systems design for robot application, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 784.)



From industrial robots to service robots — the evolution of machine intelligence. (From Hagele, M. and Schraft, R.D., Present state and furture trends in mechanical systems design for robot application, in *The Mechanical Systems Design Handbook*, Nwokah, O.D.I., and Hurmuzlu, Y., Eds., CRC Press, Boca Raton, FL, 2002, p. 795.)

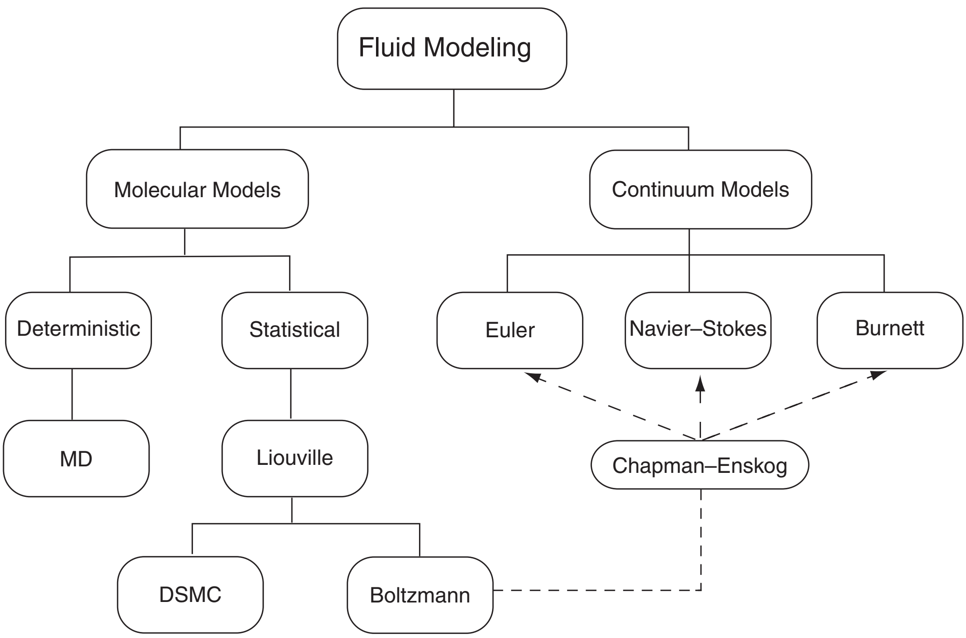


Scale of things, in meters. Lower scale continues in the upper bar from left to right. One meter is 10^6 µm, 10^9 nm, or 10^{10} Å. (From Gal-el-Hak, M., Introduction, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-2.)

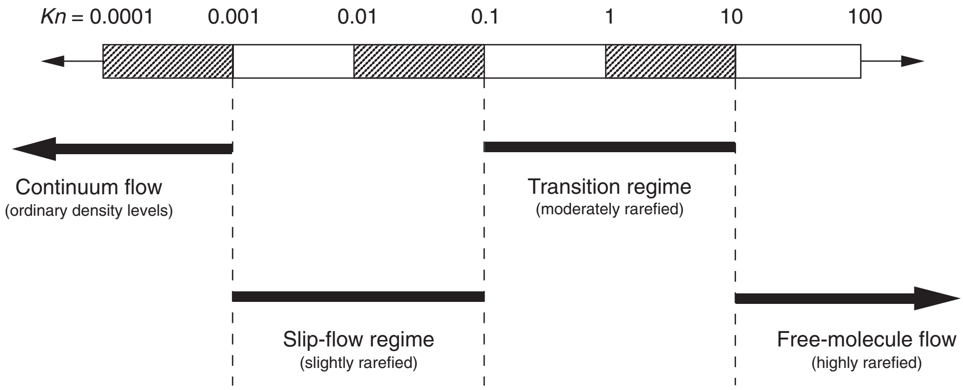
Metals

	Young's Modulus (GPa)	Yield Strength (GPa)	Ultimate Strength (GPa)	Method	Comments
Aluminum; modulus of bulk material = 69 GPa	8–38	—	0.04–0.31	Tension	110–160 μm thick
	40	—	0.15	Tension	1.0 μm thick
	69–85	—	—	Bending	Various lengths
Copper; modulus of bulk material = 117 GPa	86–137	0.12–0.24	0.33–0.38	Tension	Plated; annealed
	108–145	—	—	Indentation	Various locations
	98 ± 4	—	—	Tension	Laser speckle
Gold; modulus of bulk material = 74 GPa	40–80	—	0.2–0.4	Tension	0.06–16 μm thick
	57	0.26	—	Bending	~1 μm thick
	74	—	—	Indentation	~1 μm thick
	82	—	0.33–0.36	Tension	0.8 μm thick
	—	—	0.22–0.27	Bending	Composite beam
Titanium; modulus of bulk material = 110 GPa	96 ± 12	—	0.95 ± 0.15	Tension	0.5 μm thick
Ti–Al–Ti	—	0.07–0.12	0.14–0.19	Tension	Composite film

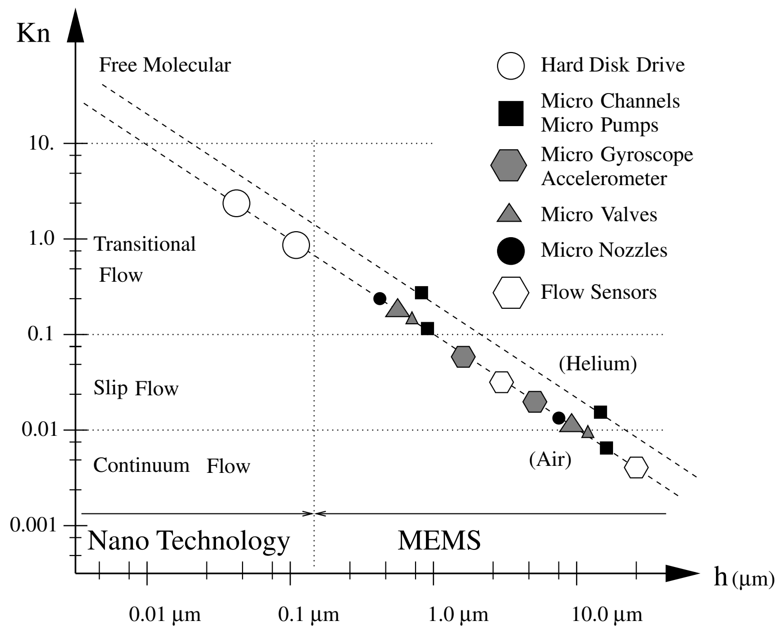
From Sharpe, Jr., W.N., Mechanical properties of MEMS materials, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **3**-19.



Molecular and continuum flow models. (From Gad-el-Hak, M., Flow physics, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **4**-3. Originally from Gad-el-Hak, M. (1999) *J. Fluids Eng.* **121**, pp. 5–33, ASME, New York. With permission.)



Knudsen number regimes. (From Gad-el-Hak, M., Flow physics, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **4**-6. Originally from Gad-el-Hak, M. (1999) *J. Fluids Eng.* **121**, pp. 5–33, ASME, New York. With permission.)



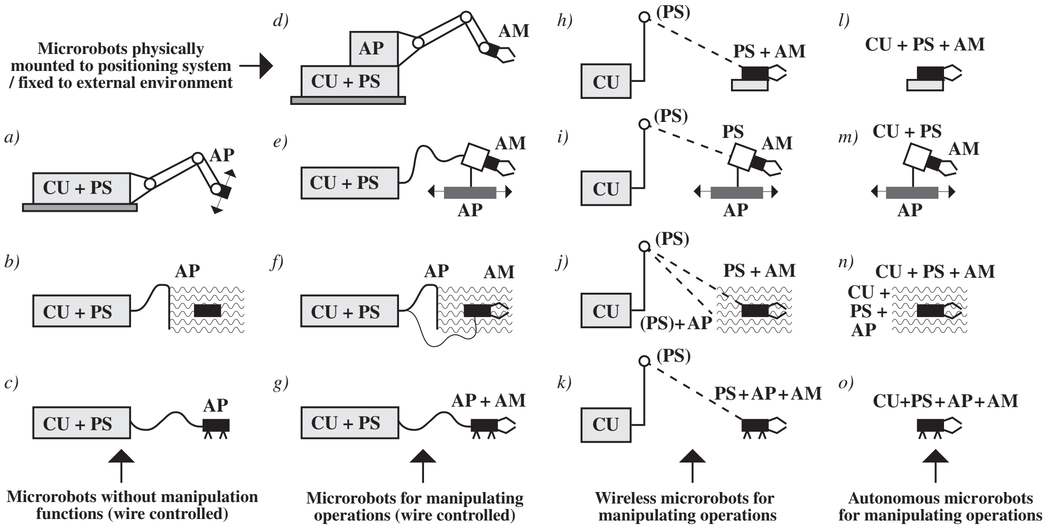
The operation range for typical MEMS and nanotechnology applications under standard conditions spans the entire Knudsen regime (continuum, slip, transition and free molecular flow regimes). (From Bestok, A., Molecular-based microfluidic simulation models, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **8**-3.)

Classification of Microrobots According to Size and Fabrication Technology

Robot Class	Size and Fabrication Technology
Miniature robots or minirobots:	Having a size on the order of a few cubic centimeters and fabricated by assembling conventional miniature components as well as some micromachines (such as MEMS-based microsensors)
MEMS-based microrobots (or microrobots[a])	Defined as a sort of "modified chip" fabricated by silicon MEMS-based technologies (such as batch-compatible bulk or surface micromachining or by micromolding and/or replication method) having features in the micrometer range
Nanorobots	Operating at a scale similar to the biological cell (on the order of a few hundred nanometers) and fabricated by nonstandard mechanical methods such as protein engineering

[a] To distinguish a MEMS-based microrobot with *micro*meter-sized components from the whole class of microrobots (including mini-, micro-, and nanorobots), several more or less confusing notations have been proposed. In this publication, the term *MEMS-based microrobot* is introduced and used. The term *MEMS-based microrobot* differs from the notation originally used by Dario et al., but the content is the same.

From Ebefors, T. and Stemme, G., Microrobotics, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **28**-4.

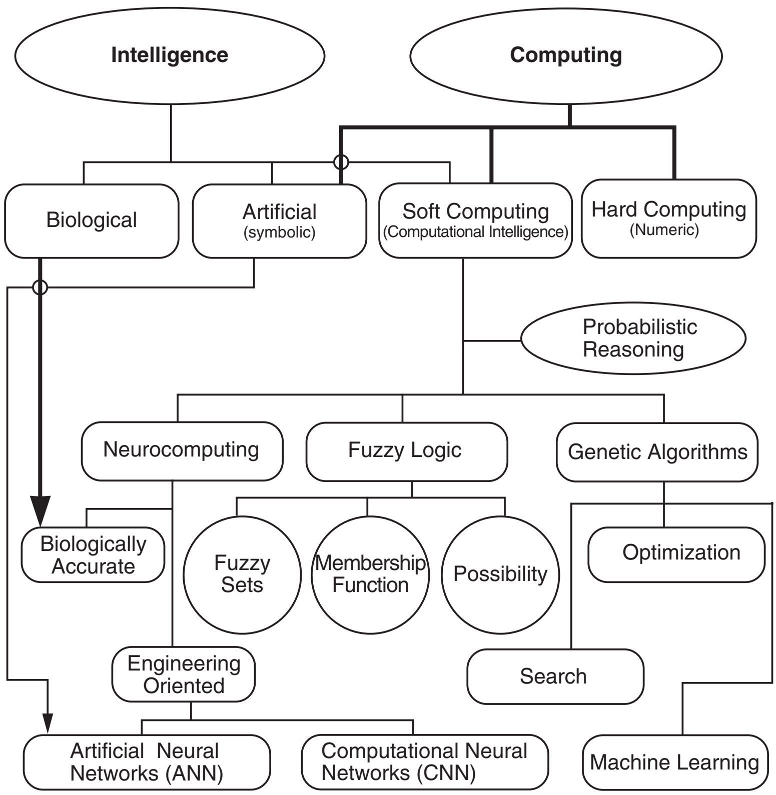


Classification of microrobots by functionality (modification of earlier presented classification schemes). CU indicates the control unit; PS, the power source or power supply; AP, the actuators for positioning; AM, the actuators for manipulation. (From Ebefors, T. and Stemme, G., Microrobotics, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **28**-5.)

Thermal Conductivity, Coefficient of Thermal Expansion, Cost Estimates, and Scaling Trends of Current and Potential Substrate Materials

Materials	Thermal Conductivity (W/cm-K)	Coefficient of Thermal Expansion (10^{-6}/K)	Cost of Substrate ($/in^2)	Scaling with Area Cost Trend
Alumina	0.25	6.7	0.09	6" limit
FR-4	Depends on copper	13.0	0.07	Constant to 36"
A1N	1.00–2.00	4.1	0.35	6" limit
Silicon	1.48	4.7	1.00	6–10" limit
Heat pipe in silicon	8.00 → 20.00 (?)	4.7	3.00	6–10" limit
A1	2.37	41.8	0.0009	Scales as area
Cu	3.98	28.7	0.0015	Scales as area
Diamond	10.00–20.00	1.0–1.5	1000.00	Scales as area^2
Kovar	0.13	5.0	0.027	Scales as area
Heat pipe in Kovar	>8.00	5.0	0.10	Scales as area
A1SiC	2.00 (at 70%)	7.0 (?)	1.00	Casting size limited

From Peterson, G.P., Micro heat pipes and micro heat spreaders, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **31**-17.



Tools for soft computing. (From Gal-el-Hak, M., Flow control, in *The MEMS Handbook*, Gal-el-Hak, M., Ed., CRC Press, Boca Raton, FL, 2002, p. **33**-36. Originally from Gad-el-Hak, M. (2000) *Flow Control: Passive, Active, and Reactive Flow Management*. Reprinted with permission of Cambridge University Press, New York.)

Saturated Steam, Water, and Ice — SI Units

Subscripts:

- *f* refers to a property of liquid in equilibrium with vapor
- *g* refers to a property of vapor in equilibrium with liquid
- *i* refers to a property of solid in equilibrium with vapor
- *fg* refers to a change by evaporation
- *ig* refers to a change by sublimation

Temperature		Pressure, MN/m²	Specific Volume, m³/kg		Specific Internal Energy, kJ/kg		Specific enhalpy, kJ/kg			Specific Entropy, kJ/kg·K	
C	K										
Solid—Vapor			v_i	v_g	u_i	u_g	h_i	h_{ig}	h_g	s_i	s_g
–40	233.15	0.000 012 9	0.000 084 1	83.54	–411.70	2 319.6	–411.70	2 838.9	2 427.2	–1.532	10.644
–30	243.15	0.000 038 1	0.001 085 8	29.43	–393.23	2 333.6	–393.23	2 839.0	2 445.8	–1.455	10.221
–20	253.15	0.000 103 5	0.001 087 4	11.286	–374.03	2 347.5	–374.03	2 838.4	2 464.3	–1.377	9.835
–10	263.15	0.000 260 2	0.001 089 1	4.667	–354.09	2 361.4	–354.09	2 837.0	2 482.9	–1.299	9.481
0	273.15	0.000 610 8	0.001 090 8	2.063	–333.43	2 375.3	–333.43	2 834.8	2 501.3	–1.221	9.157
0.01	273.16	0.000 611 3	0.001 090 8	2.061	–333.40	2 375.3	–333.40	2 834.8	2 501.4	–1.221	9.156
Liquid—Vapor			v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_g
0	273.15	0.000 610 9	0.001 000 2	206.278	–0.03	2 375.3	–0.02	2 501.4	2 501.3	–0.000 1	9.156 5
0.01	273.16	0.000 611 3	0.001 000 2	206.136	0	2 375.3	+0.01	2 501.3	2 501.4	0	9.156 2
5.00	278.15	0.000 872 1	0.001 000 1	147.120	+20.97	2 382.3	20.98	2 489.6	2 510.6	+0.076 1	9.025 7
6.98	280.13	0.001 000 0	0.001 000 2	129.208	29.30	2 385.0	29.30	2 484.9	2 514.2	0.105 9	8.975
10.00	283.15	0.001 227 6	0.001 000 4	106.379	42.00	2 389.2	42.01	2 477.7	2 519.8	0.151 0	8.900 8
13.03	286.18	0.001 500 0	0.001 000 7	87.980	54.71	2 393.3	54.71	2 470.6	2 525.3	0.195 7	8.827 9
15.00	288.15	0.001 705 1	0.001 000 9	77.926	62.99	2 396.1	62.99	2 465.9	2 528.9	0.224 5	8.781 4
17.50	290.65	0.002 000 0	0.001 001 3	67.004	73.48	2 399.5	73.48	2 460.0	2 533.5	0.260 7	8.723 7
20.00	293.15	0.002 339	0.001 001 8	57.791	83.95	2 402.9	83.96	2 454.1	2 538.1	0.296 6	8.667 2
24.08	297.23	0.003 000 0	0.001 002 7	45.665	101.04	2 408.5	101.05	2 444.5	2 545.5	0.354 5	8.577 6
25.00	298.15	0.003 169	0.001 002 9	43.360	104.88	2 409.8	104.89	2 442.3	2 547.2	0.367 4	8.558 0
28.96	302.11	0.004 000	0.001 004 0	34.800	121.45	2 415.2	121.46	2 432.9	2 554.4	0.422 6	8.474 6
30.00	303.15	0.004 246	0.001 004 3	32.894	125.78	2 416.6	125.79	2 430.5	2 556.3	0.436 9	8.453 3
32.88	306.03	0.005 000	0.001 005 3	28.192	137.81	2 420.5	137.82	2 423.7	2 561.5	0.476 4	8.395 1
35.00	308.15	0.005 628	0.001 006 0	25.216	146.67	2 423.4	146.68	2 418.6	2 565.3	0.505 3	8.353 1
36.16	309.31	0.006 000	0.001 006 4	23.739	151.53	2 425.0	151.53	2 415.9	2 567.4	0.521 0	8.330 4
39.00	312.15	0.007 000	0.001 007 4	20.530	163.39	2 428.8	163.40	2 409.1	2 572.5	0.559 2	8.275 8
40.00	313.15	0.007 384	0.001 007 8	19.523	167.56	2 430.1	167.57	2 406.7	2 574.3	0.572 5	8.257 0
41.51	314.66	0.008 000	0.001 008 4	18.103	173.87	2 432.2	173.88	2 403.1	2 577.0	0.592 6	8.228 7
43.76	316.91	0.009 000	0.001 009 4	16.203	183.27	2 435.2	183.29	2 397.7	2 581.0	0.622 4	8.187 2
45.00	318.15	0.009 593	0.001 009 9	15.258	188.44	2 436.8	188.45	2 394.8	2 583.2	0.638 7	8.164 8
45.81	318.96	0.010 000	0.001 010 2	14.674	191.82	2 437.9	191.83	2 392.8	2 584.7	0.649 3	8.150 2
50.00	323.15	0.012 349	0.001 012 1	12.032	209.32	2 443.5	209.33	2 382.7	2 592.1	0.703 8	8.076 3
53.97	327.12	0.015 000	0.001 014 1	10.022	225.92	2 448.7	225.94	2 373.1	2 599.1	0.754 9	8.008 5
55.00	328.15	0.015 758	0.001 014 6	9.568	230.21	2 450.1	230.23	2 370.7	2 600.9	0.767 9	7.991 3
60.00	333.15	0.019 940	0.001 017 2	7.671	251.11	2 456.6	251.13	2 358.5	2 609.6	0.831 2	7.909 6
60.06	333.21	0.020 000	0.001 017 2	7.649	251.38	2 456.7	251.40	2 358.3	2 609.7	0.832 0	7.908 5
65.00	338.15	0.025 030	0.001 019 9	6.197	272.02	2 463.1	272.06	2 346.2	2 618.3	0.893 5	7.831 0
69.10	342.25	0.030 000	0.001 022 3	5.22l9	289.20	2 468.4	289.23	2 336.1	2 625.3	0.943 9	7.768 6
70.00	343.15	0.031 190	0.001 022 8	5.042	292.95	2 469.6	292.98	2 333.8	2 626.8	0.954 9	7.755 3
75.00	348.15	0.038 580	0.001 025 9	4.131	313.90	2 475.9	313.93	2 221.4	2 635.3	1.015 5	7.682 4
75.87	349.02	0.040 000	0.001 026 5	3.993	317.53	2 477.0	317.58	2 319.2	2 636.8	1.025 9	7.670 0
80.00	353.15	0.047 390	0.001 029 1	3.407	334.86	2 482.2	334.91	2 308.8	2 643.7	1.075 3	7.612 2
81.33	354.48	0.050 000	0.001 030 0	3.240	340.44	2 483.9	340.49	2 305.4	2 645.9	1.091 0	7.593 9
85.00	358.15	0.057 830	0.001 032 5	2.828	355.84	2 488.4	355.90	2 296.0	2 651.9	1.134 3	7.544 5
85.94	359.09	0.060 000	0.001 033 1	2.732	359.79	2 489.6	359.86	2 293.6	2 653.5	1.145 3	7.532 0
89.95	363.10	0.070 000	0.001 036 0	2.365	376.63	2 494.5	376.70	2 283.3	2 660.0	1.191 9	7.479 7
90.00	363.15	0.070 140	0.001 036 0	2.361	376.85	2 494.5	376.92	2 283.2	2 660.1	1.192 5	7.479 1
93.50	366.65	0.080 000	0.001 038 6	2.087	391.58	2 498.8	391.66	2 274.1	2 665.8	1.232 9	7.434 6
95.00	368.15	0.084 550	0.001 039 7	1.981 9	397.88	2 500.6	397.96	2 270.2	2 668.1	1.250 0	7.415 9

Saturated Steam, Water, and Ice — SI Units (continued)

Liquid—Vapor			v_f	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_g
96.71	369.86	0.090 000	0.001 041 0	1.869	405.06	2 502.6	405.15	2 265.7	2 670.9	1.269 5	7.394 9
99.63	372.78	0.100 000	0.001 043 2	1.694 0	417.36	2 506.1	417.46	2 258.0	2 675.5	1.302 6	7.359 4
100.00	373.15	0.101 350	0.001 043 5	1.672 9	418.94	2 506.5	419.04	2 257.0	2 676.1	1.306 9	7.354 9
110.00	383.15	0.143 270	0.001 051 6	1.210 2	461.14	2 518.1	461.30	2 230.2	2 691.5	1.418 5	7.238 7
111.37	384.52	0.150 000	0.001 052 8	1.159 3	466.94	2 519.7	467.11	2 226.5	2 693.6	1.433 6	7.223 3
120.00	393.15	0.198 530	0.001 060 3	0.891 9	503.50	2 529.3	503.71	2 202.6	2 706.3	1.527 6	7.129 6
120.23	393.38	0.200 000	0.001 060 5	0.885 7	504.49	2 529.5	504.70	2 201.9	2 706.7	1.530 1	7.127 1
130.00	403.15	0.270 000	0.001 069 7	0.668 5	546.02	2 539.9	546.31	2 174.2	2 720.5	1.634 4	7.026 9
133.55	406.70	0.300 000	0.001 073 2	0.605 8	561.15	2 543.6	561.47	1 163.8	2 725.3	1.671 8	6.991 9
140.00	413.15	0.361 300	0.001 079 7	0.508 9	588.74	2 550.0	589.13	2 144.7	2 733.9	1.739 1	6.929 9
143.63	416.78	0.400 000	0.001 083 6	0.462 5	604.31	2 553.6	604.74	2 133.8	2 738.6	1.776 6	6.895 9
150.00	423.15	0.475 800	0.001 090 5	0.392 8	631.68	2 559.5	632.20	2 114.3	2 746.5	1.841 8	6.837 9
151.86	425.01	0.500 000	0.001 092 6	0.374 9	639.68	2 561.2	640.23	2 108.5	2 748.7	1.860 7	6.821 3
160.00	433.15	0.617 800	0.001 102 0	0.307 1	674.87	2 568.4	675.55	2 082.6	2 758.1	1.942 7	6.750 2
170.00	443.15	0.791 700	0.001 114 3	0.242 8	718.33	2 576.5	719.21	2 049.5	2 768.7	2.041 9	6.666 3
179.91	453.06	1.000 000	0.001 127 3	0.194 44	761.68	2 583.6	762.81	2 015.3	2 778.1	2.138 7	6.586 5
180.00	453.15	1.002 100	0.001 127 4	0.194 05	762.09	2 583.7	763.22	2 015.0	2 778.2	2.139 6	6.585 7
190.00	463.15	1.254 400	0.001 141 4	0.156 54	806.19	2 590.0	807.62	1 978.8	2 786.4	2.235 9	6.507 9
198.32	471.47	1.500 000	0.001 153 9	0.131 77	843.16	2 594.5	844.89	1 947.3	2 792.2	2.315 0	6.444 8
200.00	473.15	1.553 800	0.001 156 5	0.127 36	850.65	2 595.3	852.45	1 940.7	2 793.2	2.330 9	6.432 3
210.00	483.15	1.906 200	0.001 172 6	0.104 41	895.53	2 599.5	897.76	1 900.7	2 798.5	2.424 8	6.358 5
212.42	485.57	2.000 000	0.001 176 7	0.099 63	906.44	2 600.3	908.79	1 890.7	2 799.5	2.447 4	6.340 9
220.00	493.15	2.318 000	0.001 190 0	0.086 19	940.87	2 602.4	943.62	1 858.5	2 802.1	2.517 8	6.286 1
223.99	497.14	2.500 000	0.001 197 3	0.079 98	959.11	2 603.1	962.11	1 841.0	2 803.1	2.554 7	6.257 5
230.00	503.15	2.795 000	0.001 208 8	0.071 58	986.74	2 603.9	990.12	1 813.8	2 804.0	2.609 9	6.214 6
233.90	507.05	3.000 000	0.001 216 5	0.066 68	1 004.78	2 604.1	1 008.42	1 795.7	2 804.2	2.645 7	6.186 9
240.00	513.15	3.344 000	0.001 229 1	0.059 76	1 033.21	2 604.0	1 037.32	1 766.5	2 803.8	2.701 5	6.143 7
242.60	515.75	3.500 000	0.001 234 7	0.057 07	1 045.43	2 603.7	1 049.75	1 753.7	2 803.4	2.725 3	6.125 3
250.00	523.15	3.973 000	0.001 251 2	0.050 13	1 080.39	2 602.4	1 085.36	1 716.2	2 801.5	2.792 7	6.073 0
250.40	523.55	4.000 000	0.001 252 2	0.049 78	1 082.31	2 602.3	1 087.31	1 714.1	2 801.4	2.796 4	6.070 1
260.00	533.15	4.688 000	0.001 275 5	0.042 21	1 128.39	2 599.0	1 134.37	1 662.5	2 796.9	2.883 8	6.001 9
263.99	537.14	5.000 000	0.001 285 9	0.039 44	1 147.81	2 597.1	1 154.23	1 640.1	2 794.3	2.920 2	5.973 4
270.00	543.15	5.499 000	0.001 302 3	0.035 64	1 177.36	2 593.7	1 184.51	1 605.2	2 789.7	2.975 1	5.930 1
275.64	548.79	6.000 000	0.001 318 7	0.032 44	1 205.44	2 589.7	1 213.35	1 571.0	2 784.3	3.026 7	5.889 2
280.00	553.15	6.412 000	0.001 332 1	0.030 17	1 227.46	2 586.1	1 235.99	1 543.6	2 779.6	3.066 8	5.857 1
285.88	559.03	7.000 000	0.001 351 3	0.027 37	1 257.55	2 580.5	1 267.00	1 505.1	2 772.1	3.121 1	5.813 3
290.00	563.15	7.436 000	0.001 365 6	0.025 57	1 278.92	2 576.0	1 289.07	1 477.1	2 766.2	3.159 4	5.782 1
295.06	568.21	8.000 000	0.001 384 2	0.023 52	1 305.57	2 569.8	1 316.64	1 441.3	2 758.0	3.206 8	5.743 2
300.00	573.15	8.581 000	0.001 403 6	0.021 67	1 332.0	2 563.0	1 344.0	1 404.9	2 749.0	3.253 4	5.704 5
303.40	576.55	9.000 000	0.001 417 8	0.020 48	1 350.51	2 557.8	1 363.26	1 378.9	2 742.1	3.285 8	5.677 2
310.00	583.15	9.856 000	0.001 447 4	0.018 350	1 387.1	2 546.4	1 401.3	1 326.0	2 727.3	3.349 3	5.623 0
311.06	584.21	10.000 000	0.001 452 4	0.018 026	1 393.04	2 544.4	1 407.56	1 317.1	2 724.7	3.359 3	5.614 1
320.00	593.15	11.274 000	0.001 498 8	0.015 488	1 444.6	2 525.5	1 461.5	1 238.6	2 700.1	3.448 0	5.536 2
324.75	597.90	12.000 000	0.001 526 7	0.014 263	1 473.0	2 513.7	1 491.3	1 193.6	2 684.9	3.496 2	5.492 4
330.00	603.15	12.845 000	0.001 560 7	0.012 996	1 505.3	2 498.9	1 525.3	1 140.6	2 665.9	3.550 7	5.441 7
336.75	609.90	14.000 000	0.001 610 7	0.011 485	1 548.6	2 476.8	1 571.1	1 066.5	2 637.6	3.623 2	5.371 7
340.00	613.15	14.586 000	0.001 637 9	0.001 079 7	1 570.3	2 464.6	1 594.2	1 027.9	2 622.0	3.659 4	5.335 7
347.44	620.59	16.000 000	0.001 710 7	0.009 306	1 622.7	2 431.7	1 650.1	930.6	2 580.6	3.746 1	5.245 5
350.00	623.15	16.513 000	0.001 740 3	0.008 813	1 641.9	2 418.4	1 670.6	893.4	2 563.9	3.777 7	5.211 2
357.06	630.21	18.000 000	0.001 839 7	0.007 489	1 698.9	2 374.3	1 732.0	777.1	2 509.1	3.871 5	5.104 4
360.00	633.15	18.651 000	0.001 892 5	0.006 945	1 725.2	2 351.5	1 760.5	720.5	2 481.0	3.914 7	5.052 6
365.81	638.96	20.000 000	0.002 036	0.005 834	1 785.6	2 293.0	1 826.3	583.4	2 409.7	4.013 9	4.926 9
370.00	643.15	21.030 000	0.002 213	0.004 925	1 844.0	2 228.5	1 890.5	441.6	2 332.1	4.110 6	4.797 1
373.80	646.95	22.000 000	0.002 742	0.003 568	1 961.9	2 087.1	2 022.2	143.4	2 165.6	4.311 0	4.532 7
374.136	647.286	22.090 000	0.003 155	0.003 155	2 029.6	2 029.6	2 099.3	0	2 099.3	4.429 8	4.429 8

From Bolz, R.E. and Tuve, G.L., Gases and vapors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 24–25. Originally condensed from Keenan, J.H., Keyes, F.G., Hill, P.G., and Moore, J.G., *Steam Tables: Thermodynamic Properties of Water Including Vapor, Liquid, and Solid Phases*, John Wiley & Sons, New York, 1969.

Viscosity and Thermal Conductivity of Steam and Water—SI Units

Symbols and Units

μ = dynamic viscosity. For N·s/m² (= kg/m·s) multiply tabulated values by 10^{-6}

ν = kinematic viscosity. For m²/s multiply tabulated values by 10^{-6}

k = thermal conductivity in MW/m·K

Temperature		Pressure 0.1 MN/m²			0.5 MN/m²			1.0 MN/m²		
C	*K*	μ	*ν*	*k*	μ	*ν*	*k*	μ	*ν*	*k*
0	273.15	1 750	1.75	569	1 750	1.75	569	1 750	1.75	570
50	323.15	544	0.551	643	544	0.551	644	544	0.550	644
100	373.15	12.11	20.54	24.8	279	0.291	681	279	0.291	681
150	423.15	14.15	27.39	28.7	181	0.198	687	181	0.198	687
200	473.15	16.18	35.14	33.2	16.02	6.81	33.8	15.85	0.327	35.1
250	523.15	18.22	48.83	38.2	18.14	8.61	38.6	18.06	0.420	39.3
300	573.15	20.25	53.44	43.4	20.23	10.57	43.8	20.22	0.522	44.4
350	623.15	22.3	64.02	49.0	—	—	49.4	—	—	49.9
400	673.15	24.3	75.40	54.9	24.4	15.06	55.3	24.4	7.48	55.7
450	723.15	26.4	88.0	61.1	26.4	17.5	61.4	26.5	0.88	61.8
500	773.15	28.4	101.3	67.4	28.4	20.2	67.7	28.5	0.101	68.2
550	823.15	30.4	115.4	73.9	30.5	23.1	74.3	30.5	0.115	74.7
600	873.15	32.5	130.9	80.6	32.5	26.1	80.9	32.6	0.131	81.4
650	923.15	34.5	146.9	87.4	34.5	29.3	87.7	34.6	0.147	88.2
700	973.15	36.5	163.9	94.3	36.6	32.8	94.6	36.6	0.164	95.0

Temperature		Pressure 5.0 MN/m²			10 MN/m²			20 MN/m²		
C	*K*	μ	*ν*	*k*	μ	*ν*	*k*	μ	*ν*	*k*
0	273.15	1 750	1.75	573	1 750	1.74	577	1 740	1.72	585
50	323.15	545	0.550	647	545	0.549	651	546	0.548	659
100	373.15	280	0.291	684	281	0.292	688	283	0.293	695
150	423.15	182	0.198	690	183	0.199	693	186	0.200	700
200	473.15	135	0.155	668	136	0.156	672	138	0.158	681
250	523.15	107	0.134	618	108	0.134	625	111	0.136	639
300	573.15	20.06	0.909	52.5	90.5	0.126	545	93	0.127	571
350	623.15	—	—	55.4	—	—	68.8	73.5	0.122	454
400	673.15	25.0	1.45	60.2	25.8	0.682	68.6	28.6	0.285	107
450	723.15	26.9	1.70	65.9	27.6	0.821	72.4	29.6	0.376	93
500	773.15	28.9	1.98	72.0	29.5	0.967	77.6	31.1	0.459	93
550	823.15	30.9	2.28	78.4	31.5	1.123	83.5	32.8	0.543	96
600	873.15	32.9	2.59	85.0	33.4	1.282	89.8	34.6	0.629	101
650	923.15	34.9	2.92	91.7	35.4	1.452	96	36.5	0.719	107
700	973.15	36.9	3.27	98.6	37.4	1.630	103	38.4	0.812	113

Temperature		Pressure 30 MN/m²			40 MN/m²			50 MN/m²		
C	*K*	μ	*ν*	*k*	μ	*ν*	*k*	μ	*ν*	*k*
0	273.15	1.740	1.71	592	1 730	1.70	599	1 720	1.68	606
50	323.15	547	0.547	666	548	0.545	672	549	0.544	678
100	373.15	285	0.293	701	287	0.294	707	289	0.295	713
150	423.15	188	0.201	706	190	0.203	713	192	0.204	720
200	473.15	140	0.159	689	143	0.161	697	145	0.162	704
250	523.15	113	0.137	652	116	0.139	662	118	0.140	671
300	573.15	95.5	0.127	592	98.1	0.128	609	101	0.130	622

Viscosity and Thermal Conductivity of Steam and Water—SI Units (continued)

350	623.15	78.5	0.122	496	82.5	0.122	529	85	0.123	522
400	673.15	45.8	0.128	264	62.8	0.120	390	28.6	0.120	436
450	723.15	33.1	0.223	138	41.1	0.152	220	29.6	0.130	301
500	773.15	33.4	0.290	116	36.9	0.208	153	31.1	0.164	206
550	823.15	34.6	0.352	112	36.9	0.258	134	32.8	0.205	163
600	873.15	36.1	0.413	114	37.9	0.307	130	34.6	0.245	149
650	923.15	37.7	0.475	118	39.2	0.355	132	36.5	0.286	147
700	973.15	39.5	0.540	124	40.8	0.406	135	38.4	0.327	148

From Bolz, R.E. and Tuve, G.L., Gases and vapors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p 37. Originally adapted from Keenan, J.H., Keyes, F.G., Hill, P.G., and Moore, J.G., *Steam Tables: Thermodynamic Properties of Water Including Vapor, Liquid, and Solid Phases*, John Wiley & Sons, New York, 1969.

Properties of Gases

Gases and Vapors, Including Fuels and Refrigerants, English and Metric Units
The properties of pure gases are given at 25 deg C (77 deg F, 298 K) and atmospheric pressure (except as stated).

Common Name(s) Chemical Formula Refrigerant Number	Acetylene (Ethyne) C_2H_2 —	Air [Mixture] 729	Ammonia, anhyd. NH_3 717	Argon Ar 740
Chemical and Physical Properties				
Molecular weight	26.04	28.966	17.02	39.948
Specific gravity, air = 1	0.90	1.00	0.59	1.38
Specific volume, ft^3/lb	14.9	13.5	23.0	9.80
Specific volume, m^3/kg	0.93	0.842	1.43	0.622
Density of liquid (at atm bp), lb/ft^3	43.0	54.6	42.6	87.0
Density of liquid (at atm bp), kg/m^3	693.	879.	686.	1 400.
Vapor pressure at 25 deg C, psia			145.4	
Vapor pressure at 25 deg C, MN/m^2			1.00	
Viscosity (abs), lbm/ft·sec	6.72×10^{-6}	12.1×10^{-6}	6.72×10^{-6}	13.4×10^{-6}
Viscosity (abs), centipoises[a]	0.01	0.018	0.010	0.02
Sound velocity in gas, m/sec	343	346	415	322
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.40	0 240.3	0.52	0.125
Specific heat, c_p, J/kg·K	1 674.	1 005.	2 175.	523.
Specific heat ratio, c_p/c_{pv}	1.25	1.40	1.3	1.67
Gas constant R, ft-lb/lb·deg F	59.3	53.3	90.8	38.7
Gas constant R, J/kg·deg C	319	286.8	488.	208.
Thermal conductivity, Btu/hr·ft·deg F	0.014	0.0151	0.015	0.010 2
Thermal conductivity, W/m·deg C	0.024	0.026	0.026	0.017 2
Boiling point (sat 14.7 psia), deg F	–103	–320	–28.	–303.
Boiling point (sat 760 mm), deg C	–75	–195	–33.3	–186
Latent heat of evap (at bp), Btu/lb	264	88.2	589.3	70.
Latent heat of evap (at bp), J/kg	614 000	205 000	1 373 000	163 000
Freezing (melting) point, deg F (1 atm)	–116	–357.2	–107.9	–308.5
Freezing (melting) point, deg C (1 atm)	–82.2	–216.2	–77.7	–189.2
Latent heat of fusion, Btu/lb	23.	10.0	143.0	
Latent heat of fusion, J/kg	53 500	23 200	332 300	
Critical temperature, deg F	97.1	–220.5	271.4	–187.6
Critical temperature, deg C	36.2	–140.3	132.5	–122
Critical pressure, psia	907.	550.	1 650.	707.

Properties of Gases (continued)

Critical pressure, MN/m²	6.25	3.8	11.4	4.87
Critical volume, ft³/lb		0.050	0.068	0.029 9
Critical volume, m³/kg		0.003	0.004 24	0.001 86
Flammable (yes or no)	Yes	No	No	No
Heat of combustion, Btu/ft³	1 450	—	—	—
Heat of combustion, Btu/lb	21 600	—	—	—
Heat of combustion, kJ/kg	50 200	—	—	—

[a] For N·sec/m² divide by 1 000.

Common Name(s)	Butadiene	*n*-Butane	Isobutane (2-Methylpropane)	l-Butene (Butylene)
Chemical Formula	C_4H_6	C_4H_{10}	C_4H_{10}	C_4H_8
Refrigerant Number	—	600	600a	—
Chemical and Physical Properties				
Molecular weight	54.09	58.12	58.12	56.108
Specific gravity, air = 1	1.87	2.07	2.07	1.94
Specific volume, ft³/lb	7.1	6.5	6.5	6.7
Specific volume, m³/kg	0.44	0.405	0.418	0.42
Density of liquid (at atm bp), lb/ft³		37.5	37.2	
Density of liquid (at atm bp), kg/m³		604.	599.	
Vapor pressure at 25 deg C, psia		35.4	50.4	
Vapor pressure at 25 deg C, MN/m²		0.024 4	0.347	
Viscosity (abs), lbm/ft·sec		4.8×10^{-6}		
Viscosity (abs), centipoises[a]		0.007		
Sound velocity in gas, m/sec	226	216	216	222
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.341	0.39	0.39	0.36
Specific heat, c_p, J/kg·K	1 427.	1 675.	1 630.	1 505.
Specific heat ratio, c_p/c_{pv}	1.12	1.096	1.10	1.112
Gas constant *R*, ft-lb/lb·deg F	28.55	26.56	26.56	27.52
Gas constant *R*, J/kg·deg C	154.	143.	143.	148.
Thermal conductivity, Btu/hr·ft·deg F		0.01	0.01	
Thermal conductivity, W/m·deg C		0.017	0.017	
Boiling point (sat 14.7 psia), deg F	24.1	31.2	10.8	20.6
Boiling point (sat 760 mm), deg C	–4.5	–0.4	–11.8	–6.3
Latent heat of evap (at bp), Btu/lb		165.6	157.5	167.9
Latent heat of evap (at bp), J/kg		386 000	366 000	391 000
Freezing (melting) point, deg F (1 atm)	–164	–217.	–229	–301 6
Freezing (melting) point, deg C (1 atm)	–109.	–138.	–145	–185.3
Latent heat of fusion, Btu/lb		19.2		16.4
Latent heat of fusion, J/kg		44 700		38 100
Critical temperature, deg F		306	273.	–291.
Critical temperature, deg C	171.	152.	134.	144.
Critical pressure, psia	652.	550.	537.	621.
Critical pressure, MN/m²		3.8	3.7	4.28
Critical volume, ft³/lb		0.070		0.068
Critical volume, m³/kg		0.004 3		0.004 2
Flammable (yes or no)	Yes	Yes	Yes	Yes
Heat of combustion, Btu/ft³	2 950	3 300	3 300	3 150
Heat of combustion, Btu/lb	20 900	21 400	21 400	21 000
Heat of combustion, kJ/kg	48 600	49 700	49 700	48 800

[a] For N·sec/m² divide by 1 000.

Properties of Gases (continued)

Common Name(s)	cis-2-Butene	trans-2-Butene	Isobutene	Carbon Dioxide CO_2
Chemical Formula	C_4H_8	C_4H_8	C_4H_8	CO_2
Refrigerant Number	—	—	—	744
Chemical and Physical Properties				
Molecular weight	56.108	56.108	56.108	44.01
Specific gravity, air = 1	1.94	1.94	1.94	1.52
Specific volume, ft^3/lb	6.7	6.7	6.7	8.8
Specific volume, m^3/kg	0.42	0.42	0.42	0.55
Density of liquid (at atm bp), lb/ft^3				—
Density of liquid (at atm bp), kg/m^3				—
Vapor pressure at 25 deg C, psia				931.
Vapor pressure at 25 deg C, MN/m^2				6.42
Viscosity (abs), lbm/ft·sec				9.4×10^{-6}
Viscosity (abs), centipoises[a]				0.014
Sound velocity in gas, m/sec	223.	221.	221.	270.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.327	0.365	0.37	0.205
Specific heat, c_p, J/kg·K	1 368.	1 527.	1 548.	876.
Specific heat ratio, c_p/c_{pv}	1.121	1.107	1.10	1.30
Gas constant R, ft-lb/lb·deg F				35.1
Gas constant R, J/kg·deg C				189.
Thermal conductivity, Btu/hr·ft·deg F				0.01
Thermal conductivity, W/m·deg C				0.017
Boiling point (sat 14.7 psia), deg F	38.6	33.6	19.2	–109.4[b]
Boiling point (sat 760 mm), deg C	3.7	0.9	–7.1	–78.5
Latent heat of evap (at bp), Btu/lb	178.9	174.4	169.	246.
Latent heat of evap (at bp), J/kg	416 000.	406 000.	393 000.	572 000.
Freezing (melting) point, deg F (1 atm)	–218.	–158.		
Freezing (melting) point, deg C (1 atm)	–138.9	–105.5		
Latent heat of fusion, Btu/lb	31.2	41.6	25.3	—
Latent heat of fusion, J/kg	72 600.	96 800.	58 800.	—
Critical temperature, deg F				88.
Critical temperature, deg C	160.	155.		31.
Critical pressure, psia	595.	610.		1 072.
Critical pressure, MN/m^2	4.10	4.20		7.4
Critical volume, ft^3/lb				
Critical volume, m^3/kg				
Flammable (yes or no)	Yes	Yes	Yes	No
Heat of combustion, Btu/ft^3	3 150.	3 150.	3 150.	—
Heat of combustion, Btu/lb	21 000.	21 000.	21 000.	—
Heat of combustion, kJ/kg	48 800.	48 800.	48 800.	—

[a] For $N{\cdot}sec/m^2$ divide by 1 000.
[b] Sublimes.

Common Name(s)	Carbon Monoxide	Chlorine	Deuterium	Ethane
Chemical Formula	CO	Cl_2	D_2	C_2H_6
Refrigerant Number	—	—	—	170
Chemical and Physical Properties				
Molecular weight	28.011	70.906	2.014	30.070
Specific gravity, air = 1	0.967	2.45	0.070	1.04
Specific volume, ft^3/lb	14.0	5.52	194.5	13.025
Specific volume, m^3/kg	0.874	0.344	12.12	0.815
Density of liquid (at atm bp), lb/ft^3		97.3		28.
Density of liquid (at atm bp), kg/m^3		1 559.		449.

Properties of Gases (continued)

Vapor pressure at 25 deg C, psia			0.756	
Vapor pressure at 25 deg C, MN/m²			0.005 2	
Viscosity (abs), lbm/ft·sec	12.1×10^{-6}	9.4×10^{-6}	8.75×10^{-6}	$64. \times 10^{-6}$
Viscosity (abs), centipoises[a]	0.018	0.014	0.013	0.095
Sound velocity in gas, m/sec	352.	215.	930.	316.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.25	0.114	1.73	0.41
Specific heat, c_p, J/kg·K	1 046.	477.	7 238.	1 715.
Specific heat ratio, c_p/c_{pv}	1.40	1.35	1.40	1.20
Gas constant *R*, ft-lb/lb·deg F	55.2	21.8	384.	51.4
Gas constant *R*, J/kg·deg C	297.	117.	2 066.	276.
Thermal conductivity, Btu/hr·ft·deg F	0.014	0.005	0.081	0.010
Thermal conductivity, W/m·deg C	0.024	0.008 7	0.140	0.017
Boiling point (sat 14.7 psia), deg F	–312.7	–29.2		–127.
Boiling point (sat 760 mm), deg C	–191.5	–34.	—	–88.3
Latent heat of evap (at bp), Btu/lb	92.8	123.7		210.
Latent heat of evap (at bp), J/kg	216 000.	288 000.		488 000.
Freezing (melting) point, deg F (1 atm)	–337.	–150.		–278.
Freezing (melting) point, deg C (1 atm)	–205.	–101.		–172.2
Latent heat of fusion, Btu/lb	12.8	41.0		41.
Latent heat of fusion, J/kg		95 400.		95 300.
Critical temperature, deg F	–220.	291.	–390.6	90.1
Critical temperature, deg C	–140.	144.	–234.8	32.2
Critical pressure, psia	507.	1 120.	241.	709.
Critical pressure, MN/m²	3.49	7.72	1.66	4.89
Critical volume, ft³/lb	0.053	0.028	0.239	0.076
Critical volume, m³/kg	0.003 3	0.001 75	0.014 9	0.004 7
Flammable (yes or no)	Yes	No		Yes
Heat of combustion, Btu/ft³	310.	—		
Heat of combustion, Btu/lb	4 340.	—		22 300.
Heat of combustion, kJ/kg	10 100.	—		51 800.

[a] For N·sec/m² divide by 1 000.

Common Name(s)	Ethyl Chloride	Ethylene (Ethene)	Fluorine
Chemical Formula	C_2H_5Cl	C_2H_4	F_2
Refrigerant Number	160	1150	—
Chemical and Physical Properties			
Molecular weight	64.515	28.054	37.996
Specific gravity, air = 1	2.23	0.969	1.31
Specific volume, ft³/lb	6.07	13.9	10.31
Specific volume, m³/kg	0.378	0.87	0.706
Density of liquid (at atm bp), lb/ft³	56.5	35.5	
Density of liquid (at atm bp), kg/m³	905.	569.	
Vapor pressure at 25 deg C, psia			
Vapor pressure at 25 deg C, MN/m²			
Viscosity (abs), lbm/ft·sec		6.72×10^{-6}	16.1×10^{-6}
Viscosity (abs), centipoises[a]		0.010	0.024
Sound velocity in gas, m/sec	204.	331.	290.
Thermal and Thermodynamic Properties			
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.27	0.37	0.198
Specific heat, c_p, J/kg·K	1 130.	1 548.	828.
Specific heat ratio, c_p/c_p	1.13	1.24	1.35
Gas constant *R*, ft-lb/lb·deg F	24.0	55.1	40.7
Gas constant *R*, J/kg·deg C	129.	296.	219.

Properties of Gases (continued)

Thermal conductivity, Btu/hr·ft·deg F		0.010	0.016
Thermal conductivity, W/m·deg C		0.017	0.028
Boiling point (sat 14.7 psia), deg F	54.	–155.	–306.4
Boiling point (sat 760 mm), deg C	12.2	–103.8	–188.
Latent heat of evap (at bp), Btu/lb	166.	208.	74.
Latent heat of evap (at bp), J/kg	386 000.	484 000.	172 000.
Freezing (melting) point, deg F (1 atm)	–218.	–272.	–364.
Freezing (melting) point, deg C (1 atm)	–138.9	–169.	–220.
Latent heat of fusion, Btu/lb	29.3	51.5	11.
Latent heat of fusion, J/kg	68 100.	120 000.	25 600.
Critical temperature, deg F	368.6	49.	–200
Critical temperature, deg C	187.	9.5	–129.
Critical pressure, psia	764.	741.	810.
Critical pressure, MN/m^2	5.27	5.11	5.58
Critical volume, ft^3/lb	0.049	0.073	
Critical volume, m^3/kg	0.003 06	0.004 6	
Flammable (yes or no)	No	Yes	
Heat of combustion, Btu/ft^3	—	1 480.	
Heat of combustion, Btu/lb	—	20 600.	
Heat of combustion, kJ/kg	—	47 800.	

[a] For $N·sec/m^2$ divide by 1 000.

Common Name(s)	Fluorocarbons			
Chemical Formula	CCl_3F	CCl_2F_2	$CClF_3$	$CBrF_3$
Refrigerant Number	11	12	13	13B1
Chemical and Physical Properties				
Molecular weight	137.37	120.91	104.46	148.91
Specific gravity, air = 1	4.74	4.17	3.61	5.14
Specific volume, ft^3/lb	2.74	3.12	3.58	2.50
Specific volume, m^3/kg	0.171	0.195	0.224	0.975
Density of liquid (at atm bp), lb/ft^3	92.1	93.0	95.0	124.4
Density of liquid (at atm bp), kg/m^3	1 475.	1 490.	1 522.	1 993.
Vapor pressure at 25 deg C, psia		94.51	516.	234.8
Vapor pressure at 25 deg C, MN/m^2		0.652	3.56	1.619
Viscosity (abs), lbm/ft·sec	7.39×10^{-6}	8.74×10^{-6}		
Viscosity (abs), centipoises[a]	0.011	0.013		
Sound velocity in gas, m/sec				
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.14	0.146	0.154	
Specific heat, c_p, J/kg·K	586.	611.	644.	
Specific heat ratio, c_p/c_{pv}	1.14	1.14	1.145	
Gas constant R, ft-lb/lb·deg F				
Gas constant R, J/kg·deg C				
Thermal conductivity, Btu/hr·ft·deg F	0.005	0.006		
Thermal conductivity, W/m·deg C	0.008 7	0.010 4		
Boiling point (sat 14.7 psia), deg F	74.9	–21.8	–114.6	–72
Boiling point (sat 760 mm), deg C	23.8	–29.9	–81.4	–57.8
Latent heat of evap (at bp), Btu/lb	77.5	71.1	63.0	51.1
Latent heat of evap (at bp), J/kg	180 000.	165 000.	147 000.	119 000.
Freezing (melting) point, deg F (1 atm)	–168.	–252.	–294.	–270.
Freezing (melting) point, deg C (1 atm)	–111.	–157.8	–181.1	–167.8
Latent heat of fusion, Btu/lb				
Latent heat of fusion, J/kg				

Properties of Gases (continued)

Critical temperature, deg F	388.4	233.	83.9	152.
Critical temperature, deg C	198.	111.7	28.8	66.7
Critical pressure, psia	635.	582.	559.	573.
Critical pressure, MN/m^2	4.38	4.01	3.85	3.95
Critical volume, ft^3/lb	0.028 9	0.287	0.027 7	0.021 5
Critical volume, m^3/kg	0.001 80	0.018	0.001 73	0.001 34
Flammable (yes or no)	No	No	No	No
Heat of combustion, Btu/ft^3	—	—	—	—
Heat of combustion, Btu/lb	—	—	—	—
Heat of combustion, kJ/kg	—	—	—	—

[a] For $N \cdot sec/m^2$ divide by 1 000.

Common Name(s)	Fluorocarbons			
Chemical Formula	CF_4	$CHCl_2F$	$CHClF_2$	$C_2Cl_2F_4$
Refrigerant Number	14	21	22	114
Chemical and Physical Properties				
Molecular weight	88.00	102.92	86.468	170.92
Specific gravity, air = 1	3.04	3.55	2.99	5.90
Specific volume, ft^3/lb	4.34	3.7	4.35	2.6
Specific volume, m^3/kg	0.271	0.231	0.271	0.162
Density of liquid (at atm bp), lb/ft^3	102.0	87.7	88.2	94.8
Density of liquid (at atm bp), kg/m^3	1 634.	1 405.	1 413.	1 519.
Vapor pressure at 25 deg C, psia		26.4	151.4	30.9
Vapor pressure at 25 deg C, MN/m^2		0.182	1.044	0.213
Viscosity (abs), lbm/ft·sec		8.06×10^{-6}	8.74×10^{-6}	8.06×10^{-6}
Viscosity (abs), centipoises[a]		0.012	0.013	0.012
Sound velocity in gas, m/sec				
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC		0.139	0.157	0.158
Specific heat, c_p, J/kg·K		582.	657.	661.
Specific heat ratio, c_p/c_{pv}		1.18	1.185	1.09
Gas constant R, ft-lb/lb·deg F				
Gas constant R, J/kg·deg C				
Thermal conductivity, Btu/hr·ft·deg F			0.007	0.006
Thermal conductivity, W/m·deg C			0.012	0.010
Boiling point (sat 14.7 psia), deg F	–198.2	48.1	–41.3	38.4
Boiling point (sat 760 mm), deg C	–127.9	9.0	–40.7	3.55
Latent heat of evap (at bp), Btu/lb	58.5	104.1	100.4	58.4
Latent heat of evap (at bp), J/kg	136 000.	242 000.	234 000.	136 000.
Freezing (melting) point, deg F (1 atm)	–299.	–211.	–256.	–137.
Freezing (melting) point, deg C (1 atm)	–183.8	–135.	–160.	–93.8
Latent heat of fusion, Btu/lb	2.53			
Latent heat of fusion, J/kg	5 880			
Critical temperature, deg F	–49.9	353.3	204.8	294.
Critical temperature, deg C	–45.5	178.5	96.5	
Critical pressure, psia	610.	750.	715.	475.
Critical pressure, MN/m^2	4.21	5.17	4.93	3.28
Critical volume, ft^3/lb	0.025	0.030 7	0.030 5	0.027 5
Critical volume, m^3/kg	0.001 6	0.001 91	0.001 90	0.001 71
Flammable (yes or no)	No	No	No	No
Heat of combustion, Btu/ft^3	—	—	—	—
Heat of combustion, Btu/lb	—	—	—	—
Heat of combustion, kJ/kg	—	—	—	—

[a] For $N \cdot sec/m^2$ divide by 1 000.

Properties of Gases (continued)

Common Name(s)	Fluorocarbons			Helium
Chemical Formula	C_2ClF_5	$C_2H_3ClF_2$	$C_2H_4F_2$	He
Refrigerant Number	115	142b	152a	704
Chemical and Physical Properties				
Molecular weight	154.47	100.50	66.05	4.002 6
Specific gravity, air = 1	5.33	3.47	2.28	0.138
Specific volume, ft³/lb	2.44	3.7	5.9	97.86
Specific volume, m³/kg	0.152	0.231	0.368	6.11
Density of liquid (at atm bp), lb/ft³	96.5	74.6	62.8	7.80
Density of liquid (at atm bp), kg/m³	1 546.	1 195.	1 006.	125.
Vapor pressure at 25 deg C, psia	132.1	49.1	86.8	
Vapor pressure at 25 deg C, MN/m²	0.911	0.338 5	0.596	
Viscosity (abs), lbm/ft·sec				13.4×10^{-6}
Viscosity (abs), centipoises[a]				0.02
Sound velocity in gas, m/sec				1 015.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.161			1.24
Specific heat, c_p, J/kg·K	674.			5 188.
Specific heat ratio, c_p/c_{pv}	1.091			1.66
Gas constant R, ft-lb/lb·deg F				386.
Gas constant R, J/kg·deg C				2 077.
Thermal conductivity, Btu/hr·ft·deg F				0.086
Thermal conductivity, W/m·deg C				0.149
Boiling point (sat 14.7 psia), deg F	–38.0	14.	–13.	–452.
Boiling point (sat 760 mm), deg C	–38.9	–10.0	–25.0	4.22 K
Latent heat of evap (at bp), Btu/lb	53.4	92.5	137.1	10.0
Latent heat of evap (at bp), J/kg	124 000.	215 000.	319 000.	23 300.
Freezing (melting) point, deg F (1 atm)	–149.			[b]
Freezing (melting) point, deg C (1 atm)	–100.6			—
Latent heat of fusion, Btu/lb				
Latent heat of fusion, J/kg				
Critical temperature, deg F	176.		387.	–450.3
Critical temperature, deg C				5.2 K
Critical pressure, psia	457.6			33.22
Critical pressure, MN/m²	3.155			
Critical volume, ft³/lb	0.026 1			0.231
Critical volume, m³/kg	0.001 63			0.014 4
Flammable (yes or no)	No	No	No	No
Heat of combustion, Btu/ft³	—	—	—	—
Heat of combustion, Btu/lb	—	—	—	—
Heat of combustion, kJ/kg	—	—	—	—

[a] For N·sec/m² divide by 1 000.

[b] Helium cannot be solidified at atmospheric pressure.

Common Name(s)	Hydrogen	Hydrogen Chloride	Hydrogen Sulfide	Krypton
Chemical Formula	H_2	HCl	H_2S	Kr
Refrigerant Number	702	—	—	—
Chemical and Physical Properties				
Molecular weight	2.016	36.461	34.076	83.80
Specific gravity, air = 1	0.070	1.26	1.18	2.89
Specific volume, ft³/lb	194.	10.74	11.5	4.67
Specific volume, m³/kg	12.1	0.670	0.093 0	0.291
Density of liquid (at atm bp), lb/ft³	4.43	74.4	62.	150.6
Density of liquid (at atm bp), kg/m³	71.0	1 192.	993.	2 413.

Properties of Gases (continued)

Vapor pressure at 25 deg C, psia				
Vapor pressure at 25 deg C, MN/m^2				
Viscosity (abs), lbm/ft Viscosity (abs), lbm/ft× 10^{-6}	6.05×10^{-6}	10.1×10^{-6}	8.74×10^{-6}	16.8×10^{-6}
Viscosity (abs), centipoises[a]	0.009	0.015	0.013	0.025
Sound velocity in gas, m/sec	1 315.	310.	302.	223.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	3.42	0.194	0.23	0.059
Specific heat, c_p, J/kg·K	14 310.	812.	962.	247.
Specific heat ratio, c_p/c_{pv}	1.405	1.39	1.33	1.68
Gas constant R, ft-lb/lb·deg F	767.	42.4	45.3	18.4
Gas constant R, J/kg·deg C	4 126.	228.	244.	99.0
Thermal conductivity, Btu/hr·ft·deg F	0.105	0.008	0.008	0.005 4
Thermal conductivity, W/m·deg C	0.018 2	0.014	0.014	0.009 3
Boiling point (sat 14.7 psia), deg F	–423.	–121.	–76.	–244.
Boiling point (sat 760 mm), deg C	20.4 K	–85.	–60.	–153.
Latent heat of evap (at bp), Btu/lb	192.	190.5	234.	46.4
Latent heat of evap (at bp), J/kg	447 000.	443 000.	544 000.	108 000.
Freezing (melting) point, deg F (1 atm)	–434.6	–169.6	–119.2	–272.
Freezing (melting) point, deg C (1 atm)	–259.1	–112.	–84.	–169.
Latent heat of fusion, Btu/lb	25.0	23.4	30.2	4.7
Latent heat of fusion, J/kg	58 000.	54 400.	70 200.	10 900.
Critical temperature, deg F	–399.8	124.	213.	
Critical temperature, deg C	–240.0	51.2	100.4	–63.8
Critical pressure, psia	189.	1 201.	1 309.	800.
Critical pressure, MN/m^2	1.30	8.28	9.02	5.52
Critical volume, ft^3/lb	0.53	0.038	0.046	0.017 7
Critical volume, m^3/kg	0.033	0.002 4	0.002 9	0.001 1
Flammable (yes or no)	Yes	No	Yes	No
Heat of combustion, Btu/ft^3	320.	—	700.	—
Heat of combustion, Btu/lb	62 050.	—	8 000.	—
Heat of combustion, kJ/kg	144 000.	—	18 600.	—

[a] For $N{\cdot}sec/m^2$ divide by 1 000.

Common Name(s)	Methane	Methyl Chloride	Neon	Nitric Oxcide
Chemical Formula	CH_4	CH_3Cl	NE	NO
Refrigerant Number	50	40	720	—
Chemical and Physical Properties				
Molecular weight	16,044	50,488	20.179	30.006
Specific gravity, air = 1	0.554	1.74	0.697	1.04
Specific volume, ft^3/lb	24.2	7.4	19.41	13.05
Specific volume, m^3/kg	1.51	0.462	1.211	0.814
Density of liquid (at atm bp), lb/ft^3	26.3	62.7	75.35	
Density of liquid (at atm bp), kg/m^3	421.	1 004.	1 207.	
Vapor pressure at 25 deg C, psia		82.2		
Vapor pressure at 25 deg C, MN/m^2		0.567		
Viscosity (abs), lbm/ft·sec	7.39×10^{-6}	7.39×10^{-6}	21.5×10^{-6}	12.8×10^{-6}
Viscosity (abs), centipoises[a]	0.011	0.011	0.032	0.019
Sound velocity in gas, m/sec	446.	251.	454.	341.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.54	0.20	0.246	0.235
Specific heat, c_p, J/kg·K	2 260.	837.	1 030.	983.
Specific heat ratio, c_p/c_{pv}	1.31	1.28	1.64	1.40
Gas constant R, ft-lb/lb·deg F	96.	30.6	76.6	51.5
Gas constant R, J/kg·deg C	518.	165.	412.	277.

Properties of Gases (continued)

Thermal conductivity, Btu/hr·ft·deg F	0.02	0.006	0.028	0.015
Thermal conductivity, W/m·deg C	0.035	0.010	0.048	0.026
Boiling point (sat 14.7 psia), deg F	–259.	–10.7	–410.9	–240.
Boiling point (sat 760 mm), deg C	–434.2	–23.7	–246.	–151.5
Latent heat of evap (at bp), Btu/lb	219.2	184.1	37.	
Latent heat of evap (at bp), J/kg	510 000.	428 000.	86 100.	
Freezing (melting) point, deg F (1 atm)	–296.6	–144.	–415.6	–258.
Freezing (melting) point, deg C (1 atm)	–182.6	–97.8	–248.7	–161.
Latent heat of fusion, Btu/lb	14.	56.	6.8	32.9
Latent heat of fusion, J/kg	32 600.	130 000.	15 800.	76 500.
Critical temperature, deg F	–116.	289.4	–379.8	–136.
Critical temperature, deg C	–82.3	143.	–228.8	–93.3
Critical pressure, psia	673.	968.	396.	945.
Critical pressure, MN/m²	4.64	6.67	2.73	6.52
Critical volume, ft³/lb	0.099	0.043	0.033	0.033 2
Critical volume, m³/kg	0.006 2	0.002 7	0.002 0	0.002 07
Flammable (yes or no)	Yes	Yes	No	No
Heat of combustion, Btu/ft³	985.		—	—
Heat of combustion, Btu/lb	2 290.		—	—
Heat of combustion, kJ/kg				—

[a] For N·sec/m² divide by 1 000.

Common Name(s)	Nitrogen	Nitrous Oxide	Oxygen	Ozone
Chemical Formula	N_2	N_2O	O_2	O_3
Refrigerant Number	728	744A	732	—
Chemical and Physical Properties				
Molecular weight	28.013 4	44.012	31.998 8	47.998
Specific gravity, air = 1	0.967	1.52	1.105	1.66
Specific volume, ft³/lb	13.98	8.90	12.24	8.16
Specific volume, m³/kg	0.872	0.555	0.764	0.509
Density of liquid (at atm bp), lb/ft³	50.46	76.6	71.27	
Density of liquid (at atm bp), kg/m³	808.4	1 227.	1 142.	
Vapor pressure at 25 deg C, psia				
Vapor pressure at 25 deg C, MN/m²				
Viscosity (abs), lbm/ft·sec	12.1×10^{-6}	10.1×10^{-6}	13.4×10^{-6}	8.74×10^{-6}
Viscosity (abs), centipoises[a]	0.018	0.015	0.020	0.013
Sound velocity in gas, m/sec	353.	268.	329.	
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.249	0.21	0.220	0.196
Specific heat, c_p, J/kg·K	1040.	879.	920.	820.
Specific heat ratio, c_p/c_{pv}	1.40	1.31	1.40	
Gas constant R, ft-lb/lb·deg F	55.2	35.1	48.3	32.2
Gas constant R, J/kg·deg C	297.	189.	260.	173.
Thermal conductivity, Btu/hr·ft·deg F	0.015	0.010	0.015	0.019
Thermal conductivity, W/m·deg C	0.026	0.017	0.026	0.033
Boiling point (sat 14.7 psia), deg F	–320.4	–127.3	–297.3	–170.
Boiling point (sat 760 mm), deg C	–195.8	–88.5	–182.97	–112.
Latent heat of evap (at bp), Btu/lb	85.5	161.8	91.7	
Latent heat of evap (at bp), J/kg	199 000.	376 000.	213 000.	
Freezing (melting) point, deg F (1 atm)	–346.	–131.5	361.1	–315.5
Freezing (melting) point, deg C (1 atm)	–210.	–90.8	–218.4	–193.
Latent heat of fusion, Btu/lb	11.1	63.9	5.9	97.2
Latent heat of fusion, J/kg	25 800.	149 000.	13 700.	226 000.
Critical temperature, deg F	–232.6	97.7	–181.5	16.
Critical temperature, deg C	–147.	36.5	–118.6	–9.

Properties of Gases (continued)

Critical pressure, psia	493.	1 052.	726.	800.
Critical pressure, MN/m^2	3.40	7.25	5.01	5.52
Critical volume, ft^3/lb	0.051	0.036	0.040	0.029 8
Critical volume, m^3/kg	0.003 18	0.002 2	0.002 5	0.001 86
Flammable (yes or no)	No	No	No	No
Heat of combustion, Btu/ft^3	—	—	—	—
Heat of combustion, Btu/lb	—	—	—	—
Heat of combustion, kJ/kg	—	—	—	—

[a] For $N{\cdot}sec/m^2$ divide by 1 000.

Common Name(s)	Propane	Propylene (Propene)	Sulfur Dioxide	Xenon
Chemical Formula	C_3H_8	C_3H_6	SO_2	Xe
Refrigerant Number	290	1 270	764	—
Chemical and Physical Properties				
Molecular weight	44.097	42.08	64.06	131.30
Specific gravity, air = 1	1.52	1.45	2.21	4.53
Specific volume, ft^3/lb	8.84	9.3	6.11	2.98
Specific volume, m^3/kg	0.552	0.58		
Density of liquid (at atm bp), lb/ft^3	36.2	37.5	42.8	190.8
Density of liquid (at atm bp), kg/m^3	580.	601.	585.	3 060.
Vapor pressure at 25 deg C, psia	135.7	166.4	56.6	
Vapor pressure at 25 deg C, MN/m^2	0.936	1.147	0.390	
Viscosity (abs), lbm/ft·sec	53.8×10^{-6}	57.1×10^{-6}	8.74×10^{-6}	15.5×10^{-6}
Viscosity (abs), centipoises[a]	0.080	0.085	0.013	0.023
Sound velocity in gas, m/sec	253.	261.	220.	177.
Thermal and Thermodynamic Properties				
Specific heat, c_p, Btu/b·deg F or cal/g·degC	0.39	0.36	0.11	0.115
Specific heat, c_p, J/kg·K	1 630.	1 506.	460.	481.
Specific heat ratio, c_p/c_{pv}	1.2	1.16	1.29	1.67
Gas constant R, ft-lb/lb·deg F	35.0	36.7	24.1	11.8
Gas constant R, J/kg·deg C	188.	197.	130.	63.5
Thermal conductivity, Btu/hr·ft·deg F	0.010	0.010	0.006	0.003
Thermal conductivity, W/m·deg C	0.017	0.017	0.010	0.005 2
Boiling point (sat 14.7 psia), deg F	–44.	–54.	14.0	–162.5
Boiling point (sat 760 mm), deg C	–42.2	–48.3	–10.	–108.
Latent heat of evap (at bp), Btu/lb	184.	188.2	155.5	41.4
Latent heat of evap (at bp), J/kg	428 000.	438 000.	362 000.	96 000.
Freezing (melting) point, deg F (1 atm)	–309.8	–301.	–104.	–220.
Freezing (melting) point, deg C (1 atm)	–189.9	–185.	–75.5	–140.
Latent heat of fusion, Btu/lb	19.1		58.0	10.
Latent heat of fusion, J/kg	44 400.		135 000.	23 300.
Critical temperature, deg F	205.	197.	315.5	61.9
Critical temperature, deg C	96.	91.7	157.6	16.6
Critical pressure, psia	618.	668.	1 141.	852.
Critical pressure, MN/m^2	4.26	4.61	7.87	5.87
Critical volume, ft^3/lb	0.073	0.069	0.03	0.014 5
Critical volume, m^3/kg	0.004 5	0.004 3	0.001 9	0.000 90
Flammable (yes or no)	Yes	Yes		Yes
Heat of combustion, Btu/ft^3	2 450.	2 310.	—	—
Heat of combustion, Btu/lb	21 660.	21 500.	—	—
Heat of combustion, kJ/kg	50 340.	50 000.	—	—

[a] For $N{\cdot}sec/m^2$ divide by 1 000.

From Bolz, R.E. and Tuve, G.L., Gases and vapors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 38–49.

Typical Composition, Properties, and Uses of Common Materials
For MN/m^2 multiply strength in thousands of psi by 6.895.

No.	Material	Nominal Composition	Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
	FERROUS ALLOYS							

Ferrous alloys comprise the largest volume of metal alloys used in engineering. The actual range of mechanical properties in any particular grade of alloy steel depends on the particular history and heat treatment. The steels listed in this table are intended to give some idea of the range of properties readily obtainable. Many hundreds of steels are available. Cost is frequently an important criterion in the choice of material; in general the greater the percentage of alloying elements present in the alloy, the greater will be the cost.

No.	Material	Nominal Composition	Form and Condition	Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
	Iron							
1	Ingot iron (Included for comparison)	Fe 99.9	Hot-rolled	29	45	26	90	
			Annealed	19	38	45	67	
	Plain Carbon Steels							
2	AISI-SAE 1020	C 0.20 Mn 0.45	Hot-rolled	30	55	25	111	Bolts, crankshafts, gears, connecting rods; easily weldable
		Si 0.25 Fe bal.	Hardened (water-quenched, 1000˚F-tempered)	62	90	25	179	
3	AISI 1025	C 0.25 Fe bal.	Bar stock					
		Mn 0.45	Hot-rolled	32	58	25	116	
			Cold-drawn	54	64	15	126	
4	AISI-SAE 1035	C 0.35 Mn 0.75	Hot-rolled	39	72	18	143	Medium-strength, engineering steel
			Cold-rolled	67	80	12	163	
5	AISI-SAE 1045	C 0.45 Fe bal.	Bar stock					
		Mn 0.75	Annealed	73	80	12	170	
			Hot-rolled	45	82	16	163	
			Cold-drawn	77	91	12	179	
6	AISI-SAE 1078	C 0.78 Fe bal.	Bar stock					
		Mn 0.45	Hot-rolled; spheroidized	55	100	12	207	
			Annealed	72	94	10	192	
7	AISI-SAE 1095	C 0.95 Fe bal.						
		Mn 0.40						

8	AISI-SAE 1120	C	0.2	Mn	0.8	Cold-drawn	58	69	—	137	Free-cutting, leaded,
		S	0.1								resulphurized steel;
											high-speed, automatic
											machining
	Alloy Steels										
9	ASTM A202/56	C	0.17	Mn	1.2	Stress-relieved	45	75	18	—	Low alloy; boilers,
		Cr	0.5	Si	0.75						pressure vessels
10	AISI 4140	C	0.40	Si	0.3	Fully-tempered	95	108	22	240	High strength; gears,
		Cr	1.0	Mo	0.2	Optimum properties	132	150	18	—	shafts
		Mn	0.9								
11	12% Manganese steel	12%	Mn	C		Tempered 600°F	200	220	10	—	Machine tool parts;
						Rolled and heat-treated stock	44	160	40	170	wear, abrasion-
											resistant
12	VASCO 300	Ni	18.5	Ti	0.6	Solution treatment 1 500°F;	110	150	18	—	Very high strength,
		Co	9.0	C	0.03	aged 900·F					maraging, good
		Mo	4.8								machining properties
											in annealed state
13	TI (AISI)	W	18.0	V	1.0	Quenched; tempered				R(c)	High speed tool steel,
		Cr	4.0	C	0.7						cutting tools, punches,
											etc.
14	M2 (AISI)	W	6.5	Mo	5.0	Quenched; tempered				65–66	M-grade, cheaper,
		Cr	4.0	C	0.85						tougher
		V	2.0								
15	Stainless steel type 304	Ni	9.0	C	0.08	Annealed; cold-rolled	35–160	85–185	60	160–400	General purpose,
		Cr	19.0		max				8		weldable;
											nonmagnetic
											austenitic steel
16	Stainless steel type 316	Cr	18.0	C	0.10	Annealed	30–120	90–150	50	165	For severe corrosive
		Ni	11.0		max				8		media, under stress;
		Mo	2.5	Fe bal.							nonmagnetic
											austenitic steel
17	Stainless steel type 431	Cr	16.0	Si	1.0	Annealed	85	120	25	250	Heat-treated stainless
		Ni	2.0	C	0.20	Heat-treated	150	195	20	400	steel, with good
		Mn	1.0	Fe bal.							mechanical strength;
											magnetic
18	Stainless steel 17–4 PH	Cr	17.0	Co	0.35	Annealed	110	150	10	363	Precipitation
		Ni	4.0	C	0.07						hardening; heat-
		Cu	4.0	Fe bal.							resisting type; retains
											strength up to approx.
											600°F

Mechanical Properties of Metals and Alloys (continued)

No.	Material	Nominal Composition	Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Typical Mechanical Properties: Tensile Strength 1000 lb/sq in.	Typical Mechanical Properties: Elongation in 2 in., %	Typical Mechanical Properties: Harness, Brinell	Comments
	CAST IRONS AND CAST STEELS							
	Cast Irons							
19	Cast gray iron ASTM A48–48, Class 25	C 34, Si 1.8 Mn 0.5	Cast (as cast)	—	25 min	0.5 max	180	Engine blocks, fly-wheels, gears, machine-tool bases
20	White	C 3.4, Si 0.7 Mn 0.6	Cast	—	25	0	450	
21	Malleable iron ASTM A47	C 2.5, Si 1.0 Mn 0.55 max	Cast (annealed)	33	52	12	130	Automotives, axle bearings, track wheels, crankshafts
22	Ductile or nodular iron (Mg-containing) ASTM A339 ASTM A395	C 3.4, P 0.1 max Mn 0.40 Ni 1%, Mg 0.06 Si 2.5, Fe bal.	Cast Cast (as cast) Cast (quenched, tempered)	53 68 108	70 90 135	18 7 5	170 235 310	Heavy-duty machines, gears, cams, crankshafts
23	Ni-hard type 2	C 2.7, Si 0.6 Mn 0.5, Ni 4.5 Cr 2.0, Fe bal.	Sand-cast Chill-cast (tempered)	— —	55 75	— —	550 625	Strength, with heat- and corrosion-resistance
24	Ni-resist type 2	C 3.0, Si 2.0 Mn 1.0, Ni 20.0 Cr 2.5, Fe bal.	Cast (as cast)	—	27	2	140	
	Cast Steels							
25	ASTM A27-62 (60-30)	C 0.3, Mn 0.6 Si 0.8, Ni 0.5 Cr 0.4, Mo 0.2		30	60	24	—	Low alloy, medium strength, general application
26	ASTM A148-60 (105-85)			85	105	17	—	High strength; structural application

These alloys are used where large and/or intricate-shaped articles are required or where overall dimensional tolerances are not critical. Thus the article can be produced with the fabrication and machining costs held to a minimum. Except for a few heat-treatable cast steels, this class of alloys does not demonstrate high-strength qualities.

27	Cast 12 Cr alloy (CA-15)	C 0.15 max	Mn 1.00 max	Air-cooled from 1800°F; tempered at 600°F	150	200	7	390	Stainless, corrosion-resistant to mildly corrosive alkalis and acids
		Si 150 max	Cr 11.5–14	Air-cooled from 1800°F; tempered at 1400°F	75	100	30	185	
		Ni 1.00 max	Fe bal.						
28	Cast 29-9 alloy (CE-30) ASTM–A296 63T	C 0.30 max	Min 1.50 max	As cast	60	95	15	170	Greater corrosion resistance, especially for oxidizing condition
		Si 2.00 max	Cr 26–30						
		Ni 8–11	Fe bal.						
29	Cast 28-7 alloy (HD) ASTM–A97-63T	C 0.50 max	Mn 1.50 max	As cast	48	85	16	190	Heat-resistant
		Si 2.00	Cr 26–30						
		Ni 4–7	Fe bal.						

SUPER ALLOYS

The advent of engineering applications requiring high temperature and high strength, as in jet engines and rocket motors, has lead to the development of a range of alloys collectively called super alloys. These alloys require excellent resistance to oxidation together with strength at high temperatures, typically 1800°F in existing engines. These alloys are continually being modified to develop better specific properties, and therefore entries in this group of alloys should be considered "fluid". Both wrought and casting-type alloys are represented. As the high temperature properties of cast materials improve, these alloys become more attractive, since great dimensional precision is now attainable in investment castings.

	Nickel Base								
30	Hastelloy X	Co 1.5 max	Fe 18.5	Wrought sheet	52	113.2	43	194	
			Mo 9.0	Mill-annealed	—	67	17	172	
		Cr 22.0	C 0.15 max (wrought)	As investment cast	46.5	—	—	—	
		W 0.6							
		C 0.20 max (cast)	Ni bal.						
31	Hastelloy C	Cr 16.0	Fe 6.0	Sand-cast (annealed)	50	78	5	199	
				Rolled (annealed)	71	130	45	204	
		W 4.0	C 0.15 max	Investment cast	50	80	10	215	
		Mo 17.0	Ni bal.						
32	Inconel 712C	Ni (+Co) bal.	Cr 13.0	Investment cast	102	120	6	—	
			Cb 2.0						
		Mo 4.5	Ti 0.6						
		Al 6.0							
33	In 100	C 18.0	Cr 10.0	Cast					
		Mo 3.0	Ti 4.7						
		Al 55.0	Co 15.0						
		V 1.0							

Mechanical Properties of Metals and Alloys (continued)

				Typical Mechanical Properties				
No.	Material	Nominal Composition	Form and Condition	Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
34	Taz 8	C 125.0 Cr 6.0 Mo 4.0 Al 6.0 W 4.0 Zr 1.0 Ta 8.0 V 2.5	Cast					
35	Nimonic 90	Ni (+Co) 57.00 C 0.05 Fe 0.45 Mn 0.50 Si 0.20 S 0.007 Cr 20.55 Cu 0.05 Ti 2.60 Al 1.65 Co 16.90	Annealed; wrought	90	155	—	260	General elevated temperature applications
36	Inconel X	Ni (+Co) 72.85 C 0.04 Fe Mn 0.65 Si 6.80 S 0.007 Cr 0.30 Cu 0.05 Ti 15.0 Al 0.75 2.50 Cb (+Ta) 0.85	Annealed	50	115	50	150	
			Annealed; age hardened	115	175	25	300	
37	Waspaloy	C 0.08 Cr 19.5 Mo 4.3 Ti 3.0 Co 13.5	Cold-rolled	270	275	8	Rc 51	
38	Rene 41	C 0.09 Cr 19.0 Mo 10.0 Ti 3.1 Al 1.5 Co 11.0	Wrought	100	145	—	—	
39	Udimet 700	C 0.08 Cr 15.0 Mo 5.0 Ti 3.5 Al 4.3 Co 18.5	Cold-rolled	280	285	6	Rc 53	
40	T.D. Nickel	Ni 97.5 ThO_2 2.4	Extended and cold-worked	85	100	13	—	High temperature; jet engine parts

	Cobalt Base										
41	Haynes Stellite alloy 25 (L605)	C	0.15 max	Cr	20.0	Wrought sheet; mill annealed	63	140	60	244	
				W	15.0						
		Ni	10.0	Co bal.							
		Mn	1.5	Mo	5.5						
42	Haynes Stellite alloy 21 AMS 5385 (cast)	C	0.25	Co. bal.		As investment cast	82	103	8	313 max	For castings
		Ni	2.5								
		Cr	28.5								

ALUMINUM ALLOYS

Although the strength of aluminum alloys is in general less than that attainable in ferrous alloys or copper-base alloys, their major advantage lies in their high strength-to-weight ratio due to the low density of aluminum. Aluminum alloys have good corrosion resistance for most applications except in alkaline solutions.

43	3003 ASTM B221	Cu	0.12	Al bal.		Annealed-O	6	16	40	28	Good formability, weldable, medium strength; chemical equipment
		Mn	1.2			Cold-rolled-H14	21	22	16	40	
						Cold-rolled-H18	27	29	10	55	
44	2017 ASTM B221	Mn	0.5	Mg	0.5	Annealed-O	10	26	22	45	High strength; structural parts, aircraft, heavy forgings
		Cu	4.0	Al bal.		Heat-treated-T4	40	62	22	105	
45	2024 ASTM B211	Cu	4.5	Mg	1.5	Heat-treated-T4	47	68	19	120	
		Mn	0.6	Al bal.							
46	5052 ASTM B211	Cr	0.25	Al bal.		Annealed-O	13	28	30	47	Medium strength, good fatigue properties; street-light standards
		Mg	2.5			Cold-rolled and stabilized H34	31	38	14	68	
47	ASTM B208					Cold-rolled and stabilized H38	37	42	8	77	
48	7075 ASTM B211	Cu	1.6	Mg	2.5	Annealed-O	15	33	17	60	High strength, good corrosion resistance
		Cr	0.3	Al bal.		Heat-treated and artificially aged-T6	73	83	11	150	
		Zn	5.6								
49	380 ASTM SC84B	Si	9.0	Al bal.		Die-cast	24	48	3	—	General purpose die casting
		Cu	3.5								
50	195 ASTM C4A	Si	0.8	Al bal.		Sand-cast; heat-treated-T4	16	32	8.5	60	Structural elements, aircraft, and machines
		Cu	4.5			Sand-cast; heat-treated and artificially aged-T6	24	36	5	75	
51	214 ASTM G4A	Mg	3.8	Al bal.		Sand-cast-F	12	25	9	50	Chemical equipment, marine hardware, architectural
52	220 ASTM G10A	Mg	10.0	Al bal.		Sand-cast; heat-treated-T4	26	48	16	75	Strength with shock resistance; aircraft

No.	Material	Nominal Composition				Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments

COPPER ALLOYS

Because of their corrosion resistance and the fact that copper alloys have been used for many thousands of years, the number of copper alloys available is second only to the ferrous alloys. In general copper alloys do not have the high-strength qualities of the ferrous alloys, while their density is comparable. The cost per strength-weight ratio is high; however, they have the advantage of ease of joining by soldering, which is not shared by other metals that have reasonable corrosion resistance.

No.	Material	Nominal Composition				Form and Condition	Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
53	Copper	Cu	99.9 plus			Annealed	10	32	45	42	Bus-bars, switches, architectural, roofing, screens
	ASTM B152					Cold-drawn	40	45	15	90	
	ASTM B124, B133					Cold-rolled	40	46	5	100	
	ASTM B1, B2, B3										
54	Gilding metal	Cu	95.0	Zn	5.0	Cold-rolled	50	56	5	114	Coinage, ammunition
	ASTM B36										
55	Cartridge 70-30 brass	Cu	70.0	Zn	30.0	Cold-rolled	63	76	8	155	Good cold-working poperties; radiator covers, hardware, electrical
	ASTM B14										
	ASTM B19										
	ASTM B36										
	ASTM B134										
	ASTM B135										
56	Phosphor bronze 10%	Cu	90.0	Sn	10.0	Spring temper	—	122	4	241	Good spring qualities, high-fatigue strength
	ASTM B103	P	0.25								
	ASTM B130										
	ASTM B159										
57	Yellow brass (high brass)	Cu	65.0	Zn	35.0	Annealed	18	48	60	55	Good corrosion resistance; plumbing, architectural
	ASTM B36					Cold-drawn	55	70	15	115	
	ASTM B134					Cold-rolled (HT)	60	74	10	180	
	ASTM B135										
58	Manganese bronze	Cu	58.5	Zn	39.2	Annealed	30	60	30	95	Forgings
	ASTM B138	Fe	1.0	Sn	1.0	Cold-drawn	50	80	20	180	
		Mn	0.3								
59	Naval brass	Cu	60.0	Zn	39.25	Annealed	22	56	40	90	Condensor tubing; high resistance to salt-water corrosion
	ASTM B21	Sn	0.75			Cold-drawn	40	65	35	150	
60	Muntz metal	Cu	60.0	Zn	40.0	Annealed	20	54	45	80	Condensor tubes; valve stress
	ASTM B111										

61	Aluminum bronze	Cu	92.0	Al	8.0	Annealed	25	70	60	80	
	ASTM B169, alloy A					Hard	65	105	7	210	
	ASTM B124										
	ASTM B150										
62	Beryllium copper 25	Be	1.9	Cu bal.		Annealed, solution-treated	32	70	45	B60	Bellows, fuse clips,
	ASTM B194	Co or Ni								(Rockwell)	electrical relay parts,
	ASTM B197		0.25			Cold-rolled	104	110	5	B81	valves, pumps
	ASTM B196					Cold-rolled	70	190	3	C40	
63	Free-cutting brass	Cu	62.0	Zn	35.5	Cold-drawn	44	70	18	B80	Screws, nuts, gears, keys
		Pb	2.5							(Rockwell)	
64	Nickel silver 18%	Cu	65.0	Zn	17.0	Annealed	25	58	40	70	Hardware, optical
	Alloy A (wrought)	Ni	18.0			Cold-rolled	70	85	4	170	goods, camera parts
	ASTM B122, No. 2					Cold-drawn wire	—	105	—	—	
65	Nickel silver 13% (cast)	Ni	12.5	Pb	9.0	Cast	18	35	15	55	Ornamental castings,
	10A	Sn	2.0	Cu bal.							plumbing; good
	ASTM B149, No. 10A	Zn	20.0								machining qualities
66	Cupronickel 10%	Cu	88.35	Ni	10.0	Annealed	22	44	45	—	Condensor, salt-water
	ASTM B111	Fe	1.25	Mn	0.4	Cold-drawn tube	57	60	15	—	piping
	ASTM B171										
67	Cupronickel	Cu	70.0	Ni	30.0	Wrought					Heat-exchanger process equipment, valves
68	Red brass (cast)	Cu	85.0	Zn	5.0	As-cast	17	35	25	60	
	ASTM B30, No. 4A	Pb	5.0	Sn	5.0						
69	Silicon bronze	Si	4.0	Fe	2.0	Castings					Cheaper substitute for
	ASTM B30, alloy 12A	Zn	4.0	Al	1.0						tin bronze
		Mn	1.0								
70	Tin bronze	Sn	8%	Zn	4.0	Castings					Bearings, high-pressure
	ASTM B30, alloy B										brushings, pump impellers
71	Navy bronze					Cast					

TIN AND LEAD-BASE ALLOYS

Major uses for these alloys are as "white"-metal bearing alloys, extruded cable sheathing, and solders. Tin forms the basis of pewter used for culinary applications.

72	Lead-base Babbitt	Pb	85.0	Sn	5.0	Chill east	—	10	5	19	Bearings, light loads
	ASTM B23, alloy 19	Sb	10.0	As	0.6						and low speeds
		Cu	0.5								
73	Arsenical-lead Babbitt	Pb	83.0	Sn	1.0	Chill cast	—	10.3	2	20	Bearings, high loads
	ASTM B23, alloy 15	Sb	16.0	As	1.1						and speeds, diesel
		Cu	0.6								engines, steel mills

No.	Material	Nominal Composition	Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
74	Chemical lead	Pb 99.9 Cu 0.06 Bi 0.005 max	Rolled 95%	1.9	2.5	50	5	
75	Antimonial lead (hard lead)	Pb 94.0 Sb 6.0	Chill east	—	6.8	22	(500 kg)	Good corrosion resistance and strength
			Rolled 95%	—	4.1	47	9	
76	Calcium lead	Pb 99.9 Ca 0.025 Cu 0.10	Extruded and aged	—	4.5	25	—	Cable sheathing, creep-resistant pipe
77	Tin Babbitt alloy ASTM B23–61, grade 1	Sb 4.5 Sn bal. Cu 4.5	Chill east	—	9.3	2	17	General bearings and die casting
78	Tin die-casting alloy ASTM B102–52	Sb 13.0 Sn bal. Cu 5.0	Die-cast	—	10	1	29	Die-casting alloy
79	Pewter	Sn 91.0 Sb 7.0 Cu 2.0	Rolled sheet, annealed	—	8.6	40	9.5	Ornamental and household items
80	Solder 50-50	Sn 50.0 Pb 50.0	Cast	4.8	6.1	60	14	General-purpose solder
81	Solder	Sn 20.0 Pb 80.0	Cast	3.6	5.8	16	11	Coating and joining, filling seams on automobile bodies

MAGNESIUM ALLOYS

Because of their low density these alloys are attractive for use where weight is at a premium. The major drawback to the use of these alloys is their ability to ignite in air (this can be a problem in machining); they are also costly. Magnesium alloys are used in both the wrought and die-cast forms, the latter being the most frequently used form.

No.	Material	Nominal Composition	Form and Condition	Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
82	Magnesium alloy AZ31B	Zn 1.0 Mn 0.20 min Al 3.0 Mg. bal.	Rolled-plate (strain-hardened, then partially annealed)	24	37	18	—	Structural applications of medium strength
			Rolled-sheet (strain-hardened, then partially annealed)	32	42	15	73	
			Annealed	22	37	21	56	
			Extruded	28	38	14	—	
83	Magnesium alloy AZ80A	Zn 0.5 Mn 0.15 min Al 8.5 Mg. bal.	Extruded	36	49	11	60	General extruded and forged products
			Extruded (age-hardened)	39	53	6	82	
			Forged (age-hardened)	34	50	6	72	

84	Magnesium alloy AZ92A	Zn	2.0	Mn	0.10	Sand-cast (as cast)	14	24	6	50	
		Al	9.0		min	Sand-cast (solution heat-treated)	14	40	12	55	
				Mg bal.							
						Sand-cast (solution heat-treated and aged)	19	40	5	83	
						Sand-cast (age-hardened)	16	30	18	—	
						Sand-cast and tempered	22	40	3	81	Pressure-tight sand and permanent mold castings; high UTS and good yield strength
85	Magnesium alloy ZK60A	Zn	5.7	Mg bal.		Extruded	43	52	12	82	
		Zr	0.55								
86	Magnesium alloy AZ91A and AZl91B	Zn	0.6	Mn	0.13	Die-cast (as cast)	22	33	3	67	General die-casting applications
		Al	9.0		min						
				Mg bal.							
						BERYLLIUM					
87	Beryllium						27	33	1–3	—	Windows, X-ray tubes
						Hot-pressed	38	51			
						Cross-rolled	40	60	10–40	—	Moderator- and reflector-cladding nuclear reactors; heat-shield and structural-member missiles
							60	90			

NICKEL ALLOYS

Nickel and its alloys are expensive and used mainly either for their high-corrosion resistance in many environments or for high-temperature and strength applications. (See Super Alloys, above.)

88	Nickel (cast)	Ni	95.6	Cu	0.5	As cast	25	57	22	110	Good corrosion-resistance applications
		Fe	0.5	Mn	0.8						
		Si	1.5	C	0.8						
89	K Monel	Ni(+ Co)	65.25	C	0.15	Annealed	45	100	40	155	High strength and corrosion resistance; aircraft parts, valve stems, pumps
				Fe	1.00	Annealed, age-hardened	100	155	25	270	
		Mn	0.60	Si	0.15	Spring	140	150	5	300	
		S	0.005	Al	2.75	Spring, age-hardened	160	185	10	335	
		Cu	29.60								
		Ti	0.45								

No.	Material	Nominal Composition		Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
90	A nickel	Ni(+ Co)	C 0.06	Annealed	20	70	40	100	Chemical industry for
	ASTM B160	99.40	Fe 0.15	Hot-rolled	25	75	40	110	resistance to strong
	ASTM B161	Mn 0.25	Si 0.05	Cold-drawn	70	95	25	170	alkalis, plating nickel
	ASTM B162	S 0.005		Cold-rolled	95	105	5	210	
		Cu 0.05							
91	Duranickel	Ni(+ Co)	C 0.15	Annealed	45	100	40	160	High strength and
		93.90	Fe 0.15	Annealed, age-hardened	125	170	25	330	corrosion resistance;
		Mn 0.25	Si 0.55	Spring	—	175	5	320	pump rods, shafts,
		S 0.005	Al 4.50	Spring, age-hardened	—	205	10	370	springs
		Cu 0.05							
		Ti 0.45							
92	Cupronickel 55–45	Cu 55.0	Ni 45.0	Annealed	30	60	45	—	Electrical-resistance
	(Constantan)			Cold-drawn	50	65	30	—	wire; low temperature
				Cold-rolled	65	85	20	—	coefficient, high
									resistivity
93	Nichrome	Ni 80.0	Cr 20.0						Heating elements for
									furnaces
94	"S" Monel	Ni 60.0	Cu 29.0	Sand-casting	80–115	110–145	2	270–350	High-strength casting
		Fe 2.50	Mn 1.5						alloy; good bearing
		max	max						properties for valve
		Si 4.0	Al 0.5						seats
			max						

TITANIUM ALLOYS

The main application for these alloys is in the aerospace industry. Because of the low density and high strength of titanium alloys, they present excellent strength-to-weight ratios.

No.	Material	Nominal Composition		Form and Condition	Typical Mechanical Properties: Yield Strength (0.2% offset), 1000 lb/sq in.	Tensile Strength 1000 lb/sq in.	Elongation in 2 in., %	Harness, Brinell	Comments
95	Commercial titanium	Ti 99.4		Annealed at 1100 to 1350°F	70	80	20	—	Moderate strength,
	ASTM B265-58T			(593 to 732°C)					excellent fabricability;
									chemical industry
									pipes
96	Titanium alloy			Water-quenched from 1750°F	160	170	13	—	High-temperature
	ASTM B265-58T-5			(954°C); aged at 1000°F					strength needed in
	Ti-6-Al-4V			(538°C) for 2 hr					gas-turbine
									compressor blades

97	Titanium alloy Ti-4 Al-4Mn					Water-quenched from 1450°C); aged at 900°F (482°C) for 8 hr	170	185	13	—	Aircraft forgings and compressor parts
98	Ti-Mn alloy ASTM B265-58T-7	Fe Mn	0.5 7.0–8.0	Ti bal.		Sheet	140	150	18	—	Good formability, moderate high-temperature strength; aircraft skin

ZINC ALLOYS

A major use for these alloys is for low-cost die-cast products, such as household fixtures, automotive, parts, and trim.

99	Zinc ASTM B69	Cd Pb	0.35 0.08	Zn bal.		Hot-rolled	—	19.5	65	38	Battery cans, grommets, lithographer's sheet
100	Zilloy–15	Cu Mg	1.00 0.010	Zn lbal.		Hot-rolled Cold-rolled	— —	29 36	20 25	61 80	Corrugated roofs, articles with maximum stiffness
101	Zilloy–40	Cu	1.00	Zn bal.		Hot-rolled Cold-rolled	— —	24 31	50 40	52 60	Weatherstrip, spun articles
102	Zamac–5 ASTM 25	Zn (99.99% pure reminder) Mg	 0.03–0.08	Al Cu	3.5–4.3 0.75–1.25	Die-cast	—	47.6	7	91	Die casting for automobile parts, padlocks; used also for die material.

ZIRCONIUM ALLOYS

These alloys have good corrosion resistance but are easily oxidized at elevated temperatures in air: The major application is for use in nuclear reactors.

103	Zirconium, commercial	O2 Hf	0.07 1.90	C Zr bal.	0.15	Annealed	40	65	27	B80 (Rockwell)	
104	Zircaloy 2	Hf Fe Sn	0.02 0.15 1.46	Ni Other Zr bal.	0.05 0.25	Annealed	50	75	22	B90 (Rockwell)	Nuclear power-reactor cores at elevated temperatures

From Bolz, R.E. and Tuve, G.L., Solids — Metals, in *CRC Handbook of Tables for Applied Engineering Science,* CRC Press, Boca Raton, FL, 1973, pp. 103–115.

Thermal Properties of Pure Metals—Metric Units

	At Atmospheric Pressure								Liquid Metal			
				At 100°K		At 25°C (77°F)				Vapor Pressure		
										10^{-3} atm	10^{-6} atm	10^{-9} atm
Metal	Melting Point, °C	Boiling Point, °C	Latent Heat of Fusion cal/g	Thermal Conductivity, watts/cm°C	Specific Heat, cal/g°C	Specific Heat, cal/g°C	Coeff. of Linear Expansion ($\times 10^6$) $(°C)^{-1}$	Thermal Conductivity, watts/cm°C	Specific Heat (Liquid) at 2000°K, calg°C	Boiling Point Temperature, °K		
Aluminum	660.	2441.	95	3.00*	.115	0.215	25	2.37	.26	1,782	1,333	1,063
Antimony	630.	1440.	38.5	—	.040	.050	9	.185	.062	1,007	741	612
Beryllium	1285.	2475.	324.	—	.049	.436	12	2.18	.78	1,793	1,347	1,085
Bismuth	271.4	1660.	12.4	—	.026	.030	13	.084	.036	1,155	851	677
Cadmium	321.	767.	13.2	1.03	.047	.055	30	.93	.063	655	486	388
Chromium	1860.	2670.	79	1.58	.046	.110	6	.91	.224	1,992	1,530	1,247
Cobalt	1495.	2925.	66	—	.057	.10	12	.69	.164	2,167	1,652	1,345
Copper	1084.	2575.	49	4.83*	.061	.092	16.6	3.98	.118	1,862	1,391	1,120
Gold	1063.	2800.	15	3.45*	.026	.031	14.2	3.15	.0355	2,023	1,510	1,211
Iridium	2450.	4390.	33	—	.022	.031	6	1.47	.0434	3,253	2,515	2,062
Iron	1536.	2870.	65	1.32*	.052	.108	12	.803	.197	2,093	1,594	1,297
Lead	327.5	1750.	5.5	0.396	.028	.031	29	.346	.033	1,230	889	698
Magnesium	650.	1090.	88.0	1.69	.016	.243	25	1.59	.32	857	638	509
Manganese	1244.	2060.	64	—	.064	.114	22	—	.20	1,495	1,131	913
Mercury	−38.86	356.55	2.7	—	.029	.033	—	.0839	—	393	287	227
Molybdenum	2620.	4651.	69	1.79	.033	.060	5	1.4	.089	3,344	2,558	2,079

Nickel	1453.	2800.	71	1.58	.055	.106	13	.899	.175	2,156	1,646	1,343
Niobium (Columbium)	2470.	4740.	68	0.552	.045	.064	7	.52	.083	3,523	2,721	2,232
Osmium	3025.	4225.	34	—	—	.031	5	.61	.039	—	—	—
Platinum	1770.	3825.	24	0.79*	.024	.032	9	.73	.043	2,817	2,155	1,757
Plutonium	640.	3230.	3	—	.019	.032	54	.08	.041	2,200	1,596	1,252
Potassium	63.3	760.	14.5	—	.150	.180	83	.99	—	606	430	335
Rhodium	1965.	3700.	50	—	—	.058	8	1.50	.092	—	—	—
Selenium	217.	700.	16	—	—	.077	37	.005	—	—	—	—
Silicon	1411.	3280.	430	—	.062	.17	3	.835	.217	2,340	1,749	1,427
Silver	961.	2212.	26.5	4.50*	.045	.057	19	4.27	.068	1,582	1,179	952
Sodium	97.83	884.	27	—	.234	.293	70	1.34	—	701	504	394
Tantalum	2980.	5365.	41	0.592	.026	.034	6.5	.54	.040	3,959	3,052	2,495
Thorium	1750.	4800.	17	—	.024	.03	12	.41	.047	3,251	2,407	1,919
Tin	232.	2600.	14.1	0.85	.039	.054	20	.64	.058	1,857	1,366	1,080
Titanium	1670.	3290.	100	0.312	.072	.125	8.5	.2	.188	2,405	1,827	1,484
Tungsten	3400.	5550.	46	2.35*	.021	.032	4.5	1.78	.040	4,139	3,228	2,656
Uranium	1132.	4240.	12	—	.022	.028	13.4	.25	.048	2,861	2,128	1,699
Vanadium	1900.	3400.	98	—	.061	.116	8	.60	.207	2,525	1,948	1,591
Zinc	419.5	910.	27	1.32	.063	.093	35	1.15	—	752	559	449

* Temperatures of maximum thermal conductivity (conductivity values in watts/cm°C): Aluminum 13°K, cond. = 71.5; copper 10°K, cond. = 196; gold 10°K, cond. = 28.2; iron 20°K, cond. = 9.97; platinum 8°K, cond. = 12.9; silver 7°K, cond. = 193; tungsten 8°K, cond. = 85.3.

From Bolz, R.E. and Tuve, G.L., Solids — Metals, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Boca Raton, FL, 1973, p. 119.

Terms and Units for Radiant Energy and Illumination

Note: Any of the following quantities may be restricted to a narrow wavelength interval by addition of the world *spectral*.

Measure of	Terms in Use	Meaning or Definition	Usual Units
Quantity	Radiant energy Luminous energy	Total quantity of radiant energy	Erg, joule, calorie, kilowatt-hour, Btu
Rate	Radiant flux Luminous flux	Time rate of flow of radiant energy (power)	Erg/sec, watt, Bu/hr, lumen
Intensity	Radiant intensity Luminous intensity	Radiant flux per unit solid angle (point source)	Watts per steradian, candela* = lumens/steradian
Density at surface	Radiant emittance Radiant excitance Irradiance Illumination Illuminance (Emittance)	Density of radiant flux incident upon (or emitted from) a surface	Watts/sq cm, foot-candle = lumens/sq ft, lux = lumens/sq m, phot = lumens sq cm, Btu/hr × sq ft
Density of beam (at surface)	Radiance	Unit intensity normal to the beam per unit of projected area in that direction	$\text{Watts/sr} \times \text{sq cm}, \dfrac{\text{Btu/hr}}{\text{sr} \times \text{sq ft}}$
Effectiveness (radiating)	Emissivity (Absorptivity)	Ratio of radiant emittance (or absorptance) to that of a perfect blackbody	Dimensionless
Brightness	Luminance	Photometric brightness per unit area	Candela/sq ft, stilb = cd/sq cm, nit = cd/sq m, foot-lambert = cd/π sq ft, lambert = cd/π sq cm, apostilb = cd/π sq m

* The candela (cd) was formerly called "candlepower." (One international candle will illuminate a sphere at one foot distance with 4π lumens, or one sq ft of the sphere with one lumen.)

From Bolz, R.E. and Tuve, G.L., Electromagnetic radiation, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 205.

Blackbody Radiation

Temperature		Wavelength of Maximum Intensity,	Maximum Normal Intensity†		Total Maximum Hemispherical Radiation†	
°K	°R	Microns, μ	W/cm² μ	Btu/hr ft² μ	W/cm²	Btu/hr ft²
10	18	290	1.290×10^{-10}	4.092×10^{-7}	5.679×10^{-8}	1.801×10^{-4}
50	90	58.0	4.030×10^{-7}	1.278×10^{-3}	3.549×10^{-5}	1.126×10^{-1}
100	180	29.0	1.290×10^{-5}	4.092×10^{-2}	5.679×10^{-4}	1.801
200	360	14.5	4.127×10^{-4}	1.309	9.086×10^{-3}	2.882×10
300	540	9.66	3.134×10^{-3}	9.941	4.600×10^{-2}	1.459×10^{2}
350	630	8.28	6.774×10^{-3}	2.149×10	8.522×10^{-2}	2.703×10^{2}
400	720	7.25	1.321×10^{-2}	4.190×10	1.454×10^{-1}	4.612×10^{2}
450	810	6.44	2.380×10^{-2}	7.550×10	2.328×10^{-1}	7.385×10^{2}
500	900	5.80	4.030×10^{-2}	1.278×10^{2}	3.549×10^{-1}	1.126×10^{3}
550	990	5.27	6.484×10^{-2}	2.057×10^{2}	5.207×10^{-1}	1.652×10^{3}
600	1080	4.83	1.003×10^{-1}	3.181×10^{2}	7.360×10^{-1}	2.335×10^{3}
700	1260	4.14	2.168×10^{-1}	6.877×10^{2}	1.364	4.327×10^{3}
800	1440	3.63	4.226×10^{-1}	1.341×10^{3}	2.326	7.378×10^{3}
900	1620	3.22	7.616×10^{-1}	2.417×10^{3}	3.726	1.182×10^{4}
1000	1800	2.90	1.290	4.092×10^{3}	5.679	1.801×10^{4}
1200	2160	2.42	3.209	1.018×10^{4}	1.178×10	3.737×10^{4}
1400	2520	2.07	6.936	2.200×10^{4}	2.181×10	6.918×10^{4}
1600	2880	1.81	1.352×10	4.289×10^{4}	3.722×10	1.181×10^{5}
1800	3240	1.61	2.437×10	7.730×10^{4}	5.961×10	1.891×10^{5}
2000	3600	1.49	4.127×10	1.309×10^{5}	9.096×10	2.882×10^{5}
2500	4500	1.156	1.260×10^{2}	3.997×10^{5}	2.218×10^{2}	7.036×10^{5}
3000	5400	0.966	3.134×10^{2}	9.941×10^{5}	4.600×10^{2}	1.459×10^{6}
4000	7200	0.725	1.321×10^{3}	4.190×10^{6}	1.454×10^{3}	4.612×10^{6}
6000	10,800	0.483	1.003×10^{4}	3.181×10^{7}	7.360×10^{3}	2.335×10^{7}
8000	14,400	0.363	4.226×10^{4}	1.340×10^{8}	2.326×10^{4}	7.378×10^{7}

Notes: One half of the blackbody radiation lies on either side of the wavelength computed from $\lambda = 4107/T$, where λ is in microns and T is °K.

1 cm = 0.3937 in. = 10,000 microns = 10^8 Angstrom units. To convert Btu/hr·ft² to W/m², multiply by 3.1525.

† Zero temperature receiver; no reradiation.

From Bolz, R.E. and Tuve, G.L., Electromagnetic radiation, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 207.

Thermodynamic Nonflow Process Equations

For a System Containing a Perfect Gas with Constant Specific Heats
$_1Q_2 = {}_1W_2 + (U_2 - U_1)$

Process	Constant Pressure	Constant Volume	Isothermal	Isentropic S = constant	Polytropic pV^n = constant
p, V, T $pV = mRT$‡	p = constant $p = p_1 = p_2$	V = constant $V = V_1 = V_2$	T = constant $T = T_1 = T_2$	$p_1V_1^{k} = p_2V_2^{k}$ = constant	$p_1V_1^{n} = p_2V_2^{n}$ = constant
$pu = RT$‡	$\frac{V}{T} = constant$ $\frac{V_1}{T_1} = \frac{V_2}{T_2}$	$\frac{P}{T} = constant$ $\frac{P_1}{T_1} = \frac{P_2}{T_2}$	pV = constant $p_1V_1 = p_2V_2$	$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}$ $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1}$	$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$ $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{n-1}$
Specific heat $c = {}_1Q_2/(T_2 - T_1)$‡	$c_p = \left(\frac{kR‡}{k-1}\right)$	$c_p = \left(\frac{R‡}{k-1}\right)$	∞	0	$c_n = c_v\frac{(k-n)}{(1-n)}$
Exponent n for polytropic process	0	∞	1	$k = \left(\frac{c_p†}{c_v}\right)$	n = any value
Quantity of heat $_1Q_2 = \int TdS$ positive for heat into system from surroundings	$mc_p(T_2 - T_1)$ $c_p(p/R)(V_2 - V_1)$ $\frac{k}{k-1}\,{}_1W_2$ $H_2 - H_1$	$mc_v(T_2 - T_1)$ $\frac{V(p_2 - p_1)}{k-1}$ $U_2 - U_1$	$p_1V_1\ln(V_2/V_1)$ $p_1V_1\ln(p_1/p_2)$ $mRT\ln(V_2/V_1)$ $mRT\ln(p_1/p_2)$ $_1Q_2 = {}_1W_2$	Adiabatic 0	$mc_n(T_2 - T_1)$
Quantity of work $_1W_2 = \int pdV$ positive for work done by system on surroundings	$p(V_2/V_1)$ $mR(T_2 - T_1)$ $\frac{k-1}{k}\,{}_1Q_2$	0		$\frac{p_2V_2 - p_1V_1}{1-k}$ $mc_v(T_1 - T_2)$ $U_1 - U_2$ $\frac{p_1V_1}{k-1}\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right]$	$\frac{p_2V_2 - p_1V_1}{1-n}$ $\frac{mR(T_2 - T_1)}{1-n}$ $\frac{p_1V_1}{n-1}\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]$
Internal energy $U_2 - U_1$ $dU = mc_u dT$‡	$mc_v(T_2 - T_1)$† $\frac{p(V_2 - V_1)‡}{(k-1)}$	$mc_v(T_2 - T_1)$† $\frac{V(p_2 - p_1)‡}{(k-1)}$	0	$mc_v(T_2 - T_1)$† $\frac{p_2V_2 - p_1V_1‡}{(k-1)}$	$mc_v(T_2 - T_1)$† $\frac{p_2V_2 - p_1V_1‡}{(k-1)}$
Enthalpy $H_2 - H_1$ d $H = mc_p dT$‡	$mc_p(T_2 - T_1)$† $\frac{kp(V_2 - V_1)‡}{(k-1)}$	$mc_p(T_2 - T_1)$† $\frac{kV(p_2 - p_1)‡}{(k-1)}$	0	$mc_p(T_2 - T_1)$† $\frac{k(p_2V_2 - p_1V_1)‡}{(k-1)}$	$mc_p(T_2 - T_1)$† $\frac{k(p_2V_2 - p_1V_1)‡}{(k-1)}$
Entropy $S_2 - S_1$ $ds = \frac{dH}{T} - \frac{Vdp†}{T}$ $= \frac{dU}{TG} + \frac{pdV†}{T}$	$mc_p\ln(T_2/T_1)$ $mc_p\ln(V_2/V_1)$	$mc_\upsilon\ln(T_2/T_1)$ $mc_\upsilon\ln(p_2/p_1)$	$mR\ln(V_2/V_1)$ $mR\ln(p_1/p_2)$	0	$mc_n\ln(T_2/T_1)$

† Valid in general, not only for process or processes listed, and not only for perfect gases.
‡ Valid in general for perfect gases, not only for process listed.
From Bolz, R.E. and Tuve, G.L., Thermodynamics, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 473.

Thermodynamic Cycle Efficiencies

Symbols: $\eta_c = (T_H - T_L)/T_H$ = Carnot cycle efficiency, present

$\eta_o = 1 - r^{1-k}$ = Otto cycle efficiency, percent

$\eta_D = 1 - r^{1-k}\,\dfrac{(S^k - 1)}{k(S-1)}$ = Diesel cycle efficiency, percent

$\eta_\beta = 1 - r_p^{(1-k)/k}$ = Brayton (or Joule) cycle efficiency, percent

where T_H = absolute temperature of energy reservoir from which energy is drawn

T_L = absolute temperatue of energy reservoir to which energy is rejected

r = compression ratio for Otto and Diesel cycles, maximum volume/minimum volume

r_p = pressure ratio for Brayton (or Joule) cycle, maximum pressure/minimum pressure

S = cut-off ratio for Diesel cycle, volume at end of constant pressure heat addition process/minimum volume

$k = C_p/C_v$ = specific heat ratio

Otto Cycle Efficiency, η_o, Percent

$k = \frac{c_p}{c_v}$	Compression Ratio, r												
	5	6	7	8	9	10	11	12	13	14	15	20	50
1.30	38.3	41.6	44.2	46.4	48.3	49.9	51.3	52.5	53.7	54.7	55.6	59.3	69.1
1.35	43.1	46.6	49.4	51.7	53.7	55.3	56.8	58.1	59.3	60.3	61.2	65.0	74.6
1.40	47.5	51.2	54.1	56.5	58.5	60.2	61.7	63.0	64.2	65.2	66.1	69.8	79.1
5/3	65.8	69.7	72.7	75.0	76.9	78.5	79.8	80.9	81.9	82.7	83.6	86.4	92.6

Diesel Cycle Efficiency, η_D, Percent

$k = \frac{c_p}{c_v}$	Cut-Off Ratio, S	Compression Ratio, r											
		5	10	14	15	16	17	18	19	20	25	30	50
1.30	2	30.6	43.6	49.0	50.1	51.0	51.9	52.7	53.5	54.2	57.2	59.5	65.2
1.30	3	24.7	38.9	44.7	45.9	46.9	47.9	48.8	49.6	50.3	53.6	56.0	62.3
1.30	4	19.9	34.9	41.2	42.4	43.5	44.5	45.5	46.3	47.2	50.6	53.2	59.9
1.30	5	15.7	31.5	38.1	39.4	40.5	41.6	42.6	43.5	44.4	48.0	50.8	57.8
1.35	2	34.7	48.7	54.4	55.5	56.5	57.4	58.3	59.1	59.8	62.8	65.1	70.8
1.35	3	28.2	43.6	49.9	51.1	52.2	53.2	54.1	55.0	55.8	59.1	61.6	67.9
1.35	4	22.7	39.4	46.1	47.4	48.6	49.6	50.6	51.6	52.4	56.0	58.7	65.5
1.35	5	18.0	35.6	42.8	44.1	45.4	46.5	47.6	48.6	49.5	53.3	56.2	63.3
1.40	2	38.5	53.4	59.3	60.4	61.4	62.3	63.2	63.9	64.7	67.7	70.0	75.5
1.40	3	31.4	48.0	54.6	55.8	56.9	58.0	58.9	59.8	60.6	64.0	66.5	72.7
1.40	4	25.4	43.5	50.6	51.9	53.2	54.3	55.3	56.3	57.2	60.8	63.6	70.3
1.40	5	20.1	39.4	47.1	48.5	49.8	51.0	52.1	53.2	54.1	58.0	61.0	68.2

Brayton (or Joule) Cycle Efficiency, η_β, Percent

$k = \frac{c_p}{c_v}$	Pressure Ratio, r_p												
	3	4	5	6	7	8	9	10	12	14	15	20	50
1.30	22.4	27.4	31.0	33.9	36.2	38.1	39.8	41.2	43.6	45.5	46.5	49.9	59.5
1.35	24.8	30.2	34.1	37.2	39.6	41.7	43.4	45.0	47.5	49.4	50.4	54.0	63.7
1.40	27.0	32.7	36.9	40.1	42.7	44.8	46.6	48.2	50.8	52.9	53.9	57.5	67.3
5/3	35.6	42.6	47.5	51.2	54.1	56.5	58.5	60.2	63.0	65.1	66.1	69.8	79.1

Carnot Cycle Efficiency, η_c, Percent[a]

T_L		T_H, K(R)										
K	R	200 (360)	300 (540)	400 (720)	500 (900)	1000 (1800)	1500 (2700)	2000 (3600)	2500 (4500)	3000 (5400)	4000 (7200)	5000 (9000)
100	180	50.0	66.7	75.0	80.0	90.0	93.3	95.0	96.0	96.7	97.5	98.0
200	360	0	33.3	50.0	60.0	80.0	86.7	90.0	92.0	93.3	95.0	96.0
300	540	—	0	25.0	40.0	70.0	80.0	85.0	88.0	90.0	92.5	94.0

Thermodynamic Cycle Efficiencies (continued)

T_L		T_H, K(R)										
K	R	200 (360)	300 (540)	400 (720)	500 (900)	1000 (1800)	1500 (2700)	2000 (3600)	2500 (4500)	3000 (5400)	4000 (7200)	5000 (9000)
400	720	—	—	0	20.0	60.0	73.3	80.0	84.0	86.7	90.0	92.0
500	900	—	—	—	0	50.0	66.7	75.0	80.0	83.3	87.5	90.0
1000	1800	—	—	—	—	0	33.3	50.0	40.0	66.7	75.0	80.0

[a] These values are valid for any reversible cycle with heat addition at T_H and heat rejection at T_L. Stirling and Ericcson cycles with ideal regeneration meet this requirement, for example.

Otto Cycle. The Otto cycle consists of isentropic compression, constant-volume heat addition, isentropic expansion, and constant-volume heat rejection.
Diesel Cycle. The Diesel cycle consists of isentropic compression, constant-pressure heat addition, isentropic expansion, and constant-volume heat rejection.
Brayton Cycle. The Brayton, or Joule, cycle consists of isentropic compression, constant-pressure heat addition, isentropic expansion, and constant-pressure heat rejection.
Carnot Cycle. The Carnot cycle consists of isothermal compression (with heat rejection), isentropic compression, isothermal expansion (with heat addition), and isentropic expansion.
Stirling Cycle. The Stirling cycle consists of isothermal compression (with heat rejection), constant-volume heat addition, isothermal expansion (with heat addition), and constant-volume heat rejection.
Ericcson Cycle. The Ericcson cycle consists of isothermal compression (with heat rejection), constant-pressure heat addition, isothermal expansion (with heat addition), and constant-pressure heat rejection.

From Bolz, R.E. and Tuve, G.L., Thermodynamics, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 477–478.

Heat of Fusion of Some Inorganic Compounds*

For heat of fusion in J/kg, multiply values in cal/g by 4184. For heat of fusion in J/mol, multiply values in cal/g·mol (= cal/mol) by 4.184. For melting point in K, add 273.15 to values in ˚C. Values in parentheses are of uncertain reliability.

Compound	Formula	Melting Point, ˚C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Actinium^{227}	Ac	1050 ± 50	(20.)	(11.0)	(3400)
Aluminum	Al	658.5	170.	94.5	2250
Aluminum bromide	Al_2Br_6	87.4	18.2	10.1	5420
Aluminum chloride	Al_2Cl_6	192.4	114.	63.6	19600
Aluminum iodide	Al_2I_6	190.9	17.6	9.8	7960
Aluminum oxide	Al_2O_3	2045.0	(461.)	(256.0)	(26000)
Antimony	Sb	630	70.4	39.1	4770
Antimony pentachloride	$SbCl_5$	4.0	14.4	8.0	2400
Antimony tribromide	$SbBr_3$	96.8	17.5	9.7	3510
Antimony trichloride	$SbCl_3$	73.3	23.9	13.3	3030
Antimony trioxide	Sb_4O_6	655.0	(83.3)	(46.3)	(26990)
Antimony trisulfide	Sb_4S_6	546.0	59.4	33.0	11200
Argon	Ar	–190.2	13.1	7.25	290
Arsenic	As	816.8	(39.6)	(22.0)	(6620)
Arsenic pentafluoride	AsF_5	–80.8	29.7	16.5	2800
Arsenic tribromide	$AsBr_3$	30.0	16.0	8.9	2810
Arsenic trichloride	$AsCl_3$	–16.0	23.9	13.3	2420
Arsenic trifluoride	AsF_3	–6.0	34.0	18.9	2486
Arsenic trioxide	As_4O_6	312.8	40.0	22.2	8000
Barium	Ba	725	23.9	13.3	1830
Barium bromide	$BaBr_2$	846.8	39.4	21.9	6000

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, °C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Barium chloride	$BaCl_2$	959.8	46.6	25.9	5370
Barium fluoride	BaF_2	1286.8	30.8	17.1	3000
Barium iodide	BaI_2	710.8	(31.1)	(17.3)	(6800)
Barium nitrate	$Ba(NO_3)_2$	594.8	(40.7)	(22.6)	(5900)
Barium oxide	BaO	1922.8	168.	93.2	13800
Barium phosphate	$Ba_3(PO_4)_2$	1727	55.6	30.9	18600
Barium sulfate	$BaSO_4$	1350	74.9	41.6	9700
Beryllium	Be	1278	468.	260.0	—
Beryllium bromide	$BeBr_2$	487.8	(47.9)	(26.6)	(4500)
Beryllium chloride	$BeCl_2$	404.8	(54)	(30)	(3000)
Beryllium oxide	BeO	2550.0	1223.	679.7	17000
Bismuth	Bi	271	21.6	12.0	2505
Bismuth trichloride	$BiCl_3$	223.8	14.8	8.2	2600
Bismuth trifluoride	BiF_3	726.0	(41.9)	(23.3)	(6200)
Bismuth trioxide	Bi_2O_3	815.8	26.3	14.6	6800
Boron	B	2300	(882)	(490)	(5300)
Boron tribromide	BBr_3	–48.8	(5.2)	(2.9)	(700)
Boron trichloride	BCl_3	–107.8	(7.7)	(4.3)	(500)
Boron trifluoride	BF_3	–128.0	12.6	7.0	480
Boron trioxide	B_2O_3	448.8	142.	78.9	5500
Bromine	Br_2	–7.2	29.0	16.1	2580
Bromine pentafluoride	BrF_5	–61.4	12.7	7.07	1355
Cadmium	Cd	320.8	23.2	12.9	1460
Cadmium bromide		567.8	(33.1)	(18.4)	(5000)
Cadmium chloride	$CdCl_2$	567.8	51.8	28.8	5300
Cadmium fluoride	CdF_2	1110	(64.6)	(35.9)	(5400)
Cadmium iodide	CdI_2	386.8	18.0	10.0	3660
Cadmium sulfate	$CdSO_4$	1000	41.2	22.9	4790
Calcium	Ca	851	100.	55.7	2230
Calcium bromide	$CaBr_2$	729.8	37.6	20.9	4180
Calcium carbonate	$CaCO_3$	1282	(227)	(126)	(12700)
Calcium chloride	$CaCl_2$	782	99	55	6100
Calcium fluoride	CaF_2	1382	94.5	52.5	4100
Calcium metasilicate	$CaSiO_2$	1512	208.	115.4	13400
Calcium nitrate	$Ca(NO_3)_2$	560.8	56.2	31.2	5120
Calcium oxide	CaO	2707	(393.)	(218.1)	(12240)
Calcium sulfate	$CaSO_4$	1297	88.6	49.2	6700
Carbon dioxide	CO_2	–57.6	77.8	43.2	1900.
Carbon monoxide	CO	–205	12.8	7.13	199.7
Cerium	Ce	775	27.2	15.1	2120
Cesium	Cs	28.3	6.7	3.7	500
Cesium chloride	CsCl	641.8	38.5	21.4	3600
Cesium nitrate	$CsNO_3$	406.8	29.9	16.6	3250
Chlorine	Cl_2	–103 ± 5	41.0	22.8	1531
Chromium	Cr	1890	112.	62.1	3600
Chromium (II) chloride	$CrCl_2$	814	119.	65.9	7700
Chromium (III) sequioxide	Cr_2O_3	2279	49.7	27.6	4200
Chromium trioxide	CrO_3	197	67.9	37.7	3770
Cobalt	Co	1490	112.	62.1	3640
Cobalt (II) chloride	$CoCl_2$	727	102.	56.9	7390
Copper	Cu	1083	88.2	49.0	3110
Copper (I) chloride	CuCl	429	47.5	26.4	2620
Copper (I) cyanide	$Cu_2(CN)_2$	473	(54.2)	(30.1)	(5400)
Copper (I) iodide	CuI	587	(24.5)	(13.6)	(2600)
Copper (I) oxide	Cu_2O	1230	(168.)	(93.6)	(13400)

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, °C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Copper (I) sulfide	Cu_2S	1129	62.3	34.6	5500
Copper (II) chloride	$CuCl_2$	430	44.5	24.7	4890
Copper (II) oxide	CuO	1446	63.7	35.4	2820
Cyanogen	C_2N2	–27.2	71.3	39.6	2060
Cyanogen chloride	CNCl	–5.2	65.5	36.4	2240
Deuterium oxide	D_2O	3.78	136.	75.8	1516
Dysprosium	Dy	1407	45.4	25.2	4100
Erbium	Er	1496	44.1	24.5	4100
Europium	Eu	826	29.5	16.4	2500
Europium trichloride	$EuCl_3$	622	(37.6)	(20.9)	(8000)
Fluorine	F_2	–219.6	11.5	6.4	244.0
Gadolinium	Gd	1312	42.8	23.8	3700
Gallium	Ga	29	(34.4)	19.1	1336
Germanium	Ge	959	(206.)	(114.3)	(8300)
Gold	Au	1063	(27.5)	15.3	3030
Hafnium	Hf	2214	(61.4)	(34.1)	(6000)
Holmium	Ho	1461	44.6	24.8	4100
Hydrogen	H_2	–259.25	24.8	13.8	28
Hydrogen bromide	HBr	–86.96	12.8	7.1	575.1
Hydrogen chloride	HCl	–114.3	23.4	13.0	476.0
Hydrogen fluoride	HF	–83.11	98.5	54.7	1094
Hydrogen iodide	HI	–50.91	9.7	5.4	686.3
Hydrogen nitrate	HNO_3	–47.2	17.1	9.5	601
Hydrogen oxide (water)	H_2O	0	138.	79.72	1436
Hydrogen peroxide	H_2O_2	–0.7	15.4	8.58	2920
Hydrogen selenate	H_2SeO_4	57.8	42.8	23.8	3450
Hydrogen sulfate	H_2SO_4	10.4	43.2	24.0	2360
Hydrogen sulfide	H_2S	–85.6	30.2	16.8	5683
Hydrogen sulfide, di-	H_2S_2	–89.7	49.1	27.3	1805
Hydrogen telluride	H_2Te	–49.0	23.2	12.9	1670
Indium	In	156.3	12.2	6.8	781
Iodine	I_2	112.9	25.7	14.3	3650
Iodine chloride (α)	ICl	17.1	29.5	16.4	2660
Iodine chloride (β)	ICl	13.8	23.9	13.3	2270
Iron	Fe	1530.0	115.	63.7	3560
Iron (II) chloride	$FeCl^2$	677	111.	61.5	7800
Iron (II) oxide	FeO	1380	(193.)	(107.2)	(7700)
Iron (II) sulfide	FeS	1195	102.	56.9	5000
Iron (III) chloride	Fe_2Cl_6	303.8	114.	63.2	20500
Iron carbide	Fe_3C	1226.8	123.	68.6	12330
Iron oxide	Fe_3O_4	1596	257.	142.5	33000
Iron pentacarbonyl	$Fe(CO)_2$	–21.2	29.7	16.5	3250
Lanthanum	La	920	31.3	17.4	2400
Lead	Pb	327.3	10.6	5.9	1224
Lead bromide	$PbBr_2$	487.8	21.1	11.7	4290
Lead chloride	$PbCl_2$	497.8	36.5	20.3	5650
Lead fluoride	PbF_2	823	13.7	7.6	1860
Lead iodide	Pbl2	412	32.2	17.9	5970
Lead molybdate	$PbMoO_4$	1065	(127.)	70.8	(25800)
Lead oxide	PbO	890	22.7	12.6	2820
Lead sulfate	$PbSO_4$	1087	56.9	31.6	9600
Lead sulfide	PbS	1114	31.1	17.3	4150
Lithium	Li	178.8	285.	158.5	1100
Lithium bromide	LiBr	552	60.1	33.4	2900
Lithium chloride	LiCl	614	136.	75.5	3200

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, °C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Lithium fluoride	LiF	896	(164.)	(91.1)	(2360)
Lithium hydroxide	LiOH	462	186.	103.3	2480
Lithium iodide	Lil	440	(19.1)	(10.6)	(1420)
Lithium metasilicate	Li_2SiO_3	1177	144.	80.2	7210
Lithium molybdate	Li_2MoO_4	705	43.4	24.1	4200
Lithium nitrate	$LiNO_3$	250	158.	87.8	6060
Lithium orthosilicate	Li_4SiO_4	1249	109.	60.5	7340
Lithium sulfate	Li_2SO_4	857	49.7	27.6	3040
Lithium tungstate	Li_2WO_4	742	(46.1)	(25.6)	(6700)
Lutetium	Lu	1651	47.3	26.3	4600
Magnesium	Mg	650	160.	88.9	2160
Magnesium bromide	$MgBr_2$	711	81.0	45.0	8300
Magnesium chloride	$MgCl_2$	712	149.	82.9	8100
Magnesium fluoride	MgF_2	1221	170.	94.7	5900
Magnesium oxide	MgO	2642	826.	459.0	18500
Magnesium silicate	$MgSiO_3$	1524	264.	146.4	14700
Magnesium sulfate	$MgSO_4$	1327	52.0	28.9	3500
Manganese	Mn	1220	113.	62.7	3450
Manganese (II) oxide	MnO	1784	330.	183.3	13000
Manganese dichloride	$MnCl_2$	650	105.	58.4	7340
Manganese metasilicate	$MnSiO_3$	1274	(113.)	(62.6)	(8200)
Manganese oxide	Mn_3O_4	1590	(307.)	(170.4)	(39000)
Mercury	Hg	–39	4.9	2.7	557.2
Mercury bromide	$HgBr_2$	241	19.6	10.9	3960
Mercury chloride	$HgCl_2$	276.8	27.5	15.3	4150
Mercury iodide	HgI_2	250	17.8	9.9	4500
Mercury sulfate	$HgSO_4$	850	8.6	(4.8)	(1440)
Molybdenum	Mo	2622	(123.)	(68.4)	(6600)
Molybdenum dichloride	$MoCl_2$	726.8	64.4	3.58	6000
Molybdenum hexafluoride	MoF_4	17	21.4	11.9	2500
Molybdenum trioxide	MoO_3	795	(31.1)	(17.3)	(2500)
Neodymium	Nd	1020	21.2	11.8	1700
Neon	Ne	–248.6	6.89	3.83	77.4
Nickel	Ni	1452	129.	71.5	4200
Nickel chloride	$NiCl_2$	1030	257.	142.5	18470
Nickel subsulfide	Ni_3S_2	790	46.4	25.8	5800
Niobium	Nb	2496	(124.)	(68.9)	(6500)
Niobium pentachloride	$NbCl_5$	211	55.4	30.8	8400
Niobium pentoxide	Nb_2O_5	1511	164.	91.0	24200
Nitric oxide	NO	–163.7	32.9	18.3	549.5
Nitrogen	N_2	–210	11.1	6.15	172.3
Nitrogen tetroxide	N_2O_4	–13.2	108.	60.2	5540
Nitrous oxide	N_2O	–90.9	63.9	35.5	1563
Osmium	Os	2700	(66.1)	(36.7)	(7000)
Osmium tetroxide (white)	OsO_4	41.8	16.6	9.2	2340
Osmium tetroxide (yellow)	OsO_4	55.8	27.9	15.5	4060
Oxygen	O_2	–218.8	5.9	3.3	106.3
Palladium	Pd	1555	69.5	38.6	4120
Phosphoric acid	H_3PO_4	42.3	46.4	25.8	2520
Phosphoric acid, hypo-	$H_4P_2O_6$	54.8	92.2	51.2	8300
Phosphorus acid, hypo	H_3PO_2	17.3	63.0	35.0	2310
Phosphorus acid, ortho-	H_3PO_3	73.8	67.3	37.4	3070
Phosphorus oxychloride	$POCl_3$	1.0	36.5	20.3	3110
Phosphorus pentoxide	P_4O_{10}	569.0	108.	60.1	17080
Phosphorus trioxide	P_4O_6	23.7	27.5	15.3	3360

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, °C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Phosphorus, yellow	P_4	44.1	8.6	4.8	600
Platinum	Pt	1770	43.4	24.1	4700
Potassium	K	63.4	26.3	14.6	574
Potassium borate, meta-	KBO_2	947	(124.)	(69.1)	(5600)
Potassium bromide	KBr	742	75.6	42.0	5000
Potassium carbonate	K_2CO_3	897	102.	56.4	7800
Potassium chloride	KCl	770	155.	85.9	6410
Potassium chromate	K_2CrO_4	984	64.1	35.6	6920
Potassium cyanide	KCN	623	(96.7)	(53.7)	(3500)
Potassium dichromate	$K_2Cr_2O_7$	398	53.6	29.8	8770
Potassium fluoride	KF	875	201.	111.9	6500
Potassium hydroxide	KOH	360	(63.5)	(35.3)	(1980)
Potassium iodide	KI	682	44.5	24.7	4100
Potassium nitrate	KNO_3	338	50.6	28.1	2840
Potassium peroxide	K_2O_2	490	99.5	55.3	6100
Potassium phosphate	K_3PO_4	1340	75.4	41.9	8900
Potassium pyrophosphate	$K_4P_2O_7$	1092	76.3	42.4	14000
Potassium sulfate	K_2SO_4	1074	83.5	46.4	8100
Potassium thiocyanate	KSCN	179	41.6	23.1	2250
Praseodymium	Pr	931	34.2	19.0	2700
Rhenium	Re	3167 ± 60	(76.3)	(42.4)	(7900)
Rhenium heptoxide	Re_2O_7	296	54.2	30.1	15340
Rhenium hexafluoride	ReF_6	19.0	29.9	16.6	5000
Rubidium	Rb	38.9	11.0	6.1	525
Rubidium bromide	RbBr	677	40.3	22.4	3700
Rubidium chloride	RbCl	717	65.5	36.4	4400
Rubidium fluoride	RbF	833	71.1	39.5	4130
Rubidium iodide	RbI	638	25.2	14.0	2990
Rubidium nitrate	$RbNO_3$	305	16.4	9.1	1340
Samarium	Sm	1072	31.1	17.3	2600
Scandium	Sc	1538	152.	84.4	3800
Selenium	Se	217	27.7	15.4	1220
Selenium oxychloride	$SeOCl_3$	9.8	11.0	6.1	1010
Silane, hexafluoro-	Si_2F_6	–28.6	41.2	22.9	3900
Silicon	Si	1427	607.	337.0	9470
Silicon dioxide (Cristobalite)	SiO_2	2100	63.0	35.0	2100
Silicon dioxide (Quartz)	SiO_2	1470	102.	56.7	3400
Silicon tetrachloride	$SiCl_4$	–67.7	19.4	10.8	1845
Silver	Ag	961	45.0	25.0	2700
Silver bromide	AgBr	430	20.9	11.6	2180
Silver chloride	AgCl	455	39.6	22.0	3155
Silver cyanide	AgCN	350	36.9	20.5	2750
Silver iodide	AgI	557	17.1	9.5	2250
Silver nitrate	$AgNO_3$	209	29.2	16.2	2755
Silver sulfate	Ag_2SO_4	657	(24.7)	(13.7)	(4280)
Silver sulfide	Ag_2S	841	24.3	13.5	3360
Sodium	Na	97.8	49.3	27.4	630
Sodium borate, meta-	$NaBO_2$	966	242.	134.6	8600
Sodium bromide	NaBr	747	107.	59.7	6140
Sodium carbonate	Na_2CO_3	854	119.	66.0	7000
Sodium chlorate	$NaClO_3$	255	89.5	49.7	5290
Sodium chloride	NaCl	800	222.	123.5	7220
Sodium cyanide	NaCN	562	(160.)	(88.9)	(4360)
Sodium fluoride	NaF	992	300.	166.7	7000
Sodium hydroxide	NaOH	322	90.0	50.0	2000

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, °C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Sodium iodide	NaI	662	63.2	35.1	5340
Sodium molybdate	Na_2MoO_4	687	31.5	17.5	3600
Sodium nitrate	NaNO3	310	79.6	44.2	3760
Sodium peroxide	Na_2O_2	460	135.	75.1	5860
Sodium phosphate, meta-	$NaPO_3$	988	(87.5)	(48.6)	(4960)
Sodium pyrophosphate	$Na_4P_2O_7$	970	(92.7)	(51.5)	(13700)
Sodium silicate, aluminum-	$NaAlSi_3O_8$	1107	90.2	50.1	13150
Sodium silicate, di-	$Na_2Si_2O_5$	884	83.5	46.4	8460
Sodium silicate, meta-	Na_2SiO_3	1087	152.	84.4	10300
Sodium sulfate	Na_2SO_4	884	73.8	41.0	5830
Sodium sulfide	Na_2S	920	(27.7)	15.4	(1200)
Sodium thiocyanate	NaSCN	323	98.6	54.8	4450
Sodium tungstate	Na_2WO_4	702	35.3	19.6	5800
Strontium	Sr	757	45.0	25.0	2190
Strontium bromide	$SrBr_2$	643	34.7	19.3	4780
Strontium chloride	$SrCl_2$	872	47.7	26.5	4100
Strontium fluoride	SrF_2	1400	61.2	34.0	4260
Strontium oxide	SrO	2430	290.	161.2	16700
Sulfur (monatomic)	S	119	16.6	9.2	295
Sulfur dioxide	SO_2	–73.2	58.0	32.2	2060
Sulfur trioxide (α)	SO_3	16.8	46.4	25.8	2060
Sulfur trioxide (β)	SO_3	32.3	65.0	36.1	2890
Sulfur trioxide (γ)	SO_3	62.1	142.	79.0	6310
Tantalum	Ta	2996 ± 50	(62.3) 74.7	34.6–41.5	(7500)
Tantalum pentachloride	$TaCl_5$	206.8	45.2	25.1	9000
Tantalum pentoxide	Ta_2O_5	1877	195.	108.6	48000
Tellurium	Te	453	45.5	25.3	3230
Terbium	Tb	1356	44.3	24.6	3900
Thallium	Tl	302.4	9.0	5.0	1030
Thallium bromide, mono-	TlBr	460	37.8	21.0	5990
Thallium carbonate	Tl_2CO_3	273	17.1	9.5	4400
Thallium chloride, mono-	TlCl	427	31.9	17.7	4260
Thallium iodide, mono-	TlI	440	16.9	9.4	3125
Thallium nitrate	$TlNO_3$	207	15.5	8.6	2290
Thallium sulfate	Tl_2SO_4	632	19.6	10.9	5500
Thallium sulfide	Tl_2S	449	12.2	6.8	3000
Thorium	Th	1845	(<35.6)	(<19.8)	(<4600)
Thorium chloride	$ThCl_4$	765	111.	61.6	22500
Thorium dioxide	ThO_2	2952	1984.	1102.0	291100
Thulium	Tm	1545	46.8	26.0	4400
Tin	Sn	231.7	25.9	14.4	1720
Tin bromide, di-	$SnBr_2$	231.8	(11.0)	(6.1)	(1720)
Tin bromide, tetra-	$SnBr_4$	29.8	12.2	6.8	3000
Tin chloride, di-	$SnCl_2$	247	28.8	16.0	3050
Tin chloride, tetra-	$SnCl_4$	–33.3	15.1	8.4	2190
Tin iodide, tetra-	SnI_4	143.4	(12.4)	(6.9)	(4330)
Tin oxide	SnO	1042	(84.2)	(46.8)	(6400)
Titanium	Ti	1800	(188.)	(104.4)	(5000)
Titanium bromide, tetra-	$TiBr_4$	38	(10.1)	(5.6)	(2060)
Titanium chloride, tetra-	$TiCl_4$	–23.2	21.4	11.9	2240
Titanium dioxide	TiO_2	1825	(257.)	(142.7)	(11400)
Titanium oxide	TiO	991	394	219	14000
Tungsten	W	3387	(82.4)	(45.8)	(8420)
Tungsten dioxide	WO_2	1270	108.	60.1	13940
Tungsten hexafluoride	WF_6	–0.5	10.8	6.0	1800

Heat of Fusion of Some Inorganic Compounds* (continued)

Compound	Formula	Melting Point, °C	Heat of Fusion Btu/lb	cal/g	cal/g Mole
Tungsten tetrachloride	WCl_4	327	33.1	18.4	6000
Tungsten trioxide	WO_3	1470	108.	60.1	13940
Uranium^{235}	U	~1133	36	20	3700
Uranium tetrachloride	UCl_4	590	48.8	27.1	10300
Vanadium	V	1917	(126)	(70)	(4200)
Vanadium dichloride	VCl_2	1027	118.	65.6	8000
Vanadium oxide	VO	2077	403.	224.0	15000
Vanadium pentoxide	V_2O_5	670	154.	85.5	15560
Xenon	Xe	–111.6	10.1	5.6	740
Ytterbium	Yb	823	22.9	12.7	2200
Yttrium	Y	1504	83.0	46.1	4100
Yttrium oxide	Y_2O_3	2227	199.	110.7	25000
Zinc	Zn	419.4	43.9	24.4	1595
Zinc chloride	$ZnCl_2$	283	(73.1)	(40.6)	(5540)
Zinc oxide	ZnO	1975	98.8	54.9	4470
Zinc sulfide	ZnS	1745	168.	(93.3)	(9100)
Zirconium	Zr	1857	(108)	(60)	(5500)
Zirconium dichloride	$ZrCl_2$	727	81.0	45.0	7400
Zirconium oxide	ZrO_2	2715	304.	168.8	20800

From Bolz, R.E. and Tuve, G.L., Thermodynamics, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 479–483.

Conservation Equations of a Viscous, Heat-Conducting Fluid

In Curvillnear Orthogonal Coordinates

NOMENCLATURE:

e_{ij} = components of rate of strain tensor
E = internal energy per unit mass
f = scalar
F = body force per unit volume
$h_1h_2h_3$ = scale factors
H = static enthalpy per unit mass
H_t = total enthalpy, $H_t = H + V^2/2$
k = thermal conductivity
p = static pressure
q = heat-flux vector
q_β = heat-flux component normal to the surface
t = time
T = temperature
u = velocity component in α direction
v = velocity component in β direction
V = velocity vector
w = velocity component in y direction
W = heat generation per unit volume
α, β, γ = orthogonal coordinates
κ = bulk viscosity
λ = second viscosity coefficient
μ = shear viscosity
ρ = density
τ = viscous stress tensor

I. Introduction

Although formulation of the conservation equations of a viscous, heat-conducting fluid in curvilinear orthogonal coordinates is well known through vector and tensor analysis (Refs. 1 and 2), a complete, written-out set of equations, including the energy equation, is not readily available in any given source. The momentum equation was given by Goldstein (Ref. 3) in curvilinear orthogonal coordinates for an incompressible, constant-property fluid, and by Tsien (Ref. 4) for a compressible, variable-property fluid. Only the commonly used special cases of the set of equations in rectangular, cylindrical, and spherical coordinates appear in the literature (e.g., Ref. 5). The purpose of this paper is to briefly present the complete set of equations in stationary, curvilinear orthogonal coordinates. For convenience in expressing the equations in various coordinates, scale factors for eleven coordinate systems are tabulated.

II. Conservation Equations

Three forms of the energy equation are considered, one form of which may be best suited for a particular application. These relations involve the total enthalpy H_t,

$$\rho\frac{\partial H_t}{\partial t}+\rho(\mathbf{V}\cdot\nabla)H_t=\frac{\partial p}{\partial t}-\nabla\cdot\mathbf{q}+\nabla\cdot(\tau\cdot\mathbf{V})+\mathbf{F}\cdot\mathbf{V}+W$$

the internal energy E,

$$\rho\frac{\partial E}{\partial t}+\rho(\mathbf{V}\cdot\nabla)E+p\nabla\cdot\mathbf{V}=-\nabla\cdot\mathbf{q}+\tau:(\nabla\mathbf{V})+W$$

and the enthalpy H,

$$\rho\frac{\partial H}{\partial t}+\rho(\mathbf{V}\cdot\nabla)H-\left[\frac{\partial p}{\partial t}+(\mathbf{V}\cdot\nabla)p\right]=-\nabla\cdot\mathbf{q}+\tau:(\nabla\mathbf{V})+W$$

To complete the set of conservation equations, the continuity and momentum equations are, respectively,

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{V})=0$$

$$\frac{\partial\mathbf{V}}{\partial t}+(\mathbf{V}\cdot\nabla)\mathbf{V}=-\frac{1}{\rho}\nabla p+\frac{\mathbf{F}}{\rho}+\frac{1}{\rho}\nabla\cdot\tau$$

The quantities that appear in these equations are identified in the nomenclature.

By use of the same notation as used by Goldstein (Ref. 3), the orthogonal coordinates are taken as α, β, and γ such that the elements of length at α, β, and γ in the directions of increasing α, β, and γ are $h_1d\alpha$, $h_2d\beta$, and $h_2d\gamma$, respectively. The differential arc length ds is, then,

$$(ds)^2=h_1^2(d\alpha)^2+h_2^2(d\beta)^2+h_3^2(d\gamma)^2$$

Conservation Equations of a Viscous, Heat-Conducting Fluid (continued)

u, *v*, and *w* are components of the velocity vector **V** in the direction of increasing α, β, and γ, the continuity equation is

$$+\frac{1}{h_1h_2h_3}$$

$$\times\left[\frac{\partial}{\partial\alpha}\left(h_2h_3\rho u\right)+\frac{\partial}{\partial\beta}\left(h_1h_3\rho v\right)+\frac{\partial}{\partial\gamma}\left(h_1h_2\rho w\right)\right]=0$$

the momentum equation written in the α, β, and γ directions is

$$\frac{\partial u}{\partial t}+\frac{u}{h_1}\frac{\partial u}{\partial\alpha}+\frac{v}{h_2}\frac{\partial u}{\partial\beta}+\frac{w}{h_2}\frac{\partial u}{\partial\gamma}+\frac{uv}{h_1h_2}\frac{\partial h_1}{\partial\beta}+\frac{uw}{h_1h_3}\frac{\partial h_1}{\partial\gamma}$$

$$\frac{v^2}{h_1h_2}\frac{\partial h_2}{\partial\alpha}-\frac{w^2}{h_1h_3}\frac{\partial h_3}{\partial\alpha}=-\frac{1}{\rho}\frac{1}{h_1}\frac{\partial p}{\partial\alpha}+\frac{F_\alpha}{\rho}+\frac{1}{\rho}\left(\nabla\cdot\tau\right)_\alpha$$

$$\frac{\partial v}{\partial t}+\frac{u}{h_1}\frac{\partial v}{\partial\alpha}+\frac{v}{h_2}\frac{\partial v}{\partial\beta}+\frac{w}{h_3}\frac{\partial v}{\partial\gamma}+\frac{vu}{h_1h_2}\frac{\partial h_2}{\partial\alpha}+\frac{vw}{h_2h_3}\frac{\partial h_2}{\partial\gamma}$$

$$\frac{u^2}{h_1h_2}\frac{\partial h_1}{\partial\beta}-\frac{w^2}{h_2h_3}\frac{\partial h_3}{\partial\beta}=-\frac{1}{\rho}\frac{1}{h_2}\frac{\partial p}{\partial\beta}+\frac{F_\beta}{\rho}+\frac{1}{\rho}\left(\nabla\cdot\tau\right)_\beta$$

$$\frac{\partial w}{\partial t}+\frac{u}{h_1}\frac{\partial w}{\partial\alpha}+\frac{v}{h_2}\frac{\partial w}{\partial\beta}+\frac{w}{h_3}\frac{\partial w}{\partial\gamma}+\frac{wu}{h_1h_3}\frac{\partial h_3}{\partial\alpha}+\frac{wv}{h_2h_3}\frac{\partial h_2}{\partial\beta}$$

$$\frac{u^2}{h_1h_3}\frac{\partial h_1}{\partial\beta}-\frac{v^2}{h_2h_3}\frac{\partial h_2}{\partial\gamma}=-\frac{1}{\rho}\frac{1}{h_3}\frac{\partial p}{\partial\gamma}+\frac{F_\gamma}{\rho}+\frac{1}{\rho}\left(\nabla\cdot\tau\right)_\gamma$$

ε components of the divergence of the symmetric stress tensor τ in the α, β, and γ direction (Ref. 6)[1] are:

$$\left(\nabla\cdot\tau\right)_\alpha=$$

$$\frac{1}{h_1h_2h_3}\left[\frac{\partial}{\partial\alpha}\left(h_2h_3\tau_{\alpha\alpha}\right)+\frac{\partial}{\partial\beta}\left(h_1h_3\tau_{\alpha\beta}\right)+\frac{\partial}{\partial\gamma}\left(h_1h_2\tau_{\gamma\alpha}\right)\right]$$

$$+\tau_{\alpha\beta}\frac{1}{h_1h_2}\frac{\partial h_1}{\partial\beta}+\tau_{\gamma c}\frac{1}{h_1h_3}\frac{\partial h_1}{\partial\gamma}$$

$$-\tau_{\beta\beta}\frac{1}{h_1h_2}\frac{\partial h_2}{\partial\alpha}-\tau_{\gamma\gamma}\frac{1}{h_1h_3}\frac{\partial h_3}{\partial\alpha}$$

$$\left(\nabla\cdot\tau\right)_\beta=$$

$$\frac{1}{h_1h_2h_3}\left[\frac{\partial}{\partial\alpha}\left(h_2h_3\tau_{\alpha\beta}\right)+\frac{\partial}{\partial\beta}\left(h_1h_3\tau_{\beta\beta}\right)+\frac{\partial}{\partial\gamma}\left(h_1h_2\tau_{\beta\gamma}\right)\right]$$

$$+\tau_{\alpha\beta}\frac{1}{h_1h_2}\frac{\partial h_2}{\partial\alpha}+\tau_{\beta\gamma}\frac{1}{h_2h_3}\frac{\partial h_2}{\partial\gamma}$$

$$-\tau_{\alpha\alpha}\frac{1}{h_1h_2}\frac{\partial h_1}{\partial\beta}-\tau_{\gamma\gamma}\frac{1}{h_2h_3}\frac{\partial h_3}{\partial\beta}$$

[1] ε, h_1, h_2, and h_3 used by Love are the reciprocals of those used herein.

Conservation Equations of a Viscous, Heat-Conducting Fluid (continued)

$$
\begin{aligned}
&(\nabla\cdot\tau)_\gamma = \\
&\frac{1}{h_1h_2h_3}\left[\frac{\partial}{\partial\alpha}\left(h_2h_3\tau_{\gamma\alpha}\right)+\frac{\partial}{\partial\beta}\left(h_1h_3\tau_{\beta\gamma}\right)+\frac{\partial}{\partial\gamma}\left(h_1h_2\tau_{\gamma\gamma}\right)\right] \\
&\qquad +\tau_{\gamma\alpha}\frac{1}{h_1h_3}\frac{\partial h_3}{\partial\alpha}+\tau_{\beta\gamma}\frac{1}{h_2h_3}\frac{\partial h_3}{\partial\beta} \\
&\qquad -\tau_{\alpha\alpha}\frac{1}{h_1h_3}\frac{\partial h_1}{\partial\gamma}-\tau_{\beta\beta}\frac{1}{h_2h_3}\frac{\partial h_2}{\partial\gamma}
\end{aligned}
$$

The components of the viscous stress tensor for a Stokes' fluid are related to the components of the rate of strain tensor by

$$
\begin{aligned}
\tau_{\alpha\alpha} &= \lambda\nabla\cdot\mathbf{V}+\mu e_{\alpha\alpha} \\
\tau_{\beta\beta} &= \lambda\nabla\cdot\mathbf{V}+\mu e_{\beta\beta} \\
\tau_{\gamma\gamma} &= \lambda\nabla\cdot\mathbf{V}+\mu e_{\gamma\gamma} \\
\tau_{\alpha\beta} &= \tau_{\beta\alpha} = \mu e_{\alpha\beta} \\
\tau_{\alpha\gamma} &= \tau_{\gamma\alpha} = \mu e_{\alpha\gamma} \\
\tau_{\beta\gamma} &= \tau_{\gamma\beta} = \mu e_{\beta\gamma}
\end{aligned}
$$

where the divergence of the velocity vector is

$$
\nabla\cdot\mathbf{V}=\frac{1}{h_1h_2h_3}\left[\frac{\partial}{\partial\alpha}\left(h_2h_3u\right)+\frac{\partial}{\partial\beta}\left(h_1h_3v\right)+\frac{\partial}{\partial\gamma}\left(h_1h_2w\right)\right]
$$

and the components of the rate of strain tensor are (Ref. 3):

$$
\begin{aligned}
\frac{1}{2}e_{\alpha\alpha} &= \frac{1}{h_1}\frac{\partial u}{\partial\alpha}+\frac{v}{h_1h_2}\frac{\partial h_1}{\partial\beta}+\frac{w}{h_3h_1}\frac{\partial h_1}{\partial\gamma} \\
\frac{1}{2}e_{\beta\beta} &= \frac{1}{h_2}\frac{\partial v}{\partial\beta}+\frac{w}{h_2h_3}\frac{\partial h_2}{\partial\gamma}+\frac{u}{h_1h_2}\frac{\partial h_2}{\partial\alpha} \\
\frac{1}{2}e_{\gamma\gamma} &= \frac{1}{h_3}\frac{\partial w}{\partial y}+\frac{u}{h_1h_3}\frac{\partial h_3}{\partial\alpha}+\frac{v}{h_2h_3}\frac{\partial h_3}{\partial\beta} \\
e_{\alpha\beta} &= \frac{h_2}{h_1}\frac{\partial}{\partial\alpha}\left(\frac{v}{h_2}\right)+\frac{h_1}{h_2}\frac{\partial}{\partial\beta}\left(\frac{u}{h_1}\right) \\
e_{\alpha\gamma} &= \frac{h_1}{h_3}\frac{\partial}{\partial\gamma}\left(\frac{u}{h_1}\right)+\frac{h_3}{h_1}\frac{\partial}{\partial\alpha}\left(\frac{w}{h_3}\right) \\
e_{\beta\gamma} &= \frac{h_3}{h_2}\frac{\partial}{\partial\beta}\left(\frac{w}{h_3}\right)+\frac{h_2}{h_3}\frac{\partial}{\partial\gamma}\left(\frac{v}{h_2}\right)
\end{aligned}
$$

The second viscosity coefficient λ is related to the shear viscosity μ (first viscosity coefficient) by $\lambda = 2/3\ \mu$ if the bulk viscosity coefficient defined by $\kappa = \lambda + 2/3\ \mu$ is *zero*. Otherwise, λ is given by

$$
\lambda=\kappa-\frac{2}{3}\mu
$$

Conservation Equations of a Viscous, Heat-Conducting Fluid (continued)

In the various forms of the energy equations, the operator ($\mathbf{V}\cdot\nabla$) applied to a scalar f, such as H_t, E, p, or H, gives the convection of that quantity by the flow,

$$(\mathbf{V}\cdot\nabla)f = u\frac{1}{h_1}\frac{\partial f}{\partial \alpha} + v\frac{1}{h_2}\frac{\partial f}{\partial \beta} + w\frac{1}{h_3}\frac{\partial f}{\partial \gamma}$$

The divergence of the heat flux vector **q** is

$$\nabla\cdot\mathbf{q} = \frac{1}{h_1h_2h_3}\left[\frac{\partial}{\partial\alpha}\left(h_2h_3q_\alpha\right) + \frac{\partial}{\partial\beta}\left(h_1h_3q_\beta\right) + \frac{\partial}{\partial\gamma}\left(h_1h_2q_\gamma\right)\right]$$

In particular, if the heat flux vector is given by Fourier's heat-conduction law, $\mathbf{q} = k\,\nabla\,T$, then the components are

$$q_\alpha = -k\frac{1}{h_1}\frac{\partial T}{\partial\alpha},\quad q_\beta = -k\frac{1}{h_2}\frac{\partial T}{\partial\beta},\quad q_\gamma = -k\frac{1}{h_3}\frac{\partial T}{\partial\gamma}$$

The rate at which work is done by body forces is, simply,

$$\mathbf{F}\cdot\mathbf{V} = F_\alpha u + F_\beta v + F_\gamma w$$

The rate at which work is done by the viscous stresses is given by

$$\begin{aligned}\nabla\cdot(\tau\cdot\mathbf{V}) = \frac{1}{h_1h_2h_3}\Bigg\{&\frac{\partial}{\partial\alpha}\left[h_2h_3\left(\tau_{\alpha\alpha}u + \tau_{\beta\alpha}v + \tau_{\gamma\alpha}w\right)\right]\\ &+\frac{\partial}{\partial\beta}\left[h_1h_3\left(\tau_{\alpha\beta}u + \tau_{\beta\beta}v + \tau_{\gamma\beta}w\right)\right]\\ &+\frac{\partial}{\partial\gamma}\left[h_1h_2\left(\tau_{\alpha\gamma}u + \tau_{\beta\gamma}v + \tau_{\gamma\gamma}w\right)\right]\Bigg\}\end{aligned}$$

Lastly, the rate of dissipation of energy takes the form

$$\begin{aligned}\tau:(\nabla\mathbf{V}) = {}&\tau_{\alpha\alpha}\left(\frac{1}{h_1}\frac{\partial u}{\partial\alpha} + \frac{v}{h_1h_2}\frac{\partial h_1}{\partial\beta} + \frac{w}{h_1h_3}\frac{\partial h_1}{\partial\gamma}\right)\\ &+\tau_{\beta\beta}\left(\frac{1}{h_2}\frac{\partial v}{\partial\beta} + \frac{u}{h_1h_2}\frac{\partial h_2}{\partial\alpha} + \frac{w}{h_2h_3}\frac{\partial h_2}{\partial\gamma}\right)\\ &+\tau_{\gamma\gamma}\left(\frac{1}{h_3}\frac{\partial w}{\partial\gamma} + \frac{u}{h_1h_3}\frac{\partial h_2}{\partial\alpha} + \frac{v}{h_2h_3}\frac{\partial h_3}{\partial\beta}\right)\\ &+\tau_{\alpha\beta}\left(\frac{1}{h_2}\frac{\partial u}{\partial\beta} + \frac{1}{h_1}\frac{\partial v}{\partial\alpha} - \frac{v}{h_1h_2}\frac{\partial h_2}{\partial\alpha} - \frac{u}{h_1h_2}\frac{\partial h_1}{\partial\beta}\right)\\ &+\tau_{\alpha\gamma}\left(\frac{1}{h_3}\frac{\partial u}{\partial\gamma} + \frac{1}{h_1}\frac{\partial w}{\partial\alpha} - \frac{w}{h_1h_3}\frac{\partial h_3}{\partial\alpha} - \frac{u}{h_1h_2}\frac{\partial h_1}{\partial\gamma}\right)\\ &+\tau_{\beta\gamma}\left(\frac{1}{h_3}\frac{\partial v}{\partial\gamma} + \frac{1}{h_2}\frac{\partial w}{\partial\beta} - \frac{w}{h_2h_3}\frac{\partial h_2}{\partial\beta} - \frac{v}{h_2h_3}\frac{\partial h_2}{\partial\gamma}\right)\end{aligned}$$

This rate of dissipation of energy term usually appears in the literature as Φ.

Table 1 presents descriptive information on a number of orthogonal coordinate systems for which the conservation equations can be readily written by use of the foregoing relations. The last two entries in Table 1, in which the coordinates are taken along and normal to the surface, are useful in analyzing internal and external boundary-layer flows. For many flow problems in these coordinates, the dominant viscous stress is the shear stress that lies in the plane of β = const ($\tau_{\alpha\beta}$ for a two-dimensional flow and $\tau_{\alpha\beta}$, $\tau_{\gamma\beta}$ for a three-dimensional flow), and the important heat-flux component is normal to the surface, q_β.

Table 1. COORDINATE SYSTEMS AND SCALE FACTORS

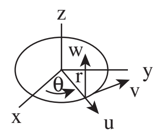
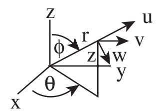
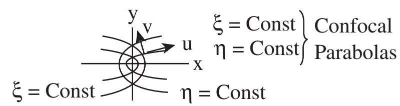
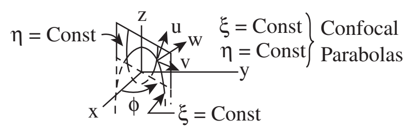
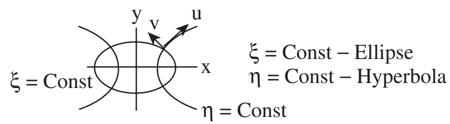
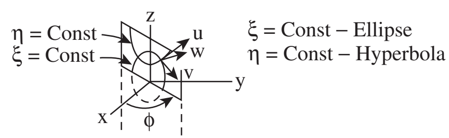
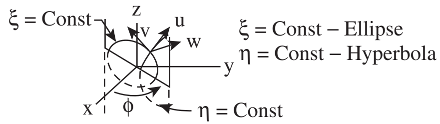
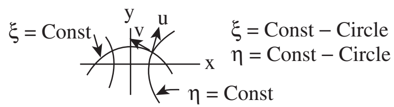
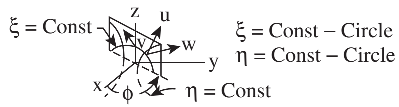
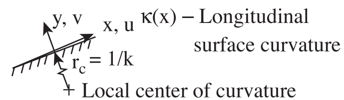
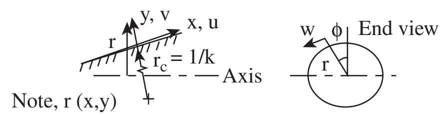
1. Orthogonal Coordinate System, and 2. Orthogonal coordinates α, β, γ	Rectangular Coordinates			Scale Factors h_1, h_2, h_α			
	x	y	z	h_1	h_2	h_3	Coordinate Configuration
Cylindrical r, θ, z	$r \cos q$	$r \sin q$	z	1	r	1	
Spherical r, ϕ, θ	$r \cos \theta \sin \phi$	$r \sin \theta \sin \phi$	$r \cos \phi$	1	r	$r \sin \theta$	
Parabolic cylindrical ξ, η, z	$\frac{1}{2}\left(\xi^2 - \eta^2\right)$	$\zeta\eta$	z	$\sqrt{\xi^2 + \eta^2}$	$\sqrt{\xi^2 + \eta^2}$	1	
Paraboloidal ξ, η, ϕ	$\xi\eta \cos \phi$	$\xi\eta \sin \phi$	$\frac{1}{2}\left(\xi^2 - \eta^2\right)$	$\sqrt{\xi^2 + \eta^2}$	$\sqrt{\xi^2 + \eta^2}$	$\xi\eta$	
Elliptic cylindrical ξ, η, z	$\alpha \cosh \xi \cos \eta$ α = const	$\alpha \sinh \xi \sin \eta$	z	$\alpha\sqrt{\sinh^2 \xi + \sin^2 \eta}$	$\alpha\sqrt{\sinh^2 \xi + \sin^2 \eta}$	1	
Prolate spheroidal ξ, η, ϕ	$\alpha \sinh \xi \sin \eta$ $\cos \phi$ α = const	$\alpha \sinh \xi \sin \eta$ $\sin \phi$	$\alpha \cosh \xi \cos \eta$	$\alpha\sqrt{\sinh^2 \xi + \sin^2 \eta}$	$\alpha\sqrt{\sinh^2 \xi + \sin^2 \eta}$	$\alpha \sinh \xi \sin \eta$	

Table 1. COORDINATE SYSTEMS AND SCALE FACTORS (continued)

Oblate spheroidal ξ, η, ϕ	$\alpha \cosh \xi \cos \eta \cos \phi$ α = const	$\alpha \cosh \xi \cos \eta \sin \phi$	$\alpha \sinh \xi \sin \eta$	$\alpha\sqrt{\sinh^2 \xi + \sin^2 \eta}$	$\alpha\sqrt{\sinh^2 \xi + \sin^2 \eta}$	$\alpha \cosh \xi \cos \eta$	
Bipolar ξ, η, x	$\frac{\alpha \sinh \eta}{\cosh \eta - \cos \xi}$ $\alpha = \text{const}$	$\frac{\alpha \sinh \xi}{\cosh \eta - \cos \xi}$	z	$\frac{\alpha}{\cosh \eta - \cos \xi}$	$\frac{\alpha}{\cosh \eta - \cos \xi}$	1	
Toroidal ξ, η, ϕ	$\frac{\alpha \sinh \eta \cos \phi}{\cosh \eta - \cos \xi}$ $\alpha = \text{const}$	$\frac{\alpha \sinh \eta \sin \phi}{\cosh \eta - \cos \xi}$	$\frac{\alpha \sinh \xi}{\cosh \eta - \cos \xi}$	$\frac{\alpha}{\cosh \eta - \cos \xi}$	$\frac{\alpha}{\cosh \eta - \cos \xi}$	$\frac{\alpha \sinh \eta}{\cosh \eta - \cos \xi}$	
Local coordinates along surface (Ref. 3) x, y, z	—	—	—	$1 + \kappa\gamma$	1	1	
Local coordinates along surface (Ref. 3) Symmetric about axis x, y, ϕ	—	—	—	$1 + \kappa\gamma$	1	r	

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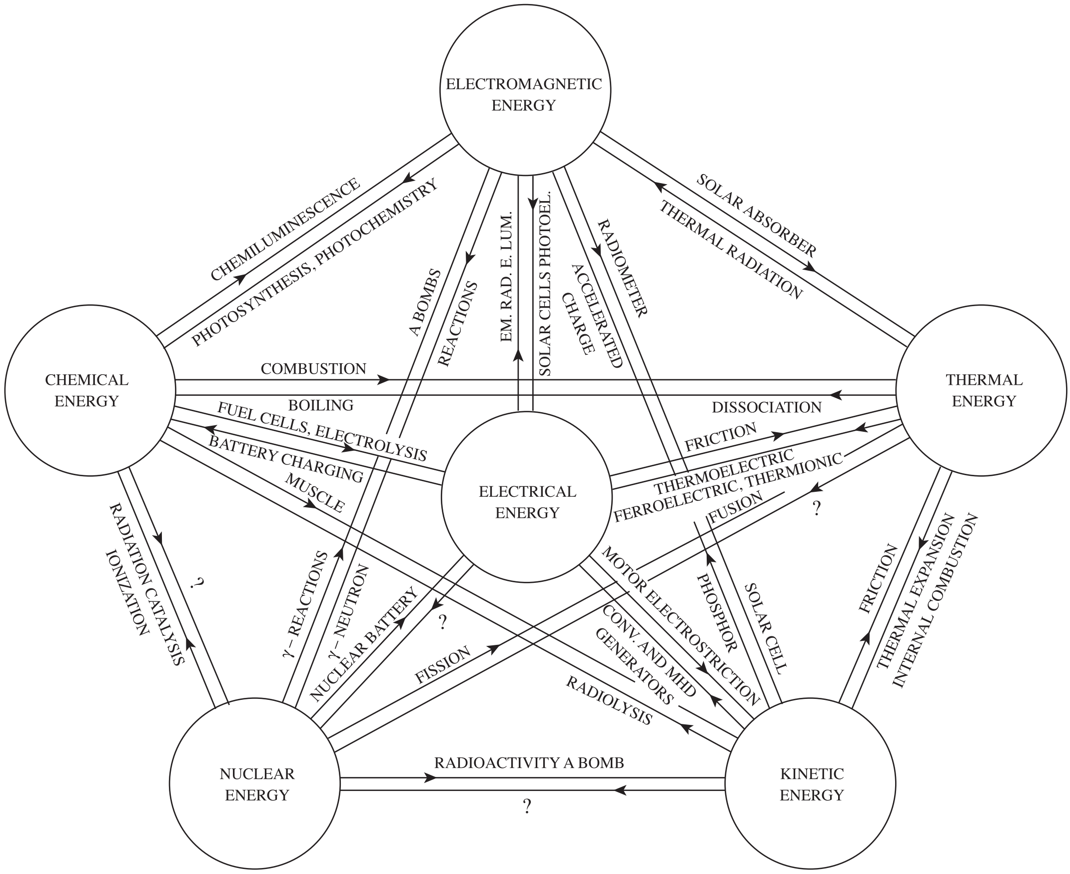
Energy Conversions

Directions and Methods for Energy Conversion



Energy conversion chart. The circles represent the different forms of energy and the arrows the ways of converting energy from one form to another.

From Bolz, R.E. and Tuve, G.L., Fluid and aero mechanics, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 550. Originally from Kettani, M.A., *Direct Energy Conversion,* Addison-Wesley Publishing Company, 1970, p. 6.

Helical Steel Springs*

Compression or Tension

The upper figure is the load in pounds at 100 000 psi (689 MN/m^2) stress by the "corrected" stress equation. The lower figure gives spring stiffness in lb/in per single coil, based on a shear modulus of 11.5×10^6 psi (79.3 GN/M^2). The stiffness is independent of load. Both figures may be adjusted in direct proportion to selected stress or modulus. For multicoil springs divide the stiffness per coil by the number of active coils. For load in N, multiply the values in lbf by 4.4482. For stiffness in N/m, multiply the values in lbf/in. by 175.13.

Helical Springs—Load and Stiffness

Wire Diam. in.	Outside Diameter of Coil, in.												
	1/8	3/16	1/4	5/16	3/8	7/16	1/2	9/16	5/8	11/16	3/4	7/8	1
.010	.305												
	9.47												
.012	.522	.350											
	20.7	5.43											
.014	.823	.560	.422										
	40.3	10.5	4.18										
.016	1.21	.824	.626										
	72.9	18.4	7.37										
.018	1.71	1.17	.889										
	124	30.7	12.1										
.020	2.32	1.60	1.22	.972									
	200	48.6	18.9	9.06									
.022	3.03	2.12	1.60	1.30									
	306	73.9	28.2	13.7									
.024	3.90	2.72	2.09	1.68	1.41	1.21							
	464	108	41.4	19.9	11.1	6.67							
.028	5.98	4.25	3.29	2.65	2.24	1.92	1.69	1.51					
	965	216	80.6	38.0	21.1	12.9	8.37	5.79					
.032		6.25	4.84	3.95	3.33	2.85	2.51	2.24	2.03				
		398	146	68.0	37.5	22.4	14.8	10.0	7.27				
.037		9.42	7.41	6.01	5.07	4.41	3.88	3.44	3.10	2.83	2.61		
		785	280	128	69.6	42.2	27.3	18.5	13.3	9.77	7.43		
.043		14.4	11.4	9.33	7.91	6.82	6.07	5.36	4.89	4.44	4.10	3.52	
		1618	559	249	134	80.0	51.6	34.9	25.0	18.3	14.0	8.60	
.049			16.4	13.7	11.6	10.1	8.84	7.95	7.14	6.54	6.00	5.17	4.55
			1019	452	240	141	90.8	60.7	43.2	32.0	24.1	14.6	9.66
.055			22.8	18.9	16.2	14.1	12.4	11.2	10.0	9.23	8.50	7.32	6.40
			1767	768	401	234	149	101	70.4	51.9	39.5	23.9	15.6
.063				27.9	23.8	20.9	18.6	16.6	15.1	13.8	12.7	10.9	9.60
				1461	721	429	272	181	128	92.6	70.0	42.3	27.5
.071				38.7	33.4	29.4	26.1	23.6	21.3	19.5	18.0	15.5	13.6
				2563	1295	741	463	307	215	156	117	70.6	45.3
.080					47.1	41.3	36.9	33.4	30.2	27.8	25.7	22.2	19.5
					2300	1285	795	525	364	262	196	117	75.6
.090						57.9	51.7	46.9	42.9	39.0	36.2	31.2	27.6
						2236	1368	890	617	442	329	195	125
.100						77.5	69.7	63.3	58.0	53.0	49.2	42.6	37.6
						3726	2248	1449	993	707	525	309	197
.112							95.6	87.4	79.7	73.8	68.1	59.3	52.2
							3886	2462	1678	1186	871	509	323
.125							130	119	109	101	93.8	81.9	72.5
							6701	4205	2817	1977	1436	832	525
.148									175	163	151	133	119
									6350	4380	3166	1802	1119
.177											250	222	198
											7485	4150	2526
.207												341	307
												8857	5266
.244													484
													11,805

Helical Steel Springs*

Wire Diam. in.	Outside Diameter of Coil, in.											
	1 1/8	1 1/4	1 3/8	1 1/2	1 3/4	2	2 1/4	2 1/2	2 3/4	3	3 1/4	3 1/2	4
.055	5.70												
	10.7												
.063	8.55	7.75											
	18.8	13.6											
.071	12.2	11.1	9.97	9.21									
	31.5	22.4	16.4	12.6									
.080	17.3	15.7	14.2	13.1									
	51.4	37.0	27.0	20.5									
.090	24.7	22.2	20.2	18.6									
	85.1	60.3	44.3	33.5									
.100	33.5	30.5	27.7	25.5	22.1	19.3							
	132	94.5	69.0	52.4	32.1	20.9							
.112	47.0	42.4	38.6	35.8	30.7	27.0	24.1						
	218	152	112	84.5	51.7	33.5	23.1						
.125	65.0	58.8	53.9	49.4	42.6	37.6	33.4	30.2					
	350	246	180	135	82.0	53.3	36.6	26.2					
.148	106	96.3	88.0	81.2	70.5	62.0	55.1	49.7	45.3	41.7			
	741	514	375	279	168	109	74.3	53.1	39.1	29.7			
.177	178	163	149	137	119	105	94.0	84.7	77.2	71.0	65.5	61.2	
	1664	1145	819	609	361	234	159	113	83.3	63.2	48.4	38.4	
.207	279	255	235	217	188	166	150	134	122	113	104	97.2	85.2
	3419	2320	1658	1218	716	457	310	218	160	121	93.6	74.1	48.5
.244	444	406	376	306	349	269	241	218	199	183	170	158	139
	7462	4988	3498	2562	1488	941	631	443	322	243	188	148	95.9
.283		614	574	534	467	415	374	338	309	285	263	247	216
		10,199	7086	5154	2919	1820	1210	849	616	460	352	276	180
.331			882	824	733	652	589	534	491	453	421	391	343
			15,207	10,785	6048	3713	2449	1693	1217	911	694	543	348
.375				1166	1038	932	844	767	704	652	605	567	497
				19,966	10,903	6652	4302	2960	2124	1575	1195	933	597
.437					1587	1433	1307	1201	1102	1019	951	888	783
					23,202	13,859	8861	6005	4243	3132	2367	1835	1166
.500						2073	1897	1742	1617	1500	1396	1310	1160
						26,645	16,817	11,268	7880	5736	4325	3330	2097
.562							2623	2426	2251	2096	1956	1832	1628
							29,977	19,533	13,751	9957	7412	5686	3546
.625								3239	3010	2825	2649	2491	2221
								33,289	22,872	16,386	12,135	9240	5710

From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science,* CRC Press, Boca Raton, FL, 1973, pp. 605–606. Originally from Ross, H.F., *Trans. ASME*, 69, 727, 1947.

Ultrasonic Energy and Applications

Table A. Applications of Ultrasonics

Processes	Typical Frequencies, kc/s
HIGH POWER RANGE[a]	
Surface cleaning; grease and film removal	15–60
Emulsifying; homogenizing; production of dispersions	10–40
Degassing of liquids and molten metals (grain refinement)	10–40
Stimulating mechanical processes; mixing, diffusion, defoaming, atomizing, drying, plastic sealing, particle agglomeration, flow of powders, adhesion in soldering and welding, grain refinement in casting	10–500
Cutting and forming; impact grinding of brittle materials; abrasive cutting; die forming with reduced friction	15–100
Stimulating chemical processes; combustion and other reactions	10–200
LOW POWER RANGE (ABSORPTION AND ECHO)	
Inspection and flow detection	500–5000
Pulse-echo counting and inspection	700–10,000
Medical examination, diagnosis, and therapy	500–2500
Measurement and control (flow, thickness, density, liquid level, viscosity)	500–20,000
Sonic detection and ranging; command signaling; delay lines	10 000–20 000

[a] The desired effects in this range are largely accomplished by cavitation (in a liquid) or by vibrations and high accelerations that affect materials in contact with each other. *Cavitation* is bubble formation at a nucleus (such as a particle), followed by bubble growth and collapse. High pressures and temperatures occur at the instant of collapse, and the number of bubbles collapsing can be millions per second. Cavitation is suppressed by high static pressure and varies with liquid temperature. As the ultrasonic frequency is increased, up to a practical limit of about 10^7 cps (hz), the sound intensity must be increased to pass the threshold at which cavitation begins. Intensities very much above the threshold are not advantageous. Cavitation is increased in a liquid of low viscosity, low vapor pressure, and high surface tension.

Transmission and matching of acoustics power to the load is often not simple; in fact this step is an art in itself (see references).

Table B. Generators or Transducers

Type of Generator	Typical Limits: Mechanical Power,[a] W	Frequency, kc/s	Efficiency,[b] %
Air whistles	75	40	15
Jet-edge vibrators (gas or liquid)	50	20	15
Cavity resonators	500	12	15
Sirens (jet interruption)	1000	25	70
Piezoelectric-quartz		5000	90
Piezoelectric-ceramic (e.g., barium titanate)	4000	5000	75
Magnetostrictive (Ni, Fe, Co, ferrites)	5000	90	50
Electron tube	1000	30	50
Rotating alternator	25,000	25	50

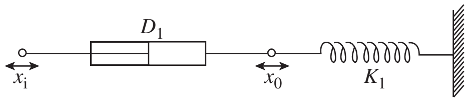
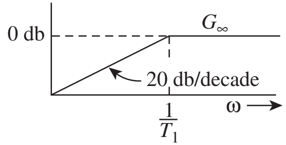
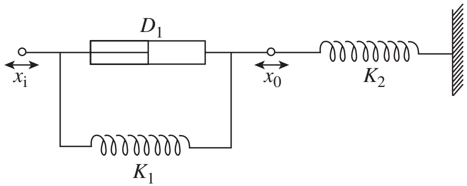
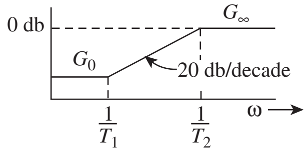
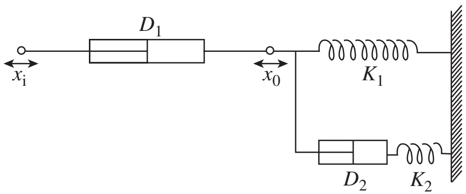
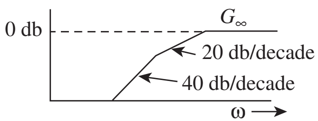
[a] Power intensity per unit area at point of use depends on methods for transmission and focusing.
[b] The efficiencies of available equipment for industrial use are often much below these values.

References

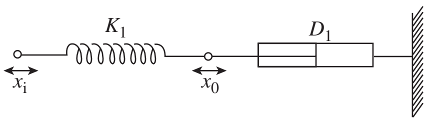
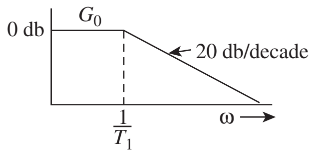
"High-Intensity Ultrasonics: Industrial Applications," B. Brown and J.E. Goodman, D. Van Nostrand Co., 1965.
"Sources of High-Intensity Ultrasound," L.D. Rozenberg, Ed., 2 volumes, Plenum Press, 1968.
"Ultrasonic Engineering," J.R. Frederick, John Wiley & Sons, Inc., 1965.
"Ultrasonic Machining of Intractable Materials," A.I. Markov, Ed., Butterworth & Co., 1967.
"Ultrasonics: Theory and Application," G.L. Gooberman, English Universities Press, 1968.

From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 607.

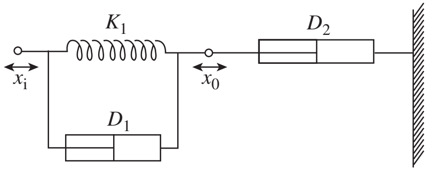
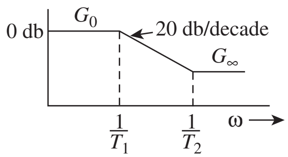
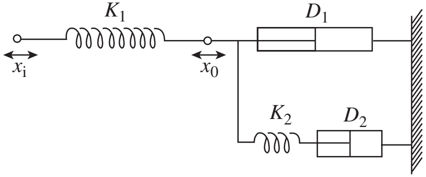
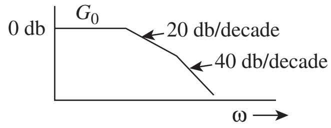
LEAD

Mechanical Lead Network	Log Magnitude Characteristic	Transfer Function	T_1	T_2
	 $G_0 = 0$ $G_\infty = 1$	$\dfrac{T_1 s}{T_1 s+1}$	$\dfrac{D_1}{K_1}$	…
	 $G_0 = \dfrac{1}{1+\dfrac{K_2}{K_1}}$ $G_\infty = 1$	$G_0 \dfrac{T_1 s+1}{T_2 s+1}$	$\dfrac{D_1}{K_1}$	$G_0 T_1$
	 $G_0 = 0$ $G_\infty = 1$	$\dfrac{T_1 T_2 s^2}{T_1 T_2 s^2 + \left[T_1 + \left(1+\dfrac{K_2}{K_1}\right)T_2\right]s+1}$	$\dfrac{D_1}{K_1}$	$\dfrac{D_2}{K_2}$

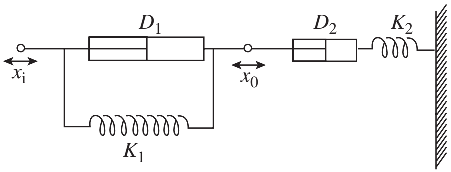
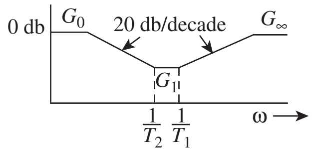
LAG

Mechanical Lag Network	Log Magnitude Characteristic	Transfer Function	T_1	T_2
	 $G_0 = 1$ $G_\infty = 0$	$\dfrac{1}{T_1 s+1}$	$\dfrac{D_1}{K_1}$	…

Mechanical Components (continued)

Mechanical Lag Network	Log Magnitude Characteristic	Transfer Function	T_1	T_2
	 $G_0 = 1$ $G_\infty = \dfrac{1}{1 + D_2/D_1}$	$\dfrac{T_2 s + 1}{T_1 s + 1}$	$\dfrac{T_2}{G_\infty}$	$\dfrac{D_1}{K_1}$
	 $G_0 = 1$ $G_\infty = 0$	$\dfrac{1}{T_1T_2s^2 + \left[T_1 + \left(1 + \frac{K_2}{K_1}\right)T_2\right]s + 1}$	$\dfrac{D_1}{K_1}$	$\dfrac{D_2}{K_2}$

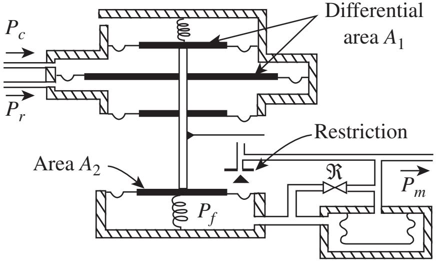
LAG-LEAD

Mechanical Lag-Lead Network	Log Magnitude Characteristic	Transfer Function	T_1	T_2
	 $G_0 = G_\infty = 1 \quad G_1 = \dfrac{T_1 + T_2}{T_1 + (1 + \frac{K_2}{K_1})\,T_2}$	$\dfrac{(T_1 s + 1)(T_2 s + 1)}{T_1T_2s^2 + \left[T_1 + \left(1 + \frac{K_2}{K_1}\right)T_2\right]s + 1}$	$\dfrac{D_1}{K_1}$	$\dfrac{D_2}{K_2}$

From Bolz, R.E. and Tuve, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 1088–1089. Originally from *Handbook of Automation, Computation, and Control*, Vol. 1, Grabbe, E.M., Ramo, S., and Wooldridge, D.E., Eds., John Wiley & Sons, New York, 1958.

Approximate Relationships for High Loop Gain Controllers, $\varepsilon \ll 1$

LEAD

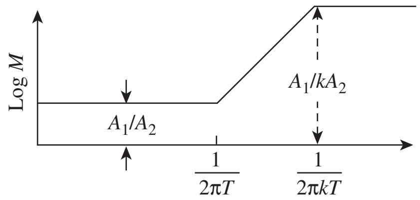


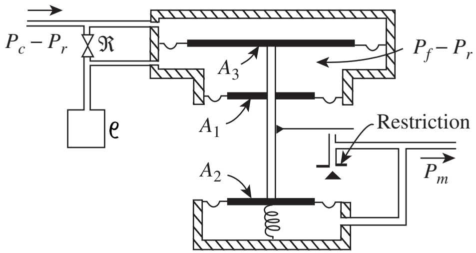
$$\frac{P_m - P_0}{P_c - P_r} = \frac{A_1}{A_2}\left[\frac{1 + T_1 s}{1 + kT_1 s}\right]$$

$$T_1 = \mathfrak{R}\mathcal{C}$$

k = change in P_f for a unit change in P_m when $\mathfrak{R}$ is completely closed.

Plot for $T = T_1$

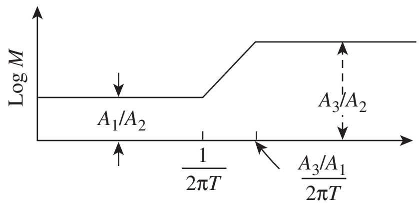




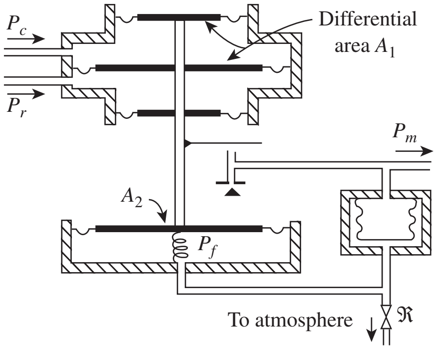
$$\frac{P_m - P_0}{P_c - P_r} = \frac{A_1}{A_2}\left[\frac{1 + (A_3/A_2)T_1 s}{1 + kT_1 s}\right]$$

$$T_1 = \mathfrak{R}\mathcal{C}$$

Plot for $T = T_1$



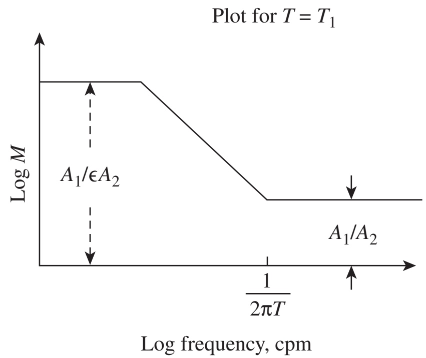
LAG



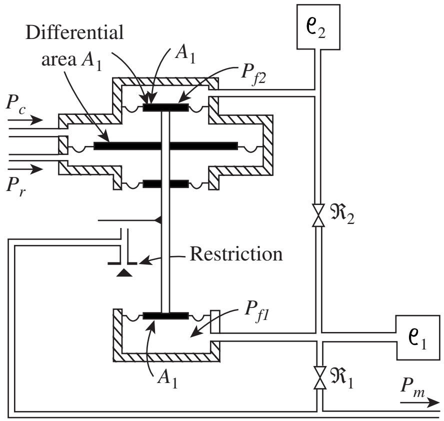
$$\frac{P_m - P_0}{P_c - P_r} = \frac{A_1}{A_2 k}\left[\frac{1 + 1/T_1 s}{1 + \epsilon/kT_1 s}\right]$$

$$T_1 = \Re e$$

ϵ = a system constant related to the loop gain.



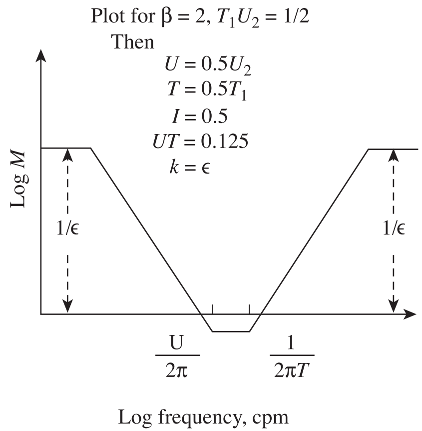
LAG-LEAD



$$\frac{P_m - P_0}{P_c - P_r}$$

$$= (1 + \beta T_1 U_2)\cdot\left[\frac{\frac{U_2/s}{1+\beta T_1 U_2} + 1 + \frac{T_1 s}{1 + \beta T_1 U_2}}{\epsilon U_2/s + \epsilon T_1 s + 1}\right],$$

where $\epsilon\beta T_1 U_2 \ll 1$, $T_1 = \Re_1\mathcal{C}_1$, $U_2 = 1/\Re_2\mathcal{C}_2$,
$\beta = 1 + \mathcal{C}_2/\mathcal{C}_1$, I = interaction factor.

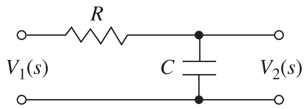


From Bolz, R.E. and Tuve, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 1090–1091. Originally from *Handbook of Automation, Computation, and Control*, Vol. 1, Grabbe, E.M., Ramo, S., and Wooldridge, D.E., Eds., John Wiley & Sons, New York, 1958, pp. **23**-46 and **23**-47.

Dynamic Elements and Networks

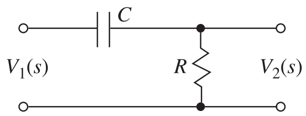
Element or System	G(s)

1. Integrating circuit



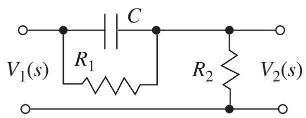
$$\frac{V_2(s)}{V_1(s)} = \frac{1}{RCS+1}$$

2. Differentiating circuit



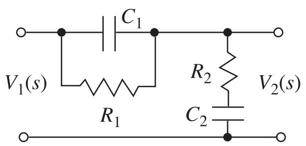
$$\frac{V_2(s)}{V_1(s)} = \frac{RCS}{RCS+1}$$

3. Differentiating circuit



$$\frac{V_2(s)}{V_1(s)} = \frac{s+1/RCS}{s+(R_1+R_2)/R_1R_2C}$$

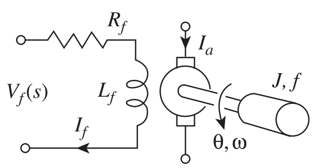
4. Lead-lag filter circuit



$$\tau_a = R_1C_1,$$
$$\tau_b = R_2C_2$$
$$\tau_{ab} = R_1C_1$$
$$\tau_1\tau_2 = \tau_a\tau_b,$$
$$\tau_1 + \tau_2 = \tau_a + \tau_b + \tau_{ab}$$

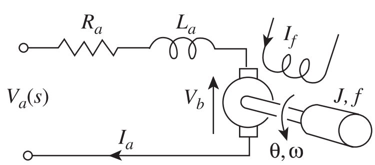
$$\frac{V_2(s)}{V_1(s)} = \frac{(1+s\tau_a)(1+s\tau_b)}{\tau_a\tau_b s^2 + (\tau_a+\tau_b+\tau_{ab})s+1} = \frac{(1+s\tau_a)(1+s\tau_b)}{(1+s\tau_1)(1+s\tau_2)}$$

5. dc-motor, field controlled



$$\frac{\theta(s)}{V_f(s)} = \frac{K_m}{s(Js+f)(L_f s+R_f)}$$

6. dc-motor, armature controlled

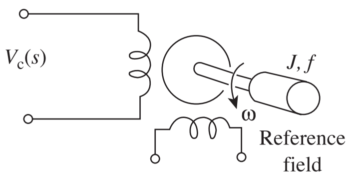


$$\frac{\theta(s)}{V_a(s)} = \frac{K_m}{s\left[(R_a+L_a s)(J_s+f)+K_bK_m\right]}$$

Dynamic Elements and Networks (continued)

Element or System	G(s)

7. ac-motor, two-phase control field

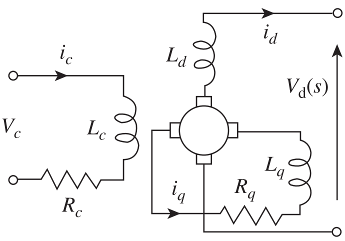


$$\frac{\theta(s)}{V_c(s)} = \frac{K_m}{s(\tau s+1)}$$

$$\tau = J/(f-m)$$

$m =$ slope of linearized torque-speed curve (normally negative)

8. Amplidyne



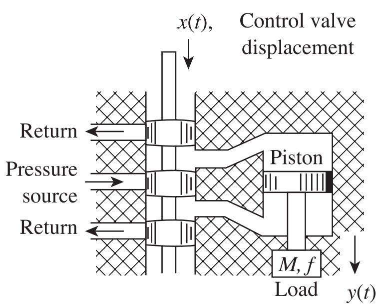
$$\frac{V_d(s)}{V_c(s)} = \frac{(K/R_cR_q)}{(s\tau_c+1)(s\tau_q+1)}$$

$$\tau_c = L_c/R_c, \quad \tau_q = L_q/R_q$$

For the unloaded case, $i_d \simeq 0, \tau_c \simeq \tau_q$,

0.05 sec $< \tau_c < 0.5$ sec

9. Hydraulic actuator



$$\frac{Y(s)}{X(s)} = \frac{K}{s(Ms+B)}$$

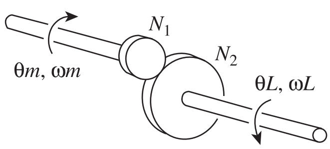
$$K = \frac{Ak_z}{k_p}, \quad B = \left(f + \frac{A^2}{k_p}\right)$$

$$k_z = \left.\frac{\partial g}{\partial x}\right|_{x_0}, \quad k_p = \left.\frac{\partial g}{\partial P}\right|_{P_0},$$

$$g = g(x, P)$$

$A =$ area of piston

10. Gear Train

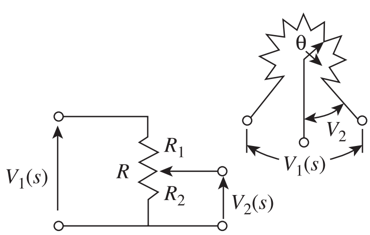


$$\text{Gear ratio} = n = \frac{N_1}{N_2}$$

$$N_2\theta_L = N_1\theta_m, \quad \theta_L = n\theta_m$$

$$\omega_L = n\omega_M$$

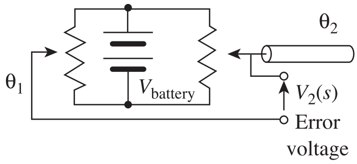
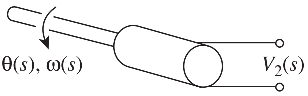
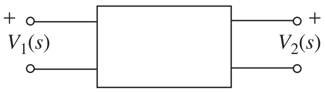
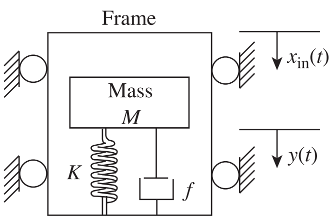
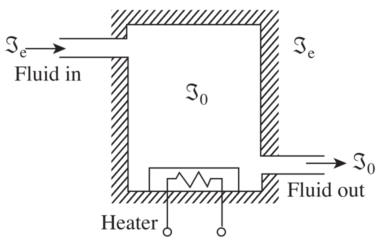
11. Potentiometer



$$\frac{V_2(s)}{V_1(s)} = \frac{R_2}{R} = \frac{R_2}{R_1+R_2}$$

$$\frac{R_2}{R} = \frac{\theta}{\theta_{\max}}$$

Dynamic Elements and Networks (continued)

Element or System	G(s)
12. Potentiometer error detector bridge 	$V_2(s)=k_s(\theta_1(s)-\theta_2(s))$ $V_2(s)=k_s\theta_{error}(s)$ $k_2=\frac{V_{battery}}{\theta_{max}}$
13. Tachometer 	$V_2(s)=K_t\omega(s)$ $=K_t s\theta(s)$
14. dc-amplifier 	$\frac{V_2(s)}{V_1(s)}=\frac{k_a}{s\tau+1}$ R_0 = output resistance C_0 = output capacitance $\tau=R_0C_0$, $\tau \ll 1$ and is often negligible for servomechanism amplifier
15. Accelerometer 	$x_0(t)=y(t)-x_{in}(t)$, $\frac{X_0(s)}{X_{in}(s)}=\frac{-s^2}{s^2+(f/M)s+K/M}$ For low-frequency oscillations, where $\omega<\omega_n$, $\frac{X_0(j\omega)}{X_{in}(j\omega)}\simeq\frac{\omega^2}{K/M}$
16. Thermal Heating System 	$\frac{\Im(s)}{q(s)}=\frac{1}{C_t s+(QS+1/R)}$, where $\Im=\Im_0-\Im_e$ = temperature difference due to thermal process C_t = thermal capacitance Q = fluid flow rate = constant S = specific heat of water R_t = thermal resistance of insulation $q(s)$ = rate of heat flow of heating element

From Bolz, R.E. and Tuve, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 1092–1094. Originally from Dorf, R.C., *Modern Control Systems*, Addison-Wesley, Reading, MA, 1967.

Properties of Saturated Water and Steam (Temperature)

	Pressure	Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			
t (°C)	MPa	v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	t (°C)
0	*0.000 611 2	0.001 000 2	206.14	206.14	–0.042	2500.9	2500.9	–0.0002	9.1559	9.1558	0
0.01	0.000 611 7	0.001 000 2	206.00	206.00	0.001	2500.9	2500.9	0.0000	9.1555	9.1555	0.01
1	0.000 657 1	0.001 000 1	192.44	192.44	4.177	2498.6	2502.7	0.0153	9.1138	9.1291	1
2	0.000 706 0	0.001 000 1	179.76	179.76	8.392	2496.2	2504.6	0.0306	9.0721	9.1027	2
3	0.000 758 1	0.001 000 1	168.01	168.01	12.604	2493.8	2506.4	0.0459	9.0306	9.0765	3
4	0.000 813 5	0.001 000 1	157.12	157.12	16.813	2491.4	2508.2	0.0611	8.9895	9.0506	4
5	0.000 872 6	0.001 000 1	147.02	147.02	21.019	2489.1	2510.1	0.0763	8.9486	9.0249	5
6	0.000 935 4	0.001 000 1	137.64	137.64	25.224	2486.7	2511.9	0.0913	8.9081	8.9994	6
7	0.001 002	0.001 000 1	128.93	128.93	29.426	2484.3	2513.7	0.1064	8.8678	8.9742	7
8	0.001 073	0.001 000 2	120.83	120.83	33.626	2481.9	2515.6	0.1213	8.8278	8.9492	8
9	0.001 148	0.001 000 3	113.31	113.31	37.824	2479.6	2517.4	0.1362	8.7882	8.9244	9
10	0.001 228	0.001 000 3	106.31	106.31	42.021	2477.2	2519.2	0.1511	8.7488	8.8998	10
11	0.001 313	0.001 000 4	99.792	99.792	46.216	2474.8	2521.1	0.1659	8.7096	8.8755	11
12	0.001 403	0.001 000 5	93.723	93.724	50.410	2472.5	2522.9	0.1806	8.6708	8.8514	12
13	0.001 498	0.001 000 7	88.059	88.070	54.602	2470.1	2524.7	0.1953	8.6322	8.8275	13
14	0.001 599	0.001 000 8	82.797	82.798	58.794	2467.7	2526.5	0.2099	8.5939	8.8038	14
15	0.001 706	0.001 000 9	77.880	77.881	62.984	2465.4	2528.4	0.2245	8.5559	8.7804	15
16	0.001 819	0.001 001 1	73.290	73.291	67.173	2463.0	2530.2	0.2390	8.5181	8.7571	16
17	0.001 938	0.001 001 3	69.005	69.006	71.361	2460.6	2532.0	0.2534	8.4806	8.7341	17
18	0.002 065	0.001 001 5	65.002	65.003	75.548	2458.3	2533.8	0.2678	8.4434	8.7112	18
19	0.002 198	0.001 001 6	61.260	61.261	79.734	2455.9	2535.7	0.2822	8.4064	8.6886	19
20	0.002 339	0.001 001 8	57.760	57.761	83.920	2453.5	2537.5	0.2965	8.3696	8.6661	20
21	0.002 488	0.001 002 1	54.486	54.487	88.105	2451.2	2539.3	0.3108	8.3331	8.6439	21
22	0.002 645	0.001 002 3	51.421	51.422	92.289	2448.8	2541.1	0.3250	8.2969	8.6218	22
23	0.002 811	0.001 002 5	48.551	48.552	96.473	2446.4	2542.9	0.3391	8.2609	8.6000	23
24	0.002 986	0.001 002 8	45.862	45.863	100.66	2444.1	2544.7	0.3532	8.2251	8.5783	24
25	0.003 170	0.001 003 0	43.340	43.341	104.84	2441.7	2546.5	0.3673	8.1895	8.5568	25
26	0.003 364	0.001 003 3	40.976	40.977	109.92	2439.3	2548.4	0.3813	8.1542	8.5355	26
27	0.003 568	0.001 003 5	38.757	38.758	113.20	2437.0	2550.2	0.3952	8.1192	8.5144	27
28	0.003 783	0.001 003 8	36.674	36.675	117.38	2434.6	2552.0	0.4091	8.0843	8.4934	28
29	0.004 009	0.001 004 1	34.718	34.719	121.56	2432.2	2553.8	0.4230	8.0497	8.4727	29
30	0.004 247	0.001 004 4	32.881	32.882	125.75	2429.8	2555.6	0.4368	8.0153	8.4521	30
31	0.004 497	0.001 004 7	31.153	31.154	129.93	2427.5	2557.4	0.4506	7.9812	8.4317	31
32	0.004 759	0.001 005 0	29.528	29.529	134.11	2425.1	2559.2	0.4643	7.9472	8.4115	32
33	0.005 035	0.001 005 4	28.000	28.001	138.29	2422.7	2561.0	0.4780	7.9135	8.3914	33
34	0.005 325	0.001 005 7	26.561	26.562	142.47	2420.3	2562.8	0.4916	7.8800	8.3715	34
35	0.005 629	0.001 006 0	25.207	25.208	146.64	2417.9	2564.6	0.5052	7.8467	8.3518	35
36	0.005 947	0.001 006 4	23.931	23.932	150.82	2415.6	2566.4	0.5187	7.8136	8.3323	36
37	0.006 282	0.001 006 8	22.728	22.729	155.00	2413.2	2568.2	0.5322	7.7807	8.3129	37
38	0.006 632	0.001 007 1	21.594	21.595	159.18	2410.8	2570.0	0.5457	7.7480	8.2936	38
39	0.007 000	0.001 007 5	20.525	20.526	163.36	2408.4	2571.8	0.5591	7.7155	8.2746	39
40	0.007 384	0.001 007 9	19.516	19.517	167.54	2406.0	2573.5	0.5724	7.6832	8.2557	40
41	0.007 787	0.001 008 3	18.564	18.565	171.72	2403.6	2575.3	0.5858	7.6512	8.2369	41
42	0.008 209	0.001 008 7	17.664	17.665	175.90	2401.2	2577.1	0.5990	7.6193	8.2183	42
43	0.008 650	0.001 009 1	16.815	16.816	180.08	2398.8	2578.9	0.6123	7.5876	8.1999	43
44	0.009 112	0.001 009 5	16.012	16.013	184.26	2396.4	2580.7	0.6255	7.5561	8.1816	44
45	0.009 594	0.001 009 9	15.252	15.253	188.44	2394.0	2582.5	0.6386	7.5248	8.1634	45
46	0.010 099	0.001 010 3	14.534	14.535	192.62	2391.6	2584.2	0.6517	7.4937	8.1454	46
47	0.010 626	0.001 010 8	13.855	13.856	196.80	2389.2	2586.0	0.6648	7.4628	8.1276	47
48	0.011 176	0.001 011 2	13.212	13.213	200.98	2386.8	2587.8	0.6778	7.4320	8.1099	48
49	0.011 751	0.001 011 7	12.603	12.604	205.16	2384.4	2589.5	0.6908	7.4015	8.0923	49
50	0.012 351	0.001 012 1	12.027	12.028	209.34	2382.0	2591.3	0.7038	7.3711	8.0749	50
51	0.012 977	0.001 012 6	11.481	11.482	213.52	2379.6	2593.1	0.7167	7.3409	8.0576	51
52	0.013 631	0.001 031 1	10.963	10.964	217.70	2377.1	2594.8	0.7296	7.3109	8.0405	52
53	0.014 312	0.001 013 6	10.472	10.473	221.88	2374.7	2596.6	0.7424	7.2811	8.0235	53
54	0.015 022	0.001 014 0	10.006	10.007	226.06	2372.3	2598.4	0.7552	7.2514	8.0066	54
55	0.015 761	0.001 014 5	9.5639	9.5649	230.24	2369.9	2600.1	0.7680	7.2219	7.9899	55

Properties of Saturated Water and Steam (Temperature) (continued)

t (°C)	Pressure MPa	Volume, m³/kg v_L	Δv	v_v	Enthalpy, kJ/kg h_L	Δh	h_v	Entropy, kJ/(kg°K) s_L	Δs	s_v	t (°C)
56	0.016 532	0.001 015 0	9.1444	9.1454	234.42	2367.4	2601.9	0.7807	7.1926	7.9733	56
57	0.017 335	0.001 015 5	8.7461	8.7471	238.61	2365.0	2603.6	0.7934	7.1634	7.9568	57
58	0.018 171	0.001 016 1	8.3678	8.3688	242.79	2362.6	2605.4	0.8060	7.1344	7.9405	58
59	0.019 041	0.001 016 6	8.0083	8.0093	246.97	2360.1	2607.1	0.8186	7.1056	7.9243	59
60	0.019 946	0.001 017 1	7.6666	7.6677	251.15	2357.7	2608.8	0.8312	7.0770	7.9082	60
61	0.020 887	0.001 017 6	7.3418	7.3428	255.34	2355.2	2610.6	0.8438	7.0485	7.8922	61
62	0.021 866	0.001 018 2	7.0328	7.0338	259.52	2352.8	2612.3	0.8563	7.0201	7.8764	62
63	0.022 884	0.001 018 7	6.7389	6.7399	263.71	2350.3	2614.1	0.8687	6.9919	7.8607	63
64	0.023 942	0.001 019 3	6.4591	6.4601	267.89	2347.9	2615.8	0.8811	6.9639	7.8451	64
65	0.025 041	0.001 019 9	6.1928	6.1938	272.08	2345.4	2617.5	0.8935	6.9361	7.8296	65
66	0.026 183	0.001 020 4	5.9392	5.9402	276.27	2343.0	2619.2	0.9059	6.9083	7.8142	66
67	0.027 368	0.001 021 0	5.6976	5.6986	280.45	2340.5	2621.0	0.9182	6.8808	7.7990	67
68	0.028 599	0.001 021 6	5.4674	5.4684	284.64	2338.0	2622.7	0.9305	6.8534	7.7839	68
69	0.029 876	0.001 022 2	5.2479	5.2490	288.83	2335.6	2624.4	0.9428	6.8261	7.7689	69
70	0.031 201	0.001 022 8	5.0387	5.0397	293.02	2333.1	2626.1	0.9550	6.7990	7.7540	70
71	0.032 575	0.001 023 4	4.8392	4.8402	297.21	2330.6	2627.8	0.9672	6.7720	7.7392	71
72	0.034 000	0.001 024 0	4.6488	4.6498	301.40	2328.1	2629.5	0.9793	6.7452	7.7245	72
73	0.035 478	0.001 024 6	4.4671	4.4681	305.59	2325.6	2631.2	0.9915	6.7185	7.7100	73
74	0.037 009	0.001 025 2	4.2937	4.2947	309.78	2323.1	2632.9	1.0035	6.6920	7.6955	74
75	0.038 595	0.001 025 8	4.1281	4.1291	313.97	2320.6	2634.6	1.0156	6.6656	7.6812	75
76	0.040 239	0.001 026 5	3.9699	3.9709	318.17	2318.1	2636.3	1.0276	6.6393	7.6669	76
77	0.041 941	0.001 027 1	3.8188	3.8198	322.36	2315.6	2638.0	1.0396	6.6132	7.6528	77
78	0.043 703	0.001 027 7	3.6743	3.6754	326.56	2313.1	2639.7	1.0516	6.5872	7.6388	78
79	0.045 527	0.001 028 4	3.5363	3.5373	330.75	2310.6	2641.3	1.0635	6.5613	7.6248	79
80	0.047 415	0.001 029 0	3.4042	3.4053	334.95	2308.1	2643.0	1.0754	6.5356	7.6110	80
81	0.049 368	0.001 029 7	3.2780	3.2790	339.15	2305.5	2644.7	1.0873	6.5100	7.5973	81
82	0.051 387	0.001 030 4	3.1572	3.1582	343.34	2303.0	2646.4	1.0991	6.4846	7.5837	82
83	0.053 476	0.001 031 0	3.0415	3.0426	347.54	2300.5	2648.0	1.1109	6.4592	7.5701	83
84	0.055 636	0.001 031 7	2.9309	2.9319	351.74	2297.9	2649.7	1.1227	6.4340	7.5567	84
85	0.057 867	0.001 032 4	2.8249	2.8259	355.95	2295.4	2651.3	1.1344	6.4090	7.5434	85
86	0.060 174	0.001 033 1	2.7234	2.7244	360.15	2292.8	2653.0	1.1461	6.3840	7.5301	86
87	0.062 556	0.001 033 8	2.6262	2.6272	364.35	2290.3	2654.6	1.1578	6.3592	7.5170	87
88	0.065 017	0.001 034 5	2.5330	2.5341	368.56	2287.7	2656.3	1.1694	6.3345	7.7039	88
89	0.067 559	0.001 035 2	2.4437	2.4448	372.76	2285.1	2657.9	1.1811	6.3099	7.4909	89
90	0.070 182	0.001 035 9	2.3581	2.3591	376.97	2282.6	2659.5	1.1927	6.2854	7.4781	90
91	0.072 890	0.001 036 7	2.2760	2.2771	381.18	2280.0	2661.2	1.2042	6.2611	7.4653	91
92	0.075 685	0.001 037 4	2.1973	2.1983	385.38	2277.4	2662.8	1.2158	6.2368	7.4526	92
93	0.078 568	0.001 038 1	2.1217	2.1228	389.59	2274.8	2664.4	1.2273	6.2127	7.4400	93
94	0.081 542	0.001 038 9	2.0492	2.0502	393.81	2272.2	2666.0	1,2387	6.1887	7.4275	94
95	0.084 609	0.001 039 6	1.9796	1.9806	398.02	2269.6	2667.6	1.2502	6.1648	7.4150	95
96	0.087 771	0.001 040 4	1.9128	1.9138	402.23	2267.0	2669.2	1.2616	6.1411	7.4027	96
97	0.091 031	0.001 041 1	1.8486	1.8497	406.45	2264.4	2670.8	1.2730	6.1174	7.3904	97
98	0.094 390	0.001 041 9	1.7870	1.7880	410.66	2261.7	2672.4	1.2844	6.0938	7.3782	98
99	0.097 852	0.001 042 7	1.7277	1.7288	414.88	2259.1	2674.0	1.2957	6.0704	7.3661	99
100	0.101 42	0.001 043 5	1.6708	1.6719	419.10	2256.5	2675.6	1.3070	6.0471	7.3541	100
101	0.105 09	0.001 044 2	1.6161	1.6171	423.32	2253.8	2677.1	1.3183	6.0238	7.3421	101
102	0.108 87	0.001 045 0	1.5635	1.5645	427.54	2251.2	2678.7	1.3296	6.0007	7.3303	102
103	0.112 77	0.001 045 8	1.5129	1.5140	431.76	2248.5	2680.3	1.3408	5.9777	7.3185	103
104	0.116 78	0.001 046 6	1.4642	1.4653	435.99	2245.9	2681.8	1.3520	5.9548	7.3068	104
105	0.120 90	0.001 047 4	1.4174	1.4185	440.21	2243.2	2683.4	1.3632	5.9320	7.2951	105
106	0.125 15	0.001 048 3	1.3724	1.3734	444.44	2240.5	2684.9	1.3743	5.9092	7.2836	106
107	0.129 51	0.001 049 1	1.3290	1.3301	448.67	2237.8	2686.5	1.3854	5.8866	7.2721	107
108	0.134 01	0.001 049 9	1.2873	1.2883	452.90	2235.1	2588.0	1.3965	5.8641	7.2607	108
109	0.138 63	0.001 050 7	1.2471	1.2481	457.13	2232.4	2689.5	1.4076	5.8417	7.2493	109
110	0.143 38	0.001 051 6	1.2083	1.2094	461.36	2229.7	2691.1	1.4187	5.8194	7.2380	110

Properties of Saturated Water and Steam (Temperature) (continued)

	Pressure	Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			
t (°C)	MPa	v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	t (°C)
111	0.148 26	0.001 052 4	1.1710	1.1721	465.60	2227.0	2692.6	1.4297	5.7972	7.2268	111
112	0.153 28	0.001 053 3	1.1351	1.1362	469.83	2224.3	2694.1	1.4407	5.7750	7.2157	112
113	0.158 43	0.001 054 1	1.1005	1.1015	474.07	2221.5	5695.6	1.4517	5.7530	7.2047	113
114	0.163 73	0.001 055 0	1.0671	1.0681	478.31	2218.8	2697.1	1.4626	5.7310	7.1937	114
115	0.169 18	0.001 055 9	1.0349	1.0359	482.55	2216.0	2698.6	1.4735	5.7092	7.1827	115
116	0.174 77	0.001 056 8	1.0038	1.0049	486.80	2213.3	2700.1	1.4844	5.6874	7.1719	116
117	0.180 51	0.001 057 6	0.973 90	0.974 95	491.04	2210.5	2701.5	1.4953	5.6658	7.1611	117
118	0.186 40	0.001 058 5	0.945 01	0.946 07	495.29	2207.7	2703.0	1.5062	5.6442	7.1504	118
119	0.192 45	0.001 059 4	0.917 14	0.918 20	499.53	2204.9	2704.5	1.5170	5.6227	7.1397	119
120	0.198 67	0.001 060 3	0.890 24	0.891 30	503.78	2202.1	2705.9	1.5278	5.6013	7.1291	120
121	0.205 04	0.001 061 2	0.864 28	0.865 34	508.04	2199.3	2707.4	1.5386	5.5800	7.1186	121
122	0.211 58	0.001 062 2	0.839 21	0.840 28	512.29	2196.5	2708.8	1.5494	5.5587	7.1081	122
123	0.218 29	0.001 063 1	0.815 01	0.816 07	516.55	2193.7	2710.3	1.5601	5.5376	7.0977	123
124	0.225 17	0.001 064 0	0.791 63	0.792 69	520.80	2190.9	2711.7	1.5708	5.5165	7.0873	124
125	0.232 22	0.001 064 9	0.769 05	0.770 11	525.06	2188.0	2713.1	1.5815	5.4955	7.0770	125
126	0.239 46	0.001 065 9	0.747 23	0.748 29	529.32	2185.2	2714.5	1.5922	5.4746	7.0668	126
127	0.246 88	0.001 066 8	0.726 14	0.727 21	533.59	2182.3	2715.9	1.6028	5.4538	7.0566	127
128	0.254 48	0.001 067 8	0.705 76	0.706 83	537.85	2179.5	2717.3	1.6134	5.4330	7.0465	128
129	0.262 27	0.001 068 7	0.686 06	0.687 13	542.12	2176.6	2718.7	1.6240	5.4124	7.0364	129
130	0.270 26	0.001 069 7	0.667 01	0.668 08	546.39	2173.7	2720.1	1.6346	5.3918	7.0264	130
131	0.278 44	0.001 070 7	0.648 59	0.649 66	550.66	2170.8	2721.5	1.6452	5.3713	7.0165	131
132	0.286 82	0.001 071 7	0.630 78	0.631 85	554.93	2167.9	2722.8	1.6557	5.3508	7.0066	132
133	0.295 41	0.001 072 7	0.613 54	0.614 61	559.21	2165.0	2724.2	1.6662	5.5305	6.9967	133
134	0.304 20	0.001 073 6	0.596 87	0.597 94	563.49	2162.0	2725.5	1.6767	5.3102	6.9869	134
135	0.313 20	0.001 074 7	0.580 73	0.581 80	567.77	2159.1	2726.9	1.6872	5.2900	6.9772	135
136	0.322 42	0.001 075 7	0.565 11	0.566 18	572.05	2156.2	2728.2	1.6977	5.2698	6.9675	136
137	0.331 85	0.001 076 7	0.549 99	0.551 06	576.33	2153.2	2729.5	1.7081	5.2498	6.9579	137
138	0.341 51	0.001 077 7	0.535 35	0.536 42	580.62	2150.2	2730.8	1.7185	5.2298	6.9483	138
139	0.351 39	0.001 078 7	0.521 17	0.522 25	584.91	2147.2	2732.1	1.7289	5.2098	6.9388	139
140	0.361 50	0.001 079 8	0.507 44	0.508 52	589.20	2144.2	2733.4	1.7393	5.1900	6.9293	140
141	0.371 85	0.001 080 8	0.494 14	0.495 22	593.49	2141.2	2734.7	1.7496	5.1702	6.9198	141
142	0.382 43	0.001 081 9	0.481 25	0.482 33	597.79	2138.2	2736.0	1,7600	5.1505	6.9105	142
143	0.393 25	0.001 082 9	0.468 77	0.469 85	602.09	2135.2	2737.3	1.7703	5.1308	6.9011	143
144	0.404 32	0.001 084 0	0.456 66	0.457 75	606.39	2132.2	2738.5	1,7806	5.1112	6.8918	144
145	0.415 63	0.001 085 0	0.444 93	0.446 02	610.69	2129.1	2739.8	1,7909	5.0917	6.8826	145
146	0.427 21	0.001 086 1	0.433 56	0.434 65	615.00	2126.0	2741.0	1.8011	5.0723	6.8734	146
147	0.439 03	0.001 087 2	0.422 54	0.423 62	619.31	2123.0	2742.3	1.8114	5.0529	6.8642	147
148	0.451 12	0.001 088 3	0.411 84	0.412 93	623.62	2119.9	2743.5	1.8216	5.0335	6.8551	148
149	0.463 48	0.001 089 4	0.401 47	0.402 56	627.93	2116.8	2744.7	1.8318	5.0143	6.8461	149
150	0.476 10	0.001 090 5	0.391 41	0.392 50	632.25	2113.7	2745.9	1.8420	4.9951	6.8370	150
152	0.502 18	0.001 092 7	0.372 18	0.373 27	640.89	2107.4	2748.3	1.8623	4.9569	6.8191	152
154	0.529 38	0.001 095 0	0.354 07	0.355 16	649.55	2101.1	2750.6	1.8825	4.9189	6.8014	154
156	0.557 76	0.001 097 3	0.337 00	0.338 09	658.21	2094.7	2752.9	1.9027	4.8811	6.7838	156
158	0.587 33	0.001 099 6	0.320 90	0.322 00	666.89	2088.3	2755.2	1.9228	4.8436	6.7664	158
160	0.618 14	0.001 102 0	0.305 72	0.306 82	675.57	2081.9	2757.4	1.9428	4.8063	6.7491	160
162	0.650 22	0.001 104 4	0.291 38	0.292 49	684.28	2075.3	2759.6	1.9627	4.7693	6.7320	162
164	0.683 62	0.001 106 8	0.277 84	0.278 95	692.99	2068.8	2761.7	1.9826	4.7324	6.7150	164
166	0.718 36	0.001 109 3	0.265 05	0.266 16	701.71	2062.1	2763.8	2.0025	4.6957	6.6982	166
168	0.754 50	0.001 111 7	0.252 95	0.254 06	710.45	2055.4	2765.9	2.0222	4.6593	6.6815	168
170	0.792 05	0.001 114 3	0.241 50	0.242 62	719.21	2048.7	2767.9	2.0419	4.6230	6.6649	170
172	0.831 08	0.001 116 8	0.230 67	0.231 78	727.97	2041.9	2769.9	2.0616	4.5870	6.6485	172
174	0.871 61	0.001 119 4	0.220 41	0.221 53	736.75	2035.0	2771.8	2.0811	4.5511	6.6322	174
176	0.913 68	0.001 122 0	0.210 69	0.211 81	745.55	2028.1	2773.6	2.1007	4.5154	6.6161	176
178	0.957 34	0.001 124 7	0.201 47	0.202 60	754.36	2021.1	2775.4	2.1201	4.4799	6.6000	178
180	1.0026	0.001 127 4	0.192 73	0.193 86	763.19	2014.0	2777.2	2.1395	4.4445	6.5841	180

Properties of Saturated Water and Steam (Temperature) (continued)

t (°C)	Pressure MPa	Volume, m³/kg v_L	Δv	v_v	Enthalpy, kJ/kg h_L	Δh	h_v	Entropy, kJ/(kg°K) s_L	Δs	s_v	t (°C)
182	1.0496	0.001 130 1	0.184 44	0.185 57	772.03	2006.9	2778.9	2.1589	4.4094	6.5682	182
184	1.0983	0.001 132 9	0.176 57	0.177 70	780.89	1999.7	2780.6	2.1782	4.3743	6.5525	184
186	1.1487	0.001 135 7	0.169 09	0.170 23	789.76	1992.5	2782.2	2.1974	4.3395	6.5369	186
188	1.2009	0.001 138 6	0.161 99	0.163 13	798.66	1985.1	2783.8	2.2166	4.3048	6.5214	188
190	1.2550	0.001 141 4	0.155 24	0.156 38	807.57	1977.7	2785.3	2.2358	4.2702	6.5060	190
192	1.3110	0.001 144 4	0.148 81	0.149 96	816.49	1970.3	2786.8	2.2549	4.2358	6.4907	192
194	1.3689	0.001 147 3	0.142 70	0.143 85	825.44	1962.7	2788.2	2.2739	4.2015	6.4755	194
196	1.4288	0.001 150 4	0.136 88	0.138 03	834.40	1955.1	2789.5	2.2929	4.1674	6.4603	196
198	1.4907	0.001 153 4	0.131 34	0.132 50	843.39	1947.4	2790.8	2.3119	4.1334	6.4453	198
200	1.5547	0.001 156 5	0.126 07	0.127 22	852.39	1939.7	2792.1	2.3308	4.0995	6.4303	200
202	1.6208	0.001 160	0.121 04	0.122 20	861.42	1931.8	2793.2	2.3497	4.0657	6.4154	202
204	1.6891	0.001 163	0.116 24	0.117 40	870.46	1923.9	2794.4	2.3685	4.0321	6.4006	204
206	1.7596	0.001 166	0.111 66	0.112 83	879.53	1915.9	2795.4	2.3873	3.9985	6.3858	206
208	1.8323	0.001 169	0.107 30	0.108 47	888.62	1907.8	2796.4	2.4060	3.9651	6.3711	208
210	1.9074	0.001 173	0.103 13	0.104 30	897.73	1899.6	2797.4	2.4248	3.9318	6.3565	210
212	1.9848	0.001 176	0.009 15	0.100 32	906.86	1891.4	2798.2	2.4434	3.8985	6.3420	212
214	2.0647	0.001 180	0.095 345	0.096 525	916.02	1883.0	2799.0	2.4621	3.8654	6.3275	214
216	2.1470	0.001 183	0.091 710	0.092 893	925.20	1874.6	2799.8	2.4807	3.8323	6.3130	216
218	2.2319	0.001 187	0.088 235	0.089 421	934.41	1866.0	2800.4	2.4883	3.7993	6.2986	218
220	2.3193	0.001 190	0.084 911	0.086 101	943.64	1857.4	2801.1	2.5178	3.7664	6.2842	220
222	2.4093	0.001 194	0.081 730	0.082 924	952.90	1848.7	2801.6	2.5363	3.7336	6.2699	222
224	2.5020	0.001 198	0.078 685	0.079 883	962.19	1839.9	2802.1	2.5548	3.7008	6.2557	224
226	2.5975	0.001 201	0.075 770	0.076 971	971.50	1830.9	2802.4	2.5733	3.6681	6.2414	226
228	2.6957	0.001 205	0.072 977	0.074 182	980.84	1821.9	2802.8	2.5917	3.6355	6.2272	228
230	2.7968	0.001 209	0.070 301	0.071 510	990.21	1812.8	2803.0	2.6102	3.6029	6.2131	230
232	2.9008	0.001 213	0.067 736	0.068 949	999.61	1803.6	2803.2	2.6285	3.5704	6.1989	232
234	3.0077	0.001 217	0.065 277	0.066 494	1009.0	1794.2	2803.3	2.6469	3.5379	6.1848	234
236	3.1176	0.001 221	0.062 917	0.064 138	1018.5	1784.8	2803.3	2.6653	3.5054	6.1707	236
238	3.2306	0.001 225	0.060 654	0.061 879	1028.0	1775.2	2803.2	2.6836	3.4730	6.1566	238
240	3.3467	0.001 229	0.058 481	0.059 710	1037.5	1765.5	2803.1	2.7019	3.4406	6.1425	240
242	3.4659	0.001 234	0.056 394	0.057 628	1047.1	1757.7	2802.8	2.7203	3.4082	6.1285	242
244	3.5884	0.001 238	0.054 390	0.055 628	1056.7	1745.8	2802.5	2.7385	3.3759	6.1144	244
246	3.7142	0.001 243	0.052 465	0.053 707	1066.3	1735.8	2802.1	2.7568	3.3435	6.1003	246
248	3.8434	0.001 247	0.050 614	0.051 861	1076.0	1725.6	2801.6	2.7751	3.3112	6.0863	248
250	3.9759	0.001 252	0.048 835	0.050 087	1085.7	1715.3	2801.0	2.7934	3.2788	6.0722	250
252	4.1120	0.001 256	0.047 124	0.048 380	1095.4	1704.9	2800.3	2.8117	3.2465	6.0582	252
254	4.2515	0.001 261	0.045 477	0.046 739	1105.2	1694.3	2799.6	2.8299	3.2141	6.0441	254
256	4.3947	0.001 266	0.043 893	0.045 159	1115.0	1683.6	2798.7	2.8482	3.1818	6.0300	256
258	4.5415	0.001 271	0.042 368	0.043 639	1124.9	1672.8	2797.7	2.8664	3.1494	6.0158	258
260	4.6921	0.001 276	0.040 899	0.042 175	1134.8	1661.8	2796.6	2.8847	3.1170	6.0017	260
262	4.8464	0.001 281	0.039 485	0.040 766	1144.8	1650.7	2795.5	2.9030	3.0845	5.9875	262
264	5.0046	0.001 287	0.038 122	0.039 408	1154.8	1639.4	2794.2	2.9213	3.0520	5.9733	264
266	5.1667	0.001 292	0.036 808	0.038 100	1164.8	1628.0	2792.8	2.9396	3.0195	5.9590	266
368	5.3327	0.001 297	0.035 541	0.036 839	1174.9	1616.4	2791.3	2.9579	2.9869	5.9448	268
270	5.5028	0.001 303	0.034 319	0.035 622	1185.1	1604.6	2789.7	2.9762	2.9542	5.9304	270
272	5.671	0.001 309	0.033 141	0.034 450	1195.3	1592.7	2788.0	2.9945	2.9215	5.9160	272
274	5.8555	0.001 315	0.032 003	0.033 318	1205.6	1580.6	2786.1	3.0129	2.8887	5.9016	274
276	6.0381	0.001 321	0.030 905	0.032 226	1215.9	1568.3	2784.1	3.0312	2.8558	5.8871	276
278	6.2251	0.001 327	0.029 845	0.031 172	1226.2	1555.8	2782.0	3.0496	3.8228	5.8725	278
280	6.4165	0.001 333	0.028 821	0.030 154	1236.7	1543.2	2779.8	3.0681	2.7898	5.8578	280
282	6.6123	0.001 339	0.027 832	0.029 171	1247.2	1530.3	2777.5	3.0865	2.7566	5.8431	282
284	6.8126	0.001 346	0.026 875	0.028 221	1257.7	1517.3	2775.0	3.1050	2.7232	5.8283	284
286	7.0176	0.001 352	0.025 950	0.027 303	1268.3	1504.0	2772.3	3.1236	2.6898	5.8134	286
288	7.2272	0.001 359	0.025 056	0.026 415	1279.0	1490.5	2769.6	3.1421	2.6562	5.7984	288
290	7.4416	0.001 366	0.024 191	0.025 557	1289.8	1476.8	2766.6	3.1608	2.6225	5.7832	290

Properties of Saturated Water and Steam (Temperature) (continued)

t (°C)	Pressure MPa	Volume, m³/kg v_L	Δv	v_v	Enthalpy, kJ/kg h_L	Δh	h_v	Entropy, kJ/(kg°K) s_L	Δs	s_v	t (°C)
292	7.6609	0.001 373	0.023 353	0.024 727	1300.6	1462.9	2763.6	3.1794	2.5886	5.7680	292
294	7.8850	0.001 381	0.022 542	0.023 923	1311.5	1448.8	2760.3	3.1982	2.5545	5.7526	294
296	8.1142	0.001 388	0.021 757	0.023 145	1322.5	1434.4	2756.9	3.2170	2.5202	5.7372	296
298	8.3484	0.001 396	0.020 996	0.022 392	1333.6	1419.7	2753.3	3.2358	2.4857	5.7215	298
300	8.5877	0.001 404	0.020 259	0.021 663	1344.8	1404.8	2749.6	3.2547	2.4510	5.7058	300
302	8.8323	0.001 412	0.019 544	0.020 956	1356.0	1389.6	2745.6	3.2737	2.4161	5.6898	302
304	9.0822	0.001 421	0.018 851	0.020 272	1367.4	1374.1	2741.5	3.2928	2.3809	5.6737	304
306	9.3375	0.001 430	0.018 178	0.019 608	1378.8	1358.4	2737.2	3.3120	2.3455	5.6575	306
308	9.5983	0.001 439	0.017 525	0.018 964	1390.4	1342.3	2732.7	3.3312	2.3098	5.6410	308
310	9.8647	0.001 448	0.016 891	0.018 339	1402.0	1325.9	2727.9	3.3506	2.2737	5.6243	310
312	10.137	0.001 457	0.016 275	0.017 732	1413.8	1309.2	2723.0	3.3700	2.2374	5.6074	312
314	10.415	0.001 467	0.015 676	0.017 144	1425.6	1292.1	2717.8	3.3896	2.2007	5.5903	314
316	10.698	0.001 478	0.015 094	0.016 572	1437.6	1274.7	2712.3	3.4093	2.1636	5.5729	316
318	10.988	0.001 488	0.014 528	0.016 016	1449.8	1256.8	2706.6	3.4291	2.1261	5.5553	318
320	11.284	0.001 499	0.013 977	0.015 476	1462.1	1238.6	2700.7	3.4491	2.0882	5.5373	320
322	11.586	0.001 510	0.013 440	0.014 951	1474.5	1220.0	2694.4	3.4692	2.0498	5.5191	322
324	11.894	0.001 522	0.012 917	0.014 439	1487.0	1200.8	2687.9	3.4895	2.0110	5.5005	324
326	12.209	0.001 534	0.012 407	0.013 941	1499.8	1181.3	2681.0	3.5100	1.9715	5.4816	326
328	12.530	0.001 547	0.011 909	0.013 457	1512.7	1161.2	2673.8	3.5307	1.9316	5.4622	328
330	12.858	0.001 561	0.011 423	0.012 984	1525.7	1140.5	2666.2	3.5516	1.8909	5.4425	330
332	13.192	0.001 575	0.010 949	0.012 523	1539.0	1119.3	2658.3	3.5727	1.8496	5.4223	332
334	13.533	0.001 589	0.010 484	0.012 073	1552.5	1097.4	2649.9	3.5940	1.8075	5.4016	334
336	13.882	0.001 604	0.010 029	0.011 634	1566.2	1074.9	2641.1	3.6157	1.7646	5.3803	336
338	14.237	0.001 621	0.009 584	0.011 204	1580.2	1051.7	2631.9	3.6376	1.7208	5.3584	338
340	14.600	0.001 638	0.009 146	0.010 784	1594.4	1027.6	2622.1	3.6599	1.6760	5.3359	340
342	14.970	0.001 655	0.008 717	0.010 372	1609.0	1002.7	2611.7	3.6826	1.6300	5.3127	342
344	15.348	0.001 675	0.008 294	0.009 969	1623.9	976.87	2600.7	3.7058	1.5829	5.2886	344
346	15.734	0.001 695	0.007 878	0.009 573	1639.1	950.00	2589.1	3.7294	1.5344	5.2637	346
348	16.127	0.001 717	0.007 467	0.009 184	1654.8	921.99	2576.7	3.7535	1.4843	5.2378	348
350	16.529	0.001 740	0.007 061	0.008 801	1670.9	892.73	2563.6	3.7783	1.4326	5.2109	350
352	16.939	0.001 765	0.006 659	0.008 424	1687.5	862.02	2549.6	3.8039	1.3789	5.1828	352
354	17.358	0.001 793	0.006 258	0.008 051	1704.8	829.63	2534.4	3.8302	1.3229	5.1531	354
356	17.785	0.001 823	0.005 858	0.007 681	1722.8	795.33	2518.1	3.8577	1.2641	5.1218	356
358	18.221	0.001 857	0.005 456	0.007 313	1741.6	758.77	2500.4	3.8863	1.2022	5.0885	358
360	18.666	0.001 895	0.005 050	0.006 945	1761.5	719.50	2481.0	3.9164	1.1364	5.0527	360
361	18.893	0.001 915	0.004 845	0.006 760	1771.9	698.65	2470.5	3.9321	1.1017	5.0338	361
362	19.121	0.001 937	0.004 637	0.006 574	1782.6	676.87	2459.5	3.9483	1.0657	5.0140	362
363	19.352	0.001 961	0.004 425	0.006 387	1793.8	654.01	2447.8	3.9651	1.0281	4.9932	363
364	19.586	0.001 987	0.004 210	0.006 197	1805.4	629.93	2435.3	3.9827	0.9887	4.9714	364
365	19.822	0.002 016	0.003 989	0.006 004	1817.6	604.41	2422.0	4.0011	0.9471	4.9482	365
366	20.061	0.002 047	0.003 761	0.005 808	1830.4	577.19	2407.6	4.0204	0.9031	4.9235	366
367	20.302	0.002 082	0.003 524	0.005 606	1844.1	547.89	2392.0	4.0410	0.8559	4.8968	367
368	20.546	0.002 122	0.003 276	0.005 398	1858.8	515.99	2374.8	4.0631	0.8048	4.8679	368
369	20.793	0.002 167	0.003 012	0.005 179	1874.8	480.72	2355.5	4.0872	0.7486	4.8358	369
370	21.043	0.002 222	0.002 724	0.004 946	1892.6	440.86	2333.5	4.1142	0.6855	4.7996	370
371	21.296	0.002 290	0.002 401	0.004 691	1913.3	394.20	2307.5	4.1453	0.6120	4.7573	371
372	21.553	0.002 382	0.002 017	0.004 398	1938.5	336.15	2274.7	4.1836	0.5210	4.7046	372
373	21.813	0.002 526	0.001 495	0.004 021	1974.1	253.42	2227.6	4.2377	0.3922	4.6299	373.
373.5	21.945	0.002 658	0.001 087	0.003 745	2003.0	186.19	2189.1	4.2818	0.2879	4.5697	373.5
T_c	22.064	0.003 106	0.	0.003 106	2087.5	0.	2087.5	4.4120	0.	4.4120	T_c

* Values in italics indicate points where thermodynamic equilibrium state is a solid; computed values are for the metastable liquid.
T_c 373.946°C
From ASME International Steam Tables for Industrial Use, pp. 55–59.

Properties of Saturated Water and Steam (Pressure)

p MPa	t (°C)	Volume, m³/kg v_L	Δv	v_v	Enthalpy, kJ/kg h_L	Δh	h_v	Entropy, kJ/(kg°K) s_L	Δs	s_v	p MPa
$^*p_t$	0.010	0.001 000 2	206.00	206.00	0.001	2500.9	2500.9	0.0000	9.1555	9.1555	$^*p_t$
0.0007	1.881	0.001 000 1	181.22	181.22	7.890	2496.5	2504.3	0.0288	9.0770	9.1058	0.0007
0.0008	3.761	0.001 000 1	159.65	159.65	15.809	2492.0	2507.8	0.0575	8.9992	9.0567	0.0008
0.0009	5.444	0.001 000 1	142.76	142.76	22.888	2488.0	2510.9	0.0830	8.9305	9.0135	0.0009
0.0010	6.970	0.001 000 1	129.18	129.18	29.298	2484.4	2513.7	0.1059	8.8690	8.9749	0.0010
0.0012	9.654	0.001 000 3	108.67	108.67	40.569	2478.0	2518.6	0.1460	8.7624	8.9083	0.0012
0.0014	11.969	0.001 000 5	93.902	93.903	50.282	2472.5	2522.8	0.1802	8.6720	8.8521	0.0014
0.0016	14.010	0.001 000 8	82.745	82.746	58.836	2467.7	2526.6	0.2101	8.5935	8.8036	0.0016
0.0018	15.838	0.001 001 1	74.013	74.014	66.494	2463.4	2529.9	0.2366	8.5242	8.7609	0.0018
0.0020	17.495	0.001 001 4	66.989	66.990	73.435	2459.5	2532.9	0.2606	8.4621	8.7227	0.0020
0.0022	19.013	0.001 001 6	61.212	61.213	79.790	2455.9	2535.7	0.2824	8.4059	8.6883	0.0022
0.0024	20.415	0.001 001 9	56.376	56.377	85.656	3452.6	2538.2	0.3024	8.3545	8.6569	0.0024
0.0026	21.718	0.001 002 2	52.266	52.267	91.108	2449.5	2540.6	0.3210	8.3071	8.6280	0.0026
0.0028	22.936	0.001 002 5	48.730	48.731	96.204	2446.6	2542.8	0.3382	8.2632	8.6014	0.0028
0.0030	24.080	0.001 002 8	45.654	45.655	100.99	2443.9	2544.9	0.3543	8.2222	8.5766	0.0030
0.0032	25.159	0.001 003 0	42.953	42.954	105.51	2441.3	2546.8	0.3695	8.1839	8.5534	0.0032
0.0034	26.182	0.001 003 3	40.562	40.563	109.78	2438.9	2548.7	0.3838	8.1479	8.5316	0.0034
0.0036	27.153	0.001 003 6	38.431	38.432	113.84	2436.6	2550.4	0.3973	8.1138	8.5112	0.0036
0.0038	28.078	0.001 003 8	36.518	36.519	117.71	2434.4	2552.1	0.4102	8.0816	8.4918	0.0038
0.0040	28.962	0.001 004 1	34.791	34.792	121.40	2432.3	2553.7	0.4224	8.0510	8.4735	0.0040
0.0042	29.808	0.001 004 4	33.225	33.226	124.94	2430.3	2555.2	0.4341	8.0219	8.4561	0.0042
0.0044	30.619	0.001 004 6	31.798	31.799	128.33	2428.4	2556.7	0.4453	7.9941	8.4395	0.0044
0.0046	31.400	0.001 004 8	30.492	30.493	131.60	2426.5	2558.1	0.4560	7.9676	8.4236	0.0046
0.0048	32.151	0.001 005 1	29.292	29.293	134.74	2424.7	2559.5	0.4663	7.9421	8.4084	0.0048
0.0050	32.875	0.001 005 3	28.185	28.186	137.77	2423.0	2560.8	0.4763	7.9177	8.3939	0.0050
0.0055	34.583	0.001 005 9	25.762	25.763	144.90	2418.9	2563.8	0.4995	7.8605	8.3600	0.0055
0.0060	36.160	0.001 006 4	23.733	23.734	151.49	2415.2	2566.7	0.5209	7.8083	8.3291	0.0060
0.0065	37.628	0.001 007 0	22.009	22.010	157.63	2411.7	2569.3	0.5407	7.7601	8.3008	0.0065
0.0070	39.001	0.001 007 5	20.524	20.525	163.37	2408.4	2571.8	0.5591	7.7155	8.2746	0.0070
0.0075	40.292	0.001 008 0	19.233	19.234	168.76	2405.3	2574.1	0.5763	7.6739	8.2502	0.0075
0.0080	41.510	0.001 008 5	18.098	18.099	173.85	2402.4	2576.2	0.5925	7.6349	8.2274	0.0080
0.0085	42.665	0.001 008 9	17.094	17.095	178.68	2399.6	2578.3	0.6078	7.5982	8.2060	0.0085
0.0090	43.762	0.001 009 4	16.199	16.200	183.26	2397.0	2580.3	0.6223	7.5636	8.1859	0.0090
0.0095	44.808	0.001 009 8	15.395	15.396	187.63	2394.5	2582.1	0.6361	7.5308	8.1669	0.0095
0.010	45.808	0.001 010 3	14.670	14.671	191.81	2392.1	2583.9	0.6492	7.4997	8.1489	0.010
0.011	47.684	0.001 011 1	13.411	13.412	199.66	2387.6	2587.2	0.6737	7.4417	8.1155	0.011
0.012	49.420	0.001 011 9	12.358	12.359	206.91	2383.4	2590.3	0.6963	7.3887	8.0850	0.012
0.013	51.035	0.001 012 6	11.462	11.463	213.66	2379.5	2593.1	0.7172	7.3399	8.0570	0.013
0.014	52.548	0.001 013 3	10.690	10.691	219.99	2375.8	2595.8	0.7366	7.2945	8.0312	0.014
0.015	53.970	0.001 014 0	10.019	10.020	225.94	2372.4	2598.3	0.7548	7.2523	8.0071	0.015
0.016	55.314	0.001 014 7	9.4299	9.4309	231.55	2369.1	2600.7	0.7720	7.2127	7.9847	0.016
0.017	56.588	0.001 015 3	8.9079	8.9089	236.88	2366.0	2602.9	0.7882	7.1754	7.9636	0.017
0.018	57.799	0.001 016 0	8.4423	8.4433	241.95	2363.1	2605.0	0.8035	7.1403	7.9437	0.018
0.019	58.954	0.001 016 6	8.0244	8.0254	246.78	2360.2	2607.0	0.8181	7.1069	7.9250	0.019
0.020	60.059	0.001 017 1	7.6471	7.6482	251.40	2357.5	2608.9	0.8320	7.0753	7.9072	0.020
0.022	62.133	0.001 018 3	6.9927	6.9938	260.08	2352.5	2612.6	0.8579	7.0164	7.8743	0.022
0.024	64.054	0.001 019 3	6.4445	6.4455	268.12	2347.8	2615.9	0.8818	6.9624	7.8442	0.024
0.026	65.843	0.001 020 3	5.9783	5.9793	275.61	2343.4	2619.0	0.9040	6.9127	7.8167	0.026
0.028	67.518	0.001 021 3	5.5769	5.5779	282.62	2339.2	2621.8	0.9246	6.8666	7.7912	0.028
0.030	69.095	0.001 022 2	5.2275	5.2286	289.23	2335.3	2624.6	0.9439	6.8235	7.7675	0.030

Properties of Saturated Water and Steam (Pressure) (continued)

		Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			
p MPa	t (°C)	v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	p MPa
0.032	70.586	0.001 023 1	4.9206	4.9216	295.47	2331.6	2627.1	0.9621	6.7832	7.7453	0.032
0.034	72.000	0.001 024 0	4.6488	4.6498	301.40	2328.1	2629.5	0.9793	6.7452	7.7245	0.034
0.036	73.345	0.001 024 8	4.4063	4.4073	307.04	2324.8	2631.8	0.9956	6.7093	7.7050	0.036
0.038	74.629	0.001 025 6	4.1886	4.1897	312.42	2321.6	2634.0	1.0111	6.6754	7.6865	0.038
0.040	75.857	0.001 026 4	3.9921	3.9931	317.57	2318.5	2636.1	1.0259	6.6431	7.6690	0.040
0.042	77.034	0.001 027 1	3.8137	3.8147	322.50	2315.5	2638.0	1.0400	6.6123	7.6523	0.042
0.044	78.165	0.001 027 8	3.6511	3.6521	327.25	2312.7	2639.9	1.0535	6.5829	7.6365	0.044
0.046	79.254	0.001 028 6	3.5022	3.5032	331.82	2309.9	2641.8	1.0665	6.5548	7.6213	0.046
0.048	80.303	0.001 029 2	3.3653	3.3664	336.22	2307.3	2643.5	1.0790	6.5279	7.6068	0.048
0.050	81.317	0.001 029 9	3.2391	3.2401	340.48	2304.7	2645.2	1.0910	6.5020	7.5930	0.050
0.055	83.709	0.001 031 5	2.9626	2.9636	350.52	2298.7	2649.2	1.1192	6.4414	7.5606	0.055
0.060	85.926	0.001 033 1	2.7308	2.7318	359.84	2293.0	2652.9	1.1452	6.3859	7.5311	0.060
0.065	87.993	0.001 034 5	2.5337	2.5347	368.53	2287.7	2656.2	1.1694	6.3346	7.5040	0.065
0.070	89.932	0.001 035 9	2.3639	2.3649	376.68	2282.7	2659.4	1.1919	6.2871	7.4790	0.070
0.075	91.758	0.001 037 2	2.2160	2.2171	384.37	2278.0	2662.4	1.2130	6.2427	7.4557	0.075
0.080	93.485	0.001 038 5	2.0862	2.0872	391.64	2273.5	2665.2	1.2328	6.2011	7.4339	0.080
0.085	95.125	0.001 039 7	1.9711	1.9721	398.55	2269.3	2667.8	1.2516	6.1618	7.4135	0.085
0.090	96.687	0.001 040 9	1.8684	1.8695	405.13	2265.2	2670.3	1.2694	6.1248	7.3942	0.090
0.095	98.178	0.001 042 0	1.7762	1.7773	411.42	2261.3	2672.7	1.2864	6.0897	7.3760	0.095
0.10	99.606	0.001 043 1	1.6930	1.6940	417.44	2257.5	2674.9	1.3026	6.0562	7.3588	0.10
0.11	102.292	0.001 045 3	1.5485	1.5496	428.77	2250.4	2679.2	1.3328	5.9940	7.3268	0.11
0.12	104.784	0.001 047 3	1.4274	1.4284	439.30	2243.8	2683.1	1.3608	5.9369	7.2976	0.12
0.13	107.109	0.001 049 2	1.3244	1.3254	449.13	2237.5	2686.6	1.3867	5.8842	7.2708	0.13
0.14	109.292	0.001 051 0	1.2356	1.2366	458.37	2231.6	2690.0	1.4109	5.8352	7.2460	0.14
0.15	111.350	0.001 052 7	1.1583	1.1594	467.08	2226.0	2693.1	1.4335	5.7894	7.2229	0.15
0.16	113.298	0.001 054 4	1.0904	1.0914	475.34	2220.7	2696.0	1.4549	5.7464	7.2014	0.16
0.17	115.149	0.001 056 0	1.0302	1.0312	483.18	2215.6	2698.8	1.4752	5.7059	7.1811	0.17
0.18	116.912	0.001 057 6	0.976 48	0.977 53	490.67	2210.7	2701.4	1.4944	5.6677	7.1620	0.18
0.19	118.597	0.001 059 1	0.928 24	0.929 30	497.82	2206.1	2703.9	1.5127	5.6313	7.1440	0.19
0.20	120.212	0.001 060 5	0.884 67	0.885 74	504.68	2201.6	2706.2	1.5301	5.5968	7.1269	0.20
0.21	121.761	0.001 061 9	0.845 13	0.846 19	511.27	2197.2	2708.5	1.5468	5.5638	7.1106	0.21
0.22	123.251	0.001 063 3	0.809 06	0.810 12	517.62	2193.0	2710.6	1.5628	5.5323	7.0951	0.22
0.23	124.688	0.001 064 6	0.776 02	0.777 09	523.73	2188.9	2712.7	1.5782	5.5021	7.0802	0.23
0.24	126.074	0.001 065 9	0.745 65	0.746 72	529.64	2185.0	2714.6	1.5930	5.4731	7.0660	0.24
0.25	127.414	0.001 067 2	0.717 63	0.718 70	535.35	2181.2	2716.5	1.6072	5.4452	7.0524	0.25
0.26	128.711	0.001 068 5	0.691 69	0.692 76	540.88	2177.4	2718.3	1.6210	5.4183	7.0393	0.26
0.27	129.968	0.001 069 7	0.667 62	0.668 69	546.25	2173.8	2720.0	1.6343	5.3924	7.0267	0.27
0.28	131.188	0.001 070 9	0.645 20	0.646 27	551.46	2170.3	2721.7	1.6472	5.3674	7.0146	0.28
0.29	132.373	0.001 072 0	0.624 28	0.625 36	556.53	2166.8	2723.3	1.6597	5.3432	7.0029	0.29
0.30	133.525	0.001 073 2	0.604 71	0.605 79	561.46	2163.4	2724.9	1.6718	5.3198	6.9916	0.30
0.31	136.647	0.001 074 3	0.586 36	0.587 44	566.26	2160.1	2726.4	1.6835	5.2971	6.9806	0.31
0.32	135.740	0.001 075 4	0.569 12	0.570 20	570.93	2156.9	2727.9	1.6950	5.2751	6.9700	0.32
0.33	136.806	0.001 076 5	0.552 89	0.553 97	575.50	2153.8	2729.3	1.7061	5.2537	6.9597	0.33
0.34	137.845	0.001 077 5	0.537 58	0.538 66	579.96	2150.7	2730.6	1.7169	5.2329	6.9498	0.34
0.35	138.861	0.001 078 6	0.523 12	0.524 20	584.31	2147.7	2732.0	1.7275	5.2126	6.9401	0.35
0.36	139.853	0.001 079 6	0.509 43	0.510 51	588.57	2144.7	2733.3	1.7378	5.1929	6.9307	0.36
0.37	140.823	0.001 080 6	0.496 46	0.497 54	592.74	2141.8	2734.5	1.7478	5.1737	6.9215	0.37
0.38	141.773	0.001 081 6	0.484 15	0.485 23	596.81	2138.9	2735.7	1.7576	5.1550	6.9126	0.38
0.39	142.702	0.001 082 6	0.472 44	0.473 53	600.81	2136.1	2736.9	1.7672	5.1367	6.9039	0.39
0.40	143.613	0.001 083 6	0.461 31	0.462 39	604.72	2133.3	2738.1	1.7766	5.1188	6.8954	0.40

Properties of Saturated Water and Steam (Pressure) (continued)

		Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			p
p MPa	t (°C)	v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	MPa
0.42	145.380	0.001 085 5	0.440 57	0.441 66	612.33	2127.9	2740.3	1.7948	5.0843	6.8791	0.42
0.44	147.081	0.001 087 3	0.421 66	0.422 75	619.66	2122.7	2742.4	1.8122	5.0513	6.8635	0.44
0.46	148.721	0.001 089 1	0.404 34	0.405 43	626.73	2117.6	2744.4	1.8289	5.0197	6.8486	0.46
0.48	150.305	0.001 090 8	0.388 41	0.389 50	633.57	2112.7	2746.3	1.8450	4.9892	6.8343	0.48
0.50	151.836	0.001 092 6	0.373 71	0.374 80	640.19	2107.9	2748.1	1.8606	4.9600	6.8206	0.50
0.52	153.320	0.001 094 2	0.360 11	0.361 20	646.60	2103.2	2749.9	1.8756	4.9318	6.8074	0.52
0.54	154.758	0.001 095 9	0.347 48	0.348 57	652.83	2098.7	2751.5	1.8901	4.9045	6.7947	0.54
0.56	156.155	0.001 097 5	0.335 72	0.336 82	658.88	2094.2	2753.1	1.9042	4.8782	6.7824	0.56
0.58	157.512	0.001 099 1	0.324 74	0.325 84	664.77	2089.9	2754.7	1.9179	4.8528	6.7706	0.58
0.60	158.832	0.001 100 6	0.314 47	0.315 58	670.50	2085.6	2756.1	1.9311	4.8281	6.7592	0.60
0.62	160.118	0.001 102 1	0.304 85	0.305 95	676.09	2081.5	2757.6	1.9440	4.8041	6.7481	0.62
0.64	161.371	0.001 103 6	0.295 80	0.296 90	681.54	2077.4	2758.9	1.9565	4.7809	6.7374	0.64
0.66	162.594	0.001 105 1	0.287 28	0.288 39	686.86	2073.4	2760.2	1.9686	4.7583	6.7269	0.66
0.68	163.787	0.001 106 5	0.279 25	0.280 35	692.06	2069.5	2761.5	1.9805	4.7363	6.7168	0.68
0.70	164.953	0.001 108 0	0.271 66	0.272 76	697.14	2065.6	2762.7	1.9921	4.7149	6.7070	0.70
0.72	166.092	0.001 109 4	0.264 47	0.265 58	702.12	2061.8	2763.9	2.0034	4.6940	6.6974	0.72
0.74	167.207	0.001 110 8	0.257 66	0.268 77	706.99	2058.1	2765.1	2.0144	4.6737	6.6881	0.74
0.76	168.298	0.001 112 1	0.251 20	0.252 31	711.76	2054.4	2766.2	2.0252	4.6539	6.6790	0.76
0.78	169.366	0.001 113 5	0.245 06	0.246 17	716.43	2050.8	2767.3	2.0357	4.6345	6.6702	0.78
0.80	170.414	0.001 114 8	0.239 21	0.240 33	721.02	2047.3	2768.3	2.0460	4.6156	6.6615	0.80
0.82	171.440	0.001 116 1	0.233 64	0.234 76	725.52	2043.8	2769.3	2.0561	4.5970	6.6531	0.82
0.84	172.447	0.001 117 4	0.228 33	0.229 44	729.93	2040.4	2770.3	2.0659	4.5789	6.6449	0.84
0.86	173.435	0.001 118 7	0.223 25	0.224 37	734.27	2037.0	2771.2	2.0756	4.5612	6.6368	0.86
0.88	174.405	0.001 119 9	0.218 40	0.219 52	738.53	2033.6	2772.1	2.0851	4.5438	6.6289	0.88
0.90	175.358	0.001 121 2	0.213 75	0.214 87	742.72	2030.3	2773.0	2.0944	4.5268	6.6212	0.90
0.92	176.294	0.001 122 4	0.209 30	0.210 42	746.85	2027.1	2773.9	2.1035	4.5102	6.6137	0.92
0.94	177.214	0.001 123 6	0.205 03	0.206 16	750.90	2023.8	2774.7	2.1125	4.4938	6.6063	0.94
0.96	178.119	0.001 124 9	0.200 94	0.202 06	754.89	2020.7	2775.6	2.1213	4.4778	6.5991	0.96
0.98	179.010	0.001 126 0	0.197 00	0.198 13	758.82	2017.5	2776.3	2.1299	4.4620	6.5919	0.98
1.00	179.886	0.001 127 2	0.193 22	0.194 35	762.58	2014.4	2777.1	2.1384	4.4465	6.5850	1.00
1.05	182.017	0.001 130 1	0.184 37	0.185 50	772.10	2006.8	2779.0	2.1591	4.4091	6.5681	1.05
1.10	184.070	0.001 133 0	0.176 30	0.177 44	781.20	1999.5	2780.7	2.1789	4.3731	6.5520	1.10
1.15	186.050	0.001 135 8	0.168 91	0.170 05	789.99	1992.3	2782.3	2.1979	4.3386	6.5365	1.15
1.20	187.965	0.001 138 5	0.161 11	0.163 25	798.50	1985.3	2783.8	2.2163	4.3054	6.5217	1.20
1.25	189.817	0.001 141 2	0.155 84	0.156 98	806.75	1978.4	2785.2	2.2340	4.2734	6.5074	1.25
1.30	191.613	0.001 143 8	0.150 03	0.151 17	814.76	1971.7	2786.5	2.2512	4.2425	6.4936	1.30
1.35	193.355	0.001 146 4	0.144 64	0.145 79	822.55	1965.2	2787.7	2.2678	4.2126	6.4804	1.35
1.40	195.047	0.001 148 9	0.139 62	0.140 77	830.13	1958.8	2788.9	2.2839	4.1836	6.4675	1.40
1.45	196.693	0.001 151 4	0.134 93	0.136 08	837.52	1952.5	2790.0	2.2995	4.1556	6.4551	1.45
1.50	198.295	0.001 153 9	0.130 55	0.131 70	844.72	1946.3	2791.0	2.3147	4.1284	6.4431	1.50
1.55	199.856	0.001 156 3	0.126 44	0.127 59	851.74	1940.2	2792.0	2.3294	4.1019	6.4314	1.55
1.60	201.378	0.001 158 7	0.122 57	0.123 73	858.61	1934.3	2792.9	2.3438	4.0762	6.4200	1.60
1.65	202.864	0.001 161 0	0.118 94	0.120 10	865.32	1928.4	2793.7	2.3578	4.0512	6.4090	1.65
1.70	204.315	0.001 163 4	0.115 50	0.116 67	871.89	1922.6	2794.5	2.3715	4.0268	6.3983	1.70
1.75	205.733	0.001 165 7	0.112 26	0.113 43	878.32	1917.0	2795.3	2.3848	4.0030	6.3878	1.75
1.80	207.120	0.001 167 9	0.109 19	0.110 36	884.61	1911.4	2796.0	2.3978	3.9798	6.3776	1.80
1.85	208.477	0.001 170 2	0.106 29	0.107 46	890.79	1905.9	2796.6	2.4105	3.9571	6.3676	1.85
1.90	209.806	0.001 172 4	0.103 53	0.104 70	896.84	1900.4	2797.3	2.4229	3.9350	6.3579	1.90
1.95	211.108	0.001 174 6	0.100 90	0.102 08	902.79	1895.1	2797.8	2.4351	3.9133	6.3484	1.95
2.0	212.385	0.001 176 8	0.098 404	0.099 581	908.62	1889.8	2798.4	2.4470	3.8921	6.3392	2.0

Properties of Saturated Water and Steam (Pressure) (continued)

		Volume, m³/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			
p MPa	*t* (°C)	v_L	Δv	v_v	h_L	Δ*h*	h_v	s_L	Δ*s*	s_v	*p* MPa
2.1	214.865	0.001 181 0	0.093 753	0.094 934	919.99	1879.4	2799.4	2.4701	3.8511	6.3212	2.1
2.2	217.256	0.001 185 2	0.089 510	0.090 695	930.98	1869.2	2800.2	2.4924	3.8116	6.3040	2.2
2.3	219.564	0.001 189 4	0.085 623	0.086 812	941.63	1859.3	2800.9	2.5138	3.7736	6.2874	2.3
2.4	221.795	0.001 193 4	0.082 049	0.083 242	951.95	1849.6	2801.5	2.5244	3.7370	6.2714	2.4
2.5	223.956	0.001 197 4	0.078 750	0.079 947	961.98	1840.1	2802.0	2.5544	3.7015	6.2560	2.5
2.6	226.052	0.001 201 4	0.075 696	0.076 897	971.74	1830.7	2802.5	2.5738	3.6673	6.2411	2.6
2.7	228.086	0.001 205 3	0.072 860	0.074 065	981.24	1821.5	2802.8	2.5925	3.6341	6.2266	2.7
2.8	230.063	0.001 209 1	0.070 219	0.071 428	990.50	1812.5	2803.0	2.6107	3.6019	6.2126	2.8
2.9	231.986	0.001 212 9	0.067 754	0.068 967	999.54	1803.6	2803.2	2.6284	3.5706	6.1990	2.9
3.0	233.858	0.001 216 7	0.065 447	0.066 664	1008.4	1794.9	2803.3	2.6456	3.5402	6.1878	3.0
3.1	235.684	0.001 220 4	0.063 284	0.064 504	1017.0	1786.3	2803.3	2.6624	3.5105	6.1729	3.1
3.2	237.464	0.001 224 1	0.061 251	0.062 475	1025.5	1777.8	2803.2	2.6787	3.4817	6.1604	3.2
3.3	239.203	0.001 227 8	0.059 336	0.060 564	1033.7	1769.4	2803.1	2.6946	3.4535	6.1481	3.3
3.4	240.901	0.001 231 4	0.057 530	0.058 761	1041.8	1761.1	2803.0	2.7102	3.4260	6.1362	3.4
3.5	242.562	0.001 235 0	0.055 823	0.057 058	1049.8	1753.0	2802.7	2.7254	3.3991	6.1245	3.5
3.6	244.186	0.001 238 5	0.054 208	0.055 446	1057.6	1744.9	2802.5	2.7403	3.3728	6.1131	3.6
3.7	245.776	0.001 242 1	0.052 676	0.053 918	1065.2	1736.9	2802.1	2.7548	3.3471	6.1019	3.7
3.8	247.334	0.001 245 6	0.051 222	0.052 468	1072.8	1729.0	2801.8	2.7690	3.3219	6.0910	3.8
3.9	248.861	0.001 249 1	0.049 840	0.051 089	1080.2	1721.2	2801.4	2.7830	3.2973	6.0802	3.9
4.0	250.358	0.001 252 6	0.048 524	0.049 777	1087.4	1713.5	2800.9	2.7967	3.2731	6.0697	4.0
4.1	251.826	0.001 256 0	0.047 270	0.048 526	1094.6	1705.8	2800.4	2.8101	3.2493	6.0594	4.1
4.2	253.267	0.001 259 5	0.046 073	0.047 333	1101.6	1698.2	2799.9	2.8232	3.2260	6.0492	4.2
4.3	254.683	0.001 262 9	0.044 930	0.046 193	1108.6	1690.7	2799.3	2.8362	3.2031	6.0393	4.3
4.4	256.073	0.001 206 3	0.043 836	0.045 103	1115.4	1683.2	2798.7	2.8488	3.1806	6.0294	4.4
4.5	257.439	0.001 269 7	0.042 790	0.044 059	1122.1	1675.9	2798.0	2.8613	3.1585	6.0198	4.5
4.6	258.783	0.001 273	0.041 787	0.043 060	1128.8	1668.5	2797.3	2.8736	3.1367	6.0103	4.6
4.7	260.104	0.001 276	0.040 825	0.042 101	1135.3	1661.2	2796.6	2.8857	3.1153	6.0010	4.7
4.8	261.404	0.001 280	0.039 901	0.041 181	1141.8	1654.0	2795.8	2.8975	3.0942	5.9917	4.8
4.9	262.683	0.001 283	0.039 013	0.040 296	1148.2	1646.8	2795.0	2.9092	3.0734	5.9827	4.9
5.0	263.943	0.001 286	0.038 160	0.039 446	1154.5	1639.7	2794.2	2.9207	3.0530	5.9737	5.0
5.1	265.183	0.001 290	0.037 338	0.038 628	1160.7	1632.7	2793.4	2.9321	3.0328	5.9649	5.1
5.2	266.405	0.001 293	0.036 547	0.037 840	1166.9	1625.6	2792.5	2.9433	3.0129	5.9562	5.2
5.3	267.610	0.001 296	0.035 785	0.037 081	1173.0	1618.6	2791.6	2.9543	2.9933	5.9475	5.3
5.4	268.797	0.001 300	0.035 049	0.036 349	1179.0	1611.7	2790.7	2.9652	2.9739	5.9390	5.4
5.5	269.967	0.001 303	0.034 339	0.035 642	1184.9	1604.8	2789.7	2.9759	3.9548	5.9307	5.5
5.6	271.121	0.001 306	0.033 654	0.034 960	1190.8	1597.9	2788.7	2.9865	2.9359	5.9224	5.6
5.7	272.260	0.001 309	0.032 991	0.034 300	1196.6	1591.1	2787.7	2.9969	2.9173	5.9141	5.7
5.8	273.383	0.001 313	0.032 350	0.033 663	1202.4	1584.3	2786.7	3.0072	2.8988	5.9060	5.8
5.9	274.492	0.001 316	0.031 730	0.033 046	1208.1	1577.6	2785.6	3.0174	2.8806	5.8980	5.9
6.0	275.586	0.001 319	0.031 129	0.032 449	1213.7	1570.8	2784.6	3.0274	2.8626	5.8901	6.0
6.1	276.667	0.001 323	0.030 548	0.031 870	1219.3	1564.1	2783.5	3.0374	2.8448	5.8822	6.1
6.2	277.734	0.001 326	0.029 984	0.031 310	1224.9	1557.5	2782.3	3.0472	2.8272	5.8744	6.2
6.3	278.788	0.001 329	0.029 437	0.030 766	1230.3	1550.8	2781.2	3.0569	2.8098	5.8667	6.3
6.4	279.830	0.001 332	0.028 907	0.030 239	1235.8	1544.2	2780.0	3.0665	2.7926	5.8591	6.4
6.5	280.859	0.001 336	0.028 392	0.029 728	1241.2	1537.7	2778.8	3.0760	2.7755	5.8515	6.5
6.6	281.876	0.001 339	0.027 892	0.029 231	1246.5	1531.1	2777.6	3.0854	2.7586	5.8440	6.6
6.7	282.881	0.001 342	0.027 406	0.028 748	1251.8	1524.6	2776.4	3.0947	2.7419	5.8366	6.7
6.8	283.875	0.001 345	0.026 934	0.028 279	1257.1	1518.1	2775.1	3.1039	2.7253	5.8292	6.8
6.9	284.858	0.001 349	0.026 475	0.027 823	1262.3	1511.6	2773.9	3.1130	2.7089	5.8219	6.9
7.0	285.830	0.001 352	0.026 028	0.027 380	1267.4	1505.1	2772.6	3.1220	2.6926	5.8146	7.0

Properties of Saturated Water and Steam (Pressure) (continued)

		Volume, m^3/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			
p MPa	*t* (°C)	v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	*p* MPa
7.1	286.791	0.001 355	0.025 593	0.026 948	1272.6	1498.7	2771.3	3.1309	2.6765	5.8074	7.1
7.2	287.743	0.001 358	0.025 169	0.026 528	1277.7	1492.3	2769.9	3.1398	2.6605	5.8003	7.2
7.3	288.684	0.001 362	0.024 757	0.026 119	1282.7	1485.9	2768.6	3.1485	2.6447	5.7932	7.3
7.4	289.615	0.001 365	0.024 355	0.025 720	1287.7	1479.5	2767.2	3.1572	2.6290	5.7862	7.4
7.5	290.537	0.001 368	0.023 963	0.025 331	1292.7	1473.1	2765.8	3.1658	2.6134	5.7792	7.5
7.6	291.449	0.001 371	0.023 581	0.024 952	1297.6	1466.8	2764.4	3.1743	2.5979	5.7722	7.6
7.7	292.352	0.001 375	0.023 208	0.024 583	1302.5	1460.4	2763.0	3.1827	2.5826	5.7653	7.7
7.8	293.247	0.001 378	0.022 845	0.024 223	1307.4	1454.1	2761.5	3.1911	2.5673	5.7584	7.8
7.9	294.132	0.001 381	0.022 490	0.023 871	1312.3	1447.8	2760.1	3.1994	2.5522	5.7516	7.9
8.0	295.009	0.001 385	0.022 143	0.023 528	1317.1	1441.5	2758.6	3.2077	2.5372	5.7448	8.0
8.1	295.878	0.001 388	0.021 804	0.023 192	1321.9	1435.3	2757.1	3.2158	2.5223	5.7381	8.1
8.2	296.738	0.001 391	0.021 473	0.022 865	1326.6	1429.0	2755.6	3.2239	2.5075	5.7314	8.2
8.3	297.591	0.001 395	0.021 150	0.022 545	1331.3	1422.7	2754.1	3.2320	2.4928	5.7247	8.3
8.4	298.435	0.001 398	0.020 834	0.022 232	1336.0	1416.5	2752.5	3.2399	2.4782	5.7181	8.4
8.5	299.272	0.001 401	0.020 525	0.021 926	1340.7	1410.3	2751.0	3.2478	2.4637	5.7115	8.5
8.6	300.102	0.001 405	0.020 222	0.021 627	1345.3	1404.0	2749.4	3.2557	2.4493	5.7050	8.6
8.7	300.924	0.001 408	0.019 926	0.021 334	1350.0	1397.8	2747.8	3.2635	2.4349	5.6984	8.7
8.8	301.738	0.001 411	0.019 636	0.021 048	1354.5	1391.6	2746.2	3.2712	2.4207	5.6919	8.8
8.9	302.546	0.001 415	0.019 353	0.020 767	1359.1	1385.4	2744.5	3.2789	2.4065	5.6855	8.9
9.0	303.347	0.001 418	0.019 075	0.020 493	1363.7	1379.2	2742.9	3.2866	2.3924	5.6790	9.0
9.1	304.141	0.001 422	0.018 803	0.020 224	1368.2	1373.0	2741.2	3.2942	2.3784	5.6726	9.1
9.2	304.928	0.001 425	0.018 536	0.019 961	1372.7	1366.9	2739.5	3.3017	2.3645	5.6662	9.2
9.3	305.709	0.001 428	0.018 275	0.019 703	1371.1	1360.7	2737.8	3.3092	2.3507	5.6598	9.3
9.4	306.483	0.001 432	0.018 019	0.019 450	1381.6	1354.5	2736.1	3.3166	2.3369	5.6535	9.4
9.5	307.251	0.001 435	0.017 767	0.019 203	1386.0	1348.4	2734.4	3.3240	2.3232	5.6472	9.5
9.6	308.013	0.001 439	0.017 521	0.018 960	1390.4	1342.2	2732.6	3.3313	2.3095	5.6409	9.6
9.7	308.768	0.001 442	0.017 279	0.018 721	1394.8	1336.1	2730.9	3.3386	2.2960	5.6346	9.7
9.8	309.518	0.001 446	0.017 042	0.018 488	1399.2	1329.9	2729.1	3.3459	2.2824	5.6283	9.8
9.9	310.262	0.001 449	0.016 809	0.018 259	1403.5	1323.8	2727.3	3.3531	2.2690	5.6221	9.9
10.0	310.999	0.001 453	0.016 581	0.018 034	1407.9	1317.6	2725.5	3.3603	2.2556	5.6159	10.0
10.2	312.458	0.001 460	0.016 136	0.017 596	1416.5	1305.3	2721.8	3.3745	2.2290	5.6035	10.2
10.4	313.895	0.001 467	0.015 707	0.017 174	1425.0	1293.0	2718.0	3.3886	2.2026	5.5912	10.4
10.6	315.311	0.001 474	0.015 293	0.016 767	1433.5	1280.7	2714.2	3.4025	2.1764	5.5789	10.6
10.8	316.706	0.001 481	0.014 893	0.016 374	1441.9	1268.4	2710.3	3.4163	2.1504	5.5667	10.8
11.0	318.081	0.001 489	0.014 505	0.015 994	1450.3	1256.1	2706.4	3.4300	2.1246	5.5545	11.0
11.2	319.437	0.001 496	0.014 130	0.015 626	1458.6	1243.8	2702.4	3.4435	2.0989	5.5424	11.2
11.4	320.774	0.001 503	0.013 767	0.015 271	1466.8	1231.4	2698.3	3.4569	2.0734	5.5303	11.4
11.6	322.093	0.001 511	0.013 415	0.014 926	1475.0	1219.1	2694.1	3.4702	2.0480	5.5182	11.6
11.8	323.394	0.001 519	0.013 074	0.014 593	1483.2	1206.7	2689.9	3.4834	2.0228	5.5062	11.8
12.0	324.678	0.001 526	0.012 743	0.014 269	1491.3	1194.3	2685.6	3.4965	1.9977	5.4941	12.0
12.2	325.946	0.001 534	0.012 421	0.013 955	1499.4	1181.8	2681.2	3.5095	1.9726	5.4821	12.2
12.4	327.197	0.001 542	0.012 108	0.013 650	1507.5	1169.3	2676.7	3.5224	1.9477	5.4700	12.4
12.6	328.432	0.001 550	0.011 803	0.013 354	1515.5	1156.7	2672.2	3.5352	1.9228	5.4580	12.6
12.8	329.652	0.001 558	0.011 507	0.013 065	1523.4	1144.1	2667.6	3.5479	1,8980	5.4459	12.8
13.0	330.857	0.001 506	0.011 219	0.012 785	1531.4	1131.5	2662.9	3.5606	1.8733	5.4339	13.0
13.2	332.047	0.001 575	0.010 937	0.012 512	1539.3	1118.8	2658.1	3.5732	1.8486	5.4218	13.2
13.4	333.223	0.001 583	0.010 663	0.012 247	1547.2	1106.0	2653.2	3.5857	1.8240	5.4097	13.4
13.6	334.385	0.001 592	0.010 396	0.011 988	1555.1	1093.1	2648.3	3.5982	1.7993	5.3975	13.6
13.8	335.534	0.001 601	0.010 134	0.011 735	1563.0	1080.2	2643.2	3.6106	1.7747	5.3853	13.8
14.0	336.669	0.001 610	0.009 879	0.011 489	1570.9	1067.2	2638.1	3.6230	1.7500	5.3730	14.0

Properties of Saturated Water and Steam (Pressure) (continued)

		Volume, m^3/kg			Enthalpy, kJ/kg			Entropy, kJ/(kg°K)			
p MPa	*t* (°C)	v_L	Δv	v_v	h_L	Δh	h_v	s_L	Δs	s_v	*p* MPa
14.2	337.792	0.001 619	0.009 630	0.011 248	1578.7	1054.1	2632.9	3.6353	1.7254	5.3607	14.2
14.4	338.902	0.001 628	0.009 385	0.011 014	1586.6	1040.9	2627.5	3.6477	1.7007	5.3484	14.4
14.6	339.999	0.001 638	0.009 147	0.010 784	1594.4	1027.6	2622.1	3.6599	1.6760	5.3359	14.6
14.8	341.084	0.001 647	0.008 912	0.010 560	1602.3	1014.2	2616.5	3.6722	1.6512	5.3234	14.8
15.0	342.158	0.001 657	0.008 683	0.010 340	1610.2	1000.7	2610.9	3.6844	1.6264	5.3108	15.0
15.2	343.220	0.001 667	0.008 458	0.010 125	1618.0	987.07	2605.1	3.6967	1.6014	5.2981	15.2
15.4	344.270	0.001 677	0.008 237	0.009 915	1625.9	973.30	2599.2	3.7089	1.5764	5.2853	15.4
15.6	345.310	0.001 688	0.008 021	0.009 709	1633.8	959.39	2593.2	3.7212	1.5513	5.2724	15.6
15.8	346.339	0.001 699	0.007 808	0.009 506	1641.7	945.34	2587.1	3.7334	1.5260	5.2594	15.8
16.0	347.357	0.001 710	0.007 599	0.009 308	1649.7	931.13	2580.8	3.7457	1.5006	5.2463	16.0
16.2	348.364	0.001 721	0.007 393	0.009 114	1657.6	916.76	2574.4	3.7580	1.4750	5.2330	16.2
16.4	349.361	0.001 732	0.007 190	0.008 923	1665.7	902.22	2567.9	3.7703	1.4493	5.2196	16.4
16.6	350.349	0.001 744	0.006 991	0.008 736	1673.8	887.50	2561.2	3.7827	1.4234	5.2061	16.6
16.8	351.326	0.001 757	0.006 794	0.008 551	1681.9	872.55	2554.4	3.7952	1.3973	5.1924	16.8
17.0	352.293	0.001 769	0.006 600	0.008 369	1690.0	857.38	2547.4	3.8077	1.3708	5.1785	17.0
17.2	353.252	0.001 782	0.006 408	0.008 190	1698.3	841.96	2540.2	3.8203	1.3441	5.1644	17.2
17.4	354.200	0.001 796	0.006 218	0.008 014	1706.6	826.29	2532.9	3.8329	1.3171	5.1501	17.2
17.6	355.140	0.001 810	0.006 030	0.007 840	1715.0	810.34	2525.3	3.8457	1.2898	5.1355	17.6
17.8	356.070	0.001 824	0.005 844	0.007 668	1723.4	794.09	2517.5	3.8586	1.2620	5.1206	17.8
18.0	356.992	0.001 839	0.005 659	0.007 499	1732.0	777.51	2509.5	3.8717	12339	5.1055	18.0
18.2	357.905	0.001 855	0.005 476	0.007 331	1740.7	760.57	2501.3	3.8849	1.2052	5.0901	18.2
18.4	358.809	0.001 872	0.005 293	0.007 164	1749.5	743.24	2492.8	3.8982	1.1761	5.0743	18.4
18.6	359.704	0.001 889	0.005 111	0.006 999	1785.5	752.49	2484.0	3.9118	1.1464	5.0582	18.6
18.8	360.592	0.001 907	0.004 929	0.006 836	1767.6	707.27	2474.9	3.9256	1.1160	5.0416	18.8
19.0	361.471	0.001 925	0.004 747	0.006 673	1776.9	688.52	2465.4	3.9396	1.0849	5.0246	19.0
19.2	362.342	0.001 945	0.004 565	0.006 510	1786.4	669.18	2455.6	3.9540	1.0530	5.0070	19.2
19.4	363.205	0.001 966	0.004 381	0.006 348	1796.1	649.19	2445.3	3.9687	1.0202	4.9888	19.4
19.6	364.060	0.001 989	0.004 197	0.006 186	1806.1	628.46	2434.6	3.9838	0.9863	4.9700	19.6
19.8	364.907	0.002 013	0.004 010	0.006 022	1816.4	606.87	2423.3	3.9993	0.9511	4.9299	19.8
20.0	365.746	0.002 039	0.003 820	0.005 858	1827.1	584.29	2411.4	4.0154	0.9145	4.9299	20.0
20.2	366.577	0.002 067	0.003 626	0.005 692	1838.2	560.55	2398.8	4.0321	0.8762	4.9083	20.2
20.4	367.401	0.002 097	0.003 426	0.005 523	1849.8	535.43	2385.3	4.0496	0.8359	4.8855	20.4
20.6	368.218	0.002 131	0.003 220	0.005 351	1862.1	508.63	2370.8	4.0681	0.7930	4.8612	20.6
20.8	369.026	0.002 169	0.003 004	0.005 173	1875.2	479.74	2355.0	4.0879	0.7471	4.8349	20.8
21.0	369.827	0.002 212	0.002 776	0.004 988	1889.4	448.15	2337.5	4.1093	0.6970	4.8062	21.0
21.2	370.621	0.002 262	0.002 529	0.004 791	1905.0	412.91	2317.9	4.1328	0.6414	4.7742	21.2
21.4	371.406	0.002 324	0.002 255	0.004 579	1922.8	372.44	2295.2	4.1597	0.5778	4.7375	21.4
21.6	372.182	0.002 403	0.001 936	0.004 338	1944.0	323.61	2267.6	4.1918	0.5015	4.6933	21.6
21.8	372.950	0.002 517	0.001 527	0.004 044	1971.9	258.69	2230.6	4.2343	0.4004	4.6347	21.8
22.0	373.707	0.002 750	0.000 826	0.003 577	2021.9	142.27	2164.2	4.3109	0.2199	4.5308	22.0
p_c	373.946	0.003 106	0	0.003 106	2087.5	0	2087.5	4.4120	0	4.4120	p_c

*P_t = 611.657 Pa

p_c = 22.064 MPa

From ASME International Steam Tables for Industrial Use, pp. 60–64.

Thermal Conductivity of Water and Steam (mW·m⁻¹·K⁻¹)

	Pressure (MPa)													
t (°C)	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
Sat Liq.	635.7	650.8	667.8	677.6	683.6	683.6	674.7	654.4	600.5	524.5	403.7			
Sat. Vap.	19.9	21.1	23.0	24.8	27.0	31.0	35.4	41.6	55.6	79.0	226.5			
0	562.0	562.0	562.0	562.0	562.1	562.3	562.6	563.2	564.9	567.8	573.6	590.6	603.5	616.0
10	581.9	581.9	581.9	582.0	582.0	582.2	582.5	583.0	584.7	587.5	593.0	608.8	621.4	633.4
20	599.5	599.5	599.5	599.5	599.6	599.7	600.0	600.6	602.2	604.8	610.1	625.4	637.5	649.1
25	607.5	607.5	607.5	607.5	607.6	607.7	608.0	608.5	610.1	612.7	617.9	633.0	645.0	656.4
30	615.0	615.0	615.0	615.0	615.1	615.2	615.5	616.0	617.6	620.2	625.3	640.2	652.1	663.4
40	628.6	628.6	628.6	628.6	628.7	628.8	629.1	629.6	631.1	633.7	638.8	633.5	665.1	676.3
50	20.3	640.5	640.5	640.5	640.6	640.7	641.0	641.5	643.0	645.6	650.6	665.2	676.8	687.8
60	21.0	650.8	650.8	650.8	650.9	651.0	651.3	651.8	653.3	655.9	661.0	675.5	687.1	698.1
70	21.8	21.9	659.6	659.6	659.7	659.8	660.1	660.6	662.2	664.8	669.8	684.5	696.1	707.2
80	22.6	22.7	667.0	667.0	667.0	667.2	667.5	668.0	669.6	672.2	677.4	692.2	703.9	715.1
90	23.4	23.5	23.6	673.0	673.1	673.2	673.5	674.1	675.7	678.3	683.6	698.7	710.5	721.8
100	24.3	24.3	24.4	24.8	677.8	678.0	678.3	678.8	680.5	683.2	688.6	704.0	716.0	727.5
110	25.1	25.1	25.2	25.5	681.3	681.5	681.8	682.3	684.1	686.9	692.4	708.2	720.5	732.1
120	26.0	26.0	26.1	26.3	683.6	683.8	684.1	684.7	686.4	689.4	695.1	711.3	723.8	735.7
130	26.8	26.8	26.9	27.1	27.6	684.9	685.2	685.9	687.7	690.7	696.6	713.3	726.2	738.4
140	27.7	27.7	27.8	27.9	28.4	685.0	685.3	685.9	687.8	691.0	697.1	714.3	727.7	740.2
150	28.6	28.6	28.7	28.8	29.2	683.9	684.2	684.9	686.9	690.2	696.5	714.4	728.2	741.0
160	29.5	29.5	29.6	29.7	30.0	31.4	682.1	682.8	684.9	688.3	695.0	713.6	727.8	741.0
170	30.4	30.4	30.5	30.6	30.8	32.0	678.9	679.6	681.8	685.4	692.4	711.8	726.5	740.2
180	31.4	31.4	31.4	31.5	31.7	32.7	35.4	675.4	677.7	681.5	688.9	709.1	724.5	738.6
190	32.3	32.3	32.3	32.4	32.6	33.4	35.6	670.1	672.6	676.6	684.4	705.6	721.6	736.2
200	33.2	33.3	33.3	33.4	33.5	34.2	36.1	663.8	666.4	670.7	678.9	701.3	717.9	733.2
220	35.2	35.2	35.2	35.3	35.4	36.0	37.3	41.5	650.9	655.8	665.2	690.2	708.4	724.9
240	37.2	37.2	37.2	37.3	37.4	37.8	38.8	41.8	630.9	636.7	647.5	675.8	696.0	714.0
260	39.2	39.2	39.2	39.3	39.4	39.8	40.6	42.8	606.0	613.0	625.8	658.4	681.0	700.8
280	41.3	41.3	41.3	41.4	41.5	41.8	42.5	44.2	53.7	584.0	599.7	637.8	663.3	685.2
300	43.4	43.4	43.4	43.5	43.6	43.9	44.5	46.0	53.0	548.1	568.3	614.0	643.0	667.4
320	45.6	45.6	45.6	45.7	45.7	46.0	46.6	47.8	53.5	74.7	530.4	586.8	620.3	647.6
340	47.8	47.8	47.8	47.9	47.9	48.2	48.7	49.8	54.5	69.8	483.1	556.0	595.1	625.9
360	50.0	50.0	50.1	50.1	50.2	50.4	50.9	51.9	56.0	67.7	419.8	521.1	567.4	602.3
380	52.3	52.3	52.3	52.4	52.5	52.7	53.1	54.1	57.6	66.7	129.4	481.7	537.2	576.9
400	54.6	54.7	54.7	54.7	54.8	55.0	55.4	56.3	59.5	67.2	103.4	438.3	504.7	550.0
420	57.0	57.0	57.0	57.1	57.2	57.4	57.8	58.6	61.6	68.3	94.6	391.5	470.4	521.9
440	59.4	59.4	59.4	59.5	59.5	59.8	60.1	60.9	63.7	69.7	90.8	342.0	434.7	492.7
460	61.9	61.9	61.9	61.9	62.0	62.2	62.6	63.3	65.9	71.4	89.1	289.0	398.9	463.1
480	64.3	64.3	64.4	64.4	64.5	64.7	65.0	65.8	68.2	73.3	88.7	240.3	363.9	433.5
500	66.8	66.8	66.9	66.9	67.0	67.2	67.5	68.2	70.6	75.3	89.1	205.5	330.9	404.8
520	69.4	69.4	69.4	69.4	69.5	69.7	70.0	70.7	73.0	77.5	90.0	182.8	300.6	377.7
540	72.0	72.0	72.0	72.0	72.1	72.3	72.6	73.3	75.4	79.7	91.2	168.2	273.8	352.7
560	74.6	74.6	74.6	74.6	74.7	74.9	75.2	75.8	77.9	82.0	92.7	158.5	251.4	329.9
580	77.2	77.2	77.2	77.2	77.3	77.5	77.8	78.4	80.5	84.3	94.4	152.0	233.4	309.6
600	79.8	79.9	79.9	79.9	80.0	80.1	80.4	81.0	83.0	86.8	96.2	147.7	219.2	291.7
620	82.5	82.5	82.6	82.6	82.6	82.8	83.1	83.7	85.6	89.2	98.2	144.8	208.2	276.2
640	85.2	85.3	85.3	85.3	85.4	85.5	85.8	86.4	88.2	91.7	100.3	142.9	199.8	263.0
660	88.0	88.0	88.0	88.0	88.1	88.2	88.5	89.1	90.9	94.3	102.5	141.9	193.3	252.0
680	90.7	90.7	90.8	90.8	90.8	91.0	91.3	91.8	93.6	96.9	104.7	141.4	188.3	242.7
700	93.5	93.5	93.5	93.6	93.6	93.8	94.0	94.6	96.3	99.5	107.0	141.4	184.5	235.0

Thermal Conductivity of Water and Steam ($mW \cdot m^{-1} \cdot K^{-1}$) (continued)

	Pressure (MPa)													
t (°C)	0.01	0.02	0.05	0.1	0.2	0.5	1	2	5	10	20	50	75	100
720	96.3	96.3	96.3	96.4	96.4	96.6	96.8	97.4	99.0	102.1	109.4	141.8	181.7	228.7
740	99.1	99.1	99.2	99.2	99.2	99.4	99.6	100.2	101.8	104.8	111.8	142.5	179.6	223.5
760	102.0	102.0	102.0	102.0	102.1	102.2	102.5	103.0	104.6	107.5	114.3	143.5	178.2	219.3
780	104.8	104.8	104.8	104.9	104.9	105.1	105.3	105.8	107.4	110.2	116.8	144.6	177.2	215.9
800	107.7	107.7	107.7	107.7	107.8	107.9	108.2	108.6	110.2	113.0	119.3	145.9	176.7	213.2

From ASME International Steam Tables for Industrial Use, p. 149.

5

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Constants

Types of Numbers

Natural numbers

The set of *natural numbers*, {0, 1, 2, …}, is customarily denoted by $\mathbb{N}$. Many authors do not consider 0 to be a natural number.

Integers

The set of *integers*, {0, ±1, ±2, …}, is customarily denoted by $\mathbb{Z}$. The *positive integers* are {1, 2, 3, …}.

Rational numbers

The set of *rational numbers*, $\left\{\frac{p}{q} \middle| p, q \in \mathbb{Z}, q \neq 0\right\}$, is customarily denoted by $\mathbb{Q}$. Two fractions $\frac{p}{q}$ and $\frac{r}{s}$ are equal if and only if $ps = qr$.

Addition of fractions is defined by $\frac{p}{q} + \frac{r}{s} = \frac{ps + qr}{qs}$. Multiplication of fractions is defined by $\frac{p}{q} \cdot \frac{r}{s} = \frac{pr}{qs}$.

Real numbers

The set of *real numbers* is customarily denoted by $\mathbb{R}$. Real numbers are defined to be converging sequences of rational numbers or as decimals that might or might not repeat.

Real numbers are often divided into two subsets. One subset, the *algebraic numbers*, are real numbers which solve a polynomial equation in one variable with integer coefficients. For example: $\frac{1}{\sqrt{2}}$ is an algebraic number because it solves the polynomial equation $2x^2 - 1 = 0$; and all rational numbers are algebraic. Real numbers that are not algebraic numbers are called *transcendental numbers*. Examples of transcendental numbers include π and e.

Complex numbers

The set of *complex numbers* is customarily denoted by $\mathbb{C}$. They are numbers of the form $a + bi$, where $i^2 = -1$, and a and b are real numbers.

Operation	Computation	Result
addition	$(a + bi) + (c + di)$	$(a + c) + i(b + d)$
multiplication	$(a + bi)(c + di)$	$(ac - bd) + (ad + bc)i$
reciprocal	$\frac{1}{a+bi}$	$\frac{a}{a^2+b^2} - \frac{b}{a^2+b^2}i$
complex conjugate	$z = a + bi$	$\bar{z} = a - bi$

Properties include: $\overline{z + w} = \bar{z} + \bar{w}$ and $\overline{zw} = \bar{z}\bar{w}$.

From Bolinger, K., Glasser, M.L., Gross, R., and Sloane, N.J.A., Analysis, in *CRC Standard Mathematical Tables and Formulae*, 31st ed., Zwillinger, D., Ed., CRC Press, Boca Raton, FL, 2003, p. 3.

Decimal Multiples and Prefixes

The prefix names and symbols below re taken from Conference Générale des Poids et Mesures, 1991. The common names are for the U.S.

Factor	Prefix	Symbol	Common Name
$10^{(10^{100})}$			googolplex
10^{100}			googol
10^{24}	yotta	Y	heptillion
10^{21}	zetta	Z	hexillion
10^{18}	exa	E	quintillion
10^{15}	peta	P	quadrillion
10^{12}	tera	T	trillion
10^{9}	giga	G	billion
10^{6}	mega	M	million
10^{3}	kilo	k	thousand
10^{2}	hecto	H	hundred
10^{1}	deka	da	ten
10^{-1}	deci	d	tenth
10^{-2}	centi	c	hundreth
10^{-3}	milli	m	thousandth
10^{-6}	micro	μ (Greek mu)	millionth
10^{-9}	nano	n	billionth
10^{-12}	pico	p	trillionth
10^{-15}	femto	f	quadrillionth
10^{-18}	atto	a	quintillionth
10^{-21}	zepto	z	hexillionth
10^{-24}	yocto	y	heptillionth

From Bolinger, K., Glasser, M.L., Gross, R., and Sloane, N.J.A., Analysis, in *CRC Standard Mathematical Tables and Formulae*, 31st ed., Zwillinger, D., Ed., CRC Press, Boca Raton, FL, 2003, p. 6.

Powers of 10 In Hexadecimal Scale

n	10^n	10^{-n}
0	1_{16}	1_{16}
1	A_{16}	$0.19999999999999999999\ldots_{16}$
2	64_{16}	$0.028F5C28F5C28F5C28F5\ldots_{16}$
3	$3E8_{16}$	$0.004189374BC6A7EF9DB2\ldots_{16}$
4	2710_{16}	$0.00068DB8BAC710CB295E\ldots_{16}$
5	$186A0_{16}$	$0.000A7C5AC471B478412\ldots_{16}$
6	$F4240_{16}$	$0.000010C6F7A0B5ED8D36\ldots_{16}$
7	989680_{16}	$0.000001AD7F29ABCAF485\ldots_{16}$
8	$5F5E100_{16}$	$0.0000002AF31DC4611873\ldots_{16}$
9	$3B9ACA00_{16}$	$0.000000044B82FA09B5A5\ldots_{16}$
10	$2540BE400_{16}$	$0.000000006DF37F675EF6\ldots_{16}$
11	$174876E800_{16}$	$0.000000000AFEBFF0BCB2\ldots_{16}$
12	$E8D4A51000_{16}$	$0.00000000119799812DE\ldots_{16}$
13	$9184E72A000_{16}$	$0.00000000001C25C26849\ldots_{16}$
14	$5AF3107A4000_{16}$	$0.000000000002D09370D4\ldots_{16}$
15	$38D7EA4C68000_{16}$	$0.000000000000480EBE7B\ldots_{16}$
16	$2386F26FC10000_{16}$	$0.0000000000000734ACA5\ldots_{16}$

From Bolinger, K., Glasser, M.L., Gross, R., and Sloane, N.J.A., Analysis, in *CRC Standard Mathematical Tables and Formulae*, 31st ed., Zwillinger, D., Ed., CRC Press, Boca Raton, FL, 2003, p. 13.

Factorials

For non-negative integers n, the factorial of n, denoted $n!$, is the product of all positive integers less than or equal to n; $n! = n\cdot(n-1)\cdot(n-2)\cdots 2\cdot 1$. If n is a negative integer ($n = -1, -2, \ldots$) then $n! = \pm\infty$. Note that, since the empty product is 1, it follows that $0! = 1$. The generalization of the factorial function to non-integer arguments is the gamma function. When n is an integer, $\Gamma(n) = (n-1)!$.

The double factorial of n, denoted $n!!$, is the product of every other integer: $n!! = n\cdot(n-2)\cdot(n-4)\cdots$, where the last element in the product is either 2 or 1, depending on whether n is even or odd. The *shifted factorial* (also called the *rising factorial and Pochhammer's symbol*) is denoted by $(a)_n$ (sometimes $a^{\bar{n}}$) and is defined as

$$(a)_n = \underbrace{a\cdot(a+1)\cdot(a+2)\cdots(a+n-1)}_{n\ terms} = \frac{(a+n-1)!}{(a-1)!} = \frac{\Gamma(a+n)}{\Gamma(a)}$$

Approximations to $n!$ for large n include Stirling's formula

$$n! \approx \sqrt{2\pi e}\left(\frac{n}{e}\right)^{n+\frac{1}{2}}$$

and Burnsides's formula

$$n! \approx \sqrt{2\pi}\left(\frac{n+\frac{1}{2}}{e}\right)^{n+\frac{1}{2}}$$

n	$n!$	$\log_{10} n!$	$n!!$	$\log_{10} n!!$
0	1	0.00000	1	0.00000
1	1	0.00000	1	0.00000
2	2	0.30103	2	0.30103
3	6	0.77815	3	0.47712
4	24	1.38021	8	0.90309
5	120	2.07918	15	1.17609
6	720	2.85733	48	1.68124
7	5040	3.70243	105	2.02119
8	40320	4.60552	384	2.58433
9	3.6288×10^{5}	5.55976	945	2.97543
10	3.6288×10^{6}	6.55976	3840	3.58433
11	3.9917×10^{7}	7.60116	10395	4.01682
12	4.7900×10^{8}	8.68034	46080	4.66351
13	6.2270×10^{9}	9.79428	1.3514×10^{5}	5.13077
14	8.7178×10^{10}	10.94041	6.4512×10^{5}	5.80964
15	1.3077×10^{12}	12.11650	2.0270×10^{6}	6.30686
16	2.0923×10^{13}	13.32062	1.0322×10^{7}	7.01376
17	3.5569×10^{14}	14.55107	3.4459×10^{7}	7.53731
18	6.4024×10^{15}	15.80634	1.8579×10^{8}	8.26903
19	1.2165×10^{17}	17.08509	6.5473×10^{8}	8.81606
20	2.4329×10^{18}	18.38612	3.7159×10^{9}	9.57006
21	5.1091×10^{19}	19.70834	1.3749×10^{10}	10.13828
22	1.1240×10^{21}	21.05077	8.1750×10^{10}	10.91249
23	2.5852×10^{22}	22.41249	3.1623×10^{11}	11.50001
24	6.2045×10^{23}	23.79271	1.9620×10^{12}	12.29270
25	1.5511×10^{25}	25.19065	7.9059×10^{12}	12.89795
30	2.6525×10^{32}	32.42366	4.2850×10^{16}	16.63195
40	8.1592×10^{47}	47.91165	2.5511×10^{24}	24.40672
50	3.0414×10^{64}	64.48307	5.2047×10^{32}	32.71640

Factorials (continued)

60	8.3210×10^{81}	81.92017	2.8481×10^{41}	41.45456
70	1.1979×10^{100}	100.07841	3.5504×10^{50}	50.55028
80	7.1569×10^{118}	118.85473	8.9711×10^{59}	59.95284
90	1.4857×10^{138}	138.17194	4.2088×10^{69}	69.62416
100	9.3326×10^{157}	157.97000	3.4243×10^{79}	79.53457
110	1.5882×10^{178}	178.20092	4.5744×10^{89}	89.66033
120	6.6895×10^{198}	198.82539	9.5934×10^{99}	99.98197
130	6.4669×10^{219}	219.81069	3.0428×10^{110}	110.48328
140	1.3462×10^{241}	241.12911	1.4141×10^{121}	121.15050
150	5.7134×10^{262}	262.75689	9.3726×10^{131}	131.97186
500	1.2201×10^{1134}	1134.0864	5.8490×10^{567}	567.76709
1000	4.0239×10^{2567}	2567.6046	3.9940×10^{1284}	1284.6014

From Bolinger, K., Glasser, M.L., Gross, R., and Sloane, N.J.A., Analysis, in *CRC Standard Mathematical Tables and Formulae*, 31st ed., Zwillinger, D., Ed., CRC Press, Boca Raton, FL, 2003, pp. 17–18.

Prime Numbers

1. A *prime number* is a positive integer greater than 1 with no positive, integral divisors other than 1 and itself. There are infinitely many prime numbers, 2, 3, 5, 7,…. The sum of the reciprocals of the prime numbers diverges: $\sum_n \frac{1}{pn} = \frac{1}{3} + \frac{1}{5} + \frac{1}{7} + \cdots = \infty$.
2. *Twin primes* are prime numbers that differ by two: (3, 5), (5, 7), (11, 13), (17, 19),…. It is not known whether there are infinitely many twin primes. The sum of the reciprocals of the twin primes converges; the value

$$B = \left(\frac{1}{3} + \frac{1}{5}\right) + \left(\frac{1}{5} + \frac{1}{7}\right) + \left(\frac{1}{11} + \frac{1}{13}\right) + \cdots + \left(\frac{1}{p} + \frac{1}{p+2}\right) + \cdots$$

   known as Brun's constant is approximately $B \approx 1.90216054$.
3. For every integer $n \geq 2$, the numbers $\{n! + 2, n! + 3, \ldots, n! + n\}$ are a sequence of $n - 1$ consecutive composite (i.e., not prime) numbers.
4. *Dirichlet's theorem on primes in arithmetic progressions*: Let a and b be relatively prime positive integers. Then the arithmetic progression $an + b$ (for $n = 1, 2, \ldots$) contains infinitely many primes.
5. *Goldbach conjecture*: every even number is the sum of two prime numbers.
6. The function $\pi(x)$ represents the number of primes less than x. The prime number theorem states that $\pi(x) \sim x/\log x$ as $x \to \infty$. The exact number of primes less than a given number is:

x	100	1000	10,000	10^5	10^6	10^7	10^8
$\pi(x)$	25	168	1,229	9,592	78,498	664,579	5,761,455

x	10^{10}	10^{15}	10^{21}
$\pi(x)$	455,052,511	29,844,570,422,669	21,127,269,486,018,731,928

From Driscoll, P.J., Gross, R., Michaels, J., Nelsen, R.B., and Wilson, B., Algebra, in *CRC Standard Mathematical Tables and Formulae*, 31st ed., Zwillinger, D., Ed., CRC Press, Boca Raton, FL, 2003, p. 103.

Reliability

1. The *reliability* of a product is the probability that the product will function within specified limits for at least a specified period of time.
2. A *series system* is one in which the entire system will fail if any of its components fail.
3. A *parallel system* is one in which the entire system will fail only if all of its components fail.
4. Let R_i denote the reliability of the i^{th} component.
5. Let R_s denote the reliability of a series system.
6. Let R_p denote the reliability of a series system.

The *product law of reliabilities* states

$$R_s = \prod_{i=1}^{n} R_i$$

The *product law of unreliabilities* states

$$R_p = 1 - \prod_{i=1}^{n} \left(1 - R_i\right)$$

From Mascagni, M., Rinaman, W.C., Sousa, M., and Strauss, M.T., Probability and statistics, in *CRC Standard Mathematical Tables and Formulae*, 31st ed., Zwillinger, D., Ed., CRC Press, Boca Raton, FL, 2003, p. 653.

Conversion: Metric to English

Multiply	By	To Obtain
centimeters	0.3937008	inches
cubic meters	1.307951	cubic yards
cubic meters	35.31467	cubic feet
grams	0.03527396	ounces
kilograms	2.204623	pounds
kilometers	0.6213712	miles
liters	0.2641721	gallons (US)
meters	1.093613	yards
meters	3.280840	feet
milliliters	0.03381402	fluid ounces
milliliters	0.06102374	cubic inches
square centimeters	0.1550003	square inches
square meters	1.195990	square yards
square meters	10.76391	square feet

From Gross, R., Katz, V.J., and Strauss, M.T., Miscellaneous, in *CRC Standard Mathematical Tables and Formulae*, 31st ed., Zwillinger, D., Ed., CRC Press, Boca Raton, FL, 2003, p. 796.

Conversion: English to Metric

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	16.38706	milliliters
cubic yards	0.7645549	cubic meters
feet	0.3048000	meters
fluid ounces	29.57353	milliliters
gallons (US)	3.785412	liters
inches	2.540000	centimeters
miles	1.609344	kilometers
mils	25.4	micrometers

Conversion: English to Metric (continued)

Multiply	By	To Obtain
ounces	28.34952	grams
pounds	0.4535924	kilograms
square feet	0.09290304	square meters
square inches	6.451600	square centimeters
square yards	0.8361274	square meters
yards	0.9144000	meters

From Gross, R., Katz, V.J., and Strauss, M.T., Miscellaneous, in *CRC Standard Mathematical Tables and Formulae*, 31st ed., Zwillinger, D., Ed., CRC Press, Boca Raton, FL, 2003, p. 797.

Interpretations of Powers of 10

10^{-15}	the radius of the hydrogen nucleus (a proton) in meters
10^{-11}	the likelihood of being dealt 13 top honors in bridge
10^{-10}	the radius of a hydrogen atom in meters
10^{-9}	the number of seconds it takes light to travel one foot
10^{-6}	the likelihood of being dealt a royal flush in poker
10^{0}	the density of water is 1 gram per milliliter
10^{1}	the number of fingers that people have
10^{2}	the number of sable elements in the periodic table
10^{5}	the number of hairs on a human scalp
10^{6}	the number of possible chess board positions after 4 moves
10^{7}	the number of seconds in a year
10^{8}	the speed of light in meters per second
10^{9}	the number of heartbeats in a lifetime for most mammals
10^{10}	the number of people on the earth
10^{15}	the surface area of the earth in square meters
10^{16}	the age of the universe in seconds
10^{18}	the volume of water in the earth's oceans in cubic meters
10^{19}	the number of possible positions of Rubik's cube
10^{21}	the volume of the earth in cubic meters
10^{24}	the number of grains of sand in the Sahara desert
10^{28}	the mass of the earth in grams
10^{33}	the mass of the solar system in grams
10^{50}	the number of atoms in the earth
10^{78}	the volume of the universe in cubic meters

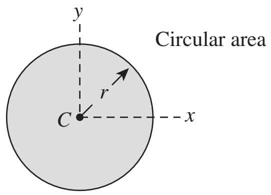
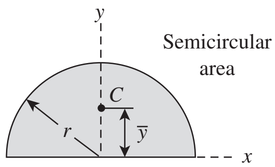
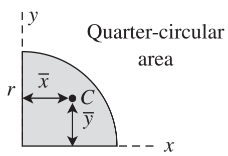
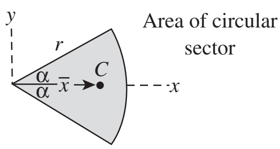
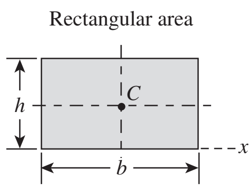
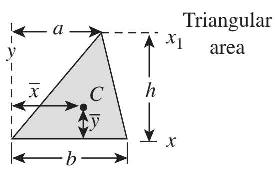
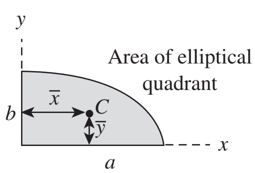
From Gross, R., Katz, V.J., and Strauss, M.T., Miscellaneous, in *CRC Standard Mathematical Tables and Formulae*, 31st ed., Zwillinger, D., Ed., CRC Press, Boca Raton, FL, 2003, pp. 798–799.

Typical Values for Coefficients of Static Friction

Materials	μ_s
Metal on ice	0.03–0.05
Wood on wood	0.30–0.70
Leather on wood	0.20–0.50
Leather on metal	0.30–0.60
Aluminum on aluminum	1.10–1.70

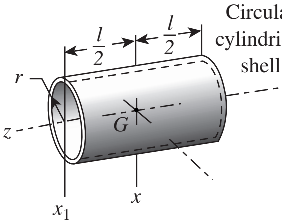
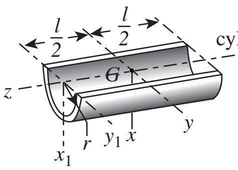
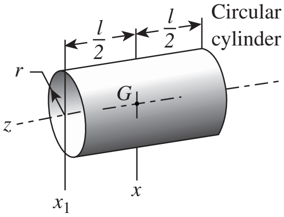
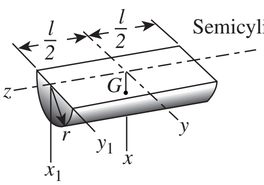
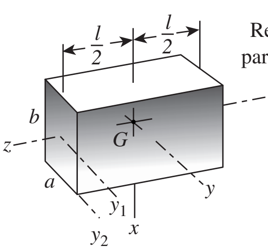
From Hibbeler, R.C., Force-system resultants and equilibrium, in *the Engineering Handbook,* Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1996, p. 8.

Properties of Plane Areas

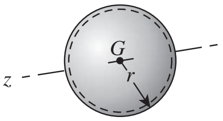
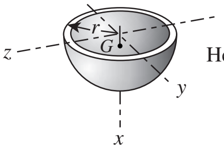
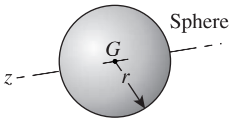
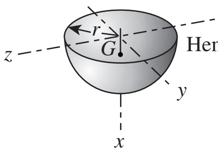
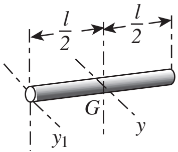
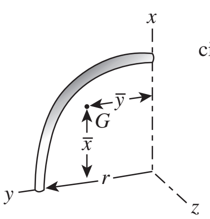
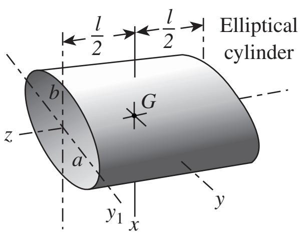
Figure	Centroid	Area Moments of Inertia
	—	$I_x = I_y = \frac{\pi r^4}{4}$ $I_z = \frac{\pi r^4}{2}$
	$\bar{y} = \frac{4r}{3\pi}$	$I_x = I_y = \frac{\pi r^4}{8}$ $\bar{I}_x = \left(\frac{\pi}{8} - \frac{8}{9\pi}\right) r^4$ $I_z = \frac{\pi r^4}{4}$
	$\bar{x} = \bar{y} = \frac{4r}{3\pi}$	$I_x = I_y = \frac{\pi r^4}{16}$ $\bar{I}_x = \bar{I}_y = \left(\frac{\pi}{16} - \frac{4}{9\pi}\right) r^4$ $I_z = \frac{\pi r^4}{8}$
	$\bar{x} = \frac{2}{3} \frac{r \sin\alpha}{\alpha}$	$I_x = \frac{r^4}{4}\left(\alpha - \frac{1}{2}\sin 2\alpha\right)$ $I_y = \frac{r^4}{4}\left(\alpha + \frac{1}{2}\sin 2\alpha\right)$ $I_z = \frac{1}{2} r^4 \alpha$
	—	$I_x = \frac{bh^3}{3}$ $\bar{I}_x = \frac{bh^3}{12}$ $\bar{I}_z = \frac{bh}{12}(b^2 + h^2)$
	$\bar{x} = \frac{a+b}{3}$ $\bar{y} = \frac{h}{3}$	$I_x = \frac{bh^3}{12}$ $I_x = \frac{bh^3}{36}$ $I_{x_1} = \frac{bh^3}{4}$
	$\bar{x} = \frac{4a}{3\pi}$ $\bar{y} = \frac{4b}{3\pi}$	$I_x = \frac{\pi ab^3}{16}, \quad \bar{I}_x = \left(\frac{\pi}{16} - \frac{4}{9\pi}\right) ab^3$ $I_y = \frac{\pi a^3 b}{16}, \quad \bar{I}_y = \left(\frac{\pi}{16} - \frac{4}{9\pi}\right) a^3 b$ $I_z = \frac{\pi ab}{16}\left(a^2 + b^2\right)$

From Meriam, J.L., Moments of inertia, in *The Engineering Handbook,* Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1996, p. 30. Originally from Meriam, J. L. and Kraige, L. G. 1992. *Engineering Mechanics*, 3rd ed. John Wiley & Sons, New York.

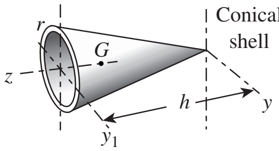
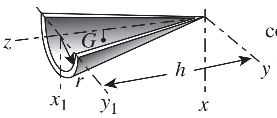
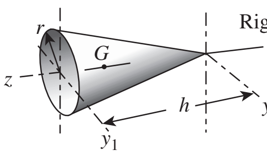
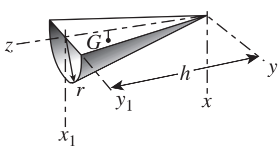
Moments of Inertia of Homogeneous Solids (m = Mass of Body Shown)

Body	Mass Center	Mass Moments of Inertia
 Circular cylindrical shell	—	$I_{xx} = \frac{1}{2}mr^2 + \frac{1}{12}ml^2$ $I_{x_1x_1} = \frac{1}{2}mr^2 + \frac{1}{3}ml^2$ $I_{zz} = mr^2$
 Half cylindrical shell	$\bar{x} = \frac{2r}{\pi}$	$I_{xx} = I_{yy}$ $= \frac{1}{2}mr^2 + \frac{1}{12}ml^2$ $I_{x_1x_1} = I_{y_1y_1}$ $= \frac{1}{2}mr^2 + \frac{1}{3}ml^2$ $I_{zz} = mr^2$ $\bar{I}_{zz} = \left(1 - \frac{4}{\pi^2}\right)mr^2$
 Circular cylinder	—	$I_{xx} = \frac{1}{4}mr^2 + \frac{1}{12}ml^2$ $I_{x_1x_1} = \frac{1}{4}mr^2 + \frac{1}{3}ml^2$ $I_{zz} = \frac{1}{2}mr^2$
 Semicylinder	$\bar{x} = \frac{4r}{3\pi}$	$I_{xx} = I_{yy}$ $= \frac{1}{4}mr^2 + \frac{1}{12}ml^2$ $I_{x_1x_1} = I_{y_1y_1}$ $= \frac{1}{4}mr^2 + \frac{1}{3}ml^2$ $I_{zz} = \frac{1}{2}mr^2$ $\bar{I}_{zz} = \left(\frac{1}{2} - \frac{16}{9\pi^2}\right)mr^2$
 Rectangular parallelepiped	—	$I_{xx} = \frac{1}{12}m(a^2 + l^2)$ $I_{yy} = \frac{1}{12}m(b^2 + l^2)$ $I_{zz} = \frac{1}{12}m(a^2 + b^2)$ $I_{y_1y_1} = \frac{1}{12}mb^2 + \frac{1}{3}ml^2$ $I_{y_2y_2} = \frac{1}{3}m(b^2 + l^2)$

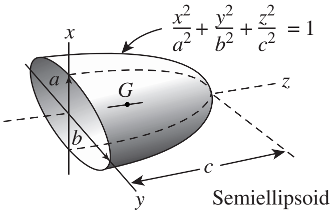
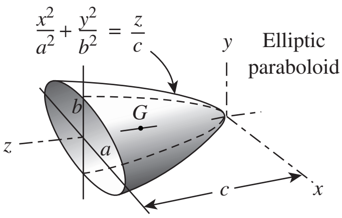
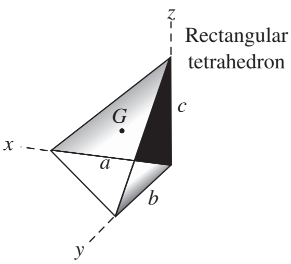
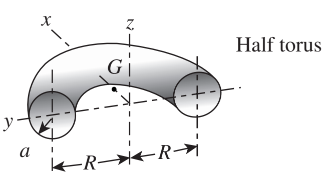
Moments of Inertia of Homogeneous Solids (m = Mass of Body Shown) (continued)

Body	Mass Center	Mass Moments of Inertia
 Spherical shell	—	$I_{zz} = \frac{2}{3}mr^2$
 Hemispherical shell	$\bar{x} = \frac{r}{2}$	$I_{xx} = I_{yy} = I_{zz} = \frac{2}{3}mr^2$ $\bar{I}_{yy} = \bar{I}_{zz} = \frac{5}{12}mr^2$
 Sphere	—	$I_{zz} = \frac{2}{5}mr^2$
 Hemisphere	$\bar{x} = \frac{3r}{8}$	$I_{xx} = I_{yy} = I_{zz} = \frac{2}{5}mr^2$ $\bar{I}_{yy} = \bar{I}_{zz} = \frac{83}{320}mr^2$
 Uniform slender rod	—	$I_{yy} = \frac{1}{12}ml^2$ $I_{y_1y_1} = \frac{1}{3}ml^2$
 Quarter-circular rod	$\bar{x} = \bar{y}$ $= \frac{2r}{\pi}$	$I_{xx} = I_{yy} = \frac{1}{2}mr^2$ $I_{zz} = mr^2$
 Elliptical cylinder	—	$I_{xx} = \frac{1}{4}ma^2 + \frac{1}{12}ml^2$ $I_{yy} = \frac{1}{4}mb^2 + \frac{1}{12}ml^2$ $I_{zz} = \frac{1}{4}m\left(a^2 + b^2\right)$ $I_{y_1y_1} = \frac{1}{4}mb^2 + \frac{1}{3}ml^2$

Moments of Inertia of Homogeneous Solids (m = Mass of Body Shown) (continued)

Body	Mass Center	Mass Moments of Inertia
 Conical shell	$\bar{z} = \frac{2h}{3}$	$I_{yy} = \frac{1}{4}mr^2 + \frac{1}{2}mh^2$ $I_{y_1y_1} = \frac{1}{4}mr^2 + \frac{1}{6}mh^2$ $I_{zz} = \frac{1}{2}mr^2$ $\bar{I}_{yy} = \frac{1}{4}mr^2 + \frac{1}{18}mh^2$
 Half conical shell	$\bar{x} = \frac{4r}{3\pi}$ $\bar{z} = \frac{2h}{3}$	$I_{xx} = I_{yy}$ $= \frac{1}{4}mr^2 + \frac{1}{2}mh^2$ $I_{x_1x_1} = I_{y_1y_1}$ $= \frac{1}{4}mr^2 + \frac{1}{6}mh^2$ $I_{zz} = \frac{1}{2}mr^2$ $\bar{I}_{zz} = \left(\frac{1}{2} - \frac{16}{9\pi^2}\right)mr^2$
 Right-circular cone	$\bar{z} = \frac{3h}{4}$	$I_{yy} = \frac{3}{20}mr^2 + \frac{3}{5}mh^2$ $I_{y_1y_1} = \frac{3}{20}mr^2 + \frac{1}{10}mh^2$ $I_{zz} = \frac{3}{10}mr^2$ $\bar{I}_{yy} = \frac{3}{20}mr^2 + \frac{3}{80}mh^2$
 Half cone	$\bar{x} = \frac{r}{\pi}$ $\bar{z} = \frac{3h}{4}$	$I_{xx} = I_{yy}$ $= \frac{3}{20}mr^2 + \frac{3}{5}mh^2$ $I_{x_1x_1} = I_{y_1y_1}$ $= \frac{3}{20}mr^2 + \frac{1}{10}mh^2$ $I_{zz} = \frac{3}{10}mr^2$ $\bar{I}_{zz} = \left(\frac{3}{10} - \frac{1}{\pi^2}\right)mr^2$

Moments of Inertia of Homogeneous Solids (m = Mass of Body Shown) (continued)

Body	Mass Center	Mass Moments of Inertia
	$\bar{z} = \frac{3c}{8}$	$I_{xx} = \frac{1}{5}m(b^2 + c^2)$ $I_{yy} = \frac{1}{5}m(a^2 + c^2)$ $I_{zz} = \frac{1}{5}m(a^2 + c^2)$ $\bar{I}_{xx} = \frac{1}{5}m\left(b^2 + \frac{19}{64}c^2\right)$ $\bar{I}_{yy} = \frac{1}{5}m\left(a^2 + \frac{19}{64}c^2\right)$
	$\bar{z} = \frac{2c}{3}$	$I_{xx} = \frac{1}{6}mb^2 + \frac{1}{2}mc^2$ $I_{yy} = \frac{1}{6}ma^2 + \frac{1}{2}mc^2$ $I_{zz} = \frac{1}{6}m(a^2 + b^2)$ $\bar{I}_{xx} = \frac{1}{6}m\left(b^2 + \frac{1}{3}c^2\right)$ $\bar{I}_{yy} = \frac{1}{6}m\left(a^2 + \frac{1}{3}c^2\right)$
	$\bar{x} = \frac{a}{4}$ $\bar{y} = \frac{b}{4}$ $\bar{z} = \frac{c}{4}$	$I_{xx} = \frac{1}{10}m(b^2 + c^2)$ $I_{yy} = \frac{1}{10}m(a^2 + c^2)$ $I_{zz} = \frac{1}{10}m(a^2 + b^2)$ $\bar{I}_{xx} = \frac{3}{80}m(b^2 + c^2)$ $\bar{I}_{yy} = \frac{3}{80}m(a^2 + c^2)$ $\bar{I}_{zz} = \frac{3}{80}m(a^2 + b^2)$
	$\bar{x} = \frac{a^2 + 4R^2}{2\pi R}$	$I_{xx} = I_{yy} = \frac{1}{2}mR^2 + \frac{5}{8}ma^2$ $I_{zz} = mR^2 + \frac{3}{4}ma^2$

From Meriam, J.L., Moments of inertia, in *The Engineering Handbook,* Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1996, p. 35–38.

Dynamic Viscosity of Liquids (μ) (mPa · s)

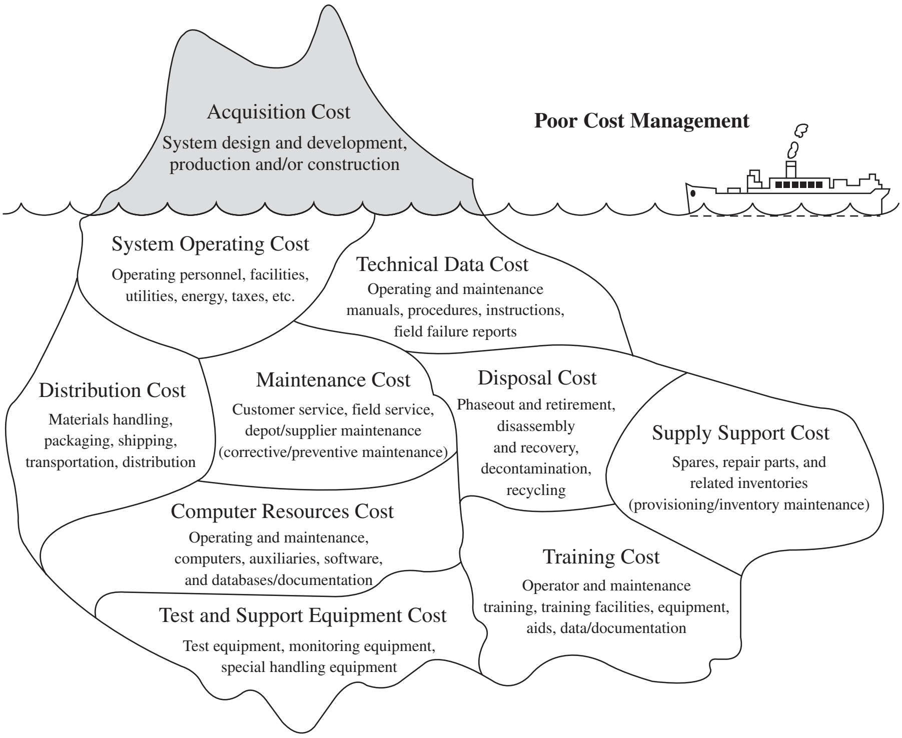
Liquid	−25°C	0°C	25°C	50°C	75°C	100°C
Water		1.793	0.890	0.547	0.378	
Mercury			1.526	1.402	1.312	
Methanol	1.258	0.793	0.544			
Isobutyl acetate			0.676	0.493	0.370	0.286
Toluene	1.165	0.778	0.560	0.424	0.333	0.270
Styrene		1.050	0.695	0.507	0.390	0.310
Acetic acid			1.056	0.786	0.599	0.464
Ethanol	3.262	1.786	1.074	0.694	0.476	
Ethylene glycol			16.1	6.554	3.340	1.975

From Braun, E.R. and Wang, P.-L., Boundary layers, in *The Engineering Handbook,* Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1996, p. 401.

Resistor Color Code

Color	First Band,[a] Significant Figure	Second Band, Significant Figure	Third Band, Multiplier	Fourth Band,[b] Tolerance (%)	Fifth Band,[b] Failure Rate (%/1000 h)
Black	0	0	1	—	—
Brown	1	1	10	—	1
Red	2	2	10^2	—	0.1
Orange	3	3	10^3	—	0.01
Yellow	4	4	10^4	—	0.001
Green	5	5	10^5	—	—
Blue	6	6	10^6	—	—
Violet	7	7	10^7	—	—
Gray	8	8	10^8	—	—
White	9	9	10^9	—	—
Silver	—	—	0.01	10	—
Gold	—	—	0.1	5	—
None	—	—	—	20	—

[a] The first band is the one closest to one end of the resistor. A first band wider than the others indicates a wire-wound resistor.
[b] Certain MIL parts.
From Domingoes, H., Passive components, in *The Engineering Handbook,* Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1996, p. 1113.



The problem of total cost visibility. From Fabrycky, W.J. and Blanchard, B.S., Life-cycle costing, in *The Engineering Handbook,* Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1996, p. 1969.

Trigonometry

Triangles

In any triangle (in a plane) with sides a, b, and c and corresponding opposite angles A, B, and C,

$$\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C} \qquad \text{(Law of sines)}$$

$$a^2 = b^2 + c^2 - 2cb\cos A \qquad \text{(Law of cosines)}$$

$$\frac{a+b}{a-b} = \frac{\tan\frac{1}{2}(A+B)}{\tan\frac{1}{2}(A-B)} \qquad \text{(Law of tangents)}$$

$$\sin\frac{1}{2}A = \sqrt{\frac{(s-b)}{bc}} \quad \text{where } s = \frac{1}{2}(a+b+c)$$

$$\cos\frac{1}{2}A = \sqrt{\frac{s(s-a)(s-c)}{bc}}$$

$$\tan\frac{1}{2}A = \sqrt{\frac{(s-b)(s-c)}{s(s-a)}}$$

$$\text{Area} = \frac{1}{2}bc\ \sin A$$

$$= \sqrt{s(s-a)(s-b)(s-c)}$$

If the vertices have coordinates (x_1, y_1), (x_2, y_2), (x_3, y_3), the area is the *absolute value* of the expression

Trigonometry (continued)

$$\frac{1}{2}\begin{vmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{vmatrix}$$

Trigonometric Functions of an Angle

With reference to the following figure, $P(x, y)$ is a point in any one of the four quadrants and A is an angle whose initial side is coincident with the positive x axis and whose terminal side contains the point $P(x, y)$. The distance from the origin $P(x, y)$ is denoted by r and is positive. The trigonometric functions of the angle A are defined as:

$$\sin A = \text{sine } A = y/r$$

$$\cos A = \text{cosine } A = x/r$$

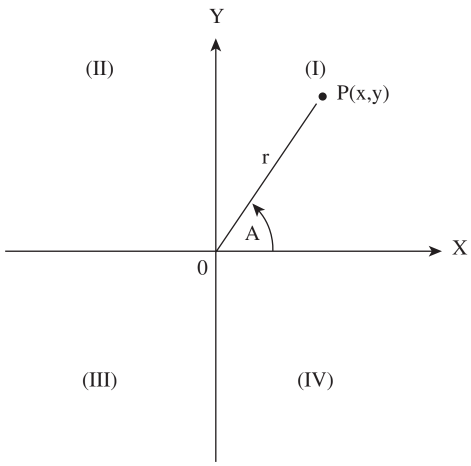
$$\tan A = \text{tangent } A = y/x$$

$$\text{ctn } A = \text{cotangent } A = x/y$$

$$\sec A = \text{secant } A = r/x$$

$$\csc A = \text{cosecant } A = r/y$$

Angles are measured in degrees or radians; 180° = π radians; 1 radian = 180/π degrees.



The trigonometric point. Angle A is taken to be positive when the rotation is counterclockwise and negative when the rotation is clockwise. The plane is divided into quadrants as shown.

The trigonometric functions of 0°, 30°, 45°, and integer multiples of these are directly computed.

	0°	30°	45°	60°	90°	120°	135°	150°	180°
sin	0	$\frac{1}{2}$	$\frac{\sqrt{2}}{2}$	$\frac{\sqrt{3}}{2}$	1	$\frac{\sqrt{3}}{2}$	$\frac{\sqrt{2}}{2}$	$\frac{1}{2}$	0
cos	1	$\frac{\sqrt{3}}{2}$	$\frac{\sqrt{2}}{2}$	$\frac{1}{2}$	0	$-\frac{1}{2}$	$-\frac{\sqrt{2}}{2}$	$-\frac{\sqrt{3}}{2}$	−1
tan	0	$\frac{\sqrt{3}}{3}$	1	$\sqrt{3}$	∞	$-\sqrt{3}$	−1	$-\frac{\sqrt{3}}{3}$	0
ctn	∞	$\sqrt{3}$	1	$\frac{\sqrt{3}}{3}$	0	$-\frac{\sqrt{3}}{3}$	−1	$-\sqrt{3}$	∞
sec	1	$\frac{2\sqrt{3}}{3}$	$\sqrt{2}$	2	∞	−2	$-\sqrt{2}$	$-\frac{2\sqrt{3}}{3}$	−1
csc	∞	2	$\sqrt{2}$	$\frac{2\sqrt{3}}{3}$	1	$\frac{2\sqrt{3}}{3}$	$\sqrt{2}$	2	∞

Trigonometry (continued)

Trigonometric Identities

$$\sin A = \frac{1}{\csc A}$$

$$\cos A = \frac{1}{\sec A}$$

$$\tan A = \frac{1}{\text{ctn } A} = \frac{\sin A}{\cos A}$$

$$\csc A = \frac{1}{\sin A}$$

$$\sec A = \frac{1}{\cos A}$$

$$\text{ctn } A = \frac{1}{\tan A} = \frac{\cos A}{\sin A}$$

$$\sin^2 A + \cos^2 A = 1$$

$$1 + \tan^2 A = \sec^2 A$$

$$1 + \text{ctn}^2 A = \csc^2 A$$

$$\sin(A \pm B) = \sin A \cos B \pm \cos A \sin B$$

$$\cos(A \pm B) = \cos A \cos B \mp \sin A \sin B$$

$$\tan(A \pm B) = \frac{\tan A \pm \tan B}{1 \mp \tan A \tan B}$$

$$\sin 2A = 2\sin A \cos A$$

$$\sin 3A = 3\sin A - 4\sin^3 A$$

$$\sin nA = 2\sin(n-1)A \cos A - \sin(n-2)A$$

$$\cos 2A = 2\cos^2 A - 1 = 1 - 2\sin^2 A$$

$$\cos 3A = 4\cos^3 A - 3\cos A$$

$$\cos nA = 2\cos(n-1)A \cos A - \cos(n-2)A$$

$$\sin A + \sin B = 2\sin\frac{1}{2}(A+B)\cos\frac{1}{2}(A-B)$$

$$\sin A - \sin B = 2\cos\frac{1}{2}(A+B)\sin\frac{1}{2}(A-B)$$

$$\cos A + \cos B = 2\cos\frac{1}{2}(A+B)\cos\frac{1}{2}(A-B)$$

$$\cos A - \cos B = -2\sin\frac{1}{2}(A+B)\sin\frac{1}{2}(A-B)$$

$$\tan A \pm \tan B = \frac{\sin(A \pm B)}{\cos A \cos B}$$

$$\text{ctn } A \pm \text{ctn } B = \pm\frac{\sin(A \pm B)}{\sin A \sin B}$$

$$\sin A \sin B = \frac{1}{2}\cos(A-B) - \frac{1}{2}\cos(A+B)$$

Trigonometry (continued)

$$\cos A \cos B = \frac{1}{2}\cos(A-B) + \frac{1}{2}\cos(A+B)$$

$$\sin A \cos B = \frac{1}{2}\sin(A+B) + \frac{1}{2}\sin(A-B)$$

$$\sin\frac{A}{2} = \pm\sqrt{\frac{1-\cos A}{2}}$$

$$\cos\frac{A}{2} = \pm\sqrt{\frac{1+\cos A}{2}}$$

$$\tan\frac{A}{2} = \frac{1-\cos A}{\sin A} = \frac{\sin A}{1+\cos A} = \pm\sqrt{\frac{1-\cos A}{1+\cos A}}$$

$$\sin^2 A = \frac{1}{2}(1-\cos 2A)$$

$$\cos^2 A = \frac{1}{2}(1+\cos 2A)$$

$$\sin^3 A = \frac{1}{4}(3\sin A - \sin 3A)$$

$$\cos^3 A = \frac{1}{4}(\cos 3A + 3\cos A)$$

$$\sin ix = \frac{1}{2}i\left(e^x - e^{-x}\right) = i\sinh x$$

$$\cos ix = \frac{1}{2}\left(e^x + e^{-x}\right) = \cosh x$$

$$\tan ix = \frac{i\left(e^x - e^{-x}\right)}{e^x + e^{-x}} = i\tanh x$$

$$e^{x+iy} = e^x(\cos y + i\sin y)$$

$$(\cos x \pm i\sin x)^n = \cos nx \pm i\sin nx$$

Inverse Trigonometric Functions

The inverse trigonometric functions are multiple valued, and this should be taken into account in the use of the following formulas.

$$\sin^{-1} x = \cos^{-1}\sqrt{1-x^2}$$

$$= \tan^{-1}\frac{x}{\sqrt{1-x^2}} = \text{ctn}^{-1}\frac{\sqrt{1-x^2}}{x}$$

$$= \sec^{-1}\frac{1}{\sqrt{1-x^2}} = \csc^{-1}\frac{1}{x}$$

$$= -\sin^{-1}(-x)$$

$$\cos^{-1} x = \sin^{-1}\sqrt{1-x^2}$$

$$= \tan^{-1}\frac{\sqrt{1-x^2}}{x} = \text{ctn}^{-1}\frac{x}{\sqrt{1-x^2}}$$

$$= \sec^{-1}\frac{1}{x} = \csc^{-1}\frac{1}{\sqrt{1-x^2}}$$

$$= \pi - \cos^{-1}(-x)$$

Trigonometry (continued)

$$\tan^{-1} x = \text{ctn}^{-1}\frac{1}{x} = \sin^{-1}\frac{x}{\sqrt{1+x^2}} = \cos^{-1}\frac{1}{\sqrt{1+x^2}} = \sec^{-1}\sqrt{1+x^2} = \csc^{-1}\frac{\sqrt{1+x^2}}{x} = -\tan^{-1}(-x)$$

From Dorf, R.C., Ed., *The Engineering Handbook,* CRC Press, Boca Raton, FL, 1996, pp. 2037–2041.

Series

Bernoulli and Euler Numbers

A set of numbers, $B_1, B_3, \ldots, B_{2n-1}$ (Bernoulli numbers) and $B_2, B_4, \ldots, B_{2n}$ (Euler numbers), appears in the series expansions of many functions. A partial listing follows; these are computed from the following equations:

$$B_{2n} - \frac{2n(2n-1)}{2!}B_{2n-2} + \frac{2n(2n-1)(2n-2)(2n-3)}{4!}B_{2n-4} - \cdots + (-1)^n = 0$$

and

$$\frac{2^{2n}(2^{2n}-1)}{2n}B_{2n-1} = (2n-1)B_{2n-2} - \frac{(2n-1)(2n-2)(2n-3)}{3!}B_{2n-4} + \cdots + (-1)^{n-1}$$

$B_1 = 1/6$	$B_2 = 1$
$B_3 = 1/30$	$B_4 = 5$
$B_5 = 1/42$	$B_6 = 61$
$B_7 = 1/30$	$B_8 = 1385$
$B_9 = 5/66$	$B_{10} = 50{,}521$
$B_{11} = 691/2730$	$B_{12} = 2{,}702{,}765$
$B_{13} = 7/6$	$B_{14} = 199{,}360{,}981$
$\vdots$	$\vdots$

Series of Functions

In the following, the interval of convergence is indicated; otherwise it is all x. Logarithms are to the base e. Bernoulli and Euler numbers (B_{2n-1} and B_{2n}) appear in certain expressions.

$$(a+x)^n = a^n + na^{n-1}x + \frac{n(n-1)}{2!}a^{n-2}x^2 + \frac{n(n-1)(n-2)}{3!}a^{n-3}x^3 + \cdots + \frac{n!}{(n-j)!\,j!}a^{n-j}x^j + \cdots \qquad [x^2 < a^2]$$

$$(a-bx)^{-1} = \frac{1}{a}\left[1 + \frac{bx}{a} + \frac{b^2x^2}{a^2} + \frac{b^3x^3}{a^3} + \cdots\right] \qquad [b^2x^2 < a^2]$$

$$(1 \pm x)^n = 1 \pm nx + \frac{n(n-1)}{2!}x^2 \pm \frac{n(n-1)(n-2)x^3}{3!} + \cdots \qquad [x^2 < 1]$$

$$(1 \pm x)^{-n} = 1 \mp nx + \frac{n(n+1)}{2!}x^2 \mp \frac{n(n+1)(n+2)}{3!}x^3 + \cdots \qquad [x^2 < 1]$$

Series (continued)

$$(1\pm x)^{1/2}=1\pm\frac{1}{2}x-\frac{1}{2\cdot 4}x^2\pm\frac{1\cdot 3}{2\cdot 4\cdot 6}x^3-\frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 8}x^4\pm\cdots \qquad [x^2<1]$$

$$(1\pm x)^{-1/2}=1\mp\frac{1}{2}x+\frac{1\cdot 3}{2\cdot 4}x^2\mp\frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6}x^3+\frac{1\cdot 3\cdot 5\cdot 7}{2\cdot 4\cdot 6\cdot 8}x^4\pm\cdots \qquad [x^2<1]$$

$$(1\pm x^2)^{1/2}=1\pm\frac{1}{2}x^2-\frac{x^4}{2\cdot 4}\pm\frac{1\cdot 3}{2\cdot 4\cdot 6}x^6-\frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 8}x^8\pm\cdots \qquad [x^2<1]$$

$$(1\pm x)^{-1}=1\mp x+x^2\mp x^3+x^4\mp x^5+\cdots \qquad [x^2<1]$$

$$(1\pm x)^{-2}=1\mp 2x+3x^2\mp 4x^3+5x^4\mp\cdots \qquad [x^2<1]$$

$$e^x=1+x+\frac{x^2}{2!}+\frac{x^3}{3!}+\frac{x^4}{4!}+\cdots$$

$$e^{-x^2}=1-x^2+\frac{x^4}{2!}-\frac{x^6}{3!}+\frac{x^8}{4!}-\cdots$$

$$a^x=1+x\log a+\frac{(x\log a)^2}{2!}+\frac{(x\log a)^3}{3!}+\cdots$$

$$\log x=(x-1)-\frac{1}{2}(x-1)^2+\frac{1}{3}(x-1)^3-\cdots \qquad [0<x<2]$$

$$\log x=\frac{x-1}{x}+\frac{1}{2}\left(\frac{x-1}{x}\right)^2+\frac{1}{3}\left(\frac{x-1}{x}\right)^3+\cdots \qquad \left[x>\frac{1}{2}\right]$$

$$\log x=2\left[\left(\frac{x-1}{x+1}\right)+\frac{1}{3}\left(\frac{x-1}{x+1}\right)^3+\frac{1}{5}\left(\frac{x-1}{x+1}\right)^5+\cdots\right] \qquad [x>0]$$

$$\log(1+x)=x-\frac{1}{2}x^2+\frac{1}{3}x^3-\frac{1}{4}x^4+\cdots \qquad [x^2<1]$$

$$\log\left(\frac{1+x}{1-x}\right)=2\left[x+\frac{1}{3}x^3+\frac{1}{5}x^5+\frac{1}{7}x^7+\cdots\right] \qquad [x^2<1]$$

$$\log\left(\frac{x+1}{x-1}\right)=2\left[\frac{1}{x}+\frac{1}{3}\left(\frac{1}{x}\right)^3+\frac{1}{5}\left(\frac{1}{x}\right)^5+\cdots\right] \qquad [x^2>1]$$

$$\sin x=x-\frac{x^3}{3!}+\frac{x^5}{5!}-\frac{x^7}{7!}+\cdots$$

$$\cos x=1-\frac{x^2}{2!}+\frac{x^4}{4!}-\frac{x^6}{6!}+\cdots$$

$$\tan x=x+\frac{x^3}{3}+\frac{2x^5}{15}+\frac{17x^7}{315}+\cdots+\frac{2^{2n}(2^{2n}-1)B_{2n-1}x^{2n-1}}{(2n)!} \qquad \left[x^2<\frac{\pi^2}{4}\right]$$

$$\operatorname{ctn} x=\frac{1}{x}-\frac{x}{3}-\frac{x^3}{45}-\frac{2x^5}{945}-\cdots-\frac{B_{2n-1}(2x)^{2n}}{(2n)!\,x}-\cdots \qquad [x^2<\pi^2]$$

Series (continued)

$$\csc x = \frac{1}{x} + \frac{x}{3!} + \frac{7x^3}{3\cdot 5!} + \frac{31x^5}{3\cdot 7!} + \cdots + \frac{2\left(2^{2n+1}-1\right)}{(2n+2)!} B_{2n+1} x^{2n+1} + \cdots \quad \left[x^2 < \pi^2\right]$$

$$\sin^{-1} x = x + \frac{x^3}{6} + \frac{(1\cdot 3)x^5}{(2\cdot 4)5} + \frac{(1\cdot 3\cdot 5)x^7}{(2\cdot 4\cdot 6)7} + \cdots \quad \left[x^2 < 1\right]$$

$$\tan^{-1} x = x - \frac{1}{3}x^3 + \frac{1}{5}x^5 - \frac{1}{7}x^7 + \cdots \quad \left[x^2 < 1\right]$$

$$\sec^{-1} x = \frac{\pi}{2} - \frac{1}{x} - \frac{1}{6x^3} - \frac{1\cdot 3}{(2\cdot 4)5x^5} - \frac{1\cdot 3\cdot 5}{(2\cdot 4\cdot 6)7x^7} - \cdots \quad \left[x^2 > 1\right]$$

$$\sinh x = x + \frac{x^3}{3!} + \frac{x^5}{5!} + \frac{x^7}{7!} + \cdots$$

$$\cosh x = 1 + \frac{x^2}{2!} + \frac{x^4}{4!} + \frac{x^6}{6!} + \frac{x^8}{8!} + \cdots$$

$$\tanh x = \left(2^2-1\right)2^2 B_1 \frac{x}{2!} - \left(2^4-1\right)2^4 B_3 \frac{x^3}{4!}$$

$$+ \left(2^6-1\right)2^6 B_5 \frac{x^5}{6!} - \cdots \quad \left[x^2 < \frac{\pi^2}{4}\right]$$

$$\text{ctnh } x = \frac{1}{x}\left(1 + \frac{2^2 B_1 x^2}{2!} - \frac{2^4 B_3 x^4}{4!} + \frac{2^6 B_5 x^6}{6!} - \cdots\right) \quad \left[x^2 < \pi^2\right]$$

$$\text{sech } x = 1 - \frac{B_2 x^2}{2!} + \frac{B_4 x^4}{4!} - \frac{B_6 x^6}{6!} + \cdots \quad \left[x^2 < \frac{\pi^2}{4}\right]$$

$$\text{csch } x = \frac{1}{x} - (2-1)2B_1 \frac{x}{2!} + \left(2^3-1\right)2B_3 \frac{x^3}{4!} - \cdots \quad \left[x^2 < \pi^2\right]$$

$$\sinh^{-1} x = x - \frac{1}{2}\frac{x^3}{3} + \frac{1\cdot 3}{2\cdot 4}\frac{x^5}{5} - \frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6}\frac{x^7}{7} + \cdots \quad \left[x^2 < 1\right]$$

$$\tanh^{-1} x = x + \frac{x^3}{3} + \frac{x^5}{5} + \frac{x^7}{7} + \cdots \quad \left[x^2 < 1\right]$$

$$\text{ctnh}^{-1} x = \frac{1}{x} + \frac{1}{3x^3} + \frac{1}{5x^5} + \cdots \quad \left[x^2 > 1\right]$$

$$\text{csch}^{-1} x = \frac{1}{x} - \frac{1}{2\cdot 3x^3} + \frac{1\cdot 3}{2\cdot 4\cdot 5x^5} - \frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 7x^7} + \cdots \quad \left[x^2 > 1\right]$$

$$\int_0^x e^{-t^2} dt = x - \frac{1}{3}x^3 + \frac{x^5}{5\cdot 2!} - \frac{x^7}{7\cdot 3!} + \cdots$$

Error Function

The following function, known as the error function, erf *x*, arises frequently in applications:

$$\text{erf } x = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$$

The integral cannot be represented in terms of a finite number of elementary functions; therefore, values of erf *x* have been compiled in tables. The following is the series for erf *x*:

Series (continued)

$$\operatorname{erf} x = \frac{2}{\sqrt{\pi}}\left[x - \frac{x^3}{3} + \frac{x^5}{5\cdot 2!} - \frac{x^7}{7\cdot 3!} + \cdots\right]$$

There is a close relation between this function and the area under the standard normal curve. For evaluation it is convenient to use z instead of x; then erf z may be evaluated from the area $F(z)$ by use of the relation

$$\operatorname{erf} z = 2F\left(\sqrt{2}z\right)$$

Example

$$\operatorname{erf}(0.5) = 2F\left[(1.414)(0.5)\right] = 2F(0.707)$$

By interpolation, $F(0.707) = 0.260$; thus, $\operatorname{erf}(0.5) = 0.520$.

Series Expansion

The expression in parentheses following certain series indicates the region of convergence. If not otherwise indicated, it is understood that the series converges for all finite values of x.

Binomial

$$(x+y)^n = x^n + nx^{n-1}y + \frac{n(n-1)}{2!}x^{n-2}y^2 + \frac{n(n-1)(n-2)}{3!}x^{n-3}y^3 + \cdots \quad \left[y^2 < x^2\right]$$

$$(1\pm x)^n = 1 \pm nx + \frac{n(n-1)x^2}{2!} \pm \frac{n(n-1)(n-2)x^3}{3!} + \cdots \quad \left[x^2 < 1\right]$$

$$(1\pm x)^{-n} = 1 \mp nx + \frac{n(n+1)x^2}{2!} \mp \frac{n(n+1)(n+2)x^3}{3!} + \cdots \quad \left[x^2 < 1\right]$$

$$(1\pm x)^{-1} = 1 \mp x + x^2 \mp x^3 + x^4 \mp x^5 + \cdots \quad \left[x^2 < 1\right]$$

$$(1\pm x)^{-2} = 1 \mp 2x + 3x^2 \mp 4x^3 + 5x^4 \mp 6x^5 + \cdots \quad \left[x^2 < 1\right]$$

Reversion of Series

Let a series be represented by

$$y = a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6 + \cdots \qquad (a_1 \neq 0)$$

To find the coefficients of the series

$$x = A_1y + A_2y^2 + A_3y^3 + A_4y^4 + \cdots$$

$$A_1 = \frac{1}{a_1} \qquad A_2 = -\frac{a_2}{a_1^3} \qquad A_3 = \frac{1}{a_1^5}\left(2a_2^2 - a_1a_3\right)$$

$$A_4 = \frac{1}{a_1^7}\left(5a_1a_2a_3 - a_1^2a_4 - 5a_2^3\right)$$

$$A_5 = \frac{1}{a_1^9}\left(6a_1^2a_2a_4 + 3a_1^2a_3^2 + 14a_2^4 - a_1^3a_5 - 21a_1a_2^2a_3\right)$$

$$A_6 = \frac{1}{a_1^{11}}\left(7a_1^3a_2a_5 + 7a_1^3a_3a_4 + 84a_1a_2^3a_3 - a_1^4a_6 - 28a_1^2a_2^2a_4 - 28a_1^2a_2a_3^2 - 42a_2^5\right)$$

$$A_7 = \frac{1}{a_1^{13}}\left(8a_1^4a_2a_6 + 8a_1^4a_3a_5 + 4a_1^4a_4^2 + 120a_1^2a_2^3a_4 + 180a_1^2a_2^2a_3^2 + 132a_2^6 - a_1^5a_7 - 36a_1^3a_2^2a_5 - 72a_1^3a_2a_3a_4 - 12a_1^3a_3^3 - 330a_1a_2^4a_3\right)$$

Series (continued)

Taylor

1. $f(x) = f(a) + (x-a)f'(a) + \frac{(x-a)^2}{2!}f''(a) + \frac{(x-a)^3}{3!}f'''(a) + \cdots + \frac{(x-a)^n}{n!}f^{(n)}(a) + \cdots$ (Taylor's series)

   (Increment form)

2. $f(x+h) = f(x) + hf'(x) + \frac{h^2}{2!}f''(x) + \frac{h^3}{3!}f'''(x) + \cdots$

   $= f(h) + xf'(h) + \frac{x^2}{2!}f''(h) + \frac{x^3}{3!}f'''(h) + \cdots$

3. If $f(x)$ is a function possessing derivatives of all orders throughout the interval $a \le x \le b$, then there is a value X, with $a < X < b$, such that

$$f(b) = f(a) + (b-a)f'(a) + \frac{(b-a)^2}{2!}f''(a) + \cdots + \frac{(b-a)^{n-1}}{(n-1)!}f^{(n-1)}(a) + \frac{(b-a)^n}{n!}f^{(n)}(X)$$

$$f(a+h) = f(a) + hf'(a) + \frac{h^2}{2!}f''(a) + \cdots + \frac{h^{n-1}}{(n-1)!}f^{(n-1)}(a) + \frac{h^n}{n!}f^{(n)}(a+\theta h),\ b = a+h, \quad 0 < \theta < 1$$

or

$$f(x) = f(a) + (x-a)f'(a) + \frac{(x-a)^2}{2!}f''(a) + \cdots + (x-a)^{n-1}\frac{f^{(n-1)}(a)}{(n-1)!} + R_n$$

where

$$R_n = \frac{f^{(n)}\left[a + \theta\cdot(x-a)\right]}{n!}(x-a)^n, \quad 0 < \theta < 1.$$

The above forms are known as Taylor's series with the remainder term.

4. Taylor's series for a function of two variables:

$$\text{If } \left(h\frac{\partial}{\partial x} + k\frac{\partial}{\partial x}\right)f(x,y) = h\frac{\partial f(x,y)}{\partial x} + k\frac{\partial f(x,y)}{\partial y};$$

$$\left(h\frac{\partial}{\partial x} + k\frac{\partial}{\partial y}\right)^2 f(x,y) = h^2\frac{\partial^2 f(x,y)}{\partial x^2} + 2hk\frac{\partial^2 f(x,y)}{\partial x\,\partial y} + k^2\frac{\partial^2 f(x,y)}{\partial y^2}$$

etc., and if

$$\left(h\frac{\partial}{\partial x} + k\frac{\partial}{\partial y}\right)^n f(x,y)\Bigg|_{\substack{x=a\\y=b}}$$

where the bar and subscripts mean that after differentiation we are to replace x by a and y by b,

$$f(a+h,b+k) = f(a,b) + \left(h\frac{\partial}{\partial x} + k\frac{\partial}{\partial y}\right)f(x,y)\Bigg|_{\substack{x=a\\y=b}} + \cdots + \frac{1}{n!}\left(h\frac{\partial}{\partial x} + k\frac{\partial}{\partial y}\right)^n f(x,y)\Bigg|_{\substack{x=a\\y=b}} + \cdots$$

MacLaurin

$$f(x) = f(0) + xf'(0) + \frac{x^2}{2!}f''(0) + \frac{x^3}{3!}f'''(0) + \cdots + x^{n-1}\frac{f^{(n-1)}(0)}{(n-1)!} + R_n$$

where

$$R_n = \frac{x^n f^{(n)}(\theta x)}{n!}, \quad 0 < \theta < 1$$

Series (continued)

Exponential

$$e = 1 + \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + \cdots$$

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \cdots \qquad \text{(all real values of } x\text{)}$$

$$a^x = 1 + x\log_e a + \frac{(x\log_e a)^2}{2!} + \frac{(x\log_e a)^3}{3!} + \cdots$$

$$e^x = e^a\left[1 + (x-a) + \frac{(x-a)^2}{2!} + \frac{(x-a)^3}{3!} + \cdots\right]$$

Logarithmic

$$\log_e x = \frac{x-1}{x} + \frac{1}{2}\left(\frac{x-1}{x}\right)^2 + \frac{1}{3}\left(\frac{x-1}{x}\right)^3 + \cdots \qquad \left(x > \frac{1}{2}\right)$$

$$\log_e x = (x-1) - \frac{1}{2}(x-1)^2 + \frac{1}{3}(x-1)^3 - \cdots \qquad (2 \geq x > 0)$$

$$\log_e x = 2\left[\frac{x-1}{x+1} + \frac{1}{3}\left(\frac{x-1}{x+1}\right)^3 + \frac{1}{5}\left(\frac{x-1}{x+1}\right)^5 + \cdots\right] \qquad (x > 0)$$

$$\log_e(1+x) = x - \frac{1}{2}x^2 + \frac{1}{3}x^3 - \frac{1}{4}x^4 + \cdots \qquad (-1 < x \leq 1)$$

$$\log_e(n+1) - \log_e(n-1) = 2\left[\frac{1}{n} + \frac{1}{3n^3} + \frac{1}{5n^5} + \cdots\right]$$

$$\log_e(a+x) = \log_e a + 2\left[\frac{x}{2a+x} + \frac{1}{3}\left(\frac{x}{2a+x}\right)^3 + \frac{1}{5}\left(\frac{x}{2a+x}\right)^5 + \cdots\right] \qquad (a > 0, -a < x < +\infty)$$

$$\log_e \frac{1+x}{1-x} = 2\left[x + \frac{x^3}{3} + \frac{x^5}{5} + \cdots + \frac{x^{2n-1}}{2n-1} + \cdots\right] \qquad (-1 < x < 1)$$

$$\log_e x = \log_e a + \frac{(x-a)}{a} - \frac{(x-a)^2}{2a^2} + \frac{(x-a)^3}{3a^3} - \cdots \qquad (0 < x \leq 2a)$$

Series (continued)

Trigonometric

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \cdots \qquad \text{(all real values of } x\text{)}$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \cdots \qquad \text{(all real values of } x\text{)}$$

$$\tan x = x + \frac{x^3}{3} + \frac{2x^5}{15} + \frac{17x^7}{315} + \frac{62x^9}{2835} + \cdots + \frac{(-1)^{n-1}2^{2n}\left(2^{2n}-1\right)B_{2n}}{(2n)!}x^{2n-1} + \cdots$$

$$\left(x^2 < \pi^2/4, \text{ and } B_n \text{ represents the } n\text{th Bernoulli number}\right)$$

$$\cot x = \frac{1}{x} - \frac{x}{3} - \frac{x^2}{45} - \frac{2x^5}{945} - \frac{x^7}{4725} - \cdots - \frac{(-1)^{n+1}2^{2n}}{(2n)!}B_{2n}x^{2n-1} + \cdots$$

$$\left(x^2 < \pi^2, \text{ and } B_n \text{ represents the } n\text{th Bernoulli number}\right)$$

From Dorf, R.C., Ed., *The Engineering Handbook,* CRC Press, Boca Raton, FL, 1996, pp. 2041–2048.

Differential Calculus

Notation

For the following equations, the symbols $f(x)$, $g(x)$, etc., represent functions of x. The value of a function $f(x)$ at $x = a$ is denoted $f(a)$. For the function $y = f(x)$ the derivative of y with respect to x is denoted by one of the following:

$$\frac{dy}{dx}, \quad f'(x), \quad D_x y, \quad y'$$

Higher derivatives are as follows:

$$\frac{d^2y}{dx^2} = \frac{d}{dx}\left(\frac{dy}{dx}\right) = \frac{d}{dx} f'(x) = f''(x)$$

$$\frac{d^3y}{dx^3} = \frac{d}{dx}\left(\frac{d^2y}{dx^2}\right) = \frac{d}{dx} f''(x) = f'''(x)$$

$$\vdots$$

and values of these at $x = a$ are denoted $f''(a)$, $f'''(a)$, and so on.

Slope of a Curve

The tangent line at point $P(x, y)$ of the curve $y = f(x)$ has a slope $f'(x)$ provided that $f'(x)$ exists at P. The slope at P is defined to be that of the tangent line at P. The tangent line at $P(x_1, y_1)$ is given by

$$y - y_1 = f'(x_1)(x - x_1)$$

The *normal line* to the curve at $P(x_1, y_1)$ has slope $-1/f'(x_1)$ and thus obeys the equation

$$y - y_1 = \left[-1/f'(x_1)\right](x - x_1)$$

(The slope of a vertical line is not defined.)

Angle of Intersection of Two Curves

Two curves, $y = f_1(x)$ and $y = f_2(x)$, that intersect at a point $P(X, Y)$ where derivatives $f_1'(X)$, $f_2'(X)$ exist, have an angle (α) of intersection given by

$$\tan\alpha = \frac{f_2'(X) - f_1'(X)}{1 + f_2'(X)\cdot f_1'(X)}$$

If $\tan\alpha > 0$, then α is the acute angle; if $\tan\alpha < 0$, then α is the obtuse angle.

Radius of Curvature

The radius of curvature R of the curve $y = f(x)$ at the point $P(x, y)$ is

$$R = \frac{\left\{1 + \left[f'(x)\right]^2\right\}^{3/2}}{f''(x)}$$

In polar coordinates (θ, r) the corresponding formula is

$$R = \frac{\left[r^2 + \left(\frac{dr}{d\theta}\right)^2\right]^{3/2}}{r^2 + 2\left(\frac{dr}{d\theta}\right)^2 - r\frac{d^2r}{d\theta^2}}$$

The *curvature* K is $1/R$.

Differential Calculus (continued)

Relative Maxima and Minima

The function f has a relative maximum at $x = a$ if $f(a) \geq f(a + c)$ for all values of c (positive or negative) that are sufficiently near zero. The function f has a relative minimum at $x = b$ if $f(b) \leq f(b + c)$ for all values of c that are sufficiently close to zero. If the function f is defined on the closed interval $x_1 \leq x \leq x_2$ and has a relative maximum or minimum at $x = a$, where $x_1 < a < x_2$, and if the derivative $f'(x)$ exists at $x = a$, then $f'(a) = 0$. It is noteworthy that a relative maximum or minimum may occur at a point where the derivative does not exist. Further, the derivative may vanish at a point that is neither a maximum nor a minimum for the function. Values of x for which $f'(x) = 0$ are called "critical values." To determine whether a critical value of x, say x_c, is a relative maximum or minimum for the function at x_c, one may use the second derivative test:

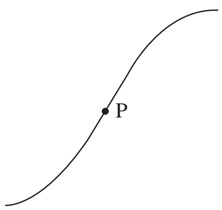
1. If $f''(x_c)$ is positive, $f(x_c)$ is a minimum.
2. If $f''(x_c)$ is negative, $f(x_c)$ is a maximum.
3. If $f''(x_c)$ is zero, no conclusion may be made.

The sign of the derivative as x advances through x_c may also be used as a test. If $f'(x)$ changes from positive to zero to negative, then a maximum occurs at x_c, whereas a change in $f'(x)$ from negative to zero to positive indicates a minimum. If $f'(x)$ does not change sign as x advances through x_c, then the point is neither a maximum nor a minimum.

Points of Inflection of a Curve

The sign of the second derivative of f indicates whether the graph of $y = f(x)$ is concave upward or concave downward:

$f''(x) > 0$: concave upward
$f''(x) < 0$: concave downward



Point of inflection.

A point of the curve at which the direction of concavity changes is called a point of inflection. Such a point may occur where $f''(x) = 0$ or where $f''(x)$ becomes infinite. More precisely, if the function $y = f(x)$ and its first derivative $y' = f'(x)$ are continuous in the interval $a \leq x \leq b$, and if $y'' = f''(x)$ exists in $a < x < b$, then the graph of $y = f(x)$ for $a < x < b$ is concave upward if $f''(x)$ is positive and concave downward if $f''(x)$ is negative.

Taylor's Formula

If f is a function that is continuous on an interval that contains a and x, and if its first $(n + 1)$ derivatives are continuous on this interval, then

$$f(x) = f(a) + f'(a)(x-a) + \frac{f''(a)}{2!}(x-a)^2 + \frac{f'''(a)}{3!}(x-a)^3 + \cdots + \frac{f^{(n)}(a)}{n!}(x-a)^n + R$$

where R is called the *remainder*. There are various common forms of the remainder:

Lagrange's Form

$$R = f^{(n+1)}(\beta) \cdot \frac{(x-a)^{n+1}}{(n+1)!}, \quad \beta \text{ between } a \text{ and } x$$

Cauchy's Form

$$R = f^{(n+1)}(\beta) \cdot \frac{(x-B)^n (x-a)}{n!}, \quad \beta \text{ between } a \text{ and } x$$

Differential Calculus (continued)

Integral Form

$$R = \int_a^x \frac{(x-t)^n}{n!} f^{(n+1)}(t)dt$$

Indeterminant Forms

If $f(x)$ and $g(x)$ are continuous in an interval that includes $x = a$, and if $f(a) = 0$ and $g(a) = 0$, the limit $\lim_{x\to a} [f(x)/g(x)]$ takes the form "0/0," called an *indeterminant form*. *L'Hôpital's rule* is

$$\lim_{x\to a} \frac{f(x)}{g(x)} = \lim_{x\to a} \frac{f'(x)}{g'(x)}$$

Similarly, it may be shown that if $f(x) \to \infty$ and $g(x) \to \infty$ as $x \to a$, then

$$\lim_{x\to a} \frac{f(x)}{g(x)} = \lim_{x\to a} \frac{f'(x)}{g'(x)}$$

(The above holds for $x \to \infty$.)

Examples

$$\lim_{x\to 0} \frac{\sin x}{x} = \lim_{x\to 0} \frac{\cos x}{1} = 1$$

$$\lim_{x\to\infty} \frac{x^2}{e^x} = \lim_{x\to\infty} \frac{2x}{e^x} = \lim_{x\to\infty} \frac{2}{e^x} = 0$$

Numerical Methods

1. *Newton's method* for approximating roots of the equation $f(x) = 0$: A first estimate x_1 of the root is made; then, provided that $f'(x_1) \neq 0$, a better approximation is x_2:

$$x_2 = x_1 - \frac{f(x)}{f'(x_1)}$$

The process may be repeated to yield a third approximation, x_3, to the root:

$$x_3 = x_2 - \frac{f(x_2)}{f'(x_2)}$$

provided $f'(x_2)$ exists. The process may be repeated. (In certain rare cases the process will not converge.)

2. *Trapezoidal rule for areas*: For the function $y = f(x)$ defined on the interval (a, b) and positive there, take n equal subintervals of width $\Delta x = (b - a)/n$. The area bounded by the curve between $x = a$ and $x = b$ [or definite integral of $f(x)$] is approximately the sum of trapezoidal areas, or

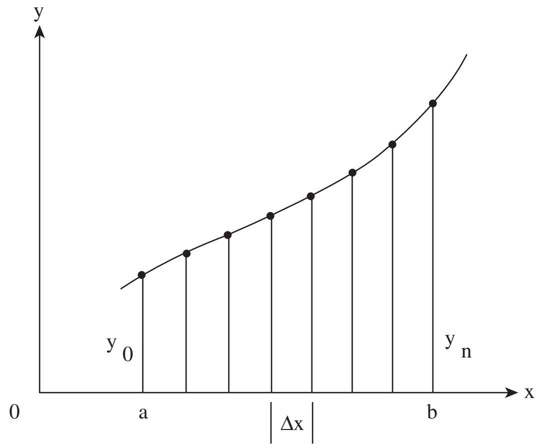
$$A \sim \left(\frac{1}{2}y_0 + y_1 + y_2 + \cdots + y_{n-1} + \frac{1}{2}y_n\right)(\Delta x)$$

Estimation of the error (E) is possible if the second derivative can be obtained:

$$E = \frac{b-a}{12} f''(c)(\Delta x)^2$$

where c is some number between a and b.

Differential Calculus (continued)



Trapezoidal rule for area.

Functions of Two Variables

For the function of two variables, denoted $z = f(x, y)$, if y is held constant, say at $y = y_1$, then the resulting function is a function of x only. Similarly, x may be held constant at x_1, to give the resulting function of y.

The Gas Laws

A familiar example is afforded by the ideal gas law relating the pressure p, the volume V, and the absolute temperature T of an ideal gas:

$$pV = nRT$$

where n is the number of moles and R is the gas constant per mole, 8.31 ($J \cdot K^{-1} \cdot mole^{-1}$). By rearrangement, any one of the three variables may be expressed as a function of the other two. Further, either one of these two may be held constant. If T is held constant, then we get the form known as Boyle's law:

$$p = kV^{-1} \qquad \text{(Boyle's law)}$$

where we have denoted nRT by the constant k and, of course, $V > 0$. If the pressure remains constant, we have Charles' law:

$$V = bT \qquad \text{(Charles' law)}$$

where the constant b denotes nR/p. Similarly, volume may be kept constant:

$$p = aT$$

where now the constant, denoted a, is nR/V.

Partial Derivatives

The physical example afforded by the ideal gas law permits clear interpretations of processes in which one of the variables is held constant. More generally, we may consider a function $z = f(x, y)$ defined over some region of the xy plane in which we hold one of the two coordinates, say y, constant. If the resulting function of x is differentiable at a point (x, y), we denote this derivative by one of the notations

$$f_x, \quad \delta f/dx, \quad \delta z/dx$$

called the *partial derivative with respect to x*. Similarly, if x is held constant and the resulting function of y is differentiable, we get the *partial derivative with respect to y*, denoted by one of the following:

$$f_y, \quad \delta f/dy, \quad \delta z/dy$$

Example. Given $z = x^4y^3 - y \sin x + 4y$, then

$$\delta z/dx = 4(xy)^3 - y\cos x$$

$$\delta z/dy = 3x^4y^2 - \sin x + 4$$

From Dorf, R.C., Ed., *The Engineering Handbook,* CRC Press, Boca Raton, FL, 1996, pp. 2048–2052.

Integral Calculus

Indefinite Integral

If $F(x)$ is differentiable for all values of x in the interval (a, b) and satisfies the equation $dy/dx = f(x)$, then $F(x)$ is an integral of $f(x)$ with respect to x. The notation is $F(x) = \int f(x)\, dx$ or, in differential form, $dF(x) = f(x)\, dx$.

For any function $F(x)$ that is an integral of $f(x)$, it follows that $F(x) + C$ is also an integral. We thus write

$$\int f(x)\, dx = F(x) + C$$

Definite Integral

Let $f(x)$ be defined on the interval $[a, b]$ which is partitioned by points $x_1, x_2, \ldots, x_j, \ldots, x_{n-1}$ between $a = x_0$ and $b = x_n$. The jth interval has length $\Delta x_j = x_j - x_{j-1}$, which may vary with j. The sum $\sum_{j=1}^{n} f(\upsilon_j)\Delta x_j$, where υ_j is arbitrarily chosen in the jth subinterval, depends on the numbers $x_0, \ldots, x_n$ and the choice of the v as well as f; but if such sums approach a common value as all Δx approach zero, then this value is the definite integral of f over the interval (a, b) and is denoted $\int_a^b f(x)dx$. The *fundamental theorem of integral calculus* states that

$$\int_a^b f(x)dx = F(b) - F(a),$$

where F is any continuous indefinite integral of f in the interval (a, b).

Properties

$$\int_a^b \left[f_1(x) + f_2(x) + \cdots + f_j(x)\right]dx = \int_a^b f_1(x)\, dx + \int_a^b f_2(x)dx + \cdots + \int_a^b f_j(x)\, dx$$

$$\int_a^b cf(x)\, dx = c\int_a^b f(x)\, dx, \quad \text{if } c \text{ is a constant}$$

$$\int_a^b f(x)\, dx = -\int_b^a f(x)\, dx$$

$$\int_a^b f(x)\, dx = \int_a^c f(x)\, dx + \int_c^b f(x)\, dx$$

Common Applications of the Definite Integral

Area (Rectangular Coordinates)

Given the function $y = f(x)$ such that $y > 0$ for all x between a and b, the area bounded by the curve $y = f(x)$, the x axis, and the vertical lines $x = a$ and $x = b$ is

$$A = \int_a^b f(x)\, dx$$

Length of Arc (Rectangular Coordinates)

Given the smooth curve $f(x, y) = 0$ from point (x_1, y_1) to point (x_2, y_2), the length between these points is

$$L = \int_{x_1}^{x_2} \sqrt{1 + \left(dy/dx\right)^2}\, dx$$

$$L = \int_{y_1}^{y_2} \sqrt{1 + \left(dx/dy\right)^2}\, dy$$

Mean Value of a Function

The mean value of a function $f(x)$ continuous on $[a, b]$ is

$$\frac{1}{(b-a)} \int_a^b f(x)dx$$

Integral Calculus (continued)

Area (Polar Coordinates)

Given the curve $r = f(\theta)$, continuous and nonnegative for $\theta_1 \le \theta \le \theta_2$, the area enclosed by this curve and the radial lines $\theta = \theta_1$ and $\theta = \theta_2$ is given by

$$A = \int_{\theta_1}^{\theta_2} \tfrac{1}{2}\left[f(\theta)\right]^2 d\theta$$

Length of Arc (Polar Coordinates)

Given the curve $r = f(\theta)$ with continuous derivative $f'(\theta)$ on $\theta_1 \le \theta \le \theta_2$, the length of arc from $\theta = \theta_1$ to $\theta = \theta_2$ is

$$L = \int_{\theta_1}^{\theta_2} \sqrt{\left[f(\theta)\right]^2 + \left[f'(\theta)\right]^2}\, d\theta$$

Volume of Revolution

Given a function $y = f(x)$ continuous and nonnegative on the interval (a, b), when the region bounded by $f(x)$ between a and b is revolved about the x axis, the volume of revolution is

$$V = \pi \int_a^b \left[f(x)\right]^2 dx$$

Surface Area of Revolution **(Revolution about the *x* Axis, Between *a* and *b*)**
If the portion of the curve $y = f(x)$ between $x = a$ and $x = b$ is revolved about the x axis, the area A of the surface generated is given by the following:

$$A = \int_a^b 2\pi f(x)\left\{1 + \left[f'(x)\right]^2\right\}^{1/2} dx$$

Work

If a variable force $f(x)$ is applied to an object in the direction of motion along the x axis between $x = a$ and $x = b$, the work done is

$$W = \int_a^b f(x)\, dx$$

Cylindrical and Spherical Coordinates

1. Cylindrical coordinates:

$$x = r\cos\theta$$

$$y = r\sin\theta$$

   Element of volume $dV = r\, dr\, d\theta\, dz$.
2. Spherical coordinates:

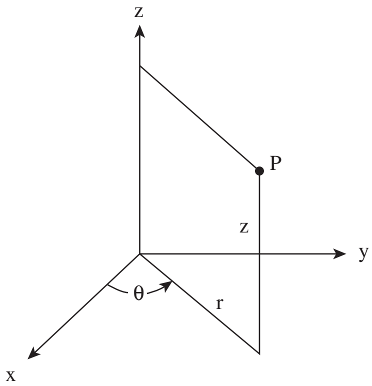
$$x = \rho\sin\phi\cos\theta$$

$$y = \rho\sin\phi\sin\theta$$

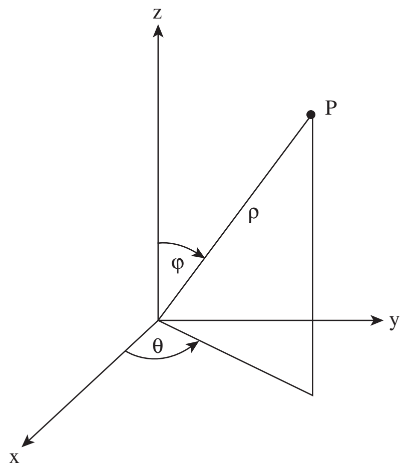
$$z = \rho\cos\phi$$

   Element of volume $dV = \rho^2 \sin\phi\, d\rho\, d\phi\, d\theta$.

Integral Calculus (continued)



Cylindrical coordinates.



Spherical coordinates.

Double Integration

The evaluation of a double integral of $f(x, y)$ over a plane region R,

$$\iint_R f(x,y)dA$$

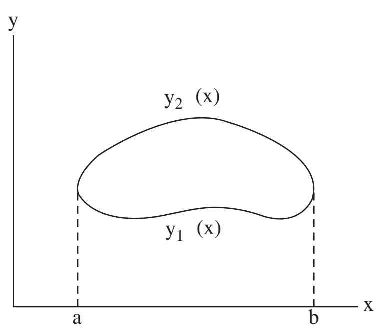
is practically accomplished by iterated (repeated) integration. For example, suppose that a vertical straight line meets the boundary of R in at most two points so that there is an upper boundary, $y = y_2(x)$, and a lower boundary, $y = y_1(x)$. Also, it is assumed that these functions are continuous from a to b (see figure below). Then

$$\iint_R f(x,y)dA = \int_a^b \left(\int_{y_1(x)}^{y_2(y)} f(x,y)dy \right) dx$$

If R has left-hand boundary, $x = x_1(y)$, and right-hand boundary, $x = x_2(y)$, which are continuous from c to d (the extreme values of y in R), then

$$\iint_R f(x,y)dA = \int_c^d \left(\int_{x_1(y)}^{x_2(y)} f(x,y)dx \right) dy$$

Such integrations are sometimes more convenient in polar coordinates, $x = r \cos \theta$, $y = r \sin \theta$, $dA = r\,dr\,d\theta$.



Region R bounded by $y_2(x)$ and $y_1(x)$.

Integral Calculus (continued)

Surface Area and Volume by Double Integration

For the surface given by $z = f(x, y)$, which projects onto the closed region R of the xy plane, one may calculate the volume V bounded above by the surface and below by R, and the surface area S by the following:

$$V = \iint_R z\,dA = \iint_R f(x,y)\,dx\,dy$$

$$S = \iint_R \left[1 + (\delta z/\delta x)^2 + (\delta z/\delta y)^2\right]^{1/2} dx\,dy$$

[In polar coordinates, (r, θ), we replace $d\,A$ by $r\,d\,r\,d\,\theta$.]

Centroid

The centroid of a region R of the xy plane is a point (x', y') where

$$x' = \frac{1}{A}\iint_R x\,d\,A, \qquad y' = \frac{1}{A}\iint_R y\,d\,A$$

and A is the area of the region.

Example. For the circular sector of angle 2α and radius R, the area A is αR^2; the integral needed for x', expressed in polar coordinates, is

$$\iint x\,dA = \int_{-\alpha}^{\alpha}\int_0^R (r\cos\theta)\,r\,dr\,d\theta$$

$$= \left[\frac{R^3}{3}\sin\theta\right]_{-\alpha}^{+\alpha} = \frac{2}{3}R^3\sin\theta$$

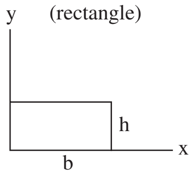
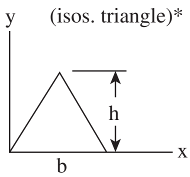
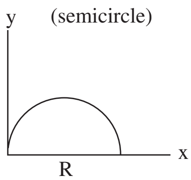
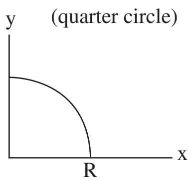
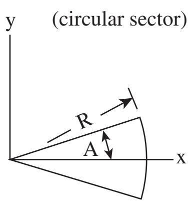
and thus,

$$x' = \frac{\frac{2}{3}R^3\sin\alpha}{\alpha R^2} = \frac{2}{3}R\frac{\sin\alpha}{\alpha}$$

Centroids of some common regions are shown in the following table.

Integral Calculus (continued)

Centroids

	Area	x'	y'
Rectangle	bh	$b/2$	$h/2$
			
Isosceles triangle*	$bh/2$	b/2	h/3
			
Semicircle	$\pi R^2/2$	R	$4R/3\pi$
			
Quarter circle	$\pi R^2/4$	4R/3π	$4R/3\pi$
			
Circular sector	R^2A	$2R \sin A/3A$	0
			

* $y' = h/3$ for any triangle of altitude h.

From Dorf, R.C., Ed., *The Engineering Handbook,* CRC Press, Boca Raton, FL, 1996, pp. 2053–2057.

Special Functions

Hyperbolic Functions

$$\sinh x = \frac{e^x - e^{-x}}{2} \qquad \operatorname{csch} x = \frac{1}{\sinh x}$$

$$\cosh x = \frac{e^x + e^{-x}}{2} \qquad \operatorname{sech} x = \frac{1}{\cosh x}$$

$$\tanh x = \frac{e^x - e^{-x}}{e^x + e^{-x}} \qquad \operatorname{ctnh} x = \frac{1}{\tanh x}$$

$$\sinh(-x) = -\sinh x \qquad \operatorname{ctnh}(-x) = -\operatorname{ctnh} x$$

$$\cosh(-x) = \cosh x \qquad \operatorname{sech}(-x) = \operatorname{sech} x$$

$$\tanh(-x) = -\tanh x \qquad \operatorname{csch}(-x) = -\operatorname{csch} x$$

$$\tanh x = \frac{\sinh x}{\cosh x} \qquad \operatorname{ctnh} x = \frac{\cosh x}{\sinh x}$$

$$\cosh^2 x - \sinh^2 x = 1 \qquad \cosh^2 x = \frac{1}{2}(\cosh 2x + 1)$$

$$\sinh^2 x = \frac{1}{2}(\cosh 2x - 1) \qquad \operatorname{ctnh}^2 x - \operatorname{csch}^2 x = 1$$

$$\operatorname{csch}^2 x - \operatorname{sech}^2 x = \operatorname{csch}^2 x \operatorname{sech}^2 x \qquad \tanh^2 x + \operatorname{sech}^2 x = 1$$

$$\sinh(x+y) = \sinh x \cosh y + \cosh x \sinh y$$

$$\cosh(x+y) = \cosh x \cosh y + \sinh x \sinh y$$

$$\sinh(x-y) = \sinh x \cosh y - \cosh x \sinh y$$

$$\cosh(x-y) = \cosh x \cosh y - \sinh x \sinh y$$

$$\tanh(x+y) = \frac{\tanh x + \tanh y}{1 + \tanh x \tanh y}$$

$$\tanh(x-y) = \frac{\tanh x - \tanh y}{1 - \tanh x \tanh y}$$

Bessel Functions

Bessel functions, also called cylindrical functions, arise in many physical problems as solutions of the differential equation

$$x^2 y'' + xy' + \left(x^2 - n^2\right) y = 0$$

which is known as Bessel's equation. Certain solutions, known as *Bessel functions of the first kind of order n*, are given by

$$J_n(x) = \sum_{k=0}^{\infty} \frac{(-1)^k}{k!\,\Gamma(n+k+1)} \left(\frac{x}{2}\right)^{n+2k}$$

$$J_{-n}(x) = \sum_{k=0}^{\infty} \frac{(-1)^k}{k!\,\Gamma(-n+k+1)} \left(\frac{x}{2}\right)^{-n+2k}$$

In the above it is noteworthy that the gamma function must be defined for the negative argument $q : \Gamma(q) = \Gamma(q+1)/q$, provided that q is not a negative integer. When q is a negative integer, $1/\Gamma(q)$ is defined to be zero. The functions $J_{-n}(x)$ and $J_n(x)$ are solutions of Bessel's equation for all real n. It is seen, for $n = 1, 2, 3, \ldots$, that

$$J_{-n}(x) = (-1)^n J_n(x)$$

and, therefore, these are not independent; hence, a linear combination of these is not a general solution. When, however, n is not a positive integer, a negative integer, or zero, the linear combination with arbitrary constants c_1 and c_2,

Special Functions (continued)

$$y = c_1 J_n(x) + c_2 J_{-n}(x)$$

is the general solution of the Bessel differential equation.

The zero-order function is especially important as it arises in the solution of the heat equation (for a "long" cylinder):

$$J_0(x) = 1 - \frac{x^2}{2^2} + \frac{x^4}{2^2 4^2} - \frac{x^6}{2^2 4^2 6^2} + \cdots$$

while the following relations show a connection to the trigonometric functions:

$$J_{1/2}(x) = \left[\frac{2}{\pi x}\right]^{1/2} \sin x$$

$$J_{-1/2}(x) = \left[\frac{2}{\pi x}\right]^{1/2} \cos x$$

The following recursion formula gives $J_{n+1}(x)$ for any order in terms of lower-order functions:

$$\frac{2n}{x} J_n(x) = J_{n-1}(x) + J_{n+1}(x)$$

Legendre Polynomials

If Laplace's equation, $\nabla^2 V = 0$, is expressed in spherical coordinates, it is

$$r^2 \sin\theta \frac{\delta^2 V}{\delta r^2} + 2r\sin\theta \frac{\delta V}{\delta r} + \sin\theta \frac{\delta^2 V}{\delta \theta^2} + \cos\theta \frac{\delta V}{\delta \theta} + \frac{1}{\sin\theta} \frac{\delta^2 V}{\delta \phi^2} = 0$$

and any of its solutions, $V(r, \theta, \phi)$, are known as *spherical harmonics*. The solution as a product

$$V(r,\theta,\phi) = R(r)\Theta(\theta)$$

which is independent of ϕ, leads to

$$\sin^2\theta\, \Theta'' + \sin\theta\cos\theta\, \Theta' + \left[n(n+1)\sin^2\theta\right]\Theta = 0$$

Rearrangement and substitution of $x = \cos\theta$ leads to

$$\left(1 - x^2\right)\frac{d^2\Theta}{dx^2} - 2x\frac{d\Theta}{dx} + n(n+1)\Theta = 0$$

known as *Legendre's equation*. Important special cases are those in which n is zero or a positive integer, and, for such cases, Legendre's equation is satisfied by polynomials called Legendre polynomials, $P_n(x)$. A short list of Legendre polynomials, expressed in terms of x and $\cos\theta$, is given below. These are given by the following general formula:

$$P_n(x) = \sum_{j=0}^{L} \frac{(-1)^j (2n-2j)!}{2^n j!(n-j)!(n-2j)!} x^{n-2j}$$

where $L = n/2$ if n is even and $L = (n-1)/2$ if n is odd.

$$P_0(x) = 1$$

$$P_1(x) = x$$

$$P_2(x) = \frac{1}{2}(3x^2 - 1)$$

$$P_3(x) = \frac{1}{2}\left(5x^3 - 3x\right)$$

Special Functions (continued)

$$P_4(x) = \frac{1}{8}\left(35x^4 - 30x^2 + 3\right)$$

$$P_5(x) = \frac{1}{8}\left(63x^5 - 70x^3 + 15x\right)$$

$$P_0(\cos\theta) = 1a$$

$$P_1(\cos\theta) = \cos\theta$$

$$P_2(\cos\theta) = \frac{1}{4}(3\cos 2\,\theta + 1)$$

$$P_3(\cos\theta) = \frac{1}{8}(5\cos 3\,\theta + 3\cos\theta)$$

$$P_4(\cos\theta) = \frac{1}{64}(35\cos 4\,\theta + 20\cos 2\theta + 9)$$

Additional Legendre polynomials may be determined from the *recursion formula*

$$(n+1)P_{n+1}(x) - (2n+1)xP_n(x) + nP_{n-1}(x) = 0 \quad (n = 1, 2, \ldots)$$

or the *Rodrigues formula*

$$P_n(x) = \frac{1}{2^n n!}\frac{d^n}{dx^n}\left(x^2 - 1\right)^n$$

Laguerre Polynomials

Laguerre polynomials, denoted $L_n(x)$, are solutions of the differential equation

$$xy'' + (1-x)y' + ny = 0$$

and are given by

$$L_n(x) = \sum_{j=0}^{n} \frac{(-1)^j}{j!} C_{(n,j)} x^j (n = 0, 1, 2, \ldots)$$

Thus,

$$L_0(x) = 1$$

$$L_1(x) = 1 - x$$

$$L_2(x) = 1 - 2x + \frac{1}{2}x^2$$

$$L_3(x) = 1 - 3x + \frac{3}{2}x^2 - \frac{1}{6}x^3$$

Additional Laguerre polynomials may be obtained from the recursion formula

$$(n+1)L_{n+1}(x) - (2n+1-x)L_n(x) + nL_{n-1}(x) = 0$$

Hermite Polynomials

The Hermite polynomials, denoted $H_n(x)$, are given by

$$H_0 = 1, \qquad H_n(x) = (-1)^n e^{x^2}\frac{d^n e^{-x^2}}{dx^n}, \qquad (n = 1, 2, \ldots)$$

and are solutions of the differential equation

$$y'' - 2xy' + 2ny = 0 \quad (n = 0, 1, 2 \ldots)$$

Special Functions (continued)

The first few Hermite polynomials are

$$H_0 = 1 \qquad H_1(x) = 2x$$

$$H_2(x) = 4x^2 - 2 \qquad H_3(x) = 8x^3 - 12x$$

$$H_4(x) = 16x^4 - 48x^2 + 12$$

Additional Hermite polynomials may be obtained from the relation

$$H_{n+1}(x) = 2xH_n(x) - H_n'(x)$$

where prime denotes differentiation with respect to x.

Orthogonality

A set of functions $\{f_n(x)\}$ $(n = 1, 2, \ldots)$ is orthogonal in an interval (a, b) with respect to a given weight function $w(x)$ if

$$\int_a^b w(x) f_m(x) f_n(x) dx = 0 \quad \text{when } m \neq n$$

The following polynomials are orthogonal on the given interval for the given $w(x)$:

$$\text{Legendre polynomials:} \quad P_n(x) \quad w(x) = 1$$
$$a = -1, b = 1$$
$$\text{Laguerre polynomials:} \quad L_n(x) \quad w(x) = \exp(-x)$$
$$a = 0, b = \infty$$
$$\text{Hermite polynomials:} \quad H_n(x) \quad w(x) = \exp\left(-x^2\right)$$
$$a = -\infty, b = \infty$$

The Bessel functions *of order n*, $J_n(\lambda_1 x)$, $J_n(\lambda_2 x)$, . . . , are orthogonal with respect to $w(x) = x$ over the interval $(0, c)$ provided that the λ_i are the positive roots of $J_n(\lambda c) = 0$:

$$\int_0^c x J_n\left(\lambda_j x\right) J_n\left(\lambda_k x\right) dx = 0 \quad (j \neq k)$$

where n is fixed and $n \geq 0$.

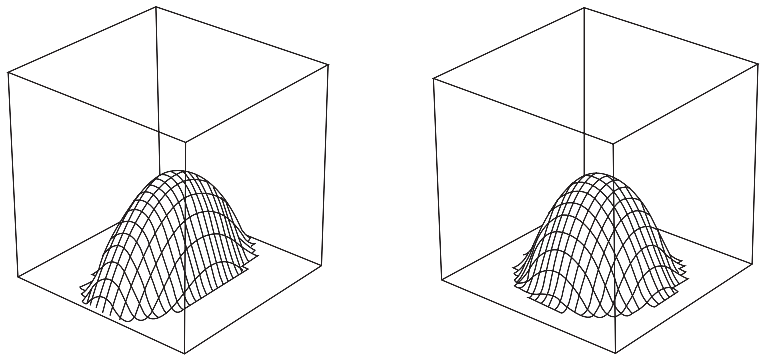
Special Functions (continued)

Functions with $x^2/a^2 \pm y^2/b^2$

Elliptic Paraboloid

$$z = c\left(x^2/a^2 + y^2/b^2\right)$$

$$x^2/a^2 + y^2/b^2 - z/c = 0$$



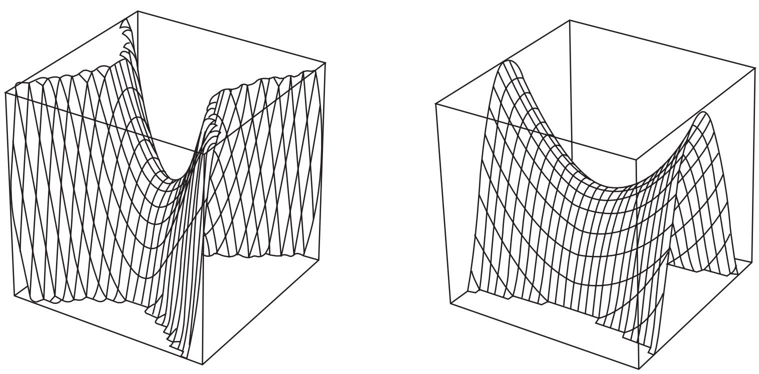
(a) (b)

Elliptic paraboloid. (a) a = 0.5, b = 1.0, c = –1.0; viewpoint = (5, –6, 4). (b) a = 1.0, b = 1.0, c = –2.0; viewpoint = (5, –6, 4).

Hyperbolic Paraboloid (Commonly Called Saddle)

$$z = c\left(x^2/a^2 - y^2/b^2\right)$$

$$x^2/a^2 - y^2/b^2 - z/c = 0$$



(a) (b)

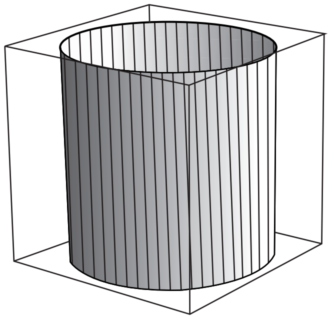
Hyperbolic paraboloid. (a) a = 0.50, b = 0.5, c = 1.0; viewpoint = (4, –6, 4). (b) a = 1.00, b = 0.5, c = 1.0; viewpoint = (4, –6, 4).

Special Functions (continued)

Elliptic Cylinder

$$1 = x^2/a^2 + y^2/b^2$$

$$x^2/a^2 + y^2/b^2 - 1 = 0$$

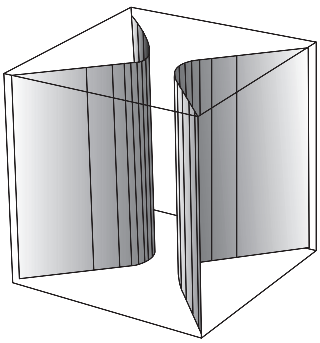


Elliptic cylinder. a = 1.0, b = 1.0; viewpoint = (4, –5, 2).

Hyperbolic Cylinder

$$1 = x^2/a^2 - y^2/b^2$$

$$x^2/a^2 - y^2/b^2 - 1 = 0$$



Hyperbolic cylinder. a = 1.0, b = 1.0; viewpoint = (4, –6, 3).

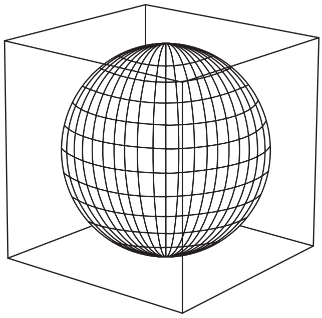
Special Functions (continued)

Functions with $(x^2/a^2 + y^2/b^2 \pm c^2)^{1/2}$

Sphere

$$z = \left(1 - x^2 - y^2\right)^{1/2}$$

$$x^2 + y^2 + z^2 - 1 = 0$$

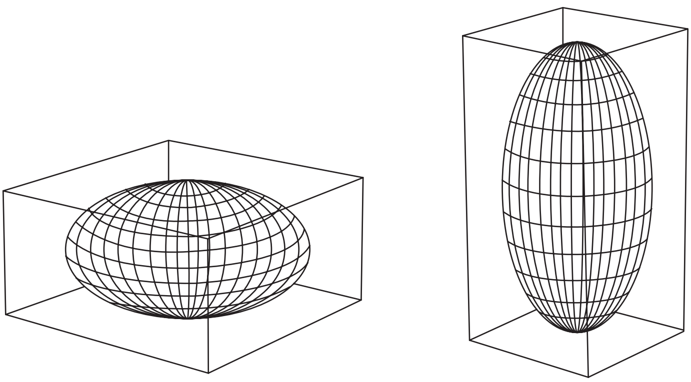


Sphere. Viewpoint = (4, –5, 2).

Ellipsoid

$$z = c\left(1 - x^2/a^2 - y^2/b^2\right)^{1/2}$$

$$x^2/a^2 + y^2/b^2 + z^2/c^2 - 1 = 0$$



(a) (b)

Ellipsoid. (a) a = 1.00, b = 1.00, c = 0.5; viewpoint = (4, –5, 2). (b) a = 0.50, b = 0.50, c = 1.0; viewpoint = (4, –5, 2).

Special cases:

$a = b > c$ gives oblate spheroid

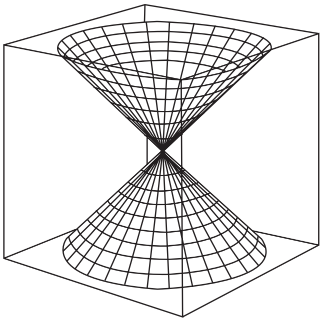
$a = b < c$ gives prolate spheroid

Special Functions (continued)

Cone

$$z = \left(x^2 + y^2\right)^{1/2}$$

$$x^2 + y^2 - z^2 = 0$$

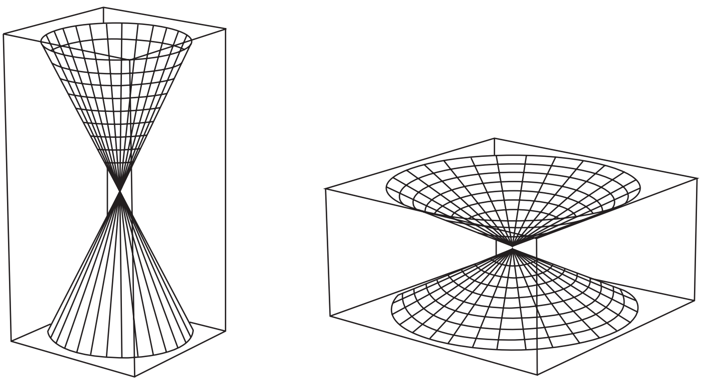


Cone. Viewpoint = (4, –5, 2).

Elliptic Cone (Circular Cone if a = b)

$$z = c\left(x^2/a^2 + y^2/b^2\right)^{1/2}$$

$$x^2/a^2 + y^2/b^2 - z^2/c^2 = 0$$



(a) (b)

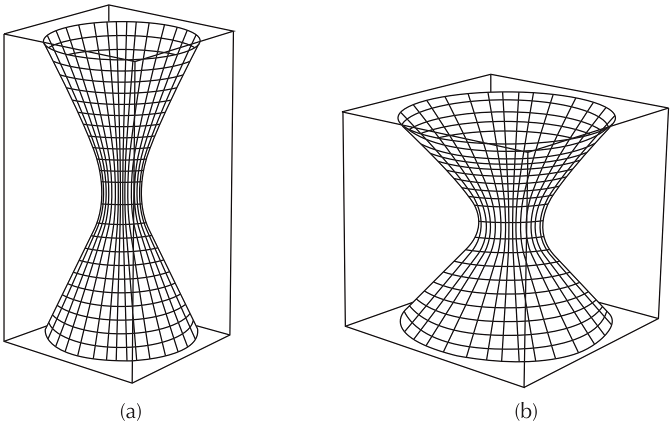
Elliptic cone. (a) a = 0.5, b = 0.5, c = 1.00; viewpoint = (4, –5, 2). (b) a = 1.0, b = 1.0, c = 0.50; viewpoint = (4, –5, 2).

Special Functions (continued)

Hyperboloid of One Sheet

$$z = c\left(x^2/a^2 + y^2/b^2 - 1\right)^{1/2}$$

$$x^2/a^2 + y^2/b^2 - z^2/c^2 - 1 = 0$$

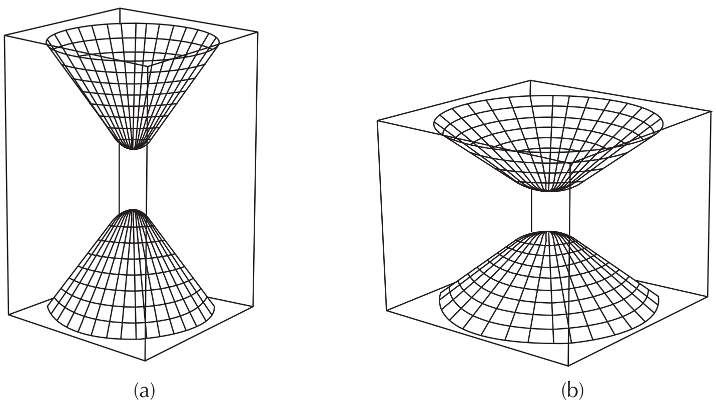


Hyperboloid of one sheet. (a) a = 0.1, b = 0.1, c = 0.2; $\pm z = c\sqrt{15}$; viewpoint = (4, –5, 2). (b) a = 0.2, b = 0.2, c = 0.2; $\pm z = c\sqrt{15}$; viewpoint = (4, –5, 2).

Hyperboloid of Two Sheets

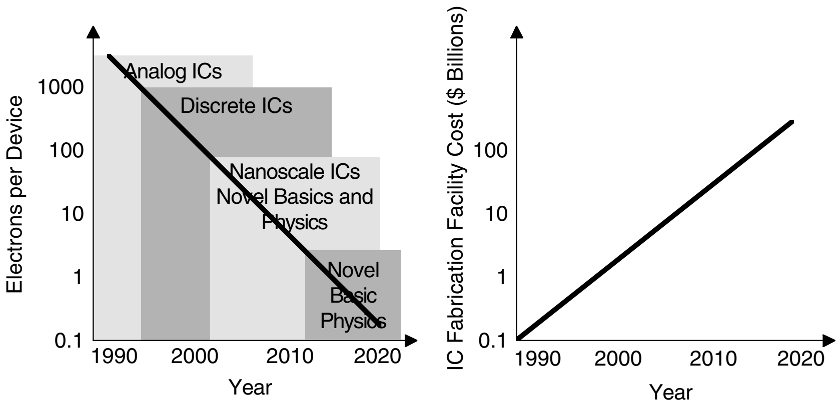
$$z = c\left(x^2/a^2 + y^2/b^2 + 1\right)^{1/2}$$

$$x^2/a^2 + y^2/b^2 - z^2/c^2 + 1 = 0$$



Hyperboloid of two sheets. (a) a = 0.125, b = 0.125, c = 0.2; $\pm z = c\sqrt{17}$; viewpoint = (4, –5, 2). (b) a = 0.25, b = 0.25, c = 0.2; $\pm z = c\sqrt{17}$; viewpoint = (4, –5, 2).

From Dorf, R.C., Ed., *The Engineering Handbook,* CRC Press, Boca Raton, FL, 1996, pp. 2058–2066.



Moore's laws. (From Lyshevski, S.E., Nanocomputer architectures and nanotechnology, in *Handbook of Nanoscience, Engineering, and Technology,* Goddard, III, W.A., Brenner, D.W., Lyshevski, S.E., and Iafrate, G.J., Eds., CRC Press, Boca Raton, FL, 2003, p. **6**-5.)

Approximate Current Densities in Electrons per Second per Square Nanometer Calculated from Experimental Data for Selected Molecular Electronic and Macroscopic Metal Devices

		Molecular Electronic Device				
Quantity	Units	1,4-Dithiol Benzene	3-Ring Poly-phenylene Wire	Poly-phenylene RTD (5 rings)	Carbon Nanotube	Copper Wire
Applied Voltage	Volts	1	1	1.4 (peak)	1	2×10^{-3} (10 cm wire)
Current Measured in Experiment	Amperes	2×10^{-8}	3.2×10^{-5}	1.4×10^{-11}	1×10^{-7}	1 (approx.)
Current Inferred	Amperes	2×10^{-8}	3.2×10^{-8}	1.4×10^{-14}	1×10^{-7}	–
per Molecule	Electrons per Sec	1.2×10^{11}	2.0×10^{11}	8.7×10^{4}	6.2×10^{11}	–
Estimated Cross-Sectional Area per Molecule	nm^2	~0.05	~0.05	~0.05	~3.1 (Radius ≈ 1 nm)	~3.1×10^{12} (Radius ≈ 1 mm)
Current Density	Electrons per Sec-nm^2	~2×10^{12}	~4×10^{12}	~2×10^{6}	~2×10^{11}	~2×10^{6}
Reference		(7)	(8)	(5,6)	(4)	

[a] Conversion factor for amperes to electrons per second is 1 Ampere ≡ 1 Coulomb/sec = $(1.6 \times 10^{-19})^{-1}$ electrons/sec = 6.2×10^{18} electrons/sec.

[b] In order to estimate the current densities per molecule from the published data on the room temperature nanopore measurements in References 5, 6, and 8, it was determined that the samples in the monolayer in the nanopore contained on the order of 1000 molecules per monolayer. This estimate is based on an average nanopore diameter of 30 nm and an estimated molecular diameter on the order of approximately 1 nm.

[c] Common copper wire generally is regarded as being highly conductive. Therefore, data for 10 cm of 1mm diameter (18 gauge) copper wire is included only for comparison as a familiar, conductive, macroscopic reference system. A current on the order of 1 ampere is the maximum recommended for such wire to avoid undue heating and danger of fire.

Sources of current measurements: (4) S.J. Tans et al., Individual single-wall carbon nanotubes as quantum wires, *Nature*, 386, 474–477, 1997; (5) M.A. Reed, Electrical Properties of Molecular Devices, presented at 1997 DARPA ULTRA Program Review Conference, Santa Fe, NM, October, 1997; (6) M.A. Reed, Molecular-scale electronics, *Proc. IEEE*, 87, 652–658, 1999; (7) C. Thou, M.R. Deshpande, M.A. Reed, and J.M. Tour, Nanoscale metal/self-assembled monolayer/metal heterostructures, *Appl. Phys. Lett.*, 71, 611–613, 1997; (8) C. Zhou, Atomic and Molecular Wires, Ph.D. dissertation, Yale University, 1999. With permission.

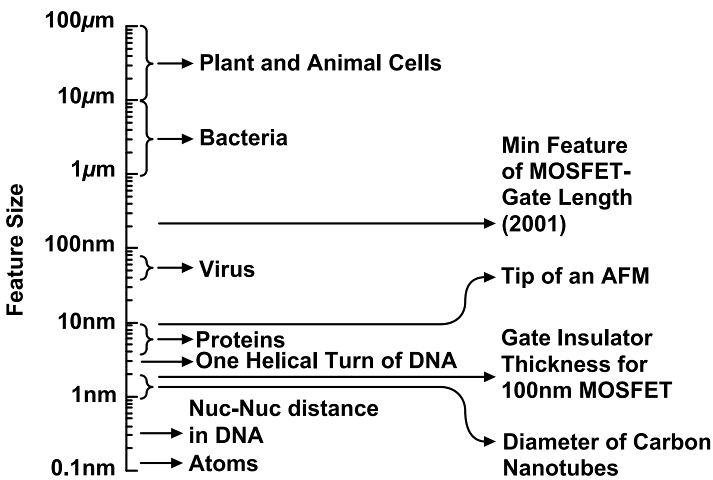
From Ellenbogen, J.C. and Love, J.C., Architectures for molecular electronic computers, in *Handbook of Nanoscience, Engineering, and Technology,* Goodard, III, W.A., Brenner, D.W., Lyshevski, S.E., and Iafrate, G.J., Eds., CRC Press, Boca Raton, FL, 2003, p. **7**-6.

Comparison of Memory Technologies for the Year 2011

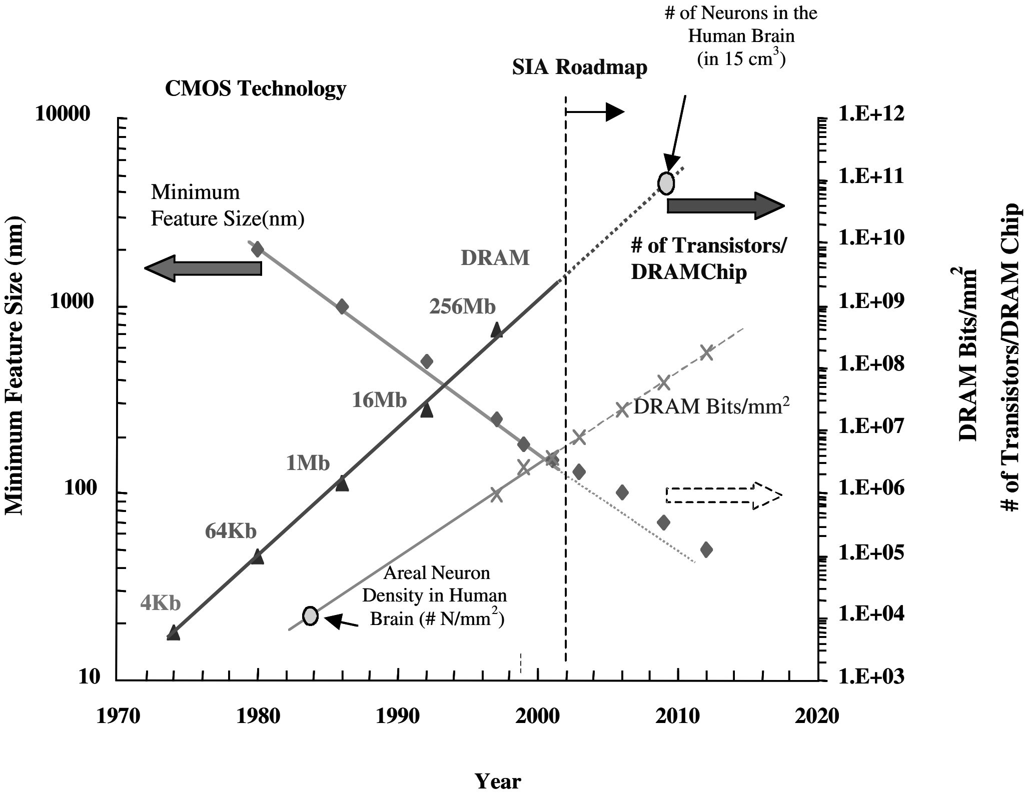
	CMOS			
Technology	DRAM	Flash	SRAM	MRAM
Reference	SIA 1999	SIA 1999	SIA 1999	
Generation at Introduction	64 GB	64 GB	180 MB/cm^2	64 GB
Circuit Speed	150 MHz	150 MHz	913 MHz	>500 MHz
Feature Size	50 nm	50 nm	35 nm	<50 nm
Access Time	10ns	10 ns	1.1 ns	<2 ns
Write Time	10 ns	10 μs	1.1 ns	<10 ns
Erase Time	<1 ns	10 μs	1.1 ns	N/A
Retention Time	2–4 s	10 years	N/A	Infinite
Endurance Cycles	Infinite	10^5	Infinite	Infinite
Operating Voltage (V)	0.5–0.6 V	5 V	0.5–0.6 V	<1 V
Voltage to Switch State	0.2 V	5 V	0.5–0.6 V	<50 mV
Cell Size	2.5 F^{2*}/bit 0.0005 μm^2	$2F^2$/bit	$12F^2$/bit	$2F^2$/bit

* F = minimal lithographic feature size.

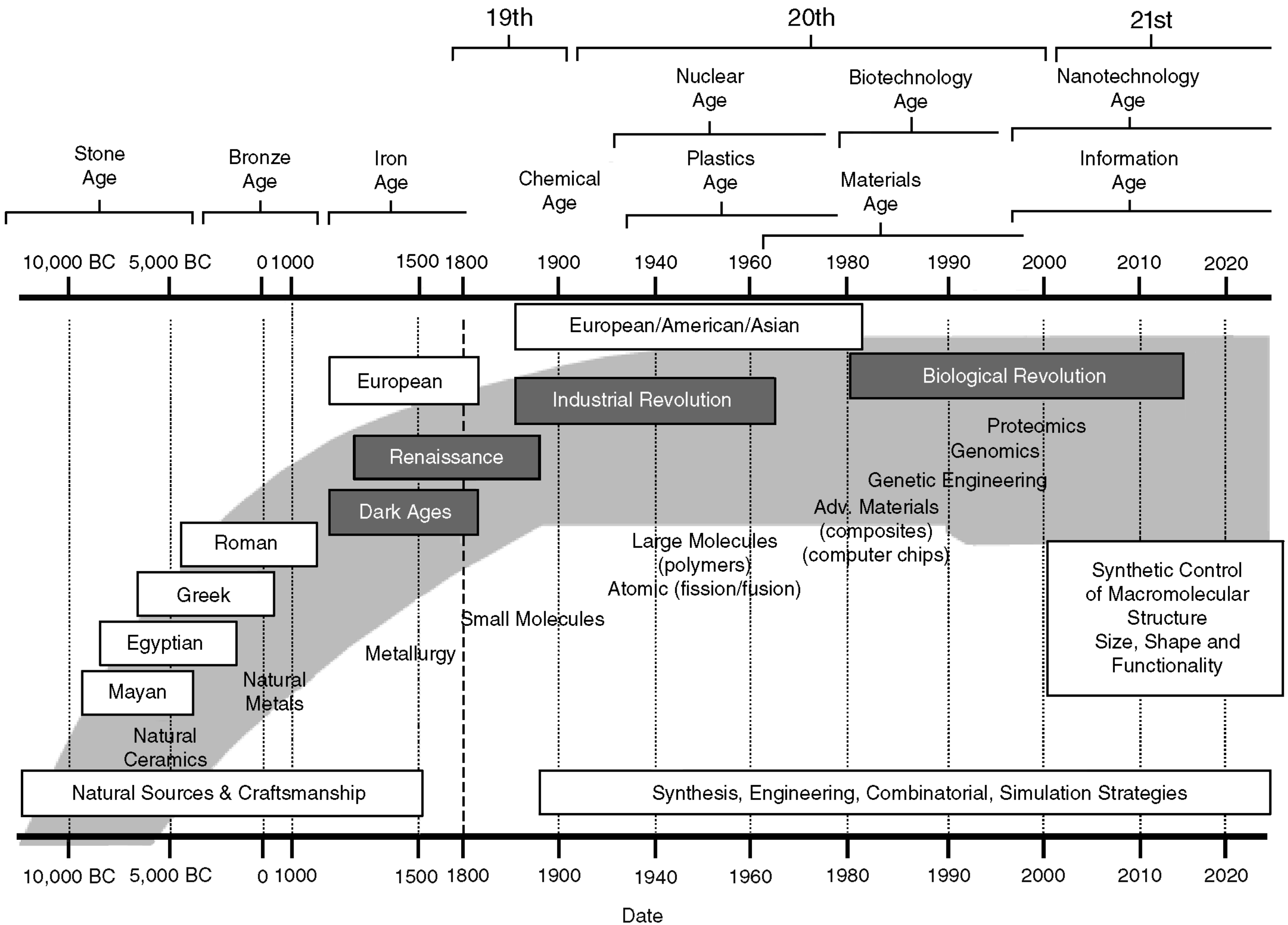
From Wolf, S.A., Chtchelkanova, A.Y., and Treger, D., Spintronics — Spin-based electronics, in *Handbook of Nanoscience, Engineering, and Technology,* Goodard, III, W.A., Brenner, D.W., Lyshevski, S.E., and Iafrate, G.J., Eds., CRC Press, Boca Raton, FL, 2003, p. **8**-6.



Size and scale of naturally occurring structures as compared with human-made structures. (From Bashir, R., Biologically mediated assembly of artificial nanostructures and microstructures, in *Handbook of Nanoscience, Engineering, and Technology,* Goddard, III, W.A., Brenner, D.W., Lyshevski, S.E., and Iafrate, G.J., Eds., CRC Press, Boca Raton, FL, 2003, p. **15**-2.)



Trends in miniaturization of integrated circuits in the last 25 years. (From Bashir, R., Biologically mediated assembly of artificial nanostructures and microstructures, in *Handbook of Nanoscience, Engineering, and Technology,* Goddard, III, W.A., Brenner, D.W., Lyshevski, S.E., and Iafrate, G.J., Eds., CRC Press, Boca Raton, FL, 2003, p. **15**-3.)



Civilizations, technology periods (ages), and historical revolutions as a function of time. (From Tomalia, D.A., Mardel, K., Henderson, S.A., Holan, G., and Estard, R., Dendrimers — An enabling synthetic science to controlled organic nanostructures, in *Handbook of Nanoscience, Engineering, and Technology,* Goddard, III, W.A., Brenner, D.W., Lyshevski, S.E., and Iafrate, G.J., Eds., CRC Press, Boca Raton, FL, 2003, p. **20**-3.)

Abbreviations

AAAS	American Association for Advancement of Science
ACS	American Chemical Society
AGI	American Geological Institute
AIChE	American Institute of Chemical Engineers
AIME	American Institute of Mining, Metallurgical and Petroleum Engineers
AIP	American Institute of Physics
AMA	actual mechanical advantage
API	American Petroleum Institute
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
BET	Brunauer-Emmet-Teller
DOD	Department of Defense (U.S.)
DOE	Department of Energy (U.S.)
e.g.	for example
eng., engr.	engineer, engineering
erf	error function
esp.	especially
est.	estimate(d)
etc.	and so forth
exp(x)	(x) is the exponent of e
ff.	and following
i.e.	that is
ISO	International Standards Organization
LH	latent heat
ln	logarithm to the base e
log	logarithm to the base 10
MTBF	mean time before failure (same as)
MTTF	mean time to failure
n.a.	not available
n.d.	no date; or undated
NAE	National Academy of Engineering (U.S.)
NAS	National Academy of Sciences (U.S.)
NASA	National Aeronautics and Space Administration (U.S.)
NBS	National Bureau of Standards (presently NIST)
NIST	National Institute of Standards and Technology (U.S.)
NIH	National Institutes of Health (U.S.)
NSF	National Science Foundation (U.S.)
NTP	normal temperature and pressure (25^{O} C at 1 atm.)
NUC	National Union Catalogue
NYPL	New York Public Library
TMA	theoretical mechanical advantage

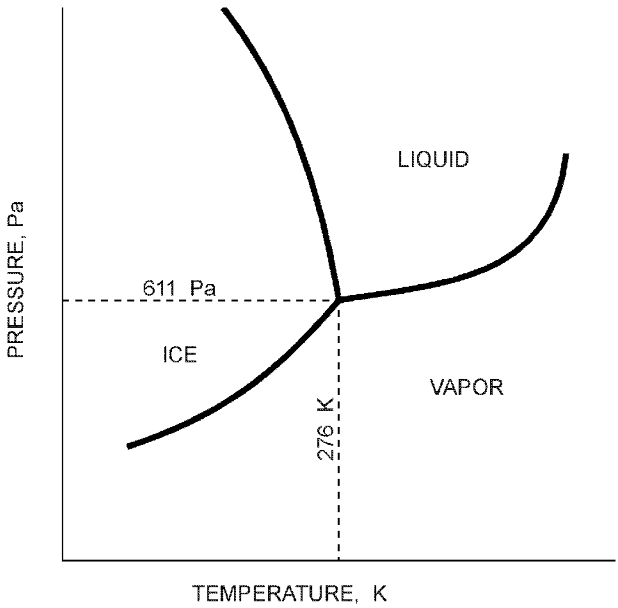
From Hall, C.W., *Laws and Models: Science, Engineering, and Technology,* CRC Press, Boca Raton, FL, 2000, p. xxvii.

Boiling Point Law, General

The decrease in vapor pressure of a nonvolatile solvent at the boiling point is proportional to the increase in mole fraction of solute as related to the moles of solute present. Thus:

$$-dp = -p\ dx/x$$

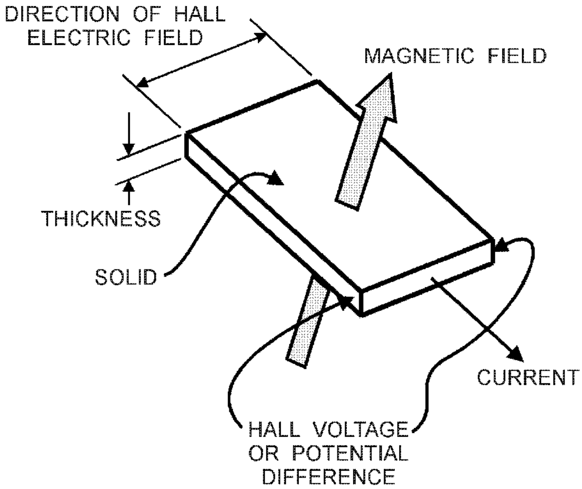
where p = vapor pressure
x = mole of solute



Triple point for water.

Hall Effect (1879)

When a steady current is flowing in a steady magnetic field, electromotive forces (voltages) are developed at right angles both to the magnetic force and to the current, and these are proportional to the product of the intensity of the current, the magnetic force, and the sine of the angle between the directions of these quantities.



Ideal Mixtures, Law of

The property of a mixture of gases and some solids and some liquids is an additive function of the same property of the components, an assumption which in many cases is far from correct:

$$W\,A = W_1\,A_1 + W_2\,A_2 + W_3\,A_3 + \ldots$$

Large Numbers, Law of (1689) (1713); Bernoulli Theorem (1713)

Various statements are used to represent the law of large numbers, but the idea is the same for each. If the size of a sample of statistically independent variables is increased indefinitely, good sample estimates of population parameters will tend to concentrate more and more closely about the true value. There are strong laws and weak laws of large numbers. Strong laws are concerned with showing that a variable, x, converges to a value μ with a probability of one. The strong law of large numbers is represented by the Borel theorem.

Weak laws consider conditions under which the probability that $|x - \mu|$ is greater than some given epsilon, ε, tends to zero. The weak law of large numbers is represented by the Bernoulli theorem. For the Bernoulli theorem, we have the following relationship:

$$\lim P\,(|x - m| > \varepsilon) = 0$$

$$\text{as } N \to \infty$$

where $\bar{x}$ = sample means
m = population
N = number of trials

S. Poisson gave the name of the law of large numbers to J. Bernoulli.

Maxwell Electromagnetic Field Equations (1864)

Maxwell, who was born in 1831, the year that Faraday published his discovery of electromagnetic induction, expressed Faraday's discoveries mathematically in field theory in 1855–1857, followed by his major work in four electromagnetic field equations, expressed in vector form as follows:

1. $\nabla \cdot D = \rho$, where D is electric displacement. The electric flux lines, if they end, will end on electric charges.
2. $\nabla \cdot \beta = 0$, where β is magnetic flux density. Those magnetic flux lines never terminate.
3. $\nabla \cdot E = -\delta\beta/\delta t$, which is a form of the Faraday law of induction, where E is the electric field density.
4. $\nabla \cdot H = i + \delta D/\delta t$, where H is magnetic field density. Based on the work by Ampere on steady currents, it shows that the line integral of magnetic intensity around a closed curve equals the current encircled, i.

Moore Law (1964)

Integrated circuits and microelectronics will double in density every other year (or every one and half years, by some references), according to a binary growth curve, and the design cost and number of functions per circuit will keep pace with complexity (on a 1960 to 1985 time frame). Elements per chip = $2^{(\text{years}/\tau)}$ where τ is 1, 2, 3, … years.

Newton Laws of Motion (Three Laws) (1687); Laws of Dynamics

These three basic laws form the basis of classical mechanics; that is, for mechanical problems not involving atomic particles or smaller, and speeds not involving the speed of light. The first law is a restatement of the discovery by Galileo that no force is required for steady, unchanging motion.

First Law (Law of Inertia)
A body at rest remains at rest, a body in motion continues in motion at constant speed along a straight line, unless the body, whether at rest or moving, is acted upon by an unbalanced force.

Second Law (Law of Constant Acceleration)
An unbalanced force acting on a body causes the body to accelerate in the direction of the force, with the acceleration directly proportional to the mass (m) of the body:

$$F = m\,a = W/g\,a$$

where F = unbalanced force
m = mass of the body
W = weight of the body
a = acceleration
g = gravitational constant

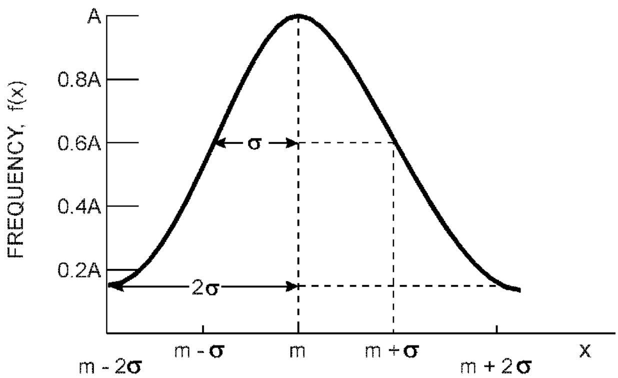
Third Law [Law of Conservation of Momentum (Motion)]
For every action there is an equal and opposite reaction, applies to all forces—electrical, gravitational, magnetic, etc.

Normal Law; Normal Law of Error; Normal or Gaussian Distribution Law; Gauss Error Curve; Probability Curve

The Gaussian distribution and the normal law of error are both often expressed as the same relationship. The Gaussian distribution law is the theoretical frequency distribution for a set of data of any normal, repetitive function, due to chance, represented by a bell-shaped curve symmetrical about a mean. The relationship of the number of events occuring and frequency when the events occur are due to chance only. The probability for distributions that occur due to chance is:

$$f(x) = p = h/(\pi)^{1/2} \exp(-h^2x^2)$$

where p = the probability, often written as y = p
h = a constant that depends on spread of the data or is a measure of precision
x = distance, plus or minus, from the center



Gaussian distribution and normal distribution.

Photoelectric Effect, Laws of (1888)(1924); (Published in 1930)

1. For a given frequency of incident light, the kinetic energy of ejected photoelectrons does not change, but their number increases in direct proportion to the light intensity.
2. When the frequency of incident light changes (increases), no electrons are emitted until a certain threshold frequency is reached (depending on the metal). For higher frequencies, the energy of photoelectrons increases in direct proportion to the difference of the frequency used and the threshold frequencies. This is represented by the Einstein equation:

$$W = h\,\gamma - \phi$$

where W = maximum kinetic energy given off by electrons
h = Planck constant
γ = frequency
ϕ = minimum energy to remove an electron from a solid (can also be applied to a gas)

Shannon Law or Formula or Theorem (1948)

The information transmitted from a message source over a communications system is represented by:

$$C = W \log_2(1 + P/N)$$

where C = channel capacity in bits per second
W = bandwidth
P = signal power
N = gaussian noise power, N = kTW where k = Boltzmann constant and T = temperature

Skin Effect

In any current carrying conductor the current tends to concentrate toward the outer surface as a result of eddy currents. An alternating current flowing through a pipe produces a magnetic field which produces eddy currents. Eddy current losses, the heat generated by eddy currents is given by:

$$P_e = K_e f^2 \beta_m{}^2 V_{ol}$$

where P_e = power loss by eddy current
K_e = eddy current loss constant
f = frequency of electricity
β_m = maximum flux density (webers/m^2)
V_{ol} = volume of pipe (conductor)

Snell Law (1613*, 1621); Snell Law of Refraction; Descartes Law

The relationship of the angle of incidence, the angle of refraction, the velocity light in a first medium, and the velocity in the second medium, gives the index of refraction:

$$n = \sin i/\sin r \qquad i = v/v'$$

where n = index of refraction
i = angle of incidence
r = angle of refraction
v = velocity in first medium
v' = velocity in second medium

Although the relationship was discovered in 1621, as stated above, and one author claims 1613*, the phenomenon was known at the time of Ptolemy (Claudius) in about the year A.D. 75.

Thermodynamics, Laws of (1847, 1850, 1851, 1906)

The First and Second Laws were stated by R. Clausius in 1850, based on previous work, and were further developed by W. Thomson in 1851.

Zeroth Law of Thermodynamics. For systems in equilibrium, there is an intrinsic property: internal energy. Any two bodies or systems in equilibrium with a third body are in equilibrium with each other. A function of the state of a substance that takes on the same value for all substances in thermal equilibrium, which is the temperature. For closed systems, changes in the internal energy are:

$$dU = dQ - dW$$

where dU = change internal energy
dQ = heat transferred to system
W = external work

First Law of Thermodynamics (1842, 1847).* The total energy change of any system together with its surroundings is zero; also called the *Law of Conservation of Energy.* The energy, including that equivalent to mass, of the universe is constant. The First law was expressed by H. Helmholtz and R. Clausius, was based on work by J. von Mayer (1842), and is an extension of the work of J. Joule. The statement of the first law is:

$$\Delta U = Q + W$$

where ΔU = the change in internal energy of the system
Q = heat absorbed by the system
W = work done on the system

Second Law of Thermodynamics (1850). A general law of the natural tendency in which the entropy of the universe and of systems in the universe is tending to a maximum, also called *Law of Entropy.* All processes in nature tend to occur with an increase in entropy; the flow of heat is always from higher to lower temperature. Not all forms of energy are equally interchangeable, with other forms of energy tending to go to heat. The Carnot theorem, $\Delta S \geq 0$, published in 1824, provides a working equation embodying the principles of the second law, which was expressed by Lord Kelvin (William Thomson) and by R. Clausius, who coined the word *entropy.* L. Boltzmann provided the statistical foundation of the second law (1877).

Third Law of Thermodynamics (1906). Solutions and gases are excluded from the third law. The Nernst heat theorem, also identified as the third law of thermodynamics, was extended by Planck by adding the postulate that the absolute entropy of a pure solid or a pure liquid approaches zero at 0 K:

$$\lim_{T \to 0} S \to 0$$

The entropy is related to thermodynamic probability by:

$$S = k \ln W$$

where S = entropy
k = Boltzmann constant
W = statistical probability

Thus, the more random the molecules are arranged, the greater the values of W and S. For a completely ordered system, W = 1 and S = 1. An exception is for a crystalline structure, for which quantum theory shows that the entropy at 0° abs. is not zero, because the crystal may exist in more than one state and have entropy residues from nuclear spin.

Young Modulus, E

The Young modulus applies to an elastic material and is the ratio of unit stress to elastic strain, produced in tension or compression:

$$E = \Delta\sigma/\Delta\varepsilon$$

The Young modulus for aluminum is 10×10^6 psi; steel, 30×10^6 psi; wood, concrete (compression), 5000 psi (34.5 MPa). Elastic materials obey the Hooke law.

The Young modulus by stretching of a wire or rod is:

$$M = mgL/\pi r^2 e$$

where M = modulus, r = radius
m = mass, e = elongation
L = length

The modulus of rigidity for twisting of a bar is:

$$M = CL/\pi r^4 \theta$$

where C = couple, C = mgx, L = length
θ = twist, radians, r = radius

From Hall, C.W., *Laws and Models: Science, Engineering, and Technology,* CRC Press, Boca Raton, FL, 2000.

Types of Manufacturing — Characteristics and Examples

Volume	Very low	High	Highest
Variety	Highest	Low	Lowest
Flexibility	Highest	Low	Lowest
1. Job-shop production	Tool and die making Casting (foundry) Baking (bakery)		
2. Mass production		Auto assembly Bottling Apparel manufacturing	
3. Continuous production			Paper milling Refining Extrusion

From Schonberger, R.J., Types of manufacturing, in *The Technology Management Handbook*, Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1999, p. **13**-2.

Coefficient of Friction—Identical Metals*

Courtesy of Edmond E. Bisson and Donald H. Buckley

The following table gives coefficients of kinetic sliding friction for polycrystalline pure metals in contact with themselves.

Metal	Coefficient of Friction: Lubricated: Oil or Grease†	Lubricated: Solid Film MoS_2	Unlubricated: Dry-Sliding in Air	Unlubricated: Vacuum, with Surfaces Cleaned
Body-Centered Cubic				
Iron on iron	0.15	.04–.08	1.0	Seizure (2)
Tantalum on tantalum	0.1	.04–.08	1.0	Seizure
Molybdenum on molybdenum	0.1	.04–.08	1.2	Seizure
Tungsten on tungsten	0.1	.04–.08	0.3	3.0 (3)
Chromium on chromium	0.34	.04–.08	0.4 (4)	—
Face-Centered Cubic				
Copper on copper	0.08	.04–.08	1.2–1.5	Seizure (6)
Nickel on nickel	0.28	.04–.08	0.8	Seizure
Silver on silver	0.55	.04–.08	1.5	Seizure
Gold on gold	0.2	.04–.08	2.0 (8)	Seizure
Aluminum on aluminum	0.12	.04–.08	1.0	Seizure
Platinum on platinum	0.25	.04–.08	1.2	Seizure
Rhodium on rhodium	0.1	.04–.08	0.4	3.0–5.0 (6)
Iridium on iridium	0.1	—	0.4	4.0
Lead on lead	0.1	—	2.0	—
Hexagonal				
Beryllium on beryllium	0.1	.04–.08	0.4	0.5 (6)
Magnesium on magnesium	0.08	.04–.08	0.4	0.6 (6)
Lanthanum on lanthanum	0.1	—	0.4 (6)	0.3 (6)
Titanium on titanium	0.1	.04–.08	0.6 (7)	1.2 (6)
Zirconium on zirconium	0.1	.04–.08	0.6	0.5 (6)
Rhenium on rhenium	0.1	.04–.08	0.4 (7)	0.3 (6)
Osmium on osmium	0.1	—	0.3	0.6 (6)
Ruthenium on ruthenium	0.1	—	0.3	0.5 (6)
Thallium on thallium	0.1	—	0.3 (6)	0.4 (6)
Cobalt on cobalt	0.1	.04–.08	0.5	0.4 (6)
Cadmium on cadmium	0.05	.04–.08	0.8 (4)	—
Zinc on zinc	0.04	—	0.9 (4)	—
Rhombohedral				
Bismuth	—	—	0.9 (4)	—

†Paraffinic oil plus 1% lauric acid.

Metal	Surface Film	Coefficient of Friction
Copper on copper	Oxide	0.8 (4)
	Sulfide	0.7 (4)
Steel on steel	Oxide	
	Fe_2O_3	0.6 (9)
	Fe_3O_4	0.4 (9)
	Sulfide (FeS)	0.5 (9)
	Chloride ($FeCl_2$)	0.1 (9)
	Oleic Acid	0.1 (9)
	Graphite	0.1 (9)
	Telfon (PTFE)	0.04 (4)

Coefficient of Friction—Identical Metals* (continued)

* Values are principally from Reference 1 and NASA data, except where indicated by other reference numbers in parentheses.

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1. "The Friction and Lubrication of Solids," F.P. Bowden and D. Tabor, Parts I and II, Oxford Press, Part I: 1958, Part II: 1964.
2. "Influence of Chemisorbed Films on Adhesion and Friction of Clean Iron," D.H. Buckley, NASA TN D–4775, 1968.
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5. "The Influence of Crystal Structure. Orientation and Solubility on the Adhesion and Sliding of Various Metal Single Crystals in Vacuum (10^{-11} Torr)," D.H. Buckley, ASTM SP–431, 1968, pp. 248–271.
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7. "Friction and Wear of Materials," E. Rabinowicz, John Wiley & Sons, 1965.
8. "The Lubrication of Gold," M. Antler, *Wear*, 6: 44–65, 1963.
9. "Advanced Bearing Technology," E.E. Bisson and W.J. Anderson, NASA SP-38, 1964

From Bolz, R.E. and Tuve, G.L., Friction and lubrication, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 610–611.

Coefficient of Friction—Identical Alloy Pairs

Courtesy of Edmond E. Bisson and Donald H. Buckley

Coefficients of Kinetic Sliding Friction for Pairs of Identical Metal Alloys

	Coefficient of Friction*			
	Lubricated		Unlubricated	
Alloy	Oil or Grease†	Solid Film MoS_2	Dry-Sliding in Air	Vacuum, with Surface Cleaned
1020 steel on 1020 steel	0.1	.04–.08	0.5 (1)	Seizure
52100 steel on 52100 steel	0.1	.04–.08	0.5 (1)	5.0 (1)
440–C S.S. on 440–C S.S.	0.1	.04–.08	0.4 (1)	2.5
304 S.S. on 304 S.S.	0.1	.04–.08	0.9 (1)	Seizure
Cast iron on cast iron	0.1	.04–.08	0.3 (4)	—
M-1 tool steel on M-1 tool steel	0.1	.04–.08	0.5 (1)	—
Brass on brass	0.1 (2)	.04–.08(2)	0.4 (4)	—
Rene 41 on Rene 41	0.1	.04–.08	0.4 (1)	4.0
Inconel on Inconel	0.1	.04–.08	0.8 (1)	Seizure
Hastelloy D on Hastelloy D	0.1	—	0.7 (1)	Seizure
Cermet K 162 B on Cermet K 162 B	0.1	.04–.08	0.2 (1)	1.0
Stellite Star J on Stellite Star J	0.1	.04–.08	0.3 (1)	0.5 (1)
Co-25 Mo on Co-25 Mo	0.08	0.04	0.5 (3)	0.3
Ti-12 Sn on Ti-12 Sn	—	—	0.8 (1)	0.6 (3)
Ti-16 Al on Ti-16 Al	—	—	0.5 (3)	0.3 (3)

† Lubricated with a mineral oil containing oxidation and corrosion inhibitors.
* Data from NASA—Lewis Research Center, except where indicated by reference numbers in parentheses.

References
1. "Advanced Bearing Technology," E.E. Bisson and W.J. Anderson, NASA SP-38, 1964.
2. "Friction and Wear," I.V. Kragelskii, Butterworths, 1965; available as an English translation.
3. "Friction and Wear of Hexagonal Metals and Alloys as Related to Crystal Structure and Lattice Parameters in Vacuum," D.H. Buckley and R.L. Johnson, *ASLE Trans.*, 9: 121–135, 1966.
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From Bolz, R.E. and Tuve, G.L., Friction and lubrication, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 611.

Coefficient of Friction—Dissimilar Metals

Courtesy of Edmond E. Bisson and Donald H. Buckley

Following are coefficients of kinetic sliding friction for dissimilar pure metals in contact with each other.

	Coefficient of Friction*			
	Lubricated		Unlubricated	
Metal Couple	Oil or Grease†	Solid Film MoS_2	Dry-Sliding in Air	Vacuum, with Surface Cleaned
Aluminum on iron	0.1	.04–.08	1.1 (2)	Seizure
Aluminum on zinc	0.1 (1)	.04–.08	0.8 (2)	—
Cadmium on aluminum	0.1 (1)	.04–.08	0.6 (2)	—
Cadmium on bismuth	0.1 (1)	.04–.08	0.8 (2)	—
Cadmium on iron	0.1	.04–.08	0.6 (2)	—
Cadmium on zinc	0.1 (1)	.04–.08	0.6 (2)	—
Cobalt on iron	0.1	.04–.08	0.5 (2)	0.7 (3)
Cobalt on copper	0.1	.04–.08	0.9 (2)	—
Cobalt on aluminum	0.1 (1)	.04–.08	1.0 (2)	—
Copper on cadmium	0.1 (1)	.04–.08	0.9 (2)	—
Copper on zinc	0.1 (1)	.04–.08	0.9 (2)	—
Copper on iron	0.1	.04–.08	1.0 (2)	5.0 (1)
Copper on nickel	0.1	.04–.08	1.2 (4)	2.0 (4)
Copper on tungsten	0.1	.04–.08	0.4 (4)	0.5 (4)
Nickel on tungsten	0.1	.04–.08	0.3 (4)	4.0 (4)
Zinc on iron	0.1 (1)	.04–.08	0.9 (2)	—
Zinc on antimony	0.1 (1)	.04–.08	0.9 (2)	—
Zinc on bismuth	0.1 (1)	.04–.08	0.7 (2)	—

†Lubricated with mineral oil containing oxidation and corrosion inhibitors.

	Coefficient of Friction*	
Material Combination	Dry-Sliding	Boundary Lubrication‡
Hard steel on Babbitt (ASTM 1)	0.33 (6)	0.16 (6)
Hard steel on Babbitt (ASTM 8)	0.35 (6)	0.14 (6)
Hard steel on Babbitt (ASTM 10)	—	0.13 (6)
Monel on SAE 52100 bearing steel	0.4 (5)	0.33 (5)
Beryllium copper on SAE 52100 bearing stgeel	0.8 (5)	0.10 (5)
Brass on SAE 52100 bearing steel	0.5 (5)	0.12 (5)
Bronze on SAE 52100 bearing steel	0.3 (5)	0.17 (5)
Gray cast iron on SAE 52100 bearing steel	0.6 (5)	0.29 (5)
Nodular iron on SAE 52100 bearing steel	0.5 (5)	0.17 (5)
Nichrome V on SAE 52100 bearing steel	0.3 (5)	0.13 (5)
24ST-aluminum on SAE 52100 bearing steel	0.3 (5)	0.17 (5)

‡ Paraffinic oil with oxidation and corrosion inhibitor.

* Values from NASA data, except where indicated by reference numbers in parentheses.

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From Bolz, R.E. and Tuve, G.L., Friction and lubrication, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 612.

Coefficient of Friction—Single Crystals*

Courtesy of Edmond E. Bisson and Donald H. Buckley

The following tables give coefficients of kinetic sliding friction for single crystals—metals and non-metals.

Metals

		Coefficient of Friction	
Metal	Atomic Plane	In Air, 20˚C	In Vacuum, Clean
Single crystal copper on single crystal copper	(100)	0.60	>40
	(110)	0.40	>40
	(111)	0.21	21.0
Single crystal cobalt on polycrystalline cobalt	(0001)	0.40	0.35
	(1010)	—	0.80
Single crystal magnesium on polycrystalline magnesium	(0001)	0.30	0.40
	(1010)	—	0.90
Single crystal rhenium on polycrystalline rhenium	(0001)	0.20	0.29
	(1010)	0.25	0.38
Single crystal beryllium on polycrystalline beryllium	(0001)	0.45	0.48
	(1010)	0.46	0.51
Single crystal titanium on polycrystalline titanium	(0001)	0.48	0.56
	(1010)	0.25	0.36
Single crystal tungsten on single crystal tungsten	(100)	0.60	3.0 (2)
	(110)	0.41	1.9 (2)
	(210)	0.40	1.3 (2)

Non-Metals

		Coefficient of Friction	
Material	Atomic Plane and Direction	In Air, 20˚C	In Vacuum, Clean
Diamond on diamond	(100) <100>	0.15 (3,4)	—
	(100) <110>	0.05 (3,4)	—
	(111) —	0.05 (3,4)	0.9 (4)
Sapphire on sapphire	(0001) <11$\bar{2}$0>	0.15	0.50
	(0001) <10$\bar{1}$0>	—	0.96
	(10$\bar{1}$0) <1120>	0.20	0.93
	(10$\bar{1}$0) <0001>	—	1.00
Diamond on magnesium oxide	(100) <100>	0.07	—
Diamond on lithium fluoride	(100) <110>	0.24	0.80
Diamond on potassium fluoride	(100) <110>	0.71	—
Diamond on sodium chloride	(100) <110>	0.47–0.70	—
Diamond on potassium bromide	(100) <110>	0.85	—

* Data from Reference 1 unless otherwise indicated by reference numbers in parentheses.

References

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From Bolz, R.E. and Tuve, G.L., Friction and lubrication, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 613.

Coefficient of Friction—Non-Metals*

Courtesy of Edmond E. Bisson and Donald H. Buckley

Listed below are coefficients of kinetic sliding friction for plastics and other non-metals in identical pairs and on steel.

	Coefficient of Friction			
	Dry-Sliding in Air		Vacuum, with Clean Surface	
Material	On Itself	On Steel	On Itself	On Steel
Teflon (PTFE)	0.1	0.04	—	.2–.3 (7)
Nylon	0.15–0.25	0.2	—	—
Perspex	0.8	0.5	—	—
Polystyrene	0.5	0.3	—	—
PCFE	0.2	0.08	—	0.3 (7)
Polyimide	—	0.25 (7)	0.5 (7)	0.2 (7)
Bakelite	0.3	0.30 (8)	—	—
Titanium carbide	0.2	0.5	0.9	—
Glass	1.0	0.6	—	—
Diamond	0.1 (2)	0.1	0.9	—
Sapphire	0.2 (3)	0.15 (4)	0.8 (5)	0.2 (5)
Mica	1.0	—	—	—
Carbon	0.2	0.15	—	0.4 (6)
Graphite	0.1	0.1	0.8	0.3 (6)

* Data from Reference 1 unless otherwise indicated by reference numbers in parentheses.

References

1. "The Friction and Lubrication of Solids," F.P. Bowden and D. Tabor, Part I, Oxford University Press, 1954.
2. "The Abrasion of Diamond," M. Seal, *Roy. Soc. Proc.*, Series A, 248:379–393, 1958.
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Coefficient of Friction—Lubricating Powders

Courtesy of Edmond E. Bisson and Donald H. Buckley

Listed below are coefficients of kinetic sliding friction for steel on steel (SAE 4620 on SAE 1020) with various powders between the surfaces.

Powder	Coefficient of Friction†	Powder	Coefficient of Friction†
Cadmium iodide, CdI_2	0.06	Zinc stearate, Zn $(C_{18}H_{35}O_2)_2$	0.11
Cadmium chloride, $CdCl_2$	0.07	Cobalt chloride, $CoCl_2$	0.10
Tungsten disulfide, WS_2	0.08	Mercury iodide, HgI_2	0.18
Silver sulfate, Ag_2SO_4	0.14	Copper bromide, $CuBr_2$	0.06
Lead iodide, PbI2	0.28	Silver iodide, AgI	0.25

† Data compiled from: "Advanced Bearing Technology," E.E. Bisson and W.J. Anderson, NASA SP-38, 1964.

From Bolz, R.E. and Tuve, G.L., Friction and lubrication, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 614.

Coefficients of Static and Sliding Friction

Reference letters indicate the lubricant used; numbers in parentheses give sources (see References).

Key to Lubricants Used;

a = oleic acid
b = Atlantic spindle oil (light mineral)
c = caster oil
d = lard oil
e = Atlantic spindle oil plus 2% oleic acid
f = medium mineral oil
g = medium mineral oil plus 1/2% oleic acid
h = stearic acid
i = grease (zinc oxide base)
j = graphite
k = turbine oil plus 1% graphite
l = turbine oil plus 1% stearic acid
m = turbine oil (medium mineral)
n = olive oil
p = palmitic acid
q = ricinoleic acid
r = dry soap
s = lard
t = water
u = rape oil
v = 3-in-1 oil
w = octyl alcohol
x = triolein
y = 1% lauric acid in paraffin oil

Materials	Static		Sliding	
	Dry	Greasy	Dry	Greasy
Hard steel on hard steel	0.78 (1)	0.11 (1, *a*)	0.42 (2)	0.029 (5, *h*)
		0.23 (1, *b*)		0.081 (5, *c*)
		0.15 (1, *c*)		0.080 (5, *i*)
		0.11 (1, *d*)		0.058 (5, *j*)
		0.0075 (18, *p*)		0.084 (5, *d*)
		0.0052 (18, *h*)		0.105 (5, *k*)
				0.096 (5, *l*)
				0.108 (5, *m*)
				0.12 (5, *a*)
Mild steel on mild steel	0.74 (19)		0.57 (3)	0.09 (3, *a*)
				0.19 (3, *u*)
Hard steel on graphite	0.21 (1)	0.09 (1, *a*)		
Hard steel on Babbitt (ASTM 1)	0.70 (11)	0.23 (1, *b*)	0.33 (6)	0.16 (1, *b*)
		0.15 (1, *c*)		0.06 (1, *c*)
		0.08 (1, *d*)		0.11 (1, *d*)
		0.085 (1, *e*)		

Coefficients of Static and Sliding Friction (continued)

Materials	Static Dry	Static Greasy	Sliding Dry	Sliding Greasy
Hard steel on Babbitt (ASTM 8)	0.42 (11)	0.17 (1, *b*)	0.35 (11)	0.14 (1, *b*)
		0.11 (1, *c*)		0.065 (1, *c*)
		0.09 (1, *d*)		0.07 (1, *d*)
		0.08 (1, *e*)		0.08 (11, *h*)
Hard steel on Babbitt (ASTM 10)		0.25 (1, *b*)		0.13 (1, *b*)
		0.12 (1, *c*)		0.06 (1, *c*)
		0.10 (1, *d*)		0.055 (1, *d*)
		0.11 (1, *e*)		
Mild steel on cadmium silver				0.097 (2, *f*)
Mild steel on phosphor bronze			0.34 (3)	0.173 (2, *f*)
Mild steel on copper lead				0.145 (2, *f*)
Mild steel on cast iron		0.183 (15, *c*)	0.23 (6)	0.133 (2, *f*)
Mild steel on lead	0.95 (11)	0.5 (1, *f*)	0.95 (11)	0.3 (11, *f*)
Nickel on mild steel			0.64 (3)	0.178 (3, *x*)
Aluminum on mild steel	0.61 (8)		0.47 (3)	
Magnesium on mild steel			0.42 (3)	
Magnesium on magnesium	0.6 (22)	0.08 (22, *y*)		
Teflon on Teflon	0.04 (22)			0.04 (22, *f*)
Teflon on steel	0.04 (22)			0.04 (22, *f*)
Tungsten carbide on tungsten carbide	0.2 (22)	0.12 (22, *a*)		
Tungsten carbide on steel	0.5 (22)	0.08 (22, *a*)		
Tungsten carbide on copper	0.325 (23)			
Tungsten carbide on iron	0.8 (23)			
Bonded carbide on copper	0.35 (23)			
Bonded carbide on iron	0.8 (23)			
Cadmium on mild steel			0.46 (3)	
Copper on mild steel	0.53 (8)		0.36 (3)	0.18 (17, *a*)
Nickel on nickel	1.10 (16)		0.53 (3)	0.12 (3, *w*)
Brass on mild steel	0.51 (8)		0.44 (6)	
Brass on cast iron			0.30 (6)	
Zinc on cast iron	0.85 (16)		0.21 (7)	
Magnesium on cast iron			0.25 (7)	
Copper on cast iron	1.05 (6)		0.29 (7)	
Tin on cast iron			0.32 (7)	
Lead on cast iron			0.43 (7)	
Aluminum on aluminum	1.05 (16)		1.4 (3)	
Glass on glass	0.94 (8)	0.01 (10, *p*)	0.40 (3)	0.09 (3, *a*)
		0.005 (10, *g*)		0.116 (3, *v*)
Carbon on glass			0.18 (3)	
Garnet on mild steel			0.39 (3)	
Glass on nickel	0.78 (8)		0.56 (3)	
Copper on glass	0.68 (8)		0.53 (3)	
Cast iron on cast iron	1.10 (16)		0.15 (9)	0.070 (9, *d*)
				0.064 (9, *n*)
Bronze on cast iron			0.22 (9)	0.077 (9, *n*)
Oak on oak (parallel to grain)	0.62 (9)		0.48 (9)	0.164 (9, *r*)
				0.067 (9, *s*)
Oak on oak (perpendicular)	0.54 (9)		0.32 (9)	0.072 (9, *s*)
Leather on oak (parallel)	0.61 (9)		0.52 (9)	
Cast iron on oak			0.49 (9)	0.075 (9, *n*)
Leather on cast iron			0.56 (9)	0.36 (9, *t*)
				0.13 (9, *n*)
Laminated plastic on steel			0.35 (12)	0.05 (12, *t*)
Fluted rubber bearing on steel				0.05 (13, *t*)

Coefficients of Static and Sliding Friction (continued)

References

(1) Campbell, *Trans. ASME*, 1939; (2) Clarke, Lincoln, and Sterrett, *Proc. API,* 1935; (3) Beare and Bowden, *Phil. Trans. Roy. Soc.*, 1935; (4) Dokos, *Trans. ASME*, 1946; (5) Boyd and Robertson, *Trans. ASME*, 1945; (6) Sachs, *zeit. f. angew. Math. und Mech.*, 1924; (7) Honda and Yamala, *Jour. I of M*, 1925; (8) Tomlinson, *Phil. Mag.*, 1929; (9) Morin, *Acad. Roy. des Sciences*. 1838; (10) Claypoole, *Trans. ASME,* 1943; (11) Tabor, *Jour. Applied Phys.*, 1945; (12) Eyssen, General Discussion on Lubrication. *ASME*, 1937; (13) Brazier and Holland-Bowyer, General Discussion on Lubrication, *ASME*, 1937; (14) Burwell, *Jour. SAE*, 1942; (15) Stanton, "Friction," Logmans; (16) Ernst and Merchant, Conference on Friction and Surface Finish, M.I.T., 1940; (17) Gongwer, Conference on Friction and Surface Finish, M.I.T., 1940; (18) Hardy and Bircumshaw, *Proc. Roy. Soc.*, 1925; (19) Hardy and Hardy, *Phil. Mag.*, 1919; (20) Bowden and Young, *Proc. Roy. Soc.*, 1951; (21) Hardy and Doubleday, *Proc. Roy. Soc.*, 1923; (22) Bowden and Tabor, "The Friction and Lubrication of Solids," Oxford; (23) Shooter, *Research*, 4, 1951.

From Bolz, R.E. and Tuve, G.L., Friction and lubrication, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 621–622.

The Greek Alphabet

Greek Letter		Greek Name	English Equivalent	Greek Letter		Greek Name	English Equivalent
Α	α	Alpha	(ä)	Ν	ϖ	Nu	(n)
Β	β	Beta	(b)	Ξ	ξ	Xi	(ks)
Γ	γ	Gamma	(g)	Ο	ο	Omicron	(o)
Δ	δ	Delta	(d)	Π	π	Pi	(p)
Ε	ε	Epsilon	(e)	Ρ	ρ	Rho	(r)
Ζ	ζ	Zeta (z)	(z)	Σ	σ ς	Sigma	(s)
Η	η	Eta	(ā)	Τ	τ	Tau	(t)
Θ	θ	Theta	(th)	Υ	υ	Upsilon	(ü, o͞o)
Ι	ι	Iota	(ē)	Φ	φ	Phi	(f)
Κ	κ	Kappa	(k)	Χ	χ	Chi	(H)
Λ	λ	Lambda	(l)	Ψ	ψ	Psi	(ps)
Μ	μ	Mu	(m)	Ω	ω	Omega	(o)

From Bolz, R.E. and Tuve, G.L., Communication, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 793.

Units and Their Conversion

Policy of this Edition

In each table in this handbook, the numerical values are preferably expressed in those units most commonly used by U.S. engineers working in the specific field, but SI metric units have also been added. In some cases two tables are given, one in English units, one in metric. In other tables parallel columns showing figures in both units are used, or the conversion factors are listed.

In a general engineering handbook complete consistency in units, abbreviations, and symbols is hardly possible, or even desirable. Such consistency would quickly defeat the objective of providing quick access to numbers of maximum immediate usefulness. Within each special field of engineering, the technical societies and industry associations have developed certain uniform practices and standards; if tables and data are given only in units that are foreign to these prevailing standards, convenience is sacrificed. In any case the practical demands of compilation and new typesetting costs, and the usual requirement of a copyright owner that reprinted material should not be changed, may well govern the units used in any given table.

The present edition of this handbook reflects the changes in abbreviations, symbols, and forms that are resulting from the efforts to reduce the diversity of practices from one specialty to another and from one nation to another. Recommendations of the International Organization for Standardization (ISO–R 1000) and of the "Metric Practice Guide," adopted by ASTM, NBS, APL, and others, have focused attention on the diversity of so-called standards.

Since the United States is the only major industrial nation that has not yet converted to metric units, some legal requirements in that direction are to be expected. It is now a contradiction to speak of the "English" system of units, and for some time to come U.S. engineers must accommodate to a wide use of conversions from one set of units to another. The extensive conversion tables that follow are offered with this expectation.

In spite of major efforts to unify engineering practices, there are many good reasons for retaining several means of expressing a physical quantity. For ease of learning and communication a descriptive name is better than one arbitrarily assigned, such as Hz for cps, celsius for centigrade, and torr for mm Hg; an opposite trend is prevalent at this time. Numerical scales directly related to the physical phenomena and to the method of their measurement have an advantage in the laboratory or field and will not soon be abandoned. Examples are barometric pressure in mm or in. of mercury, viscosity in seconds Saybolt, the calorie or the Btu, and even the "coefficients" of expansion, friction, diffusion, attenuation, and reflection. Symbols, abbreviations, and even the units themselves are not infrequently subject to change; note, for example, the now preferred *dB* in place of the well-established *db*; elimination of widely used abbreviations, such as kwh, cps, gpm, cc, and psi; and revised values for the second, the calorie, or the atomic weights. Users of this handbook are invited to call attention to places where consistency could be improved without sacrificing the objectives.

Of the many named units that might have more than one value, this book uses (unless otherwise stated) the thermochemical gram-calorie (4.184 J), the thermochemical Btu (1 054.35 J), the avoirdupois pound and ounce, the statue mile (5 280 ft), the short ton (2 000 lb), the U.S. liquid gallon (231 in.^{3}), and the electrical horsepower (746 W).

Rather than present a special and condensed table of engineering conversion factors, the editors have chosen to reprint the large table that has been developed over the years for the *Handbook of Chemistry and Physics*. Certain specialized conversion factors and tables have been included.

The Metric International System (SI)

Moves toward an international system of metric units are now following each other in quick succession, so a table of conversion factors for the most common units is given herewith. Perhaps the most definite are the moves toward the SI standards already initiated by the National Bureau of Standards, the various military services, the National Aeronautics and Space Administration, and other U.S. Government research groups. The American Society for Testing and Materials has declared in favor of SI units and will give other units only a secondary place in all newly issued ASTM Standards.[a] Other major engineering societies have committees to explore the adoption of SI units and are holding many meetings for discussion among members.

Whatever the decisions about converting to the metric system, the actual process will require many years, as can readily be seen from the experiences of other countries; in Great Britain, for example, even the single conversion to decimal monetary units and coinage moves very slowly. The practices and standards among the metric-system countries are far from uniform; no real international system exists among them.

Mere conversion of present U.S. specifications, drawings, tools, machines, and stock sizes, to equivalent metric units (so-called "soft" conversion) will not in any sense result in an "international" system. Instead, a "hard" conversion representing the abandonment of the 1/2-fractional system in favor of a 1/10-fractional system is necessary to attain the real advantages of the metric system. This means re-sizing of all round and sheet stock, lumber, bolts, screws, nails, wires, gears, containers, modules, and sub-assemblies, plus all the tools and machines related thereto. A long period of double-stocking must follow. The entire change is made the more difficult by the great penetration of U.S. products and materials into the markets of the world, e.g., airplanes and military equipment, production, and construction machinery. This is not to mention the problem of the individual engineer, technician, and user, who visualizes all his size relationships in inches

Units and Their Conversion (continued)

and feet and his weights in pounds. Realistically, more than one generation will be required for the educational conversion alone.

In presenting data in international standard metric units throughout this edition, the practices and forms used in the "Metric Practice Guide" have been carefully followed.[a] Certain conventions used in the "Metric Practice Guide" are not consistent with those originally adopted for this handbook, nor with ANSI standards. Special attention is directed to the following conventions:

1. For degrees Kelvin the degree symbol is omitted; for example, 50 K, not 50°K.
2. For multiplication a center point is used; for example, the unit of dynamic viscosity is abbreviated as N·s/m^2, not N s/m^2 or N × s/m^2.
3. Symbols for SI units are not capitalized unless the unit is derived from a proper name, as N for Sir Isaac Newton; however, *unabbreviated* units are not capitalized, such as newton, kelvin, hertz.

Conversion Factors to SI Standard Units

To Convert	To	Multiply by
Acceleration		
feet/second^2	meters/second^2	0.3048
Area		
square feet	square meters	0.09290304
Energy		
Btu (mean)	joule	1055.87
calorie (mean)	joule	4.19002
electron volt	joule	1.60210 × 10^{-19}
foot-pound	joule	1.355818
watthour	joule	3600.
Force		
dyne	Newton	0.00001
kilogram	Newton	9.80665
pound	Newton	4.448222
Length		
foot	meter	0.3048000
mil	meter	0.0000254
mile (U.S. statute)	meter	1609.344
Mass		
pound	kilogram	0.4535924
slug	kilogram	14.59390
ton (2000 lb)	kilogram	907.1847

To Convert	To	Multiply by
Power		
Btu/second	watt	1054.350
foot-pounds/ second	watt	1.355818
horsepower	watt	746.
Pressure		
atmosphere	newtons/meter^2	101325.0
bar	newtons/meter^2	100000.
kilograms/cm^2	newtons/meter^2	98066.50
pounds/in.^{2}	newtons/meter^2	6894.757
torr (mm Hg. 0°C)	newtons/meter^2	133.322
Viscosity		
centipoise	newton-second/ meter^2	0.001
pounds/foot second	newton-second/ meter^2	1.488164
Volume		
cubic foot	cubic meter	0.02831685
gallon (U.S. liquid)	cubic meter	0.003785412

[a] See "Metric Practice Guide," ASTM Standard E 380–70, American Society for Testing and Materials, 1970.

From Bolz, R.E. and Tuve, G.L., Units and conversion factors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 803–804.

International System (SI) Metric Units

Basic Units–MKS

Length	meter	m	Electric current	ampere	A
Mass	kilogram	kg	Thermodynamic temperature	kelvin	K
Time	second	s	Luminous intensity	candela	cd

Derived Units

Property	Unis†	Abbreviations and Dimensions	
Acceleration	meter per second squared	m/s^2	
Activity (of radioactive source)	1 per second	s^{-1}	
Angular acceleration	radian per second squared	$rads/s^{-1}$	
Angular velocity	radian per second	rad/s	
Area	square meter	m^2	
Density	kilogram per cubic meter	kg/m^3	
Dynamic viscosity	newton-second per sq meter	$N{\cdot}s/m^2$	
Electric capacitance	farad	F	(A·s/V)
Electric charge	coulomb	C	(A·s)
Electric field strength	volt per meter	V/m	
Electric resistance	ohm		(V/A)
Entropy	joule per kelvin	J/K	
Force	newton	N	$(kg{\cdot}m/s^2)$
Frequency	hertz	hz	(s^{-1})
Illumination	lux	lx	(lm/m^2)
Inductance	henry	H	(V·s/A)
Kinematic viscosity	sq meter per second	m^2/s	
Luminance	candela per sq meter	cd/m^2	
Luminous flux	lumen	lm	(cd·sr)
Magnetomotive force	ampere	A	
Magnetic field strength	ampere per meter	A/m	
Magnetic flux	weber	Wb	(V·s)
Magnetic flux density	tesla	T	(Wb/m^2)
Power	watt	W	(J/s)
Pressure	newton per square meter	N/m^2	
Radiant intensity	watt per steradian	W/sr	
Specific heat	joule per kilogram kelvin	J/kg K	
Thermal conductivity	watt per meter kelvin	W/m K	
Velocity	meter per second	m/s	
Volume	cubic meter	m^3	
Voltage, potential difference, electromotive force	volt	V	(W/A)
Wave number	1 per meter	m^{-1}	
Work, energy, quantity of heat	joule	J	(N·m)

International System (SI) Metric Units (continued)

Prefix Names of Multiples and Submultiples of Units

Decimal Equivalent	Prefix	Pronunciation	Symbol	Exponential Expression
1,000,000,000,000	tera	tĕr′ȧ	T	10^{+12}
1,000,000,000	giga	jĭ′gȧ	G	10^{+9}
1,000,000	mega	mĕg′ȧ	M	10^{+6}
1,000	kilo	kĭl′ō	k	10^{+3}
100	hecto	hĕk′tō	h	10^{+2}
10	deka	dĕk′ȧ	da	10
0.1	deci	dĕs′ĭ	d	10^{-1}
0.01	centi	sĕnt′ĭ	c	10^{-2}
0.001	milli	mĭl′ĭ	m	10^{-3}
0.000 001	micro	mī′krō	μ	10^{-6}
0.000 000 001	nano	năn′ō	n	10^{-9}
0.000 000 000 001	pico	pĕ′kō	p	10^{-12}
0.000 000 000 000 001	femto	fĕm′tō	f	10^{-15}
0.000 000 000 000 000 001	atto	ăt′tō	a	10^{-18}

Definitions of the Most Important International System (SI) Units

The *ampere* (unit of electric current) is the constant current that, if maintained in two straight parallel conductors of infinite length, of negligible circular sections, and placed 1 meter apart in a vacuum, will produce between these conductors a force equal to 2×10^{-7} newton per meter of length.

The *candela* is the luminous intensity, in the direction of the normal, of a blackbody surface 1/600,000 square meter in area, at the temperature of solidification of platinum under a pressure of 101,325 newtons per square meter.

The *coulomb* (unit of quantity of electricity) is the quantity of electricity transported in 1 second by a current of 1 ampere.

The *ephemeris second* (unit of time) is exactly 1/31 556 925.974 7 of the tropical year of 1900, January, 0 days, and 12 hours ephemeris time.

The *fraud* (unit of electric capacitance) is the capacitance of a capacitor between the plates of which there appears a difference of potential of 1 volt when it is charged by a quantity of electricity equal to 1 coulomb.

The *henry* (unit of electric inductance) is the inductance of a closed circuit in which an electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at a rate of 1 ampere per second.

The *International Practical Kelvin Temperature Scale* of 1960 and the *International Practical Celsius Temperature Scale* of 1960 are defined by a set of interpolation equations based on the following reference temperatures:

	K	Deg C
Oxygen, liquid-gas equilibrium	90.18	–182.97
Water, solid-liquid equilibrium	273.15	0.00
Water, solid-liquid-gas equilibrium	273.16	0.01
Water, liquid-gas equilibrium	373.15	100.00
Zinc, solid-liquid equilibrium	692.655	419.505
Sulfur, liquid-gas equilibrium	717.75	444.6
Silver, solid-liquid equilibrium	1233.95	960.8
Gold, solid-liquid equilibrium	1336.15	1063.0

The *joule* (unit of energy) is the work done when the point of application of 1 newton is displaced a distance of 1 meter in the direction of the force.

The *kelvin* (unit of thermodynamic temperature) is the fraction 1/273.16 of the thermodynamic temperature of the triple point of water. The decision was made at the 13th General Conference on Weights and Measures on October 13, 1967, that the name of the unit of thermodynamic temperature would be changed from *degree Kelvin* (symbol: °*K*) to *kelvin* (symbol: *K*). The name (*kelvin*) and symbol (*K*) are to be used for expressing temperature intervals. The former convention that expressed a temperature interval in *degrees Kelvin* or, abbreviated, *deg K* is dropped. However, the old designations are acceptable temporarily as alternatives to the new ones. One may also express temperature intervals in *degrees Celsius*.

International System (SI) Metric Units (continued)

The *kilogram* (unit of mass) is the mass of a particular cylinder of platinum iridium alloy, called the International Prototype Kilogram, which is preserved in a vault at Sèvres, France, by the International Bureau of Weights and Measures.

Length: The name *micron*, for a unit of length equal to 10^{-6} meter, and the symbol μ that has been used for it were dropped by action of the 13th General Conference on Weights and Measures on October 13, 1967. The symbol μ is to be used solely as an abbreviation for the prefix *micro*-, standing for the multiplication by 10^{-6}. Thus the length previously designated as 1 micron should be designated 1 μm.

The *lumin* (unit of luminous flux) is the luminous flux emitted in a solid angle of 1 steradian by a uniform point source having an intensity of 1 candela.

The *newton* (unit of force) is that force that gives to a mass of 1 kilogram an acceleration of 1 meter per second.

The *ohm* (unit of electric resistance) is the electric resistance between two points of a conductor when a constant difference of potential of 1 volt, applied between these two points, produces in this conductor a current of 1 ampere, this conductor not being the source of any electromotive force.

The *meter* (unit of length) is the length of exactly 1 650 763.73 wavelengths of the radiation in vacuum corresponding to the unperturbed transition between the levels $2p_{10}$ and $5d_5$ of the atom of krypton 86, the orange-red line.

The *second* is the unit of time of the International System of Units. The definition adopted at the October 13, 1967, meeting of the 13th General Conference on Weights and measures is: "The second is he duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the fundamental state of the atom of cesium 133." The frequency (9 192 631 770 hz), which the definition assigns to the cesium radiation, was carefully chosen to make it impossible, by any existing experimental evidence, to distinguish the new second from the *ephemeris second* based on the earth's motion. Therefore no changes need to be made in data stated in terms of the old standard in order to convert them to the new one. The atomic definition has two important advantages over the previous definition: (1) it can be realized (i.e., generated by a suitable clock) with sufficient precision, ± 1 part per hundred billion (10^{11}) or better, to meet the most exacting demands of modern metrology; and (2) it is available to anyone who has access to or who can build an atomic clock controlled by the specified cesium radiation.‡ In addition one can compare other high-precision clocks directly with such a standard in a relatively short time — an hour or so compared against years with the astronomical standard. Laboratory-type atomic clocks are complex and expensive, so that most clocks and frequency generators will continue to be calibrated against a standard such as the NBS Frequency Standard, controlled by a cesium atomic beam, at the Radio Standards Laboratory in Boulder, Colorado. In most cases the comparison will be by way of the standard-frequency and time-interval signals broadcast by NBS radio stations WWV, WWVH, WWVB, and WWVL.

The *volt* (unit of electric potential difference and electromotive force) is the difference of electric potential between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.

The *watt* (unit of power) is the power that gives rise to the production of energy at the rate of 1 joule per second.

The *weber* (unit of magnetic flux) is the magnetic flux that, linking a circuit of one turn, produces in it an electromotive force of 1 volt as it is reduced to zero at a uniform rate in 1 second.

† According to SI terminology, the following should be treated as obsolete:

- angstrom (now 100 picometers or 0.1 nanometer)
- bar (now 100 kilonewtons/meter^2)
- kiloliter (now cubic meter)
- kiloton (now gigagram)
- liter (now cubic decimeter)
- metric ton (now megagram)
- micron (now micrometer)

‡ A description of such clocks is given in "Atomic Frequency Standards," *NBS Tech. News Bull.*, 45:8–11, January 1961. For more developments and technical details, see R.E. Bechler, R.C. Mockler, and J.M. Richardson, "Cesium Beam Atomic Time and Frequency Standards," *Metrologia*, 1:114–131, July 1965.

From Bolz, R.E. and Tuve, G.L., Units and conversion factors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 805–807.

International Metric System

This table can be used for conversion of any quantity in English units to corresponding SI units to give significant figures (without the use of a calculator). Exact values are shown in boldface. Unless otherwise stated, values are in thermochemical calorie, thermochemical Btu, and avoirdupois mass units.[a]

Instruction: Shift decimal as required for each digit in the original quantity and add the converted results.

Example: Convert an acceleration of 15.30 ft/s^2 to m/s^2.

Solution: From first line of table, 3.048 0 + 1.524 0 + 0.091 44 = 4.663 4 m/s^2.

	1	2	3	4	5	6	7	8	9
ACCELERATION									
foot/second^2 to meter/second^2, m/s^2	**0.304 8**	0.609 6	0.914 4	1.219 2	1.524 0	1.828 8	2.133 6	2.438 4	2,743 2
g's (free fall, standard to meter/second^2, m/s^2	**9.806 65**	19.613	29.420	39.227	49.033	58.840	68.647	78.453	88.260
inch/second^2 to meter/second^2, m/s^2	**0.025 4**	0.050 8	0.076 2	0.101 6	0.127 0	0.152 4	0.177 8	0.203 2	0.228 6
AREA									
acre to meter^2, m^2	4 046.856	8 093.7	12 141	16 187	20 234	24 281	28 328	32 375	36 422
circular mil to meter^2, m^2	$5.067\ 075 \times 10^{-10}$	10.134×10^{-10}	15.201×10^{-10}	20.268×10^{-10}	25.335×10^{-10}	30.402×10^{-10}	35.470×10^{-10}	40.537×10^{-10}	45.604×10^{-10}
foot^2 to meter^2, m^2	**0.092 903 04**	0.185 81	0.278 71	0.371 61	0.464 52	0.557 42	0.650 32	0.743 22	0.836 13
inch^2 to meter^2, m^2	**0.000 645 16**	**0.001 290 32**	**0.001 935 48**	**0.002 580 64**	**0.003 225 80**	**0.003 870 96**	**0.004 516 12**	**0.005 161 28**	**0.005 806 44**
mile^2 (U.S. statute) to meter^2, m^2	2 589 988	5 180 000	7 770 000	10 360 000	12 950 000	15 540 000	18 130 000	20 720 000	23 310 000
yard^2 to meter^2, m^2	**0.836 127 36**	1.672 3	2.508 4	3.344 5	4.180 6	5.016 8	5.852 9	6.689 0	7.525 1
BENDING MOMENT OR TORQUE									
ounce-force-inch to newton-meter, N·m	0.007 061 552	0.014 123	0.021 185	0.028 246	0.035 308	0.042 369	0.049 431	0.056 492	0.063 554
pound-force-inch to newton-meter, N·m	0.112 984 8	0.225 97	0.338 95	0.451 94	0.564 92	0.677 91	0.790 89	0.903 88	1.016 9
pound-force-foot to newton-meter, N·m	1.355 818	2.711 6	4.067 5	5.423 3	6.779 1	8.134 9	9.490 7	10.847	12.202
DENSITY (MASS/VOLUME)									
grain/gallon to kilogram/meter^3, kg/m^3	0.017 118 06	0.034 236	0.051 354	0.068 472	0.085 590	0.102 71	0.119 83	0.136 94	0.154 06
ounce/gallon to kilogram/meter^3, kg/m^3	7.489 152	14.978	22.467	29.957	37.446	44.935	52.424	59.913	67.402

ounce/inch³ to kilogram/meter³, kg/m³	1 729.994	3 460.0	5 190.0	6 920.0	8 650.0	10 380	12 110	13 840	15 570
pound-mass/foot³ to kilogram/meter³, kg/m³	16.018 46	32.037	48.055	64.074	80.092	96.111	112.13	128.15	144.17
pound-mass/inch³ to kilogram/meter³, kg/m³	27 679.90	55 360	83 040	110 720	138 400	166 080	193 760	221 440	249 120
pound-mass/gallon to kilogram/meter³, kg/m³	119.826 4	239.65	359.48	479.31	599.13	718.96	838.78	958.61	1 078.4
slug/foot³ to kilogram/meter³, kg/m³	515.378 8	1 030.8	1 546.1	2 061.5	2 576.9	3 092.3	3 607 7	4 123.0	4 638.4
ELECTRICITY AND MAGNETISM									
ampere-hour to coulomb, C	**3 600**	**7 200**	**10 800**	**14 400**	**18 000**	**21 600**	**25 200**	**28 800**	**32 400**
faraday (based on C-12) to coulomb, C	96 487.00	192 970	289 460	385 950	482 440	578 920	675 410	771 900	868 380
gauss to tesla, T	**0.000 1**	**0.000 2**	**0.000 3**	**0.000 4**	**0.000 5**	**0.000 6**	**0.000 7**	**0.000 8**	**0.000 9**
gilbert to ampere-turn	0.795 774 7	1.591 5	2.387 3	3.183 1	3.978 9	4.774 6	5.570 4	6.366 2	7.162.0
oersted to ampere-meter, A/m	79.577 47	159.15	238.73	318.31	397.89	477.46	557.04	636.62	716.20
unit pole to weber, Wb	$1.256\ 637 \times 10^{-7}$	$2.513\ 3 \times 10^{-7}$	$3.769\ 9 \times 10^{-7}$	$5.026\ 5 \times 10^{-7}$	$6.283\ 2 \times 10^{-7}$	$7.539\ 8 \times 10^{-7}$	$8.796\ 5 \times 10^{-7}$	10.053×10^{-7}	11.310×10^{-7}
ENERGY AND WORK									
British thermal unit to joule, J	1 054.350	2 108.7	3 163.1	4 217.4	5 271.8	6 326.1	7 380.5	8 434.8	9 489.2
British thermal unit (IT) to joule, J[a]	1 055.056	2 220.1	3 165.2	4 220.2	5 275.3	6 330.3	7 385.4	8 440.4	9 495.5
calorie to joule, J	**4.184**	**8.368**	**12.552**	**16.736**	**20.920**	**25.104**	**29.288**	**33.472**	**37.656**
calorie (IT) to joule, J[a]	**4.186 8**	**8.373 6**	**12.560 4**	**16.747 2**	**20.934 0**	**25 120 8**	**29.307 6**	**33.494 4**	**37.681 2**
electron volt to joule, J	$1.602\ 10 \times 10^{-19}$	$3.204\ 2 \times 10^{-19}$	$4.806\ 3 \times 10^{-19}$	$6.408\ 4 \times 10^{-19}$	$8.010\ 5 \times 10^{-19}$	$9.612\ 6 \times 10^{-19}$	11.215×10^{-19}	12.817×10^{-19}	14.419×10^{-19}
foot-pound-force to joule, J	1.355 818	2.711 6	4.067 5	5.423 3	6.779 1	8.134 9	9.490 7	10.847	12.202
kilowatt-hour to joule, J	**3 600 000**	**7 200 000**	**10 800 000**	**14 400 000**	**18 000 000**	**21 600 000**	**25 200 000**	**28 800 000**	**32 400 000**
horsepower-hour to joule, J	2 684 520	5 369 039	8 053 559	10 738 078	13 422 598	16 107 117	18 791 637	21 476 156	24 160 676
FLOW RATE									
foot³/minute to meter³/second, m³/s	0.000 471 947 4	0.000 943 89	0.001 415 8	0.001 887 8	0.002 359 7	0.002 831 7	0.003 303 6	0.003 775 6	0.004 247 5
foot³/second to meter³/second, m³/s	0.028 316 85	0.056 634	0.084 951	0.113 27	0.141 58	0.169 90	0.198 22	0.226 53	0.254 85
gallon (U.S. liquid)/day to meter³/second, m³/s	$4.381\ 264 \times 10^{-8}$	8.762×10^{-8}	13.144×10^{-8}	17.525×10^{-8}	21.906×10^{-8}	26.288×10^{-8}	30.669×10^{-8}	35.050×10^{-8}	39.431×10^{-8}

Conversions to SI Units (continued)

	1	2	3	4	5	6	7	8	9
gallon (U.S. liquid)/minute to meter³/second, m³/s	0.000 063 090 20	0.000 126 18	0.000 189 27	0.000 252 36	0.000 315 45	0.000 378 54	0.000 441 63	0.000 504 72	0.000 567 81
pound-mass/hour to kilogram/second, kg/s	0.000 125 997 9	0.000 252 00	0.000 377 99	0.000 503 99	0.000 629 99	0.000 755 99	0.000 881 99	0.001 007 98	0.001 133 98
pound-mass/minute to kilogram/second, kg/s	0.007 559 873	0.015 120	0.022 680	0.030 239	0.037 799	0.045 359	0.052 919	0.060 479	0.068 039
FORCE									
kilogram-force to newton, N	**9.806 65**	19.613	29.420	39.227	49.033	58.840	68.647	78.453	88.260
ounce-force to newton, N	0.278 014 0	0.556 03	0.834 04	1.112 1	1.390 1	1.668 1	1.946 1	2.224 1	2.502 1
pound-force to newton, N	4.448 222	8.896 4	13.345	17.793	22.241	26.689	31.138	35.586	40.034
HEAT									
SPECIFIC HEAT CAPACITY									
British thermal unit/ pound-mass-deg F to joule/kilogram-kelvin, J/kg·K	**4 184**	**8 368**	**12 552**	**16 736**	**20 920**	**25 104**	**29 288**	**33 472**	**37 656**
British thermal unit (IT)/ pound-mass-deg F to joule/kilogram-kelvin, J/kg·K[a]	**4 186.8**	**8 373.6**	**12 560.4**	**16 747.2**	**20 934.0**	**25 120.8**	**29 307.6**	**33 494.4**	**37 681.2**
calorie/gram-deg C to joule/ kilogram-kelvin, J/kg·K	**4 184**	**8 368**	**12 552**	**16 736**	**20 920**	**25 104**	**29 288**	**33 472**	**37 656**
ENERGY/MASS (ENTHALPY, ETC.)									
British thermal unit/ pound-mass to joule/ kilogram, J/kg	2 324.444	4 648.9	6 973.3	9 287.8	11 622	13 947	16 271	18 596	20 920
British thermal unit (IT)/ pound-mass to joule/ kilogram, J/kg[a]	**2 326**	**4 652**	**6 978**	**9 304**	**11 630**	**13 956**	**16 282**	**18 608**	**20 934**
calorie/gram to joule/ kilogram, J/kg	**4 184**	**8 368**	**12 552**	**16 736**	**20 920**	**25 104**	**29 288**	**33 472**	**37 656**

THERMAL CONDUCTIVITY									
British thermal unit/hour-foot-deg F to watt/meter-kelvin, W/m·K	1.729 577	3.459 2	5.188 7	6.918 3	8.647 9	10.377	12.107	13.837	15.566
British thermal unit (IT)/hour-foot-deg F to watt/meter-kelvin, W/m·K[a]	1.730 735	3.461 5	5.192 2	6.922 9	8.653 7	10.384	12.115	13.846	15.577
British thermal unit-inch/hour-foot^2-deg F to watt/meter-kelvin, W/m·K	0.144 131 4	0.288 26	0.432 39	0.576 53	0.720 66	0.864 79	1.008 9	1.153 1	1.297 2
British thermal unit (IT)-inch/hour-foot^2-deg F to watt/meter-kelvin, W/m·K[a]	0.144 227 9	0.288 46	0.432 68	0.576 91	0.721 14	0.865 37	1.009 60	1.153 82	1.298 05
calorie second-centimeter-deg C to watt/meter-kelvin, W/m·K	**418.4**	**836.8**	**1 255.2**	**1 673.6**	**2 092.0**	**2 510.4**	**2 928.8**	**3 347.2**	**3 765.6**
ENERGY PER UNIT AREA									
British thermal unit/foot^2 to joule/meter^2, J/m^2	11 348.93	22 698	34 047	45 396	56 745	68 094	79 443	90 791	102 140
calorie/centimeter^2 to joule/meter^2, J/m^2	**41 840**	**836 80**	**125 520**	**167 360**	**209 200**	**251 040**	**292 880**	**334 720**	**376 560**
THERMAL DIFFUSIVITY									
foot^2/hour to meter^2/second, m^2/s	**0.000 025 806 4**	**0.000 051 612 8**	**0.000 077 419 2**	**0.000 103 256**	**0.000 129 032**	**0.000 154 838 4**	**0.000 180 644 8**	**0.000 206 451 2**	**0.000 232 257 6**
THERMAL RESISTANCE									
deg F-hour foot^2/British thermal unit to kelvin-meter^2/watt, K·m^2/W	0.176 228 0	0.352 46	0.528 68	0.704 91	0.881 14	1.057 4	1.233 6	1.409 8	1.586 1
THERMAL CONDUCTANCE									
British thermal unit/hour-foot^2-deg F to watt/meter^2-kelvin, W/m^2·K	5.674 466	11.349	17.023	22.698	28.372	34.047	39.721	45.396	51.070
British thermal unit/second-foot^2-deg F to watt/meter^2-kelvin, W/m^2·K	20 428.08	40 856	61 284	81 712	102 140	122 570	143 000	163 420	183 850

Conversions to SI Units (continued)

	1	2	3	4	5	6	7	8	9
calorie/second-centimeter²-deg C to watt/meter²-kelvin, W/m·K	**41 840**	**83 680**	**125 520**	**167 360**	**209 200**	**251 040**	**292 880**	**334 720**	**376 560**
LENGTH									
caliber to meter, m	**0.000 254**	**0.000 508**	**0.000 762**	**0.001 016**	**0.001 270**	**0.001 524**	**0.001 778**	**0.002 032**	**0.002 286**
fathom to meter, m	**1.828 8**	**3.657 6**	**5.486 4**	**7.315 2**	**9.144 0**	**10.972 8**	**12.801 6**	**14.630 4**	**16.459 2**
foot to meter, m	**0.304 8**	**0.609 6**	**0.914 4**	**1.219 2**	**1.524 0**	**1.828 8**	**2.133 6**	**2.438 4**	**2.743 2**
inch to meter, m	**0.025 4**	**0.050 8**	**0.076 2**	**0.101 6**	**0.127 0**	**0.152 4**	**0.177 8**	**0.203 2**	**0.228 6**
light year to meter, m	$9.460\ 550 \times 10^{15}$	18.921×10^{15}	28.382×10^{15}	37.842×10^{15}	47.303×10^{15}	56.763×10^{15}	55.224×10^{15}	75.684×10^{15}	85.145×10^{15}
mil to meter, m	**0.000 025 4**	**0.000 050 8**	**0.000 076 2**	**0.000 101 6**	**0.000 127 0**	**0.000 152 4**	**0.000 177 8**	**0.000 203 2**	**0.000 228 6**
mile (U.S. nautical) to meter, m	**1 852**	**3 704**	**5 556**	**7 408**	**9 260**	**11 112**	**12 964**	**14 816**	**16 668**
mile (U.S. statute) to meter, m	**1 609.344**	3 218.7	4 828.0	6 437.4	8 046.7	9 656.1	11 265	12 875	14 484
rod to meter, m	**5.029 2**	**10.058 4**	**15.087 6**	**20.116 8**	**25.146 0**	**30.175 2**	**35.204 4**	**40.233 6**	**45.262 8**
yard to meter, m	**0.914 4**	**1.828 8**	**2.743 2**	**3.657 6**	**4.572 0**	**5.486 4**	**6.400 8**	**7.315 2**	**8.229 6**
MASS									
grain to kilogram, kg	**0.000 064 798 91**	0.000 129 60	0.000 194 40	0.000 259 20	0.000 324 00	0.000 388 80	0.000 453 60	0.000 518 40	0.000 583 20
ounce-mass to kilogram, kg	0.028 349 52	0.056 699	0.085 049	0.113 40	0.141 75	0.170 10	0.198 45	0.226 80	0.255 15
ounce-mass (troy or apothecary) to kilogram, kg	0.031 103 48	0.062 207	0.093 310	0.124 41	0.155 52	0.186 62	0.217 72	0.248 83	0.279 93
pound-mass to kilogram, kg	**0.453 592 37**	0.907 18	1.360 8	1.814 4	2.268 0	2.721 6	3.175 1	3.628 7	4.082 3
pound-mass (troy or apothecary) to kilogram, kg	0.373 241 7	0.746 48	1.119 7	1.493 0	1.866 2	2.239 5	2.612 7	2.985 9	3.359 2
slug to kilogram, kg	14.593 90	29.188	43.782	58.376	72.970	87.563	102.16	116.75	131.35
ton (long, 2 240 lb_m) to kilogram, kg	1 016.047	2 032.1	3 048.1	4 064.2	5 080.2	6 096.3	7 112.3	8 128.4	9 144.4
ton (short, 2 000 lb_m) to kilogram, kg	907.184 7	1 814.4	2 721 6	3 628.7	4 535.9	5 443.1	6 350.3	7 257.5	8 164.7

POWER									
British thermal unit/second to watt, W	1 0543.350	2 108.7	3 163.1	4 217.4	5 271.8	6 326.1	7 380.5	8 434.8	9 489.2
British thermal unit/minute to watt, W	17.572 50	35.145	52.718	70.290	87.863	105.44	123.01	140.58	158.15
British thermal unit/hour to watt, W	0.292 875 1	0.585 75	0.878 63	1.171 5	1.464 4	1.757 3	2.050 1	2.343 0	2.635 9
British thermal unit (IT)/ hour to watt, W[a]	0.293 071 1	0.586 14	0.879 21	1.172 3	1.465 4	1.758 4	2.051 5	2.344 6	2.637 6
calorie/second to watt, W	**4.184**	**8.368**	**12.552**	**16.736**	**20.920**	**25.104**	**29.288**	**33.472**	**37.656**
calorie/minute to watt, W	0.069 733 33	0.139 47	0.209 20	0.278 93	0.348 67	0.418 40	0.488 13	0.557 87	0.627 60
foot-pound-force/second to watt, W	1.355 818	2.711 6	4.067 5	5.423 3	6.779 1	8.134 9	9.490 7	10.847	12 202
foot-pound-force/minute to watt, W	0.022 596 97	0.045 194	0.067 791	0.090 388	0.112 98	0.135 58	0.158 18	0.180 78	0.203 37
foot-pound-force/hour to watt, W	0.,000 376 616 1	0.000 753 23	0.001 129 8	0.001 506 5	0.001 883 1	0.002 259 7	0.002 636 3	0.003 012 9	0.003 389 5
horsepower (550 ft·lb_r/s) to watt, W	745.699 9	1 491.4	2 237.1	2 982.8	3 728.5	4 474.2	5 219.9	5 965.6	6 711.3
horsepower (electric) to watt, W	**746.**	**1 492.**	**2 238.**	**2 984.**	**3 730.**	**4 476.**	**5 222.**	**5 968.**	**6 714.**
tons of refrigeration to watt, W	3 516.853	7 033.7	10 551	14 067	17 584	21 101	24 618	28 135	31 652
POWER/AREA									
British thermal unit/foot^2-second to watt/meter^2, W/m^2	11 348.93	22 698	34 047	45 396	56 745	68 094	79 443	90 791	102 140
British thermal unit/foot^2-minute to watt/meter^2, W/m^2	189.148 9	378.30	567.45	756.60	945.74	1 134.9	1 324.0	1 513.2	1 702.3
British thermal unit/foot^2-hour to watt/meter^2, W/m^2	3.152 481	6.305 0	9.457 4	12.610	15.762	18.915	22.067	25.220	28.372
British thermal unit/inch^2-second to watt/meter^2, W/m^2	1 634 246	3 268 500	4 902 700	6 537 000	8 171 200	9 805 500	11 440 000	13 074 000	14 708 000
calorie/centimeter^2-minute to watt/meter^2, W/m^2	697.333 3	1 394.7	2 092.0	2 789.3	3 486.7	4 184.0	4 881.3	5 578.7	6 276.0

Conversions to SI Units (continued)

	1	2	3	4	5	6	7	8	9
PRESSUSRE OR STRESS (FORCE/AREA)									
atmosphere (normal = 760 torr) to newton/meter^2, N/m^2	**101 325**	**202 650**	**303 975**	**405 300**	**506 625**	**607 950**	**709 275**	**810 600**	**911 925**
bar to newton/meter^2, N/m^2	**100 000**	**200 000**	**300 000**	**400 000**	**500 000**	**600 000**	**700 000**	**800 000**	**900 000**
foot of water (39.2 F) to newton/meter^2, N/m^2	2 988.980	5 978.0	8 966.9	11 956	14 945	17 934	20 923	23 912	26 901
inch of mercury (32 F) to newton/meter^2, N/m^2	3 386.389	6 772.8	10 159	13 546	16 932	20 318	23 705	27 091	30 478
inch of water (39.2 F) to newton/meter^2, N/m^2	249.082 0	498.16	747.25	996.33	1 245.4	1 494.5	1 743.6	1 992.7	2 241.7
inch of water (60 F) to newton/meter^2, N/m^2	248.840 0	497.68	746.52	995.36	1 244.2	1 493.0	1 741.9	1 900.7	2 239.6
kilogram-force/centimeter^2 to newton/meter^2, N/m^2	**98 006.5**	**196 133**	**294 199.5**	**392 266**	**490 332.5**	**588 399**	**686 465.5**	**784 532**	**882 598.5**
millimeter of mercury (0 C), torr, to newton/meter^2, N/m^2	133.322 4	266.64	399.97	533.29	666.61	799.93	933.26	1 066.6	1 199.9
pound-force/foot^2 to newton/meter^2, N/m^2	47.880 26	95.761	143.64	191.52	239.40	287.28	335.16	383.04	430.92
pound-force/inch^2 (psi) to newton/meter^2, N/m^2	6 894.757	13 790	20 684	27 579	34 474	41 369	48 263	55 158	62 053
VELOCITY									
foot/hour to meter/second, m/s	0.000 084 666 67	0.000 169 33	0.000 254 00	0.000 338 67	0.000 423 33	0.000 508 00	0.000 592 67	0.000 677 33	0.000 762 00
foot/minute to meter/second, m/s	**0.005 08**	**0.010 16**	**0.015 24**	**0.020 32**	**0.025 40**	**0.030 48**	**0.035 56**	**0.040 64**	**0.045 72**
foot/second to meter/second, m/s	**0.304 8**	**0.609 6**	**0.914 4**	**1.219 2**	**1.524 0**	**1.828 8**	**2.133 6**	**2.438 4**	**2.743.2**
inch/second to meter/second, m/s	**0.025 4**	**0.050 8**	**0.076 2**	**0.101 6**	**0.127 0**	**0.152 4**	**0.177 8**	**0.203 2**	**0.228 6**
kilometer/hour to meter/second, m/s	0.277 777 8	0.555 56	0.833 33	1.111 1	1.388 9	1.666 7	1.944 4	2.222 2	2.500 0

knot (international) to meter/second, m/s	0.514 444 4	1.028 9	1.543 3	2.057 8	2.572 2	3.086 7	3.601 1	4.115 6	4.630 0
mile/hour (U.S. statute) to meter/second, m/s	**0.447 04**	**0.894 08**	**1.341 12**	**1.788 16**	**2.235 20**	**2.682 24**	**3.129 28**	**3.576 32**	**4.023 36**
mile/minute (U.S. statute) to meter/second, m/s	**26.822 4**	**53.644 8**	**80.467 2**	**107.289 6**	**134.112 0**	**160.934 4**	**187.756 8**	**214.587 92**	**241.401 6**
mile/second (U.S. statute) to meter/second, m/s	**1 609.344**	3 218.7	4 828.0	6 437.4	8 046.7	9 656.1	11 265	12 875	14 484
VISCOSITY									
DYNAMIC OR ABSOLUTE, μ									
centipoise to newton-second/meter^2, N·s/m^2	**0.001**	**0.002**	**0.003**	**0.004**	**0.005**	**0.006**	**0.007**	**0.008**	**0.009**
pound-mass/foot-second to newton-second/meter^2, N·s/m^2	1.488 164	2.976 3	4.464 5	5.952 7	7.440 8	8.929 0	10.417	11.905	13.393
pound-force-second/foot^2 to newton-second/meter^2, N·s/m^2	47.880 26	95.761	143.64	191.52	239.40	287.28	335.16	383.04	430.92
slug/foot-second to newton-second/meter^2, N·s/m^2	47.880 26	95.761	143.64	191.52	239.40	287.28	335.16	383.04	430.92
KINEMATIC, ν									
centistoke to meter^2/second, m^2/s	$1. \times 10^{-6}$	$2. \times 10^{-6}$	$3. \times 10^{-6}$	$4. \times 10^{-6}$	$5. \times 10^{-6}$	$6. \times 10^{-6}$	$7. \times 10^{-6}$	$8. \times 10^{-6}$	$9. \times 10^{-6}$
foot^2/second to meter^2/second, m^2/s	**0.092 903 04**	0.185 81	0.278 71	0.371 61	0.464 52	0.557 42	0.650 32	0.743 22	0.836 12
VOLUME									
acre-foot to meter^3, m^3	1 233.482	2 467.0	3 700.4	4 933.9	6 167.4	7 400.9	8 634.4	9 867.9	11 101
barrel (oil, 42 gal) to meter^3, m^3	0.158 987 3	0.217 97	0.476 96	0.635 95	0.794 94	0.953 92	1.112 9	1.271 9	1.430 9
board foot to meter^3, m^3	0.002 359 737	0.004 719 5	0.007 079 2	0.009 438 9	0.011 799	0.141 58	0.016 518	0.018 878	0.021 238
bushel (U.S.) to meter^3, m^3	0.035 239 07	0.070 478	0.105 72	0.140 96	0.176 20	0.211 43	0.246 67	0.281 91	0.317 15
foot^3 to meter^3, m^3	0.028 316 85	0.056 634	0.084 951	0.113 27	0.141.58	0.169 90	0.198 22	0.226 53	0.254 85
gallon (U.S. liquid) to meter^3, m^3	0.003 785 412	0.,007 570 8	0.011 356	0.015 142	0.018 927	0.022 712	0.026 498	0.030 283	0.034 069
inch^3 to meter^3, m^3	0.000 016 387 06	0.000 032 774	0.000 049 161	0.000 065 548	0.000 081 935	0.000 098 322	0.000 114 71	0.000 131 10	0.000 147 48

Conversions to SI Units (continued)

	1	2	3	4	5	6	7	8	9
ounce (U.S. fluid) to meter^3, m^3	0.000 029 573 53	0.000 059 147	0.000 088 721	0.000 118 29	0.000 147 87	0.000 177 44	0.000 207 01	0.000 236 59	0.000 266 16
peck (U.S.) to meter^3, m^3	0.008 809 768	0.017 620	0.026 429	0.035 239	0.044 049	0.052 859	0.061 668	0.070 478	0.079 288
quart (U.S. liquid) to meter^3, m^3	0.000 946 352 9	0.001 892 7	0.002 839 1	0.003 785 4	0.004 731 8	0.005 678 1	0.006 624 5	0.007 570 8	0.008 517 2
yard^3 to meter^3, m^3	0.764 554 9	1.529 1	2.293 7	3.058 2	3.822 8	4.587 3	5.351 9	6.116 4	6.881 0
VOLUME/MASS (SPECIFIC VOLUME)									
foot^3/pound to meter^3/kilogram, m^3/kg	0.062 427 96	0.124 86	0.187 28	0.249 71	0.312 14	0.374 57	0.437 00	0.499 42	0.561 85

[a] The thermochemical calorie is exactly 4.184 joules by definition. The international steam table (IT) calories is exactly 4.186 8 joules by definition. The thermochemical Btu is 1 054.350 joules. Each Btu is defined in terms of the corresponding calorie by 1 Btu/lbm·R ≡ 1 cal/g·K.

From Bolz, R.E. and Tuve, G.L., Units and conversion factors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 808–816.

Fundamental Physical Constants

B.N. Taylor, W.H. Parker, and D.N. Langenberg

The numbers in parentheses are the standard deviation uncertainties in the last digits of the quoted value, computed on the basis of internal consistency.

				Units	
Quantity	Symbol	Value	Error, ppm	SI	cgs
Velocity of light	c	2.997250(10)	0.33	10^8 m sec^{-1}	10^{10} cm sec^{-1}
Fine-structure constant, $[\mu_0 c^2/4\pi](e^2/hc)$	α	7.297351(11)	1.5	10^{-3}	10^{-3}
	α^{-1}	137.03602(21)	1.5		
Electron charge	e	1.6021917(70)	4.4	10^{-19}C	10^{-20} emu
		4.803250(21)	4.4		10^{-10} esu
Planck's constant	h	6.626196(50)	7.6	10^{-34} J·sec	10^{-27} erg·sec
	$h = h/2\pi$	1.0545919(80)	7.6	10^{-34} J·sec	10^{-27} erg·sec
Avogadro's number	N	6.022169(40)	6.6	10^{16} kmole^{-1}	10^{23} mole^{-1}
Atomic mass unit	amu	1.660531(11)	6.6	10^{-27} kg	10^{-24} g
Electron rest mass	m_e	9.109558(54)	6.0	10^{-31} kg	10^{-28} g
	m_e^*	5.485930(34)	6.2	10^{-4} amu	10^{-4} amu
Proton rest mass	M_p	1.672614(11)	6.6	10^{-27} kg	10^{-24} g
	M_p^*	1.00727661(8)	0.08	amu	amu
Neutron rest mass	M_n	1.674920(11)	6.6	10^{-27} kg	10^{-24} g
	M_n^*	1.00866520(10)	0.10	amu	amu
Ratio of proton mass to electron mass	M_p/m_e	1836.109(11)	6.2		
Electron charge to mass ratio	e/m_e	1.7588028(54)	3.1	10^{11} C Kg^{-1}	10^7 emu g^{-1}
		5.272759(16)	3.1		10^{17} esu g^{-1}
Magnetic flux quantum, $[c]^{-1}(hc/2e)$	Φ_o	2.0678538(69)	3.3	10^{-15} T·m^2	10^{-7} G·cm^2
	h/e	4.135708(14)	3.3	10^{-15} J·sec C^{-1}	10^{-7} erg·sec emu^{-1}
		1.3795234(46)	3.3		10^{-17} erg·sec esu^{-1}
Quantum of circulation	$h/2m_e$	3.636947(11)	3.1	10^{-4} J·sec kg^{-1}	erg sec g^{-1}
	h/m_e	7.273894(22)	3.1	10^{-4} J·sec kg^{-1}	erg sec g^{-1}
Faraday constant, Ne	F	9.648670(54)	5.5	10^7 C kmole^{-1}	10^3 emu mole^{-1}
		2.892599(16)	5.5		10^{14} esu mole^{-1}
Rydberg constant, $[\mu_0 c^2/4\pi]^2(m_e e^4/4\pi h^3 c)$	R_∞	1.09737312(11)	0.10	10^7 m^{-1}	10^5 cm^{-1}
Bohr radius, $[\mu_0 c^2/4\pi]^{-1}(h^2/m_e e^2) = \alpha/4\pi R_\infty$	a_0	5.2917715(81)	1.5	10^{-11} m	10^{-9} cm
Classical electron radius, $[\mu_0 c^2/4\pi](e^2/m_e c^2) = \alpha^3/4\pi R_\infty$	r_0	2.817939(13)	4.6	10^{-15} m	10^{-13} cm
Electron magnetic moment in Bohr magnetons	μ_e/μ_s	1.0011596389(31)	0.0031		
Bohr magneton, $[c](eh/2m_e c)$	μ_B	9.274096(65)	7.0	10^{-24} J T^{-1}	10^{-21} erg G^{-1}
Electron magnetic moment	μ_e	9.284851(65)	7.0	10^{-24} J T^{-1}	10^{-21} erg G^{-1}
Gyromagnetic ratio of proton in H_2O	γ_p	2.65751270(82)	3.1	10^8 rad sec^{-1} T^{-1}	10^4 rad sec^{-1} FG^{-1}
	$\gamma_p/2\pi$	4.257597(13)	3.1	10^7 Hz T^{-1}	10^3 Hz G^{-1}
γ_p corrected for diamagnetism of H_2O	γ_p	2.6751965(82)	3.1	10^8 rad sec^{-1} T^{-1}	10^4 rad sec^{-1} G^{-1}
	$\gamma_p/2\pi$	4.257707(13)	3.1	10^7 Hz T^{-1}	10^3 Hz G^{-1}
Magnetic moment of protons in H_2O in Bohr magnetons	μ_p/μ_s	1.52099312(10)	0.066	10^{-3}	10^{-3}
Proton magnetic moment in Bohr magnetons	μ_p/μ_s	1.52103264(46)	0.30	10^{-3}	10^{-3}
Proton magnetic moment	μ_p	1.4106203(99)	7.0	10^{-26} J T^{-1}	10^{-23} erg G^{-1}
Magnetic moment of protons in H_2O in nuclear magnetons	μ_p/μ_n	2.792709(17)	6.2		
μ_p/μ_n corrected for diamagnetism of H_2O	μ_p/μ_n	2.792782(17)	6.2		
Nuclear magneton, $[c](eh/2M_p c)$	μ_n	5.050951(50)	10	10^{-27} J T^{-1}	10^{-24} erg G^{-1}
Compton wavelength of the electron, $h/m_e c$	λ_c	2.4263096(74)	3.1	10^{-12} m	10^{-10} cm
	$\lambda_c/2\pi$	3.861592(12)	3.1	10^{-12} m	10^{-10} cm
Compton wavelength of the proton, $h/M_p c$	$\lambda_{c,p}$	1.3214409(90)	6.8	10^{-15} m	10^{-13} cm
	$\lambda_{c,p}/2\pi$	2.103139(14)	6.8	10^{-16} m	10^{-14} cm
Compton wavelength of the neutron, $h/M_n c$	$\lambda_{c,n}$	1.3196217(90)	6.8	10^{-15} m	10^{-13} cm
	$\lambda_{c,n}/2\pi$	2.100243(14)	6.8	10^{-16} m	10^{-14} cm
Gas constant	R_0	8.321434(35)	42	10^3 J kmole^{-1}·K^{-1}	10^7 erg mole^{-1}·K^{-1}
Boltzmann's constant, R_0/N	k	1.380622(59)	43	10^{-23} J K^{-1}	10^{-16} erg K^{-1}
Stefan-Boltzmann constant, $\pi^2 k^4/60h^3c^2$	σ	5.66961(96)	170	10^{-8} W m^{-2} K^4	10^{-5} erg sec^{-1} cm^{-2}·K^{-4}
First radiation constant, 8 πhc	c_1	4.992579(38)	7.6	10^{-24} J·m	10^{-15} erg·m

Fundamental Physical Constants (continued)

Quantity	Symbol	Value	Error, ppm	Units SI	Units cgs
Second radiation constant, *hc*/*k*	c_2	1.438833(61)	43	10^{-2} m·K	cm·K
Gravitational constant	*G*	6.6732(31)	460	10^{-11} N·m^2 Kg^{-2}	10^{-8} dyn·cm^{2}g^{-2}
kx-unit-to-angstrom conversion factor, Λ = λ(Å)/λ(kxu); λ(Cu$K\alpha_1$) = 1.537400 kxu	Λ	1.0020764(53)	5.3		
Å*-to-angstrom conversion factor, Λ = λ(Å)/λ(Å*); λ(W$K\alpha_1$) = 0.2090100 Å*	Λ*	1.0000197(56)	5.6		

* Note that the unified atomic mass scale ^{12}C ≡ 12 has been used throughout, that amu = atomic mass unit, C = coulomb, G = gauss, Hz = hertz = cycles/sec, J = joule, K = kelvin (degrees kelvin), T = tesla (10^4 G), V = volt, and W = watt. In cases where formulas for constants are given (e.g., R_∞), the relations are written as the product of two factors. The second factor, in parentheses, is the expression to be used when all quantities are expressed in cgs units, with the electron charge in electrostatic units. The first factor, in brackets, is to be included only if all quantities are expressed in SI units. We remind the reader that with the exception of the auxiliary constants which have been taken to the exact, the uncertainties of these constants are correlated, and therefore the general law of error propagation must be used in calculating additional quantities requiring two or more of these constants.

ENERGY CONVERSION FACTORS

Quantity	Value	Unit	Error, ppm
1 kg	5.609538(24)	10^{29} MeV	4.4
1 amu	931.4812(52)	MeV	5.5
Electron mass	0.5110041(16)	MeV	3.1
Proton mass	938.2592(52)	MeV	5.5
Neutron mass	939.5527(52)	MeV	5.5
1 electron volt	1.6021917(70)	10^{-19} J	4.4
		10^{-12} erg	
	2.4179659(81)	10^{14} Hz	3.3
	8.065465(27)	10^5 m^{-1}	3.3
		10^3 cm^{-1}	
	1.160485(49)	10^4 K	42
Energy-wavelength conversion	1.239854(41)	10^{-6} eV·m	3.3
		10^{-4} eV·cm	
Rydberg constant, R_∞	2.179914(17)	10^{-18} J	7.6
		10^{-11} erg	
	13.605826(45)	eV	3.3
	3.2898423(11)	10^{15} Hz	0.35
	1.578936(67)	10^5 K	43
Bohr magneton, μ_s	5.788381(18)	10^{-5} eV T^{-1}	3.1
	1.3996108(43)	10^{10} Hz T^{-1}	3.1
	46.68598(14)	m^{-1}·T^{-1}	3.1
		10^{-1} cm^{-1}·T^{-1}	
	0.671733(29)	K T^{-1}	43
Nuclear magneton, μ_n	3.152526(21)	10^{-8} eV T^{-1}	6.8
	7.622700(42)	10^6 Hz T^{-1}	5.5
	2.542659(14)	10^{-2} m^{-1}·T^{-1}	5.5
		10^{-4} cm^{-1}·T^{-1}	
	3.65846(16)	10^{-4} K T^{-1}	44
Gas constant, R_0	8.20562(35)	10^{-2} m^3·atm kmole^{-1}·K^{-1}	42
Standard volume of ideal gas, V_0	22.4136	m^3 kmole^{-1}	

From Bolz, R.E. and Tuve, G.L., Units and conversion factors, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 817–818. Originally from *Rev. Mod. Phys.*, 41: 375, 1969. Reprinted by permission of the publisher, American Institute of Physics.

Numerical Constants

π Constants

$\pi =$	3.14159	26535	89793	23846	26433	83279	50288	41971	69399	37510
$1/\pi =$	0.31830	98861	83790	67153	77675	26745	02872	40689	19291	48091
$\pi^2 =$	9.86960	44010	89358	61883	44909	99876	15113	53136	99407	24079
$\log_e \pi =$	1.14472	98858	49400	17414	34273	51353	05871	16472	94812	91531
$\log_{10} \pi =$	0.49714	98726	94133	85435	12682	88290	89887	36516	78324	38044
$\log_{10} \sqrt{2\pi} =$	0.39908	99341	79057	52478	25035	91507	69595	02099	34102	92127

Logarithmic Constants

$e =$	2. 71828	18284	59045	23536	02874	71352	66249	77572	47093	69995
$1/e =$	0. 36787	94411	71442	32159	55237	70161	46086	74458	11131	03176
$e^2 =$	7. 38905	60989	30650	22723	04274	60575	00781	31803	15570	55184
$M = \log_{10} e =$	0. 43429	44819	03251	82765	11289	18916	60508	22943	97005	80366
$1/M = \log_e 10 =$	2. 30258	50929	94045	68401	79914	54684	36420	76011	01488	62877
$\log_{10} M =$	9. 63778	43113	00536	78912	29674	98565	—	10		

Miscellaneous π and *e* Constants

$\pi^4 =$	22. 45915	77183	61045	47342	71522
$e^\pi =$	23. 14069	26327	79269	00572	90864
$e^{-\pi} =$	0. 04321	39182	63772	24977	44177
$e^{1/2\pi} =$	4. 81047	73809	65351	65547	30357
$i^i = e^{-1/2\pi} =$	0. 20787	95763	50761	90854	69556

Numerical Constants

$\sqrt{2} =$	1.41421	35623	73095	04880	16887	24209	69807	85696	71875	37694
$\sqrt[3]{2} =$	1.25992	10498	94873	16476	72106	07278	22835	05702	51464	70150
$\log_e 2 =$	0.69314	71805	59945	30941	72321	21458	17656	80755	00134	36025
$\log_{10} 2 =$	0.30102	99956	63981	19251	37388	94724	49302	67681	89881	46210
$\sqrt{3} =$	1.73205	08075	68877	29352	74463	41505	87326	69428	05253	81038
$\sqrt[3]{3} =$	1.44224	95703	07408	38232	16383	10780	10958	83918	69253	49935
$\log_e 3 =$	1.09861	22886	08109	69139	52452	36922	52570	46474	90557	82274
$\log_{10} 3 =$	0.47712	12547	19662	43729	50279	03255	11530	92001	28864	19069

Miscellaneous

Euler's Constant $\gamma =$	0. 57721	56649	01532	86061					
$\log_e \gamma =$	–0. 54953	93129	81644	82234					
Golden Ratio $\phi =$	1. 61803	39887	49894	84820	45868	34365	63811	77203	09180

Numerical Constants (continued)

Numbers Containing π

$\pi = 3.14159\ 26536$ $\log_{10} \pi = 0.49714\ 98727$ $\log_e \pi = 1.14472\ 98858$

	Number	Logarithm		Number	Logarithm
π	3.1415 927	0.4971 499	π^2	9.8696 044	0.9942 997
2π	6.2831 853	0.7981 799	$2\pi^2$	19.7392 088	1.2953 297
3π	9.4247 780	0.9742 711	$4\pi^2$	39.4784 176	1.5963 597
4π	12.5663 706	1.0092 099	$1/\pi^2$	0.1013 212	9.0057 003 – 10
8π	25.1327 412	1.4002 399	$1/(2\pi^2)$	0.0506 606	8.7046 703 – 10
$\pi/2$	1.5707 963	0.1961 199	$1/(4\pi^2)$	0.0253 303	8.4036 403 – 10
$\pi/3$	1.0471 976	0.0200 286	$\sqrt{\pi}$	1.7724 539	0.2485 749
$\pi/4$	0.7853 982	9.8950 899 – 10	$\sqrt{\pi/4}$ or	0.8862 269	9.9475 449 – 10
$\pi/6$	0.5235 988	9.7189 986 – 10	$\sqrt{\pi}/2$		
$\pi/8$	0.3926 991	9.5940 599 – 10	$\sqrt{\pi}/4$	0.4431 135	9.6465 149 – 10
$2\pi/3$	2.0943 951	0.3210 586	$\sqrt{\pi/2}$	1.2533 141	0.0980 599

	Number	Logarithm		Number	Logarithm
$4\pi/3$	4.1887 902	0.6220 886	$\sqrt{2/\pi}$	0.7978 846	9.9019 401 – 10
$1/\pi$	0.3183 099	9.5028 501 – 10	π^3	31.0062 767	1.4914 496
$2/\pi$	0.6366 198	9.8038 801 – 10	$\sqrt[3]{\pi}$	1.4645 919	0.1657 166
$4/\pi$	1.2732 395	0.1049 101	$1/\sqrt[3]{\pi}$	0.6827 841	9.8342 834 – 10
$1/(2\pi)$	0.1591 549	9.2018 201 – 10	$\sqrt[3]{\pi^2}$	2.1450 294	0.3314 332
$1/(4\pi)$	0.0795 775	8.9007 901 – 10	$1/\sqrt{\pi}$	0.5641 896	9.7514 251 – 10
$1/(6\pi)$	0.0530 516	8.7246 989 – 10	$1/\sqrt{2\pi}$	0.3989 423	9.6009 101 – 10
$1/(8\pi)$	0.0397 887	8.5997 601 – 10	$2/\sqrt{\pi}$	1.1283 792	0.0524 551
$\pi/180$	0.0174 553	8.2418 774 – 10			
$180/\pi$	57.2957 795	1.7581 226			

Change of Base

$$\log_a x = \log_b x / \log_b a$$

$$\log_{10} x = \log_e x / \log_e 10 \qquad \log_e x = \log_{10} x / \log_{10} e$$

$$\log_e x = 1/M \log_{10} x = 2.30258\ 50930 \log_{10} x$$

$$\log_{10} x = M \log_e x = 0.43429\ 44819 \log_e x$$

From Bolz, R.E. and Tuve, G.L., Mathematical and statistical tables, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 877.

Mathematical Constants

For Use on a Digital Computer

Constant	Decimal (Base 10)				Octgal (Base 8)					
					π Constants					
π	3.14159	26355	89793	23846	3.1103	7552	4210	2643	0215	1423
π^{-1}	0.31830	98861	83790	67153	0.2427	6301	5562	3442	0251	2376
$\sqrt{\pi}$	1.77245	38509	05516	02729	1.6133	7611	0664	7366	5247	4703
π^2	9.86960	44010	89358	61883	11.6751	7144	6762	1357	1322	2556
$\sqrt{2\pi}$	2.5062	82746	31000	50241	2.4033	1143	7754	2340	5454	5371
$(\pi/2)^{1/2}$	1.25331	41373	15500	25120	1.2015	4461	7766	1160	2626	2574
$\pi^{-1/2}$	0.56418	95835	47756	28694	0.4406	7272	4041	2333	3210	6561
$(2\pi)^{-1/2}$	0.39894	22804	01432	67793	0.3142	0424	6365	0331	2043	2077
$\pi^{1/2}$	1.46459	18875	61523	26302	1.3556	7576	3461	0113	3612	7621
$\log_{10} \pi$	0.49714	98726	94133	85435	0.3764	2466	6306	7216	7300	1457
$\ln \pi$	1.14472	98858	49400	17414	1.1120	6404	4347	5033	6413	6537
πe	8.53973	42226	73567		10.4242	6005	5056	5072		
π/e	1.15572	73497	90921		1.1175	6677	3047	0733		
π^e	22.45915	77183	61045	47342	26.3530	5534	1601	0421	1613	1026
					e Constants					
e	2.71828	18284	59045	23536	2.5576	0521	3050	5355	1246	5277
e^{-1}	0.36787	94411	71442	32159	0.2742	6530	6613	1674	6761	5272
e^{π}	23.14069	26237	79269	00572	27.1100	2156	5411	1471	4754	6647
$e^{-\pi}$	0.4321	39182	63772	24977	0.0261	0021	1732	6307	3706	4257
$e^{\pi/2}$	4.81407	73809	65351	65547	4.6367	5562	0526	2327	6476	2132
$\log_{10} e$	0.43429	44819	03251	82765	0.3362	6754	2511	5624	1614	5232
					Numerical Constants					
$\sqrt{2}$	1.41421	35623	73095	04880	1.3240	4746	3177	1674	6220	4262
$\sqrt[3]{2}$	1.25992	10498	94873	16477						
$\sqrt{3}$	1.73205	08075	68877	29641	1.5666	3656	4130	2312	5167	0145
$\sqrt[3]{3}$	1.44224	95703	07408	38232						
$\log_{10} 2$	0.30102	99956	63981	19251						
$\ln 2$	0.69314	71805	59945	30941	0.5427	1027	7575	0717	3632	5711
$\log_{10} 3$	0.47712	12547	19662	43729						
$\ln 3$	1.09861	22886	68109	69139						
$\ln 10$	2.30258	50929	94045	68401	2.2327	3067	3552	5242	5405	5651
$\log_2 10$					3.24464	741136				
					Euler's Constant: γ					
γ	0.57721	56649	01532	86060	0.4474	2147	7067	6660	6172	2321
e^{γ}	1.78107	24179	90197	98522	1.6177	2134	5261	1526	5761	
$e^{-\gamma}$	0.56145	94835	66885	16903	0.4373	5717	0177	1345	7454	
$\log^{\gamma}$	–0.23866	18912	16832	38945	–0.1721	4362	0631	1753	0063	
$\ln \gamma$	–0.54953	93129	81644	82234	–0.4312	7233	6021	7532	2777	

From Bolz, R.E. and Tuve, G.L., Mathematical and statistical tables, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 878.

Derivatives

In the following formulas u, v, w represent functions of x, while a, c, n represent fixed real numbers. All arguments in the trigonometric functions are measured in radians, and all inverse trigonmetric and hyperbolic functions represent principal values.†

1. $\frac{d}{dx}(a)=0$

2. $\frac{d}{dx}(x)=1$

3. $\frac{d}{dx}(au)=a\frac{du}{dx}$

4. $\frac{d}{dx}(u+v-w)=\frac{du}{dx}+\frac{dv}{dx}-\frac{dw}{dx}$

5. $\frac{d}{dx}(uv)=d\frac{dv}{dx}+v\frac{du}{dx}$

6. $\frac{d}{dx}(uvw)=uv\frac{dw}{dx}+vw\frac{du}{dx}+uw\frac{dv}{dx}$

7. $\frac{d}{dx}\left(\frac{u}{v}\right)=\frac{v\frac{du}{dx}-u\frac{dv}{dx}}{v^2}=\frac{1}{v}\frac{du}{dx}-\frac{u}{v^2}\frac{dv}{dx}$

8. $\frac{d}{dx}(u^n)=nu^{n-1}\frac{du}{dx}$

9. $\frac{d}{dx}(\sqrt{u})=\frac{1}{2\sqrt{u}}\frac{du}{dx}$

10. $\frac{d}{dx}\left(\frac{1}{u}\right)=-\frac{1}{u^2}\frac{du}{dx}$

11. $\frac{d}{dx}\left(\frac{1}{u^n}\right)=-\frac{n}{u^{n+1}}\frac{du}{dx}$

12. $\frac{d}{dx}\left(\frac{u^n}{v^m}\right)=\frac{u^{n-1}}{v^{m+1}}\left(nv\frac{du}{dx}-mu\frac{dv}{dx}\right)$

13. $\frac{d}{dx}(u^nv^m)=u^{n-1}v^{m-1}\left(nv\frac{du}{dx}+mu\frac{dv}{dx}\right)$

14. $\frac{d}{dx}\left[f(u)\right]=\frac{d}{du}\left[f(u)\right]\cdot\frac{du}{dx}$

† Let $y = f(x)$ and $\frac{dy}{dx} = \frac{d[f(x)]}{dx} = f'(x)$ define respectively a function and its derivative for any value x in their common domain. The differential for the function at such a value x is accordingly defined as

$$dy=d\left[f(x)\right]=\frac{dy}{dx}dx=\frac{d\left[f(x)\right]}{dx}dx=f'(x)dx$$

Each derivative formula has an associated differential formula. For example, formula 6 above has the differential formula

$$d(uvw)=uv\,dw+vw\,du+uw\,dv$$

15. $\frac{d^2}{dx^2}\left[f(u)\right]=\frac{df(u)}{du}\cdot\frac{d^2u}{dx^2}+\frac{d^2f(u)}{du^2}\cdot\left(\frac{du}{dx}\right)^2$

16. $\frac{d^n}{dx^n}[uv]=\binom{n}{0}v\frac{d^nu}{dx^n}+\binom{n}{1}\frac{dv}{dx}\frac{d^{n-1}u}{dx^{n-1}}+\binom{n}{2}\frac{d^2v}{dx^2}\frac{d^{n-2}u}{dx^{n-2}}+\cdots+\binom{n}{k}\frac{d^kv}{dx^k}\frac{d^{n-k}}{dx^{n-k}}+\cdots+\binom{n}{n}u\frac{d^nv}{dx^n}$

where $\binom{n}{r} = \frac{n!}{r!(n-r)!}$ the binomial coefficient, n non-negative integer and $\binom{n}{0} = 1$.

Derivatives (continued)

17. $\frac{du}{dx} = \frac{1}{\frac{dx}{du}} \quad \text{if } \frac{dx}{du} \neq 0$

18. $\frac{d}{dx}\left(\log_a u\right) = \left(\log_a e\right)\frac{1}{u}\frac{du}{dx}$

19. $\frac{d}{dx}\left(\log_e u\right) = \frac{1}{u}\frac{du}{dx}$

20. $\frac{d}{dx}\left(a^u\right) = a^u\left(\log_e a\right)\frac{du}{dx}$

21. $\frac{d}{dx}\left(e^u\right) = e^u\frac{du}{dx}$

22. $\frac{d}{dx}\left(u^v\right) = vu^{v-1}\frac{du}{dx} + \left(\log_e u\right)u^v\frac{dv}{dx}$

23. $\frac{d}{dx}\left(\sin u\right) = \frac{du}{dx}\left(\cos u\right)$

24. $\frac{d}{dx}\left(\cos u\right) = \frac{du}{dx}\left(\sin u\right)$

25. $\frac{d}{dx}\left(\tan u\right) = \frac{du}{dx}\left(\sec^2 u\right)$

26. $\frac{d}{dx}\left(\cot u\right) = -\frac{du}{dx}\left(\csc^2 u\right)$

27. $\frac{d}{dx}\left(\sec u\right) = \frac{du}{dx}\sec u \cdot \tan u$

28. $\frac{d}{dx}\left(\csc u\right) = -\frac{du}{dx}\csc u \cdot \cot u$

29. $\frac{d}{dx}\left(vers\ u\right) = \frac{du}{dx}\sin u$

30. $\frac{d}{dx}\left(arc \sin u\right) = \frac{1}{\sqrt{1-u^2}}\frac{du}{dx}, \quad \left(-\frac{\pi}{2} \leq arc \sin u \leq \frac{\pi}{2}\right)$

31. $\frac{d}{dx}\left(arc \cos u\right) = -\frac{1}{\sqrt{1-u^2}}\frac{du}{dx}, \quad \left(0 \leq arc \cos u \leq \pi\right)$

32. $\frac{d}{dx}\left(arc \tan u\right) = \frac{1}{1+u^2}\frac{du}{dx}, \quad \left(-\frac{\pi}{2} < arc \tan u \leq \frac{\pi}{2}\right)$

33. $\frac{d}{dx}\left(arc \cot u\right) = -\frac{1}{1+u^2}\frac{du}{dx}, \quad \left(0 \leq arc \cot u \leq \pi\right)$

34. $\frac{d}{dx}\left(arc \sec u\right) = \frac{1}{u\sqrt{u^2-1}}\frac{du}{dx}, \quad \left(0 \leq arc \sec u < \frac{\pi}{2}, -\pi \leq arc \sec u < -\frac{\pi}{2}\right)$

35. $\frac{d}{dx}\left(arc \csc u\right) = -\frac{1}{u\sqrt{u^2-1}}\frac{du}{dx}, \quad \left(0 < arc \csc u \leq \frac{\pi}{2}, -\pi < arc \csc u \leq -\frac{\pi}{2}\right)$

36. $\frac{d}{dx}\left(arc\ vers\ u\right) = \frac{1}{\sqrt{2u-u^2}}\frac{du}{dx}, \quad \left(0 \leq arc\ vers\ u \leq \pi\right)$

37. $\frac{d}{dx}\left(\sinh u\right) = \frac{du}{dx}\left(\cosh u\right)$

38. $\frac{d}{dx}\left(\cosh u\right) = \frac{du}{dx}\left(\sinh u\right)$

Derivatives (continued)

39. $\frac{d}{dx}(\tanh u) = \frac{du}{dx}(\text{sec}h^2 u)$

40. $\frac{d}{dx}(\coth u) = \frac{du}{dx}(\text{csc}h^2 u)$

41. $\frac{d}{dx}(\text{sec}h\, u) = -\frac{du}{dx}(\text{sec}h\, u \cdot \tanh u)$

42. $\frac{d}{dx}(\text{csc}h\, u) = -\frac{du}{dx}(\text{csc}h\, u \cdot \coth u)$

43. $\frac{d}{dx}(\sinh^{-1} u) = \frac{d}{dx}\left[\log\left(u + \sqrt{u^2+1}\right)\right] = \frac{1}{\sqrt{u^2+1}}\frac{du}{dx}$

44. $\frac{d}{dx}(\cosh^{-1} u) = \frac{d}{dx}\left[\log\left(u + \sqrt{u^2-1}\right)\right] = \frac{1}{\sqrt{u^2-1}}\frac{du}{dx}, \quad (u > 1, \cosh^{-1} u > 0)$

45. $\frac{d}{dx}(\tanh^{-1} u) = \frac{d}{dx}\left[\frac{1}{2}\log\frac{1+u}{1-u}\right] = \frac{1}{1-u^2}\frac{du}{dx}, \quad (u^2 < 1)$

46. $\frac{d}{dx}(\coth^{-1} u) = \frac{d}{dx}\left[\frac{1}{2}\log\frac{u+1}{u-1}\right] = \frac{1}{1-u^2}\frac{du}{dx}, \quad (u^2 > 1)$

47. $\frac{d}{dx}(\text{sec}h^{-1} u) = \frac{d}{dx}\left[\log\frac{1+\sqrt{1-u^2}}{u}\right] = -\frac{1}{u\sqrt{1-u^2}}\frac{du}{dx}, \quad (0 < u < 1, \text{sec}h^{-1} u > 0)$

48. $\frac{d}{dx}(\text{csc}h^{-1} u) = \frac{d}{dx}\left[\log\frac{1+\sqrt{1+u^2}}{u}\right] = -\frac{1}{|u|\sqrt{1-u^2}}\frac{du}{dx}$

49. $\frac{d}{dq}\int_p^q f(x)dx = f(q), \quad [p\ constant]$

50. $\frac{d}{dp}\int_p^q f(x)dx = -f(p), \quad [q\ constant]$

51. $\frac{d}{da}\int_p^q f(x,a)dx = \int_p^q \frac{\partial}{\partial a}[f(x,a)]dx + f(q,a)\frac{dq}{da} - f(p,a)\frac{dp}{da}$

From Bolz, R.E. and Tuve, G.L., Mathematical and statistical tables, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 884–887.

Facts from Algebra

Factors and Expansions

$$(a \pm b)^2 = a^2 \pm 2ab + b^2$$
$$(a \pm b)^3 = a^3 \pm 3a^2b + 3ab^2 \pm b^3$$
$$(a \pm b)^4 = a^4 \pm 4a^3b + 6a^2b^2 \pm 4\,ab^3 + b^4$$
$$a^2 - b^2 = (a - b)\,(a + b)$$
$$a^2 + b^2 = (a + b\sqrt{-1})\,(a - b\sqrt{-1})$$
$$a^3 - b^3 = (a - b)\,(a^2 + ab + b^2)$$
$$a^3 + b^3 = (a + b)\,(a^2 - ab + b^2)$$
$$a^4 + b^4 = (a^2 + ab\sqrt{2} + b^2)\,(a^2 - ab\sqrt{2} + b^2)$$
$$a^n - b^n = (a - b)\,(a^{n-1} + a^{n-2}b + \ldots + b^{n-1})$$
$$a^n - b^n = (a + b)\,(a^{n-1} - a^{n-2}b + \ldots - b^{n-1}), \text{ for even values of } n$$
$$a^n + b^n = (a + b)\,(a^{n-1} - a^{n-2}b + \ldots + b^{n-1}), \text{ for odd values of } n$$
$$a^4 + a^2b^2 + b^4 = (a^2 + ab + b^2)\,(a^2 - ab + b^2)$$
$$(a + b + c)^2 = a^2 + b^2 + c^2 + 2ab + 2ac + 2bc$$
$$(a + b + c)^3 = a^3 + b^3 + c^3 + 3a^2(b + c) + 3b^2(a + c) + 3c^2(a + b) + 6abc$$
$$(a + b + c + d + \ldots)^2 = a^2 + b^2 + c^2 + d^2 + \ldots + 2a(b + c + d + \ldots) + 2b(c + d + \ldots) + 2c(d + \ldots) + \ldots$$

Powers and Roots

$$a^x \times a^y = a^{(x+y)} \qquad a^0 = 1 \text{ [if } a - 0] \qquad (ab)^x = a^x b^x$$

$$\frac{a^x}{a^y} = a^{(x-y)} \qquad a^{-x} = \frac{1}{a^x} \qquad \left(\frac{a}{b}\right)^x = \frac{a^x}{b^x}$$

$$\left(a^x\right)^y = a^{xy} \qquad a^{\frac{1}{x}} = \sqrt[x]{a} \qquad \sqrt[x]{ab} = \sqrt[x]{a}\sqrt[x]{b}$$

$$\sqrt[x]{\sqrt[y]{a}} = \sqrt[xy]{a} \qquad a^{\frac{x}{y}} = \sqrt[y]{a^x} \qquad \sqrt[x]{\frac{a}{b}} = \frac{\sqrt[x]{a}}{\sqrt[x]{b}}$$

Proportion

$$\textit{If} \quad \frac{a}{b} = \frac{c}{d}, \qquad \text{then} \qquad \frac{a+b}{b} = \frac{c+d}{d}\ \frac{a-b}{b} = \frac{c-d}{d}, \qquad \frac{a-b}{a+b} = \frac{c-d}{c+d}$$

From Bolz, R.E. and Tuve, G.L., Mathematical and statistical tables, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 887.

Integrals—Elementary Forms

1. $\int a\,dx = ax$

2. $\int a \cdot f(x)\,dx = a\int f(x)\,dx$

3. $\int \phi(y)\,dx = \int \frac{\phi(y)}{y'}\,dy$, where $y' = \frac{dy}{dx}$

4. $\int (u+v)\,dx = \int u\,dx + \int v\,dx$, where u and v are any functions of x

5. $\int u\,dv = u\int dv - \int v\,du = uv - \int v\,du$

6. $\int u\frac{dv}{dx}dx = uv - \int v\frac{du}{dx}dx$

7. $\int x^n dx = \frac{x^{n+1}}{n+1}$, except $n = -1$

8. $\int \frac{f'(x)dx}{f(x)} = \log f(x)$, $\left(df(x) = f'(x)dx\right)$

9. $\int \frac{dx}{x} = \log x$

10. $\int \frac{f'(x)dx}{2\sqrt{f(x)}} = \sqrt{f(x)}$, $\left(df(x) = f'(x)dx\right)$

11. $\int e^x dx = e^x$

12. $\int e^{ax} dx = e^{ax}/a$

13. $\int b^{ax} dx = \frac{b^{ax}}{a\log b}$, $(b > 0)$

14. $\int \log x\,dx = x\log x - x$

15. $\int a^x \log a\,dx = a^x$, $(a > 0)$

16. $\int \frac{dx}{a^2+x^2} = \frac{1}{a}\tan^{-1}\frac{x}{a}$

17. $$\int \frac{dx}{a^2-x^2} = \begin{cases} \frac{1}{a}\tanh^{-1}\frac{x}{a} \\ \text{or} \\ \frac{1}{2a}\log\frac{a+x}{a-x}, & (a^2 > x^2) \end{cases}$$

18. $$\int \frac{dx}{x^2-a^2} = \begin{cases} -\frac{1}{a}\coth^{-1}\frac{x}{a} \\ \text{or} \\ \frac{1}{2a}\log\frac{x-a}{x+a}, & (x^2 > a^2) \end{cases}$$

Integrals—Elementary Forms (continued)

19. $$\int \frac{dx}{\sqrt{a^2 - x^2}} = \begin{cases} \sin^{-1} \dfrac{x}{|a|} \\ \text{or} \\ -\cos^{-1} \dfrac{x}{|a|}, \quad (a^2 > x^2) \end{cases}$$

20. $$\int \frac{dx}{\sqrt{x^2 \pm a^2}} = \log\left(x + \sqrt{x^2 \pm a^2}\right)$$

21. $$\int \frac{dx}{x\sqrt{x^2 - a^2}} = \frac{1}{|a|} \sec^{-1} \frac{x}{a}$$

22. $$\int \frac{dx}{x\sqrt{a^2 \pm x^2}} = -\frac{1}{a} \log\left(\frac{a + \sqrt{a^2 \pm x^2}}{x}\right)$$

From Bolz, R.E. and Tuve, G.L., Mathematical and statistical tables, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 888–889.

Series

The expression in parentheses following certain of the series indicates the region of convergence. If not otherwise indicated it is to be understood that the series converges for all finite values of x.

Binomial

$$(x-y)^n = x^n + nx^{n-1}y + \frac{n(n-1)}{2!}x^{n-2}y^2 + \frac{n(n-1)(n-2)}{3!}x^{n-3}y^3 + \cdots (y^2 < x^2)$$

$$(1\pm x)^n = 1 \pm nx + \frac{n(n-1)x^2}{2!} \pm \frac{n(n-1)(n-2)x^3}{3!} + \cdots etc. \quad (x^2<1)$$

$$(1\pm x)^{-n} = 1 \mp nx + \frac{n(n+1)x^2}{2!} \mp \frac{n(n+1)(n+2)x^3}{3!} + \cdots etc. \quad (x^2<1)$$

$$(1\pm x)^{-1} = 1 \mp x + x^2 \mp x^3 + x^4 \mp x^5 + \cdots \qquad (x^2<1)$$

$$(1\pm x)^{-2} = 1 \mp 2x + 3x^2 \mp 4x^3 + 5x^4 \mp 6x^5 + \cdots \quad (x^2<1)$$

Reversion of Series

Let a series be represented by

$$y = a_1x + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6 + \cdots \quad (a_1 \neq 0)$$

to find the coefficients of the series

$$x = A_1y + A_2y^2 + A_3y^3 + A_4y^4 + \cdots$$

$$A_1 = \frac{1}{a_1} \quad A_2 = -\frac{a_2}{a_1^3} \quad A_3 = \frac{1}{a_1^5}\left(2a_2^2 - a_1a_3\right)$$

$$A_4 = \frac{1}{a_1^7}\left(5a_1a_2a_3 - a_1^2a_4 - 5a_2^3\right)$$

$$A_5 = \frac{1}{a_1^9}\left(6a_1^2a_2a_4 + 3a_1^2a_3^2 + 14a_2^4 - a_1^3a_5 - 21a_1a_2^2a_3\right)$$

$$A_6 = \frac{1}{a_1^{11}}\left(7a_1^3a_2a_5 + 7a_1^3a_3a_4 + 84a_1a_2^3a_3 - a_1^4a_6 - 28a_1^2a_2^2a_4 - 28a_1^2a_2a_3^2 - 42a_2^5\right)$$

$$A_7 = \frac{1}{a_1^{13}}\left(8a_1^4a_2a_6 + 8a_1^4a_3a_5 + 4a_1^4a_4^2 + 120a_1^2a_2^3a_4 + 180a_1^2a_2^2a_3^2\right.$$
$$\left. + 132a_2^6 - a_1^5a_7 - 36a_1^3a_2^2a_5 - 72a_1^3a_2a_3a_4 - 12a_1^3a_3^3 - 330a_1a_2^4a_3\right)$$

Taylor

1. $$f(x) = f(a) + (x-a)f'(a) + \frac{(x-a)^2}{2!}f''(a) + \frac{(x-a)^3}{3!}f'''(a)$$
$$+ \cdots + \frac{(x-a)^n}{n!}f^{(n)}(a) + \cdots (\text{Taylor's Series})$$

(Increment form)

2. $$f(x+h) = f(x) + hf'(x) + \frac{h^2}{2!}f''(x) + \frac{h^3}{3!}f'''(x) + \cdots$$
$$= f(h) + xf'(h) + \frac{x^3}{2!}f''(h) + \frac{x^3}{3!}f'''(h) + \cdots$$

3. If $f(x)$ is a function possessing derivatives of all orders throughout the interval $a \leqq x \leqq b$, then there is a value X, with $a < X < b$, such that

Series (continued)

$$f(b) = f(a) + (b-a)f'(a) + \frac{(b-a)^2}{2!}f''(a) + \cdots$$

$$+ \frac{(b-a)^{n-1}}{(n-1)!}f^{(n-1)}(a) + \frac{(b-a)^n}{n!}f^{(n)}(X)$$

$$f(a+h) = f(a) + hf'(a) + \frac{h^2}{2!}f''(a) + \cdots + \frac{h^{n-1}}{(n-1)!}f^{(n-1)}(a)$$

$$+ \frac{h^n}{n!}f^{(n-1)}(a+\theta h), \quad b = a+h, \quad 0 < \theta < 1$$

or

$$f(x) = f(a) + (x-a)f'(a) + \frac{(x-a)^2}{2!}f''(a) + \cdots + (x-a)^{n-1}\frac{f^{(n-1)}(a)}{(n-1)!} + R_n$$

where

$$R_n = \frac{f^{(n)}\left[a + \theta \cdot (x-a)\right]}{n!}(x-a)^n, \quad 0 < \theta < 1$$

The above forms are known as Taylor's series with the remainder term.

4. *Taylor's series for a function of two variables*

If $\left(h\frac{\partial}{\partial x} + k\frac{\partial}{\partial y}\right)f(x,y) = h\frac{\partial f(x,y)}{x} + k\frac{\partial f(x,y)}{\partial y}$;

$$\left(h\frac{\partial}{\partial x} + k\frac{\partial}{y}\right)^2 f(x,y) = h^2\frac{\partial^2 f(x,y)}{\partial x^2} + 2hk\frac{\partial^2 f(x,y)}{\partial x \partial y} + k^2\frac{\partial^2 f(x,y)}{\partial y^2}$$

etc., and if $h\left(\frac{\partial}{\partial x} + k\frac{\partial}{\partial y}\right)^n f(x,y)\Big|_{\substack{x=a\\y=b}}$ with the bar and subscripts means that after differentiation we are to replace x by a and y by b,

$$f(a+h, b+k) = f(a,b) + \left(h\frac{\partial}{\partial x} + k\frac{\partial}{\partial y}\right)f(x,y)\Big|_{\substack{x=a\\y=b}} + \cdots + \frac{1}{n!}\left(h\frac{\partial}{\partial x} + k\frac{\partial}{\partial y}\right)^n f(x,y)\Big|_{\substack{x=a\\y=b}} + \cdots$$

Maclaurin

$$f(x) = f(0) + xf'(0) + \frac{x^2}{2!}f''(0) + \frac{x^3}{3!}f'''(0) + \cdots + x^{n-1}\frac{f^{(n-1)}(0)}{(n-1)!} + R_n$$

where

$$R_n = \frac{x^n f^{(n)}(\theta x)}{n!}, \quad 0 < \theta < 1$$

Exponential

$$e = 1 + \frac{1}{1!} + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + \cdots$$

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \cdots \quad (\text{all real values of } x)$$

Series (continued)

$$a^x = 1 + x\log_e a + \frac{(x\log_e a)^2}{2!} + \frac{(x\log_e a)^3}{3!} + \cdots$$

$$e^x = e^a\left[1 + (x-a) + \frac{(x-a)^2}{2!} + \frac{(x-a)^3}{3!} + \cdots\right]$$

Logarithmic

$$\log_e x = \frac{x-1}{x} + \frac{1}{2}\left(\frac{x-1}{x}\right)^2 + \frac{1}{3}\left(\frac{x-1}{x}\right)^3 + \cdots \qquad \left(x > \frac{1}{2}\right)$$

$$\log_e x = (x-1) - \frac{1}{2}(x-1)^2 + \frac{1}{3}(x-1)^3 - \cdots \qquad (2 \geq x > 0)$$

$$\log_e x = 2\left[\frac{x-1}{x+1} + \frac{1}{3}\left(\frac{x-1}{x+1}\right)^3 + \frac{1}{5}\left(\frac{x-1}{x+1}\right)^5 + \cdots\right] \qquad (x > 0)$$

$$\log_e(1+x) = x - \frac{1}{2}x^2 + \frac{1}{3}x^3 - \frac{1}{4}x^4 + \cdots \qquad (-1 < x < 1)$$

$$\log_e(n+1) - \log_e(n-1) = 2\left[\frac{1}{n} + \frac{1}{3n^3} + \frac{1}{5n^5} + \cdots\right]$$

$$\log_e(a+x) = \log_e a + 2\left[\frac{x}{2a+x} + \frac{1}{3}\left(\frac{x}{2a+x}\right)^3 + \frac{1}{5}\left(\frac{x}{2a+x}\right)^5 + \cdots\right] \qquad (a > 0, -a < x < +\infty)$$

$$\log_e \frac{1+x}{1-x} = 2\left[x + \frac{x^3}{3} + \frac{x^5}{5} + \cdots + \frac{x^{2n-1}}{2n-1} + \cdots\right], \quad -1 < x < 1$$

$$\log_e x = \log_e a + \frac{(x-a)}{a} - \frac{(x-a)^2}{2a^2} + \frac{(x-a)^2}{3a^3} - + \cdots, \quad 0 < x \leqq 2a$$

Trigonometric

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \cdots \qquad (\text{all real values of } x)$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \cdots \qquad (\text{all real values of } x)$$

$$\tan x = x + \frac{x^3}{3} + \frac{2x^5}{15} + \frac{17x^7}{315} + \frac{62x^9}{2835} + \cdots \frac{2^{2n}(2^{2n}-1)B_{2n}}{(2n)!}x^{2n-1} + \cdots,$$

$$\left[x^2 < \frac{\pi^2}{4}, \text{ and } B_n \text{ represents the } n\text{'th Bernoulli number.}\right]$$

$$\cot x = \frac{1}{x} - \frac{x}{3} - \frac{x^3}{45} - \frac{2x^5}{945} - \frac{x^7}{4725} - \cdots - \frac{2^{2n}B_{2n}}{(2n)!}x^{2n-1} - \cdots,$$

$$\left[x^2 < \pi^2, \text{ and } B_n \text{ represents the } n\text{'th Bernoulli number.}\right]$$

$$\sec x = 1 + \frac{x^2}{2} + \frac{5}{24}x^4 + \frac{61}{720}x^6 + \frac{277}{8064}x^8 + \cdots + \frac{E_{2n}x^{2n}}{(2n)!} + \cdots,$$

$$\left[x^2 < \frac{\pi^2}{4}, \text{ and } B_n \text{ represents the } n\text{'th Euler number.}\right]$$

Series (continued)

$$\csc x = \frac{1}{x} - \frac{x}{6} + \frac{7}{360}x^3 + \frac{31}{15{,}120}x^5 + \frac{127}{604{,}800}x^7 + \cdots + \frac{2\left(2^{2n-1}-1\right)}{(2n)!}B_{2n}x^{2n-1} + \cdots,$$

$\left[x^2 < \pi^2\right.$, and B_n represents the n'th Bernoulli number.$\left.\right]$

$$\sin x = x\left(1 - \frac{x^2}{\pi^2}\right)\left(1 - \frac{x^2}{2^2\pi^2}\right)\left(1 - \frac{x^2}{3^2\pi^2}\right)\cdots \qquad \left(x^2 < \infty\right)$$

$$\cos x = \left(1 - \frac{4x^2}{\pi^2}\right)\left(1 - \frac{4x^2}{3^2\pi^2}\right)\left(1 - \frac{4x^2}{5^2\pi^2}\right)\cdots \qquad \left(x^2 < \infty\right)$$

$$\sin^{-1} x = x + \frac{x^3}{2\cdot 3} + \frac{1\cdot 3}{2\cdot 4\cdot 5}x^5 + \frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 7}x^7 + \cdots \qquad \left(x^2 < 1, -\frac{\pi}{2} < \sin^{-1} x < \frac{\pi}{2}\right)$$

$$\cos^{-1} x = \frac{\pi}{2} - \left(x + \frac{x^3}{2\cdot 3} + \frac{1\cdot 3x^5}{2\cdot 4\cdot 5} + \frac{1\cdot 3\cdot 5x^7}{2\cdot 4\cdot 6\cdot 7} + \cdots\right) \qquad \left(x^2 < 1, 0 < \cos^{-1} x < \pi\right)$$

$$\tan^{-1} x = x - \frac{x^3}{3} + \frac{x^5}{5} - \frac{x^7}{7} + \cdots \qquad \left(x^2 < 1\right)$$

$$\tan^{-1} x = \frac{\pi}{2} - \frac{1}{x} + \frac{1}{3x^2} - \frac{1}{5x^5} + \frac{1}{7x^7} - \cdots \qquad (x > 1)$$

$$\tan^{-1} x = -\frac{\pi}{2} - \frac{1}{x} + \frac{1}{3x^2} - \frac{1}{5x^5} + \frac{1}{7x^7} - \cdots \qquad (x < -1)$$

$$\cot^{-1} x = \frac{\pi}{2} - x + \frac{x^3}{3} - \frac{x^5}{5} + \frac{x^7}{7} - \cdots \qquad \left(x^2 < 1\right)$$

$$\log_e \sin x = \log_e x - \frac{x^2}{6} - \frac{x^4}{180} - \frac{x^6}{2835} - \cdots \qquad \left(x^2 < \pi^2\right)$$

$$\log_e \cos x = -\frac{x^2}{2} - \frac{x^4}{12} - \frac{x^6}{45} - \frac{17x^8}{2520} - \cdots \qquad \left(x^2 < \frac{\pi^2}{4}\right)$$

$$\log_e \tan x = \log_e x + \frac{x^2}{3} + \frac{7x^4}{90} + \frac{62x^6}{2835} + \cdots \qquad \left(x^2 < \frac{\pi^2}{4}\right)$$

$$e^{\sin x} = 1 + x + \frac{x^2}{2!} - \frac{3x^4}{4!} - \frac{8x^5}{5!} - \frac{3x^6}{6!} + \frac{56x^7}{7!} + \cdots$$

$$e^{\cos x} = e\left(1 - \frac{x^2}{2!} + \frac{4x^4}{4!} - \frac{31x^6}{6!} + \cdots\right)$$

$$e^{\tan x} = 1 + x + \frac{x^2}{2!} + \frac{3x^3}{3!} + \frac{9x^4}{4!} + \frac{37x^5}{5!} + \cdots \qquad \left(x^2 < \frac{\pi^2}{4}\right)$$

$$\sin x = \sin a + (x-a)\cos a - \frac{(x-a)^2}{2!}\sin a - \frac{(x-a)^3}{3!}\cos a + \frac{(x-a)^4}{4!}\sin a + \cdots$$

Hyperbolic and Inverse Hyperbolic

Table of expansion of certain functions into power series

$$\sinh x = x + \frac{x^3}{3!} + \frac{x^5}{5!} + \frac{x^7}{7!} + \cdots + \frac{x^{2n+1}}{(2n+1)!} + \cdots \qquad |x| < \infty$$

$$\cosh x = 1 + \frac{x^2}{2!} + \frac{x^4}{4!} + \frac{x^6}{6!} + \cdots + \frac{x^{2n}}{(2n)!} + \cdots \qquad |x| < \infty$$

Series (continued)

$\tanh x = x - \frac{1}{3}x^3 + \frac{2}{15}x^5 - \frac{17}{315}x^7 + \frac{62}{2835}x^9 - \cdots + \frac{(-1)^{n+1}2^{2n}(2^{2n}-1)}{(2n)!}B_{2n}x^{2n-1} \pm \cdots^{(1)}$	$\lvert x \rvert < \frac{\pi}{2}$
$\coth x = \frac{1}{x} + \frac{x}{3} - \frac{x^3}{45} + \frac{2x^5}{945} - \frac{x^7}{4725} + \cdots + \frac{(-1)^{n+1}2^{2n}}{(2n)!}B_{2n}x^{2n-1} \pm \cdots^{(1)}$	$0 < \lvert x \rvert < \pi$
$\mathrm{sech}\, x == 1 - \frac{1}{2!}x^2 + \frac{5}{4!}x^4 - \frac{61}{6!}x^6 + \frac{1385}{8!}x^8 - \cdots + \frac{(-1)^n}{(2n)!}E_{2n}x^{2n} \pm \cdots^{(2)}$	$\lvert x \rvert < \frac{\pi}{2}$
$\mathrm{cosech}\, x = \frac{1}{x} - \frac{x}{6} + \frac{7x^3}{360} - \frac{31x^5}{15{,}120} + \cdots + \frac{2(-1)^n(2^{2n-1}-1)}{(2n)!}B_{2n}x^{2n-1} + \cdots^{(1)}$	$0 < \lvert x \rvert < \pi$
$\mathrm{argsinh}\, x = x - \frac{1}{2\cdot 3}x^3 + \frac{1\cdot 3}{2\cdot 4\cdot 5}x^5 - \frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 7}x^7 + \cdots + (-1)^n \cdot \frac{1\cdot 3\cdot 5(2n-1)}{2\cdot 4\cdot 6\ldots 2n(2n+1)}x^{2n+1} \pm \cdots$	$\lvert x \rvert < 1$
$\mathrm{argcosh}\, x = \pm\left[\ln(2x) - \frac{1}{2\cdot 2x^2} - \frac{1\cdot 3}{2\cdot 4\cdot 4x^4} - \frac{1\cdot 3\cdot 5}{2\cdot 4\cdot 6\cdot 6x^6} - \cdots\right]$	$x > 1$
$\mathrm{argtanh}\, x = x + \frac{x^3}{3} + \frac{x^5}{5} + \frac{x^7}{7} + \cdots + \frac{x^{2n+1}}{2n+1} + \cdots$	$\lvert x \rvert < 1$
$\mathrm{argcoth}\, x = \frac{1}{x} + \frac{1}{3x^3} + \frac{1}{5x^5} + \frac{1}{7x^7} + \cdots + \frac{1}{(2n+1)x^{2n+1}} + \cdots$	$\lvert x \rvert > 1$

(1) B_n denotes Bernoull's numbers.
(2) E_n denotes Euler's numbers

Fourier

1. If $f(x)$ is a bounded periodic function of period $2L$ (i.e., $f(x + 2L) = f(x)$), and satisfies the *Dirichlet conditions*:
   a) In any period $f(x)$ is continuous, except possibly for a finite number of jump discontinuities.
   b) In any period $f(x)$ has only a finie number of maxima and minima.
   Then $f(x)$ may be represented by the *Fourier series*

$$\frac{a_0}{2} + \sum_{n-1}^{\infty}\left(a_n \cos\frac{n\pi x}{L} + b_n \sin\frac{n\pi x}{L}\right)$$

   where a_n and b_n are as determined below. This series will converge to $f(x)$ at every point where $f(x)$ is continuous, and to

$$\frac{f(x^+) + f(x^-)}{2}$$

   (i.e., the average of the left-hand and right-hand limits) at every point where $f(x)$ has a jump discontinuity.

$$a_n = \frac{1}{L}\int_{-L}^{L} f(x)\cos\frac{n\pi x}{L}dx\,, \quad n = 0,1,2,3,\ldots;$$

$$b_n = \frac{1}{L}\int_{-L}^{L} f(x)\sin\frac{n\pi x}{L}dx\,, \quad n = 1,2,3,\ldots$$

Series (continued)

We may also write

$$a_n = \frac{1}{L}\int_{\alpha}^{\alpha+2L} f(x)\cos\frac{n\pi x}{L}dx \quad and \quad b_n = \frac{1}{L}\int_{\alpha}^{\alpha+2L} f(x)\sin\frac{n\pi x}{L}dx$$

where *a* is any real number. Thus if $\alpha = 0$,

$$a_n = \frac{1}{L}\int_{0}^{2L} f(x)\cos\frac{n\pi x}{L}dx\,, \quad n = 0,1,2,3,\ldots;$$

$$b_n = \frac{1}{L}\int_{0}^{2L} f(x)\sin\frac{n\pi x}{L}dx\,, \quad n = 1,2,3,\ldots$$

2. If in addition to the above restrictions, $f(x)$ is even (i.e., $f(-x) = f(x)$), the Fourier series reduces to

$$\frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos\frac{n\pi x}{L}$$

That is, $b_n = 0$. In this case, a simpler formula for a_n is

$$a_n = \frac{2}{L}\int_{0}^{L} f(x)\cos\frac{n\pi x}{L}dx\,, \quad n = 0,1,2,3,\ldots$$

3. If in addition to the restrictions in (1), $f(x)$ is an odd function (i.e., $f(-x) = -f(x)$), then the Fourier series reduces to

$$\sum_{n=1}^{\infty} b_n \sin\frac{n\pi x}{L}$$

That is, $a_n = 0$. In this case, a simpler formula for the b_n is

$$b_n = \frac{2}{L}\int_{0}^{L} f(x)\sin\frac{n\pi x}{L}dx\,, \quad n = 1,2,3,\ldots$$

4. If in addition to the restrictions in (2) above, $f(x) = -f(L - x)$, then a_n will be 0 for all even values of n, including $n = 0$. Thus in this case, the expansion reduces to

$$\sum_{m=1}^{\infty} a_{2m-1} \cos\frac{(2m-1)\pi x}{L}$$

5. If in addition to the restrictions in (3) above, $f(x) = f(L - x)$, then b_n will be 0 for all even values of n. Thus in this case, the expansion reduces to

$$\sum_{m=1}^{\infty} b_{2m-1} \sin\frac{(2m-1)\pi x}{L}$$

(The series in (4) and (5) are known as *odd-harmonic series*, since only the odd hormonics appear. Similar rules may be stated for even-harmonic series, but when a series appears in the even-harmonic form, it means that $2L$ has not been taken as the smallest period of $f(x)$. Since any integral multiple of a period is also a period, series obtained in this way will also work, but in general computation is simplified if $2L$ is taken to be the smallest period.)

6. If we write the Euler definitions for $\cos\theta$ and $\sin\theta$, we obtain the complex form of the Fourier Series known either as the "Complex Fourier Series" or the "Exponential Fourier Series" of $f(x)$. It is represented as

$$f(x) = \frac{1}{2}\sum_{n=-\infty}^{n=+\infty} c_n e^{i\omega_n x}$$

where

$$c_n = \frac{1}{L}\int_{-L}^{L} f(x) e^{-i\omega_n x} dx, \quad n = 0, \pm 1, \pm 2, \pm 3, \ldots$$

Series (continued)

with $\omega_n = \frac{n\pi}{L}, \quad n = 0, \pm 1, \pm 2, \ldots$

The set of coefficients $\{c_n\}$ is often referred to as the Fourier spectrum.

7. If both sine and cosine terms are present and if f(x) is of period $2L$ and expandable by a Fourier series, it can be represented as

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} c_n \sin\left(\frac{n\pi x}{L} + \phi_n\right), \quad where\ a_n = c_n \sin\phi_n,$$

$$b_n = c_n \cos\phi_n, \quad c_n = \sqrt{a_n^2 + b_n^2}, \quad \phi_n = arc\tan\left(\frac{a_n}{b_n}\right)$$

It can also be represented as

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} c_n \cos\left(\frac{n\pi x}{L} + \phi_n\right), \quad where\ a_n = c_n \cos\phi_n,$$

$$b_n = -c_n \sin\phi_n, \quad c_n = \sqrt{a_n^2 + b_n^2}, \quad \phi_n = arc\tan\left(-\frac{b_n}{a_n}\right)$$

where ϕ_n is chosen so as to make a_n, b_n, and c_n hold.

8. The following table of trigonometric identities should be helpful for developing Fourier Series.

	n	n even	n odd	$n/2$ odd	$n/2$ even
$\sin n\pi$	–0	0	0	0	0
$\cos n\pi$	$(-1)^n$	+1	–1	+1	+1
$^*\sin\frac{n\pi}{2}$		0	$(-1)^{(n-1)/2}$	0	0
$^*\cos\frac{n\pi}{2}$		$(-1)^{n/2}$	0	–1	+1
$\sin\frac{n\pi}{4}$			$\frac{\sqrt{2}}{2}(-1)^{\left(n^2+4n+11\right)/8}$	$(-1)^{(n-2)/4}$	0

* A useful formula for $\sin\frac{n\pi}{2}$ *and* $\cos\frac{n\pi}{2}$ is given by

$$\sin\frac{n\pi}{2} = \frac{(i)^{n+1}}{2}\left[(1-1)^n - 1\right] \ and\ \cos\frac{n\pi}{2} = \frac{(i)^n}{2}\left[(-1)^n + 1\right], \ where\ i^2 = -1$$

Auxiliary Formulas for Fourier Series

$$1 = \frac{4}{\pi}\left[\sin\frac{\pi x}{k} + \frac{1}{3}\sin\frac{3\pi x}{k} + \frac{1}{5}\sin\frac{5\pi x}{k} + \cdots\right] \qquad [0 < x < k]$$

$$x = \frac{2k}{\pi}\left[\sin\frac{\pi x}{k} - \frac{1}{2}\sin\frac{2\pi x}{k} + \frac{1}{3}\sin\frac{3\pi x}{k} - \cdots\right] \qquad [-k < x < k]$$

$$x = \frac{k}{2} - \frac{4k}{\pi^2}\left[\cos\frac{\pi x}{k} + \frac{1}{3^2}\cos\frac{3\pi x}{k} + \frac{1}{5^2}\cos\frac{5\pi x}{k} + \cdots\right] \qquad [0 < x < k]$$

Series (continued)

$$x^2 = \frac{2k^2}{\pi^3}\left[\left(\frac{\pi^2}{1}-\frac{4}{1}\right)\sin\frac{\pi x}{k}-\frac{\pi^2}{2}\sin\frac{2\pi x}{k}+\left(\frac{\pi^2}{3}-\frac{4}{3^3}\right)\sin\frac{3\pi x}{k}\right.$$

$$\left.-\frac{\pi^2}{4}\sin\frac{4\pi x}{k}+\left(\frac{\pi^2}{5}-\frac{4}{5^3}\right)\sin\frac{5\pi x}{k}+\cdots\right] \qquad [0<x<k]$$

$$x^2 = \frac{k^2}{3}-\frac{4k^2}{\pi^2}\left[\cos\frac{\pi x}{k}-\frac{1}{2^2}\cos\frac{2\pi x}{k}+\frac{1}{3^2}\cos\frac{3\pi x}{k}-\frac{1}{4^2}\cos\frac{4\pi x}{k}+\cdots\right] \qquad [-k<x<k]$$

$$1-\frac{1}{3}+\frac{1}{5}-\frac{1}{7}+\cdots=\frac{\pi}{4}$$

$$1+\frac{1}{2^2}+\frac{1}{3^2}+\frac{1}{4^2}+\cdots=\frac{\pi^2}{6}$$

$$1-\frac{1}{2^2}+\frac{1}{3^2}-\frac{1}{4^2}+\cdots=\frac{\pi^2}{12}$$

$$1+\frac{1}{3^2}+\frac{1}{5^2}+\frac{1}{7^2}+\cdots=\frac{\pi^2}{8}$$

$$\frac{1}{2^2}+\frac{1}{4^2}+\frac{1}{6^2}+\frac{1}{8^2}+\cdots=\frac{\pi^2}{24}$$

From Bolz, R.E. and Tuve, G.L., Mathematical and statistical tables, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 890–897.

Tables of Statistical Probability

Mathematical probability deals with the random or chance variation of numerical data. When the probability or statistical chance is expressed numerically (percentage or decimal), it is a specific likelihood representing the ratio of chances in favor to total chances available. In the usual probability-distribution graphs probability is represented by an area under the frequency curve.

Measures of central tendency are the *mean* (μ) or arithmetical average, the *median* or middle value, and the *mode* or most frequent value.

Measures of dispersion are the individual *deviation* (x), which is the difference between the mean and the specific value under consideration; the *standard deviation* (σ), which is the square root of the mean of the squares of the deviations (rms†); and the *variance*, which is the square of the standard deviation (σ^2). The *range* is the spread between the smallest and the largest items of data.

Frequency (y) is a measure of the importance of a given value in terms of the frequency of its occurrence. It is commonly expressed as the frequency of occurrence of stated values of the deviation from y_o, the mean, but it also refers to the frequency of occurrence of a given magnitude in original data.

Frequency distribution describes the frequency of occurrence of the various numerical values, or the frequency of occurrence of stated deviations from the mean. A frequency distribution is represented mathematically, by equations, curves, or tables. The distributions covered by the following tables include he normal, the binomial, the Poisson, the *t*, the *F*, and the chi-square distributions.

Statistical sample is a random sample representative of all the original data. The data being sampled are referred to collectively as the *population* or the *universe*.

Statistical significance is a general term for the assumed importance of the probability. The range of probabilities used to describe a very likely occurrence is often expressed as a percentage between 90 and 99.9. For very unlikely occurrences the probabilities between 0.1 percent and 10 percent are examined. The arbitrarily selected percentages are often called *confidence limits*, implying that there is a 100 percent probability, representing full or complete certainty. The borderline between a "significant" probability and one that is not significant must be arbitrarily selected. (See Student's *t*-Distribution.)

Degrees of freedom (N) refer to the number of independent properties of a sample. It is usually n-1, where n is the number of data items.

Table 1. Normal or Gaussian Probability Distribution.‡ This "continuous" distribution is applicable to a population or universe for which the number of items of data is infinitely large and in which the deviations from the mean are random and unrelated. It applies also to a large representative sample of such data, such as 50 or 100 items; the larger the sample, the closer the approximation. For this symmetrical distribution the mean, the median, and the mode all coincide and are represented by the maximum ordinate y_o. The table gives normalized values, in which the maximum probability area under the curve is unity; the deviations are measured in units of σ, the mean deviation, and the maximum ordinate is $\frac{1}{\sqrt{2\pi}} = 0.39894$.

Table 2. Student's *t*-Distribution. The *t*-test is widely used to evaluate the significance of differences, such as the difference between the means of two samples and the difference between a sample mean and the population mean. At the top of each column in the table is that probability that the difference would exist by chance alone. The probability of a match or a fit decreases as t increases. Two common borderline values are $p = 0.01$ and $p = 0.05$. For example, if the computed value of t is larger than the one given in the column headed *0.05*, the interpretation might be as follows: the probability that this difference is due to chance alone is less than one in twenty; hence the difference is significant and is due to factors other than pure chance. The ratio t must be correctly computed.** For comparing a sample with a known parent population, it is the ratio of the difference between the sample mean and the population mean to the standard deviation of the mean of the parent population (corrected for sample size):

$$t = \frac{mean_1 - mean_2}{\sigma / \sqrt{N}}$$

The *t*-distribution approaches the normal distribution as the number of degrees of freedom approaches infinity, but in any case the means themselves are assumed to be normally distributed.

Table 3. Chi-Square Distribution. This is another test for the significance of differences by evaluation of the spread of the data. There are several ways to apply the chi-square test. One involves the ratio of the squares of the two standard deviations:

$$\text{chi-square} = N(\sigma_1/\sigma_2)^2$$

† For linear correlation by a line of regression, using least squares, the standard deviation of the points from the line is called the "standard error of estimate."

‡ Also called the normal error function and the normal frequency curve.

** Consult a textbook on statistics; see References.

Tables of Statistical Probability (continued)

For example, if it is desired to test the variability or dispersion for a sample when that of a parent population is known, a value of chi-square (= *N* times the ratio of variances) larger than the one in the *0.10* column would mean that there are fewer than ten chances in one hundred that the sample represented the parent population, and that its larger variability occurred purely by chance. As the chi-square increases, the probability of matching or agreement decreases.

Another application of the chi-square table uses the summation of the squares of frequency differences for goodness of fit with the parent distribution:

$$\textit{chi-square} = \frac{\Sigma\left(y - y_c\right)^2}{y_c}$$

where the values of y_c are those of the comparison standard.

A very useful application of the chi-square test is in the evaluation of attribute data where there are a number of classes and the expectations in the different classes are unequal.

Table 4. *F*-Distribution. This distribution is used for testing dispersion in terms of variance. One use for the *F*-test is to determine whether two samples, possibly of different sizes, drawn independently from two normal populations, actually represent populations with identical standard deviations. Here *F* is the ratio of the variance of the *samples*:

$$F = \sigma_1^2 / \sigma_2^2$$

In the tables, since the two sample sizes and degrees of freedom may be unequal, the additional variable is accommodated by setting up a separate table for each probability value, the *p* values used here being in the range 0.001 to 0.10. The borderline between a significant difference and one that is not significant must be selected, and the table with that probability value is used. If the value of *F* is larger than the corresponding one in that table, the probability that the two samples came from like populations is even less than that selected as a borderline.

Table 5. Binomial Distribution. This is a "discrete" distribution representing the probabilities of "success" in *N* trials for a population or sample in which only two outcomes are possible, but for which the eventual outcome is fixed and known if an infinite number of trials are made.† This eventual outcome is fixed by the conditions, such as 0.5 for one face of a coin or 0.1667 for one face of a six-sided die. Values in the body of the table represent the cumulative probability of *X* or more successes in *N* trials. In applications to acceptance or attribute sampling, the table gives the probability of *X* or more acceptances (or rejections) in a single sample of N items. In either case the known or fixed probability of the result (success or failure) for the entire population is represented by *p*.

Table 6. Poisson Distribution. This is a discrete distribution approximating the binomial when the total number of items of data (the populations) is very large, but the probability (*p*) is very small and the sample is small compared with the population

The Poisson cumulative probability, i.e., the probability that *X* is greater than or equal to *X*′, is expressed as

$$P = \sum_{X=X'}^{\infty} \frac{e^{-N_p}\left(Np\right)^x}{X'}$$

for specified values of *X*′ and *Np*.

The table is arranged in terms of the product, *Np*, where *N* is the sample size and *p* is the fixed probability for the entire population. For this distribution $Np = \mu = \sigma^2$, i.e., both the mean and the variance are equal to *Np*. The standard deviation is $\sigma = \sqrt{Np}$. Values in the body of the table represent the cumulative probability of *X* or more successes in *N* trials (the same as for the binomial table); or in sampling, the values represent the probability of *X* or more acceptances in sample of *N* items. In either case the fixed probability for the whole population is *p*.

†Outcomes might be expressed as successes or failure, yes or no, hit or miss, accept or reject, heads or talk, plus or minus, one or zero.

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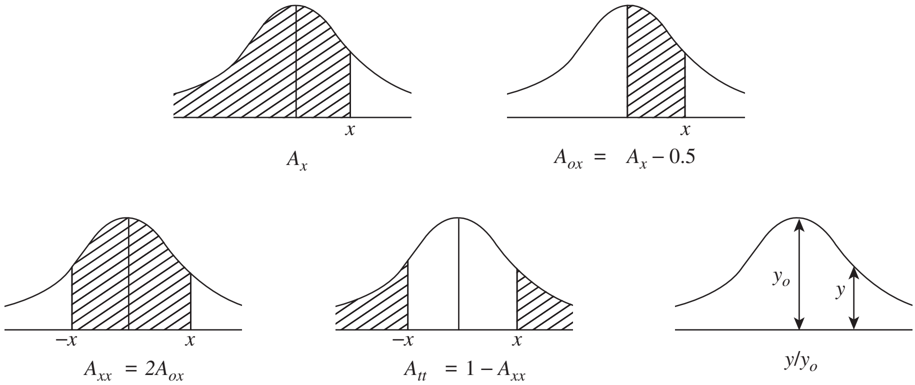
Table 1. Ordinates and Areas for Normal or Gaussian Probability Distribution



SYMBOLS:

x = deviation from the mean (or from zero error). One unit of x equals one standard deviation.

y = frequency of occurrence of the deviation ("probability density")

$$= f(x) = \frac{1}{\sqrt{2\pi}} e^{-x^2/2}$$

σ = standard deviation or error (rms) = $\sqrt{\dfrac{\Sigma x^2}{n}}$

y_o = frequency of occurrence of mean value

y/y_o = relative frequency in terms of mean frequency

A_x = area under curve from $-\alpha$ to x = $\displaystyle\int_{-\infty}^{+x} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} dx$

A_{ox} = area under curve from zero to x

A_{xx} = area under curve from $-x$ to $+x$ = probability of occurrence of values deviating from mean value in range from $-x$ to $+x$

A_{tt} = residual area, in the two "tails" = $1 - A_{xx}$

Note: All areas in the table are based on a transformation of the variable such that $A_{-\infty}^{+\infty} = 1$, with decimal values shown in the table.

Independent Variable = Deviation = x/σ

x/σ	A_{xx}	A_{ox}	A_x	A_{tt}	y	y/y_o
.00	.0000	.0000	.5000	1.0000	.3989	1.0000
.05	.0398	.0199	.5199	.9602	.3984	.9986
.10	.0797	.0398	.5398	.9203	.3971	.9950
.15	.1192	.0596	.5595	.8808	.3945	.9888
.20	.1585	.0793	.5793	.8415	.3910	.9802
.25	.1774	.0987	.5987	.8026	.3867	.9692
.30	.2358	.1179	.6179	.7642	.3814	.9560
.35	.2736	.1368	.6368	.7263	.3752	.9405
.40	.3108	.1554	.6554	.6892	.3683	.9231
.45	.3472	.1736	.6736	.6527	.3605	.9037
.50	.3829	.1915	.6915	.6171	.3521	.8825
.55	.4176	.2088	.7088	.5823	.3429	.8596
.60	.4515	.2257	.7257	.5485	.3332	.8353
.65	.4844	.2422	.7422	.5157	.3230	.8096
.70	.5161	.2580	.7580	.4839	.3123	.7827
.75	.5468	.2734	.7734	.4533	.3011	.7548
.80	.5763	.2881	.7881	.4237	.2897	.7262
.85	.6046	.3023	.8023	.3953	.2780	.6968
.90	.6319	.3159	.8159	.3681	.2661	.6670
.95	.6578	.3289	.8289	.3421	.2541	.6368

Table 1. Ordinates and Areas for Normal or Gaussian Probability Distribution (continued)

x/σ	A_{xx}	A_{ox}	A_x	A_{tt}	y	y/y_o
1.00	.6827	.3413	.8413	.3173	.2420	.6065
1.05	.7062	.3531	.8531	.2938	.2299	.5762
1.10	.7286	.3643	.8643	.2714	.2179	.5461
1.15	.7498	.3749	.8749	.2502	.2059	.5162
1.20	.7698	.3849	.8849	.2302	.1942	.4868
1.25	.7887	.3944	.8944	.2113	.1826	.4578
1.30	.8064	.4032	.9032	.1936	.1714	.4296
1.35	.8229	.4115	.9115	.1771	.1604	.4020
1.40	.8384	.4192	.9192	.1616	.1497	.3753
1.45	.8530	.4265	.9265	.1470	.1394	.3495
1.50	.8664	.4332	.9332	.1336	.1295	.3247
1.55	.8788	.4394	.9394	.1212	.1200	.3008
1.60	.8904	.4452	.9452	.1096	.1109	.2780
1.65	.9010	.4505	.9505	.0990	.1023	.2563
1.70	.9108	.4554	.9554	.0892	.0940	.2376
1.75	.9198	.4599	.9599	.0802	.0863	.2163
1.80	.9281	.4641	.9641	.0720	.0790	.1979
1.85	.9356	.4678	.9678	.0644	.0721	.1806
1.90	.9426	.4713	.9713	.0574	.0656	.1645
1.95	.9488	.4744	.9744	.0512	.0596	.1494
2.00	.9545	.4772	.9772	.0455	.0540	.1353
2.05	.9596	.4798	.9798	.0404	.0488	.1223
2.10	.9642	.4821	.9821	.0358	.0440	.1040
2.15	.9684	.4842	.9842	.0316	.0396	.0992
2.20	.9722	.4861	.9861	.0278	.0355	.0890
2.25	.9756	.4878	.9878	.0244	.0317	.0796
2.30	.9786	.4893	.9893	.0214	.0283	.0709
2.35	.9812	.4906	.9906	.0188	.0252	.0632
2.40	.9836	.4918	.9918	.0164	.0224	.0561
2.45	.9858	.4929	.9929	.0143	.0198	.0497
2.50	.9876	.4938	.9938	.0124	.0175	.0439
2.55	.9892	.4946	.9946	.0108	.0155	.0387
2.60	.9907	.4953	.9953	.0093	.0136	.0341
2.65	.9920	.4960	.9960	.0080	.0119	.0299
2.70	.9930	.4965	.9965	.0070	.0104	.0261
2.75	.9940	.4970	.9970	.0060	.0091	.0228
2.80	.9948	.4974	.9974	.0051	.0079	.0198
2.85	.9956	.4978	.9978	.0044	.0069	.0172
2.90	.9962	.4981	.9981	.0037	.0060	.0150
2.95	.9968	.4984	.9984	.0032	.0051	.0129
3.00	.9973	.4987	.9987	.0027	.0044	.0111

Independent Variable = Probability = A_{xx}

x/σ	A_{xx}	A_{ox}	A_x	A_{tt}	y	y/y_o
.005	.005	.002	.502	.995	.399	.999
.013	.010	.005	.505	.990	.399	.999
.063	.050	.025	.525	.950	.398	.998
.126	.100	.050	.550	.900	.396	.990
.189	.150	.075	.575	.850	.392	.982
.253	.200	.100	.600	.800	.386	.965
.319	.250	.125	.625	.750	.379	.950

Table 1. Ordinates and Areas for Normal or Gaussian Probability Distribution (continued)

x/σ	A_{xx}	A_{ox}	A_x	A_{tt}	y	y/y_o
.385	.300	.150	.650	.700	.370	.925
.454	.350	.175	.675	.650	.360	.900
.524	.400	.200	.700	.600	.348	.870
.598	.450	.225	.725	.550	.334	.835
.674	.500	.250	.750	.500	.318	.795
.755	.550	.275	.775	.450	.300	.749
.842	.600	.300	.800	.400	.280	.702
.935	.650	.325	.825	.350	.258	.643
1.036	.700	.350	.850	.300	.233	.583
1.150	.750	.375	.875	.250	.206	.516
1.282	.800	.400	.900	.200	.176	.440
1.440	.850	.425	.925	.150	.142	.355
1.645	.900	.450	.950	.100	.103	.257
1.960	.950	.475	.975	.050	.058	.146
2.054	.960	.480	.980	.040	.048	.121
2.170	.970	.485	.985	.030	.038	.095
2.326	.980	.490	.990	.020	.027	.066
2.576	.990	.495	.995	.010	.014	.036
2.748	.995	.497	.997	.005	.009	.022
3.090	.999	.499	.999	.001	.003	.008

Table 2. Student's *t*-Distribution*

Values of *t* at Specified Levels of Significance; Residual Area A_{tt}, Two Tails

SYMBOLS: *N* = degrees of freedom *P* = probability of agreement

N \ *P*	.50	.40	.30	.20	.10	.05	.02	.01	.005	.001
1	1.000	1.376	1.963	3.078	6.314	12.706	31.821	63.657	127.32	636.619
2	.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	14.089	31.598
3	.765	.978	1.250	1.638	2.353	3.182	4.541	5.841	7.453	12.924
4	.741	.941	1.190	1.533	2.132	2.776	3.747	4.604	5.598	8.610
5	.727	.920	1.156	1.476	2.015	2.571	3.365	4.032	4.773	6.869
6	.718	.906	1.134	1.440	1.943	2.447	3.143	3.707	4.317	5.959
7	.711	.896	1.119	1.415	1.895	2.365	2.998	3.499	4.029	5.408
8	.706	.889	1.108	1.397	1.860	2.306	2.896	3.355	3.832	5.041
9	.703	.883	1.100	1.383	1.833	2.262	2.821	3.250	3.690	4.781
10	.700	.879	1.093	1.372	1.812	2.228	2.764	3.169	3.581	4.587
11	.697	.876	1.088	1.363	1.796	2.201	2.718	3.106	3.497	4.437
12	.695	.873	1.083	1.356	1.782	2.179	2.681	3.055	3.428	4.318
13	.694	.870	1.079	1.350	1.771	2.160	2.650	3.012	3.372	4.221
14	.692	.868	1.076	1.345	1.761	2.145	2.624	2.977	3.326	4.140
15	.691	.866	1.074	1.341	1.753	2.131	2.602	2.947	3.286	4.073
16	.690	.865	1.071	1.337	1.746	2.120	2.583	2.921	3.252	4.015
17	.689	.863	1.069	1.333	1.740	2.110	2.567	2.898	3.222	3.965
18	.688	.862	1.067	1.330	1.734	2.101	2.552	2.878	3.197	3.922
19	.688	.861	1.066	1.328	1.729	2.093	2.539	2.861	3.174	3.883
20	.687	.860	1.064	1.325	1.725	2.086	2.528	2.845	3.153	3.850
21	.686	.859	1.063	1.323	1.721	1.080	2.518	2.831	3.135	3.819
22	.686	.858	1.061	1.321	1.717	2.074	2.508	2.819	3.119	3.792
23	.685	.858	1.060	1.319	1.714	2.069	2.500	2.807	3.104	3.767
24	.685	.857	1.059	1.318	1.711	2.064	2.492	2.797	3.090	3.745
25	.684	.856	1.058	1.316	1.708	2.060	2.485	2.787	3.078	3.725
26	.684	.856	1.058	1.315	1.706	2.056	2.479	2.779	3.067	3.707
27	.684	.855	1.057	1.314	1.703	2.052	2.473	2.771	3.056	3.690
28	.683	.855	1.056	1.313	1.701	2.048	2.467	2.763	3.047	3.674
29	.683	.854	1.055	1.311	1.699	2.045	2.462	2.756	3.038	3.659
30	.683	.854	1.055	1.310	1.697	2.042	2.457	2.750	3.030	3.646
40	.681	.851	1.050	1.303	1.684	2.021	2.423	2.704	2.971	3.551
60	.679	.848	1.046	1.296	1.671	2.000	2.390	2.660	2.915	3.460
120	.677	.845	1.041	1.289	1.658	1.980	2.358	2.617	2.860	3.373
∞	.674	.842	1.036	1.282	1.645	1.960	2.326	2.576	2.807	3.291

* Abridged from *Statistical Tables for Biological, Agricultural, and Medical Research,* 6th ed., R.A. Fisher and F. Yates, published by Oliver and Boyd, by permission of the authors and publishers; and *Biometrika Tables for Statisticians,* E.S. Pearson and H.O. Hartley, Eds., Vol. 1, Cambridge University Press, 1962.

Table 3. Chi-Square Distribution*

Values of Chi Square at Specified Levels of Significance; Single Tail

SYMBOLS: *N* = degrees of freedom *P* = probability of agreement

N \ *P*	.995	.990	.975	.950	.900	.750	.500	.250	.100	.050	.025	.010	.005	.001	*N*
1	—	.0002	.001	.0039	.0158	.102	.455	1.32	2.71	3.84	5.02	6.63	7.88	10.83	1
2	.0100	.0201	.0506	.103	.211	.575	1.39	2.77	4.61	5.99	7.38	9.21	10.6	13.82	2
3	.0717	.115	.216	.352	.584	1.21	2.37	4.11	6.25	7.81	9.35	11.3	12.8	16.27	3
4	.207	.297	.484	.711	1.06	1.92	3.36	5.39	7.78	9.49	11.1	13.3	14.9	18.47	4
5	.412	.554	.831	1.15	1.61	2.67	4.35	6.63	9.24	11.1	12.8	15.1	16.7	20.52	5
6	.676	.872	1.24	1.64	2.20	3.45	5.35	7.84	10.6	12.6	14.4	16.8	18.5	22.46	6
7	.989	1.24	1.69	2.17	2.83	4.25	6.35	9.04	12.0	14.1	16.0	18.5	20.3	24.32	7
8	1.34	1.65	2.18	2.73	3.49	5.07	7.34	10.2	13.4	15.5	17.5	20.1	22.0	26.13	8
9	1.73	2.09	2.70	3.33	4.17	5.90	8.34	11.4	14.7	16.9	19.0	21.7	23.6	27.88	9
10	2.16	2.56	3.25	3.94	4.87	6.74	9.34	12.5	16.0	18.3	20.5	23.2	25.2	29.59	10
11	2.60	3.05	3.82	4.57	5.58	7.58	10.3	13.7	17.3	19.7	21.9	24.7	26.8	31.26	11
12	3.07	3.57	4.40	5.23	6.30	8.44	11.3	14.8	18.5	21.0	21.3	26.2	28.3	32.91	12
13	3.57	4.11	5.01	5.89	7.04	9.30	12.3	16.0	19.8	22.4	24.7	27.7	29.8	34.53	13
14	4.07	4.66	5.63	6.57	7.79	10.2	13.3	17.1	21.1	23.7	26.1	29.1	31.3	36.12	14
15	4.60	5.23	6.26	7.26	8.55	11.0	14.3	18.2	22.3	25.0	27.5	30.6	32.8	37.70	15
16	5.14	5.81	6.91	7.96	9.31	11.9	15.3	19.4	23.5	26.3	28.8	32.0	34.3	39.25	16
17	5.70	6.41	7.56	8.67	10.1	12.8	16.3	20.5	24.8	27.6	30.2	33.4	35.7	40.79	17
18	6.26	7.01	8.23	9.39	10.9	13.7	17.3	21.6	26.0	28.9	31.5	34.8	37.2	42.31	18
19	6.84	7.63	8.91	10.1	11.7	14.6	18.3	22.7	27.2	30.1	32.9	36.2	38.6	43.82	19
20	7.43	8.26	9.59	10.9	12.4	15.5	19.3	23.8	28.4	31.4	34.2	37.6	40.0	45.32	20
21	8.03	8.90	10.3	11.6	13.2	16.3	20.3	24.9	29.6	32.7	35.5	38.9	41.4	46.80	21
22	8.64	9.54	11.0	12.3	14.0	17.2	21.3	26.0	30.8	33.9	36.8	40.3	42.8	48.27	22
23	9.26	10.2	11.7	13.1	14.8	18.1	22.3	27.1	32.0	35.2	38.1	41.6	44.2	49.73	23
24	9.89	10.9	12.4	13.8	15.7	19.0	23.3	28.2	33.2	36.4	39.4	43.0	45.6	51.18	24
25	10.5	11.5	13.1	14.6	16.5	19.9	24.3	29.3	34.4	37.7	40.6	44.3	46.9	52.62	25
26	11.2	12.2	13.8	15.4	17.3	20.8	25.3	30.4	35.6	38.9	41.9	45.6	48.3	54.05	26
27	11.8	12.9	14.6	16.2	18.1	21.7	26.3	31.5	36.7	40.1	43.2	47.0	49.6	55.48	27
28	12.5	13.6	15.3	16.9	18.9	22.7	27.3	32.6	37.9	41.3	44.5	48.3	51.0	56.89	28
29	13.1	14.3	16.0	17.7	19.8	23.6	28.3	33.7	39.1	42.6	45.7	49.6	52.3	58.30	29
30	13.8	15.0	16.8	18.5	20.6	24.5	29.3	34.8	40.3	43.8	47.0	50.9	53.7	59.70	30

*From: *Biometrika Tables for Statisticians*, E.S. Pearson and H.O. Hartley, Eds., Vol. 1, Cambridge University Press, 1962.

Table 4. F-Distribution*

For m and n Degrees of Freedom; $p = .001$ to $.100$; Single Tail

Table A. $p = .001$

$n \backslash m$	1	2	3	4	5	6	7	8	9	10	15	30	60	∞
1	4053†	5000†	5404†	5625†	5764†	5859†	5929†	5981†	6023†	6056†	6158†	6261†	6313†	6366†
2	998.5	999.0	999.2	999.2	999.3	999.3	999.4	999.4	999.4	999.4	999.4	999.5	999.5	999.5
3	167.0	148.5	141.1	137.1	134.6	132.8	131.6	130.6	129.9	129.2	127.4	125.4	124.5	123.5
4	74.14	61.25	56.18	53.44	51.71	50.53	49.66	49.00	48.47	48.05	46.76	45.43	44.75	44.05
5	47.18	37.12	33.20	31.09	29.75	28.84	28.16	27.64	27.24	26.92	25.91	24.87	24.33	23.79
6	35.51	27.00	23.70	21.92	20.81	20.03	19.46	19.03	18.69	18.41	17.56	16.67	16.21	15.75
7	29.25	21.69	18.77	17.19	16.21	15.52	15.02	14.63	14.33	14.08	13.32	12.53	12.12	11.70
8	25.42	18.49	15.83	14.39	13.49	12.86	12.40	12.04	11.77	11.54	10.84	10.11	9.73	9.33
9	22.86	16.39	13.90	12.56	11.71	11.13	10.70	10.37	10.11	9.89	9.24	8.55	8.19	7.81
10	21.04	14.91	12.55	11.28	10.48	9.92	9.52	9.20	8.96	8.75	8.13	7.47	7.12	6.76
12	18.64	12.97	10.80	9.63	8.89	8.38	8.00	7.71	7.48	7.29	6.71	6.09	5.76	5.42
15	16.59	11.34	9.34	8.25	7.57	7.09	6.74	6.47	6.26	6.08	5.54	4.95	4.64	4.31
30	13.29	8.77	7.05	6.12	5.53	5.12	4.82	4.58	4.39	4.24	3.75	3.22	2.92	2.59
60	11.97	7.76	6.17	5.31	4.76	4.37	4.09	3.87	3.69	3.54	3.08	2.55	2.25	1.89
∞	10.83	6.91	5.42	4.62	4.10	3.74	3.47	3.27	3.10	2.96	2.51	1.99	1.66	1.00

†Multiply these entries by 100.

Table B. $p = .005$

$n \backslash m$	1	2	3	4	5	6	7	8	9	10	15	30	60	∞
1	16211	20000	21615	22500	23056	24437	23715	23925	24091	24630	24224	25044	25253	25465
2	198.5	199.0	199.2	199.2	199.3	199.3	199.4	199.4	199.4	199.4	199.4	199.5	199.5	199.5
3	55.55	49.80	47.47	46.19	45.39	44.84	44.43	44.13	43.88	43.69	43.08	42.47	42.15	41.83
4	31.33	26.28	24.26	23.15	22.46	21.97	21.62	21.35	21.14	20.97	20.44	19.89	19.61	19.32
5	22.78	18.31	16.53	15.56	14.94	14.51	14.20	13.96	13.77	13.62	13.15	12.66	12.40	12.14
6	18.63	14.54	12.92	12.03	11.46	11.07	10.79	10.57	10.39	10.25	9.81	9.36	9.12	8.88
7	16.24	12.40	10.88	10.05	9.52	9.16	8.89	8.68	8.51	8.38	7.97	7.53	7.31	7.08
8	14.69	11.04	9.60	8.81	8.30	7.95	7.69	7.50	7.34	7.21	6.81	6.40	6.18	5.95
9	13.61	10.11	8.72	7.96	7.47	7.13	6.88	6.69	6.54	6.42	6.03	5.62	5.41	5.19
10	12.83	9.43	8.08	7.34	6.87	6.54	6.30	6.12	5.97	5.85	5.47	5.07	4.86	4.64

Table 4. F-Distribution* (continued)

m / n	1	2	3	4	5	6	7	8	9	10	15	30	60	∞
12	11.75	8.51	7.23	6.52	6.07	5.76	5.52	5.35	5.20	5.09	4.72	4.33	4.12	3.90
15	10.80	7.70	6.48	5.80	5.37	5.07	4.85	4.67	4.54	4.42	4.07	3.69	3.48	3.26
30	9.18	6.35	5.24	4.62	4.23	3.95	3.74	3.58	3.45	3.34	3.01	2.63	2.42	2.18
60	8.49	5.79	4.73	4.14	3.76	3.49	3.29	3.13	3.01	2.90	2.57	2.19	1.96	1.69
∞	7.88	5.30	4.28	3.72	3.35	3.09	2.90	2.74	2.62	2.52	2.19	1.79	1.53	1.00

Table C. $p = .010$

m / n	1	2	3	4	5	6	7	8	9	10	15	30	60	∞
1	4052	4999.5	5403	5625	5764	5859	5928	5982	6022	6056	6157	6261	6313	6366
2	98.50	99.00	99.17	99.25	99.30	99.33	99.36	99.37	99.39	99.40	99.43	99.47	99.48	99.50
3	34.12	30.82	29.46	28.71	28.24	27.91	27.67	27.49	27.35	27.23	26.87	26.50	26.32	26.13
4	21.20	18.00	16.69	15.98	15.52	15.21	14.98	14.80	14.66	14.55	14.20	13.84	13.65	13.46
5	16.26	13.27	12.06	11.39	10.97	10.67	10.46	10.29	10.16	10.05	9.72	9.38	9.20	9.02
6	13.75	10.92	9.78	9.15	8.75	8.47	8.26	8.10	7.98	7.87	7.56	7.23	7.06	6.88
7	12.25	9.55	8.45	7.85	7.46	7.19	6.99	6.84	6.72	6.62	6.31	5.99	5.82	5.65
8	11.26	8.65	7.59	7.01	6.63	6.37	6.18	6.03	5.91	5.81	5.52	5.20	5.03	4.86
9	10.56	8.02	6.99	6.42	6.06	5.80	5.61	5.47	5.35	5.26	5.96	4.65	4.48	4.31
10	10.04	7.56	6.55	5.99	5.64	5.39	5.20	5.06	4.94	4.85	4.56	4.25	4.08	3.91
12	9.33	6.93	5.95	5.41	5.06	4.82	4.64	4.50	4.39	4.30	4.01	3.70	3.54	3.36
15	8.68	6.36	5.42	4.89	4.56	4.32	4.14	4.00	3.89	3.80	3.52	3.21	3.05	2.87
30	7.56	5.39	4.51	4.02	3.70	3.47	3.30	3.17	3.07	2.98	2.70	2.39	2.21	2.01
60	7.08	4.98	4.13	3.65	3.34	3.12	2.95	2.82	2.72	2.63	2.35	2.03	1.84	1.60
∞	6.63	4.61	3.78	3.32	3.02	2.80	2.64	2.51	2.41	2.32	2.04	1.70	1.47	1.00

Table D. $p = .025$

m / n	1	2	3	4	5	6	7	8	9	10	15	30	60	∞
1	647.8	799.5	864.2	899.6	921.8	937.1	948.2	956.7	963.3	968.6	984.9	1001	1010	1018
2	38.51	39.00	39.17	39.25	39.30	39.33	39.36	39.37	39.39	39.40	39.43	39.46	39.48	39.50

3	17.44	16.04	15.44	15.10	14.88	14.73	14.62	14.54	14.47	14.42	14.25	14.08	13.99	13.90
4	12.22	10.65	9.98	6.60	9.36	9.20	9.07	8.98	8.90	8.84	8.66	8.46	8.36	8.26
5	10.01	8.43	7.76	7.39	7.15	6.98	6.85	6.76	6.68	6.62	6.43	6.23	6.12	6.02
6	8.81	7.26	6.60	6.23	5.99	5.82	5.70	5.60	5.52	5.46	5.27	5.07	4.96	4.85
7	8.07	6.54	5.89	5.52	5.29	5.12	4.99	4.90	4.82	4.76	4.57	4.36	4.25	4.14
8	7.57	6.06	5.42	5.05	4.82	4.65	4.53	4.43	4.36	4.30	4.10	3.89	3.78	3.67
9	7.21	5.71	5.08	4.72	4.48	4.32	4.20	4.10	4.03	3.96	3.77	3.56	3.45	3.33
10	6.94	5.46	4.83	4.47	4.24	4.07	3.95	3.85	3.78	3.72	3.52	3.31	3.20	3.08
12	6.55	5.10	4.47	4.12	3.89	3.73	3.61	3.51	3.44	3.37	3.18	2.96	2.85	2.72
15	6.20	4.77	4.15	3.80	3.58	3.41	3.29	3.20	3.12	3.06	2.86	2.64	2.52	2.40
30	5.57	4.18	3.59	3.25	3.03	2.87	2.75	2.65	2.57	2.51	2.31	2.07	1.94	1.79
60	5.29	3.93	3.34	3.01	2.79	2.63	2.51	2.41	2.33	2.27	2.06	1.82	1.67	1.48
∞	5.02	3.69	3.12	2.79	2.57	2.41	2.29	2.19	2.11	2.05	1.83	1.57	1.39	1.00

Table E. $p = .050$

$n \backslash m$	1	2	3	4	5	6	7	8	9	10	15	30	60	∞
1	161.4	199.5	215.7	224.6	230.2	234.0	236.8	238.9	240.5	241.9	245.9	250.1	252.2	254.3
2	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38	19.40	19.43	19.46	19.48	19.50
3	10.13	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81	8.79	8.70	8.62	8.57	8.53
4	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00	5.96	5.86	5.75	5.69	5.63
5	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77	4.74	4.62	4.50	4.43	4.36
6	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10	4.06	3.94	3.81	3.74	3.67
7	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68	3.64	3.51	3.38	3.30	3.23
8	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39	3.35	3.22	3.08	3.01	2.93
9	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18	3.14	3.01	2.86	2.79	2.71
10	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02	2.98	2.85	2.70	2.62	2.54
12	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80	2.75	2.62	2.47	2.38	2.30
15	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59	2.54	2.40	2.25	2.16	2.07
30	4.17	3.32	2.92	2.69	2.53	2.42	2.33	2.27	2.21	2.16	2.01	1.84	1.74	1.62
60	4.00	3.15	2.76	2.53	2.37	2.25	2.17	2.10	2.04	1.99	1.84	1.65	1.53	1.39
∞	3.84	3.00	2.60	2.37	2.21	2.10	2.01	1.94	1.88	1.83	1.67	1.46	1.32	1.00

Table 4. F-Distribution* (continued)

Table F. p = .100

n \ m	1	2	3	4	5	6	7	8	9	10	15	30	60	∞
1	39.86	49.50	53.59	55.83	57.24	58.20	58.91	59.44	59.86	60.19	61.22	62.26	62.79	63.33
2	8.53	9.00	9.16	9.24	9.29	9.33	9.35	9.37	9.38	9.39	9.42	9.46	9.47	9.49
3	5.54	5.46	5.39	5.34	5.31	5.28	5.27	5.25	5.24	5.23	5.20	5.17	5.15	5.13
4	4.54	4.32	4.19	4.11	4.05	4.01	3.98	3.95	3.94	3.92	3.87	3.82	3.79	3.76
5	4.06	3.78	3.62	3.52	3.45	3.40	3.37	3.34	3.32	3.30	3.24	3.17	3.14	3.10
6	3.78	3.46	3.29	3.18	3.11	3.05	3.01	2.98	2.96	2.94	2.87	2.80	2.76	2.72
7	3.59	3.26	3.07	2.96	2.88	2.83	2.78	2.75	2.72	2.70	2.63	2.56	2.51	2.47
8	3.46	3.11	2.92	2.81	2.73	2.67	2.62	2.59	2.56	2.54	2.46	2.38	2.34	2.29
9	3.36	3.01	2.81	2.69	2.61	2.55	2.51	2.47	2.44	2.42	2.34	2.25	2.21	2.16
10	3.29	2.92	2.73	2.61	2.52	2.46	2.41	2.38	2.35	2.32	2.24	2.16	2.11	2.06
12	3.18	2.81	2.61	2.48	2.39	2.33	2.28	2.24	2.21	2.19	2.10	2.01	1.96	1.90
15	3.07	2.70	2.49	2.36	2.27	2.21	2.16	2.12	2.09	2.06	1.97	1.87	1.82	1.76
30	2.88	2.49	2.28	2.14	2.05	1.98	1.93	1.88	1.85	1.82	1.72	1.61	1.54	1.46
60	2.79	2.39	2.18	2.04	1.95	1.87	1.82	1.77	1.74	1.71	1.60	1.48	1.40	1.29
∞	2.71	2.30	2.08	1.94	1.85	1.77	1.72	1.67	1.63	1.60	1.49	1.34	1.24	1.00

*From *Biometrika Tables for Statisticians,* E.S. Pearson and H.O. Hartley, Eds., Vol. 1, Cambridge University Press, 1962.

Table 5. Binomial Distribution—Cumulative Probabilities: P*

SYMBOLS:
N = number of trials or size of a sample
p = probability of the outcome for the entire population (success or failure, whichever is less)
P = cumulative probability of observing X or more successes within N

N	X	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50
2	1	.0975	.1900	.2775	.3600	.4375	.5100	.5775	.6400	.6975	.7500
	2	.0025	.0100	.0225	.0400	.0625	.0900	.1225	.1600	.2025	.2500
3	1	.1426	.2710	.3859	.4880	.5781	.6570	.7254	.7840	.8336	.8750
	2	.0072	.0280	.0608	.1040	.1562	.2160	.2818	.3520	.4252	.5000
	3	.0001	.0010	.0034	.0080	.0156	.0270	.0429	.0640	.0911	.1250
4	1	.1855	.3439	.4780	.5904	.6836	.7599	.8215	.8704	.9085	.9375
	2	.0140	.0523	.1095	.1808	.2617	.3483	.4370	.5248	.6090	.6875
	3	.0005	.0037	.0120	.0272	.0508	.0837	.1265	.1792	.2415	.3125
	4	.0000	.0001	.0005	.0016	.0039	.0081	.0150	.0256	.0410	.0625
5	1	.2262	.4095	.5563	.6723	.7627	.8319	.8840	.9222	.9497	.9688
	2	.0226	.0815	.1648	.2627	.3672	.4718	.5716	.6630	.7438	.8125
	3	.0012	.0086	.0266	.0579	.1035	.1631	.2352	.3174	.4069	.5000
	4	.0000	.0005	.0022	.0067	.0156	.0308	.0540	.0870	.1312	.1875
	5	.0000	.0000	.0001	.0003	.0010	.0024	.0053	.0102	.0185	.0312
6	1	.2649	.4686	.6229	.7379	.8220	.8824	.9246	.9533	.9723	.9844
	2	.0328	.1143	.2235	.3447	.4661	.5798	.6809	.7667	.8364	.8906
	3	.0022	.0158	.0473	.0989	.1694	.2557	.3529	.4557	.5585	.6562
	4	.0001	.0013	.0059	.0170	.0376	.0705	.1174	.1792	.2553	.3438
	5	.0000	.0001	.0004	.0016	.0046	.0109	.0223	.0410	.0692	.1094
	6	.0000	.0000	.0000	.0001	.0002	.0007	.0018	.0041	.0083	.0156
7	1	.3017	.5217	.6794	.7903	.8665	.9176	.9510	.9720	.9848	.9922
	2	.0444	.1497	.2834	.4233	.5551	.6706	.7662	.8414	.8976	.9375
	3	.0038	.0257	.0738	.1480	.2436	.3529	.4677	.5801	.6836	.7734
	4	.0002	.0027	.0121	.0333	.0706	.1260	.1998	.2898	.3917	.5000
	5	.0000	.0002	.0012	.0047	.0129	.0288	.0556	.0963	.1529	.2266
	6	.0000	.0000	.0001	.0004	.0013	.0038	.0090	.0188	.0357	.0625
8	1	.3366	.5695	.7275	.8322	.8999	.9424	.9681	.9832	.9916	.9961
	2	.0572	.1869	.3428	.4967	.6329	.7447	.8309	.8936	.9368	.9648
	3	.0058	.0381	.1052	.2031	.3215	.4482	.5722	.6846	.7799	.8555
	4	.0004	.0050	.0214	.0563	.1138	.1941	.2936	.4059	.5230	.6367
	5	.0000	.0004	.0029	.0104	.0273	.0580	.1061	.1737	.2604	.3633
	6	.0000	.0000	.0002	.0012	.0042	.0113	.0253	.0498	.0885	.1445
	7	.0000	.0000	.0000	.0001	.0004	.0013	.0036	.0085	.0181	.0352
9	1	.3698	.6126	.7684	.8658	.9249	.9596	.9793	.9899	.9954	.9980
	2	.0712	.2252	.4005	.5638	.6997	.8040	.8789	.9295	.9615	.9805
	3	.0084	.0530	.1409	.2618	.3993	.5372	.6627	.7682	.8505	.9102
	4	.0006	.0083	.0339	.0856	.1657	.2703	.3911	.5174	.6386	.7461
	5	.0000	.0009	.0056	.0196	.0489	.0988	.1717	.2666	.3786	.5000
	6	.0000	.0001	.0006	.0031	.0100	.0253	.0536	.0994	.1658	.2539
	7	.0000	.0000	.0000	.0003	.0013	.0043	.0112	.0250	.0498	.0898
	8	.0000	.0000	.0000	.0000	.0001	.0004	.0014	.0038	.0091	.0195
10	1	.4013	.6513	.8031	.8926	.9437	.9718	.9865	.9940	.9975	.9990
	2	.0861	.2639	.4557	.6242	.7560	.8507	.9140	.9536	.9767	.9893
	3	.0115	.0702	.1798	.3222	.4744	.6172	.7384	.8327	.9004	.9453

Table 5. Binomial Distribution—Cumulative Probabilities: P* (continued)

N	X	.05	.10	.15	.20	.25	.30	.35	.40	.45	.50
	4	.0010	.0128	.0500	.1209	.2241	.3504	.4862	.6177	.7340	.8281
	5	.0001	.0016	.0099	.0328	.0781	.1503	.2485	.3669	.4956	.6230
	6	.0000	.0001	.0014	.0064	.0197	.0473	.0949	.1662	.2616	.3770
	7	.0000	.0000	.0001	.0009	.0035	.0106	.0260	.0548	.1020	.1719
	8	.0000	.0000	.0000	.0001	.0094	.0016	.0048	.0123	.0274	.0547
	9	.0000	.0000	.0000	.0000	.0000	.0001	.0005	.0017	.0045	.0107
12	1	.4596	.7176	.8578	.9313	.9683	.9862	.9943	.9978	.9992	.9998
	2	.1184	.3410	.5565	.7251	.8416	.9150	.9576	.9804	.9917	.9968
	3	.0196	.1109	.2642	.4417	.6093	.7472	.8487	.9166	.9579	.9807
	4	.0022	.0256	.0922	.2054	.3512	.5075	.6533	.7747	.8655	.9270
	5	.0002	.0043	.0239	.0726	.1576	.2763	.4167	.5618	.6956	.8062
	6	.0000	.0005	.0046	.0194	.0544	.1178	.2127	.3348	.4731	.6128
	7	.0000	.0001	.0007	.0039	.0143	.0386	.0846	.1582	.2607	.3872
	8	.0000	.0000	.0001	.0006	.0028	.0095	.0255	.0573	.1117	.1938
	9	.0000	.0000	.0000	.0001	.0004	.0017	.0056	.0153	.0356	.0730
	10	.0000	.0000	.0000	.0000	.0000	.0002	.0008	.0028	.0079	.0193
15	1	.5367	.7941	.9126	.9648	.9866	.9953	.9984	.9995	.9999	1.0000
	2	.1710	.4510	.6814	.8329	.9198	.9647	.9858	.9948	.9983	.9995
	3	.0362	.1841	.3958	.6020	.7639	.8732	.9383	.9729	.9893	.9963
	4	.0055	.0556	.1773	.3518	.5387	.7031	.8273	.9095	.9576	.9824
	5	.0006	.0127	.0617	.1642	.3135	.4845	.6481	.7827	.8796	.9408
	6	.0001	.0022	.0168	.0611	.1484	.2784	.4357	.5968	.7392	.8491
	7	.0000	.0003	.0036	.0181	.0566	.1311	.2452	.3902	.5478	.6964
	8	.0000	.0000	.0006	.0042	.0173	.0500	.1132	.2131	.3465	.5000
	9	.0000	.0000	.0001	.0008	.0042	.0152	.0422	.0950	.1818	.3036
	10	.0000	.0000	.0000	.0001	.0008	.0037	.0124	.0338	.0769	.1509
	11	.0000	.0000	.0000	.0000	.0001	.0007	.0028	.0093	.0255	.0592
	12	.0000	.0000	.0000	.0000	.0000	.0001	.0005	.0019	.0063	.0176
20	1	.6415	.8784	.9612	.9885	.9968	.9992	.9998	1.0000	1.0000	1.0000
	2	.2642	.6083	.8244	.9308	.9757	.9924	.9979	.9995	.9999	1.0000
	3	.0755	.3231	.5951	.7939	.9087	.9645	.9879	.9964	.9991	.9998
	4	.0159	.1330	.3523	.5886	.7748	.8929	.9556	.9840	.9951	.9987
	5	.0026	.0432	.1702	.3704	.5852	.7625	.8818	.9490	.9811	.9941
	6	.0003	.0113	.0673	.1958	.3828	.5836	.7546	.8744	.9447	.9793
	7	.0000	.0024	.0219	.0867	.2142	.3920	.5834	.7500	.8701	.9423
	8	.0000	.0004	.0059	.0321	.1018	.2277	.3990	.5841	.7480	.8684
	9	.0000	.0001	.0013	.0100	.0409	.1133	.2376	.4044	.5857	.7483
	10	.0000	.0000	.0002	.0026	.0139	.0480	.1218	.2447	.4086	.5881
	11	.0000	.0000	.0000	.0006	.0039	.0171	.0532	.1275	.2493	.4119
	12	.0000	.0000	.0000	.0001	.0009	.0051	.0196	.0565	.1308	.2517
	13	.0000	.0000	.0000	.0000	.0002	.0013	.0060	.0210	.0580	.1316
	14	.0000	.0000	.0000	.0000	.0000	.0003	.0015	.0065	.0214	.0577
	15	.0000	.0000	.0000	.0000	.0000	.0000	.0003	.0016	.0064	.0207

Note: Individual binomial probability terms can be obtained by subtraction, i.e.,

$$p_x = \sum_x^N (p_x) - \sum_{x+1}^N (p_x)$$

* Condensed from: *CRC Handbook of Tables for Mathematics,* 4th ed., S.M. Selby, Ed., The Chemical Rubber Co., 1970.

Table 6. Poisson Distribution—Cumulative Probabilities: P^*

SYMBOLS:
N = number of trials or size of the sample
p = fixed probability of the outcome for entire population (success or failure, whichever is less)
P = cumulaive probability of X or more successes (or failures) within N

X' \ Np	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2
1	.095	.181	.259	.330	.394	.451	.503	.551	.593	.632	.667	.699
2	.005	.018	.037	.062	.090	.122	.156	.191	.228	.264	.301	.337
3	.000	.001	.004	.008	.014	.023	.034	.047	.063	.080	.100	.121
4	.000	.000	.000	.001	.002	.003	.006	.0009	.014	.019	.026	.034

X' \ Np	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4
1	.728	.753	.777	.798	.817	.835	.850	.865	.878	.889	.900	.909
2	.373	.408	.442	.475	.507	.537	.566	.594	.620	.645	.669	.692
3	.143	.167	.191	.217	.243	.269	.296	.323	.350	.377	.404	.430
4	.043	.054	.066	.079	.093	.109	.125	.143	.161	.181	.201	.221
5	.011	.014	.019	.024	.030	.036	.044	.053	.062	.073	.084	.096
6	.002	.003	.005	.006	.008	.010	.013	.017	.020	.025	.030	.036

X' \ Np	2.5	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5	3.6
1	.918	.926	.933	.939	.945	.950	.955	.959	.963	.967	.970	.973
2	.713	.733	.751	.769	.785	.801	.815	.829	.841	.853	.864	.874
3	.456	.482	.506	.531	.554	.577	.599	.620	.641	.660	.679	.697
4	.242	.264	.286	.308	.330	.353	.375	.398	.420	.442	.463	.485
5	.109	.123	.137	.152	.168	.185	.202	.219	.237	.256	.275	.294
6	.042	.049	.057	.065	.074	.084	.094	.105	.117	.130	.142	.156
7	.014	.017	.021	.024	.029	.034	.039	.045	.051	.058	.065	.073
8	.004	.005	.007	.008	.010	.012	.014	.017	.020	.023	.027	.031

X' \ Np	3.7	3.8	3.9	4.0	4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8
1	.975	.978	.980	.982	.983	.985	.986	.988	.989	.990	.991	.992
2	.884	.893	.901	.908	.916	.922	.928	.934	.939	.944	.948	.952
3	.715	.731	.747	.762	.776	.790	.803	.815	.826	.837	.848	.858
4	.506	.527	.547	.567	.586	.605	.623	.641	.658	.674	.690	.706
5	.313	.332	.352	.371	.391	.410	.430	.449	.468	.487	.505	.524
6	.170	.184	.199	.215	.231	.247	.263	.280	.297	.314	.332	.349
7	.082	.091	.101	.111	.121	.133	.144	.156	.169	.182	.195	.209
8	.035	.040	.045	.051	.057	.064	.071	.079	.087	.095	.104	.113
9	.014	.016	.019	.021	.025	.028	.032	.036	.040	.045	.050	.056
10	.005	.006	.007	.008	.010	.011	.013	.015	.017	.020	.022	.025

X' \ Np	4.9	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.0
1	.993	.993	.994	.995	.995	.996	.996	.996	.997	.997	.997	.998
2	.956	.960	.963	.966	.969	.971	.973	.976	.978	.979	.981	.983
3	.867	.875	.884	.891	.898	.905	.912	.918	.923	.929	.933	.938
4	.721	.735	.749	.762	.775	.787	.798	.809	.820	.830	.840	.849
5	.542	.560	.577	.594	.611	.627	.643	.658	.673	.687	.701	.715
6	.367	.384	.402	.419	.437	.454	.471	.488	.505	.522	.538	.554
7	.223	.238	.253	.268	.283	.298	.314	.330	.346	.362	.378	.394
8	.123	.133	.144	.155	.167	.178	.191	.203	.216	.229	.242	.256

Table 6. Poisson Distribution—Cumulative Probabilities: P^* (continued)

X′ \ Np	4.9	5.0	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6.0
9	.062	.068	.075	.082	.089	.097	.106	.114	.123	.133	.143	.153
10	.028	.032	.036	.040	.044	.049	.054	.059	.065	.071	.077	.084
11	.012	.014	.016	.018	.020	.023	.025	.028	.031	.035	.039	.043
12	.005	.006	.006	.007	.008	.010	.011	.013	.014	.016	.018	.020

X′ \ Np	6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7.0	7.1	7.2
1	.998	.998	.998	.998	.999	.999	.999	.999	.999	.999	.999	.999
2	.984	.985	.987	.988	.989	.990	.991	.991	.992	.993	.993	.994
3	.942	.946	.950	.954	.957	.960	.963	.966	.968	.970	.973	.975
4	.858	.866	.874	.881	.888	.895	.901	.907	.913	.918	.923	.928
5	.728	.741	.753	.765	.776	.787	.798	.808	.818	.827	.836	.845
6	.570	.586	.601	.616	.631	.645	.659	.673	.686	.699	.712	.724
7	.410	.426	.442	.458	.474	.489	.505	.520	.535	.550	.565	.580
8	.270	.284	.298	.313	.327	.342	.357	.372	.386	.401	.416	.431
9	.163	.174	.185	.197	.208	.220	.233	.245	.258	.271	.284	.297
10	.091	.098	.106	.114	.123	.131	.140	.150	.151	.170	.180	.190
11	.047	.051	.056	.061	.067	.073	.079	.085	.092	.099	.106	.113
12	.022	.025	.028	.031	.034	.037	.041	.045	.049	.053	.058	.063

X′ \ Np	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8.0	8.2	8.4	8.6	8.8
1	.999	.999	.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2	.994	.995	.995	.996	.996	.996	.997	.997	.998	.998	.998	.999
3	.976	.978	.980	.981	.983	.984	.985	.986	.988	.990	.991	.993
4	.933	.937	.941	.945	.948	.952	.955	.958	.963	.968	.972	.976
5	.853	.861	.868	.875	.882	.888	.895	.900	.911	.921	.930	.938
6	.736	.747	.759	.769	.780	.790	.799	.809	.826	.843	.858	.872
7	.594	.608	.622	.635	.649	.662	.674	.687	.710	.733	.754	.774
8	.446	.461	.475	.490	.504	.519	.533	.547	.575	.601	.627	.652
9	.311	.324	.338	.352	.366	.380	.394	.408	.435	.463	.491	.518
10	.201	.212	.224	.235	.247	.259	.271	.283	.309	.334	.360	.386
11	.121	.129	.138	.147	.156	.165	.174	.184	.205	.226	.248	.271
12	.068	.074	.079	.085	.092	.098	.105	.112	.127	.143	.160	.178
13	.036	.039	.043	.046	.050	.055	.059	.064	.074	.085	.097	.110
14	.018	.020	.022	.024	.026	.029	.031	.034	.041	.048	.056	.064

X′ \ Np	9.0	10	11	12	13	14	15	16	17	18	19	20
1	.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.1.000
3	.994	.997	.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.1.000
4	.979	.990	.995	.998	.999	1.000	1.000	1.000	1.000	1.000	1.000	.1.000
5	.945	.971	.985	.992	.996	.998	.999	1.000	1.000	1.000	1.000	.1.000
6	.884	.933	.963	.980	.989	.995	.997	.999	.999	1.000	1.000	.1.000
7	.793	.870	.921	.954	.974	.986	.992	.996	.998	.999	1.000	1.000
8	.676	.780	.857	.911	.946	.968	.982	.990	.995	.997	.999	.999
9	.544	.667	.768	.845	.900	.938	.963	.978	.987	.993	.996	.998
10	.413	.542	.660	.758	.834	.891	.930	.957	.974	.985	.991	.995
11	.294	.417	.540	.653	.748	.824	.882	.923	.951	.970	.982	.989
12	.197	.303	.421	.538	.647	.740	.815	.873	.915	.945	.965	.979

Table 6. Poisson Distribution—Cumulative Probabilities: *P** (continued)

X' \ Np	9.0	10	11	12	13	14	15	16	17	18	19	20
13	.124	.208	.311	.424	.537	.642	.732	.807	.865	.908	.939	.961
14	.074	.136	.219	.319	.427	.536	.637	.726	.799	.857	.902	.934
15	.042	.084	.146	.228	.325	.430	.534	.633	.719	.792	.850	.895
16	.022	.049	.093	.156	.236	.331	.432	.533	.629	.713	.785	.844
17	.011	.027	.056	.101	.165	.244	.336	.434	.532	.625	.708	.779
18	.005	.014	.032	.063	.110	.173	.251	.341	.436	.531	.622	.703
19	.002	.007	.018	.037	.070	.117	.181	.258	.345	.438	.531	.619
20	.001	.004	.009	.021	.043	.077	.125	.188	.264	.349	.439	.530
21	.000	.002	.005	.012	.025	.048	.083	.132	.195	.269	.353	.441
22	.000	.001	.002	.006	.014	.029	.053	.089	.139	.201	.275	.356
23	.000	.000	.001	.003	.008	.017	.033	.058	.095	.145	.207	.279
24	.000	.000	.001	.002	.004	.009	.020	.037	.063	.101	.151	.213
25	.000	.000	.000	.001	.002	.005	.011	.022	.041	.068	.107	.157
26	.000	.000	.000	.000	.001	.003	.006	.013	.025	.045	.073	.112

Note: Individual Poisson-probability terms can be obtained by subtraction, i.e.,

$$p_x = \sum_x^N (p_x) - \sum_{x+1}^N (p_x)$$

* Condensed from *CRC Handbook of Tables for Mathematics,* 4th ed., S.M. Selby, Ed., The Chemical Rubber Co., 1970.

Critical Values for the Sign Test

The observations in a random sample of size n from X and those of the same size from Y are paired according to the order of observation: (X_i, Y_i), $i = 1, 2,\ldots, n$. The differences $d_i = X_i - Y_i$ are calculated for each of the n pairs. the null hypothesis is that the difference d_i has a distribution with median zero, i.e., the true proportion of positive (negative) signs is equal to $p = \frac{1}{2}$. Thus the test is whether X and Y have the same median. The probability of x positive (negative) signs is given by the binomial probability function

$$f(x) = f\left(x; n, p = \frac{1}{2}\right) = \binom{n}{x}\left(\frac{1}{2}\right)^n$$

This table gives the critical value k such that

$$P(x \le k) = \sum_{x=0}^{k} \binom{n}{x}\left(\frac{1}{2}\right)^n < \frac{\alpha}{2}$$

Two-tail Percentage Points for the Binomial for $p = .5$

n	1%	5%	10%	25%	n	1%	5%	10%	25%
1					46	13	15	16	18
2					47	14	16	17	19
3				0	48	14	16	17	19
4				0	49	15	17	18	19
5			0	0	50	15	17	18	20
6		0	0	1	51	15	18	19	20
7		0	0	1	52	16	18	19	21
8	0	0	1	1	53	16	18	20	21
9	0	1	1	2	54	17	19	20	22
10	0	1	1	2	55	17	19	20	22
11	0	1	2	3	56	17	20	21	23
12	1	2	2	3	57	18	20	21	23
13	1	2	3	3	58	18	21	22	24
14	1	2	3	4	59	19	21	22	24
15	2	3	3	4	60	19	21	23	25
16	2	3	4	5	61	20	22	23	25
17	2	4	4	5	62	20	22	24	25
18	3	4	5	6	63	20	23	24	26
19	3	4	5	6	64	21	23	24	26
20	3	5	5	6	65	21	24	25	27
21	4	5	6	7	66	22	24	25	27
22	4	5	6	7	67	22	25	26	28
23	4	6	7	8	68	22	25	26	28
24	5	6	7	8	69	23	25	27	29
25	5	7	7	9	70	23	26	27	29
26	6	7	8	9	71	24	26	28	30
27	6	7	8	10	72	24	27	28	30
28	6	8	9	10	73	25	27	28	31
29	7	8	9	10	74	25	28	29	31
30	7	8	10	11	75	25	28	29	32
31	7	9	10	11	76	26	28	30	32
32	8	9	10	12	77	26	29	30	32
33	8	10	11	12	78	27	29	31	33
34	9	10	11	13	79	27	30	31	33
35	9	11	12	13	80	28	30	32	34
36	9	11	12	14	81	28	31	32	34
37	10	12	13	14	82	28	31	33	35
38	10	12	13	14	83	29	32	33	35
39	11	12	13	15	84	29	32	33	36
40	11	13	14	15	85	30	32	34	36
41	11	13	14	16	86	30	33	34	37
42	12	14	15	16	87	31	33	35	37
43	12	14	15	17	88	31	34	35	38
44	13	15	16	17	89	31	34	36	38
45	13	15	16	18	90	32	35	36	39

For values of n larger than 90, approximate values of r may be found by taking the nearest integer less than $(n - 1)/2 - k\sqrt{n + 1}$, where k is 1.2879, 0.9800, 0.8224, 0.5752 for the 1, 5, 10, 25% values, respectively.

From Bolz, R.E. and Tuve, G.L., Mathematical and statistical tables, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 935.

Factors for Computing Control Limits

A. Control Charts for Measurement

If the process mean and standard deviation, μ and σ, are known, and it is assumed that the underlying distribution is normal, it is possible to assert with probability 1 – α that the mean of a random sample of size n will fall between $\bar{x} - z_{\alpha/2}\frac{\sigma}{\sqrt{n}}$ and $\bar{x} + z_{\alpha/2}\frac{\sigma}{\sqrt{n}}$. These two limits on $\bar{x}$ provide upper and lower control limits. In actual practice μ and σ are usually unknown, and it is necessary to estimate their values from a large sample taken while the process is "in control." The central line of an $\bar{x}$ chart is given by μ, and the lower and upper three-sigma control limits are given by $\mu - A\sigma$ and $\mu + A\sigma$, respectively, where $A = \frac{3}{\sqrt{n}}$ and n is the sample size. Where the population parameters are unknown, it is necessary to estimate these parameters on the basis of preliminary samples. If k samples are used, each of size n, denote the mean of the ith sample by $\bar{x}_i$ and the grand mean of the k sample means by $\bar{\bar{x}}$, i.e.,

$$\bar{\bar{x}} = \frac{1}{k}\sum_{i=1}^{k}\bar{x}_i$$

Denote the range of the ith sample by R_i and by $\bar{R}$ the mean of the k sample ranges, i.e.,

$$\bar{R} = \frac{1}{k}\sum_{i=1}^{k}R_i$$

Since $\bar{x}$ is an unbiased estimate of the population mean μ, the central line for the $\bar{x}$ chart is given by $\bar{\bar{x}}$. The statistic R does not provide an unbiased estimate of σ, but $A_2\bar{R}$ is an unbiased estimate of $\frac{3\sigma}{\sqrt{n}}$. The constant multiplier A_2 depends on the assumption of normality. Thus, the central line and the lower and upper three-sigma limits, LCL and UCL, for an x chart (with μ and σ estimated from past data) are given by

$$\textit{central line} = \bar{\bar{x}}$$

$$LCL = \bar{\bar{x}} - A_2\bar{R}$$

$$UCL = \bar{\bar{x}} + A_2\bar{R}$$

The central line and control limits of an R chart are based on the distribution of the range of samples of size n from a normal population. The mean and standard deviation of the sampling distribution of R are given by $d_2\sigma$ and $d_3\sigma$, respectively, when σ is known. Here d_2 and d_3 are constants that depend on the size of the sample. The set of control-chart values for an R chart (with σ known) is given by

$$\textit{central line} = d_2\sigma$$

$$LCL = D_1\sigma$$

$$UCL = D_2\sigma$$

where $D_1 = d_2 - 3d_3$ and $D_2 = d_2 + 3d_3$.

If σ unknown, the control chart values for an R chart are given by

$$\textit{central line} = \bar{R}$$

$$LCL = D_3\bar{R}$$

$$UCL = D_4\bar{R}$$

where $D_3 = \frac{D_1}{d_2}$ and $D_4 = \frac{D_2}{d_2}$.

The central line and control limits of an s chart are based on estimates obtained from the samples. A pooled estimate of the population variance is obtained from the k samples, i.e., Factors for Computing Control Limits (continued)

$$s_p^2 = \frac{\sum_i (n_i - 1)s_i^2}{\sum_i (n_i - 1)}, \quad i = 1, 2, \ldots, k$$

If the sample sizes are all equal, the pooled estimate is

$$s_p^2 = \frac{1}{k}\sum_i s_i^2$$

The control chart values for an s chart are given by

$$\textit{central line} = C_2' s_p$$

$$LCL = B_2' s_p$$

$$UCL = B_4' s_p$$

If one uses the biased estimator of the variance s_p', as is often done in quality control work, the control chart values are given by

$$\textit{central line} = c_2 s_p'$$

$$LCL = B_2 s_p'$$

$$UCL = B_4 s_p'$$

B. Control Charts for Attributes

Control limits for a fraction-defective chart are based on the sampling theory for proportions, using the normal curve approximation to the binomial. If k samples are taken, the estimator of p is given by

$$\bar{p} = \frac{\sum_i x_i}{\sum_i n_i}, \quad i = 1, 2, \ldots, k$$

where x_i is the number of defectives in the ith sample of size n_i. The cenral line and control limits of a fraction-defective chart based on analysis of past data are given by

$$\textit{central line} = \bar{p}$$

$$LCL = \bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n_i}}$$

$$UCL = \bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n_i}}$$

When the sample sizes are approximately equal, n_i is replaced by $\bar{n} = \frac{1}{k}\sum_i n_i$.

Equivalent to the p chart for the fraction defective is the control chart for the number of defective. Here, if p is estimated by $\bar{p}$, the control-chart values for a number-of-defectives chart are given by

$$\textit{central line} = \bar{n}\,\bar{p}$$

$$LCL = \bar{n}\,\bar{p} - 3\sqrt{\bar{n}\,\bar{p}(1-\bar{p})}$$

$$UCL = \bar{n}\,\bar{p} + 3\sqrt{\bar{n}\,\bar{p}(1-\bar{p})}$$

Factors for Computing Control Limits (continued)

In many cases it is necessary to control the number of defects per unit C, where C is taken to be a value of a random variable having a Poisson distribution. If k is the number of units available for estimating λ, the parameter of the Poisson distribution, and if C_i is the number of defects in the ith unit, than λ is estimated by

$$\overline{C} = \frac{1}{k}\sum_{i=1}^{k} C_i$$

and the control-chart values for the C chart are

$$\text{central line} = \overline{C}$$

$$LCL = \overline{C} - 3\sqrt{\overline{C}}$$

$$UCL = \overline{C} + 3\sqrt{\overline{C}}$$

This table presents values of the factors for computing control limis for various sample sizes n.

	$\overline{X}$ Chart		R Chart			s Chart			σ Chart (biased)		
Number of Observations in Sample, n	Factors for Control Limits		Factor for Central Line	Factors for Control Limits		Factor for Central Line	Factors for Control Limits		Factor for Central Line	Factors for Control Limits	
	A	A_2	d_2	D_3	D_4	c'_2	B'_2	B'_4	c_2	B_2	B_4
2	2.121	1.880	1.128	0	3.267	0.798	0	2.298	0.5642	0	3.267
3	1.732	1.023	1.693	0	2.575	0.886	0	2.111	0.7236	0	2.568
4	1.500	0.729	2.059	0	2.282	0.921	0	1.982	0.7979	0	2.266
5	1.342	0.577	2.326	0	2.115	0.940	0	1.889	0.8407	0	2.089
6	1.225	0.483	2.534	0	2.004	0.951	0.085	1.817	0.8686	0.030	1.970
7	1.134	0.419	2.704	0.076	1.924	0.960	0.158	1.762	0.8882	0.118	1.882
8	1.061	0.373	2.847	0.136	1.864	0.965	0.215	1.715	0.9027	0.185	1.815
9	1.000	0.337	2.970	0.184	1.816	0.969	0.262	1.676	0.9139	0.239	1.761
10	0.949	0.308	3.078	0.223	1.777	0.973	0.302	1.644	0.9227	0.284	1.716
11	0.905	0.285	3.173	0.256	1.744	0.976	0.336	1.616	0.9300	0.321	1.679
12	0.866	0.266	3.258	0.284	1.716	0.977	0.365	1.589	0.9359	0.354	1.646
13	0.832	0.249	3.336	0.308	1.692	0.980	0.392	1.568	0.9410	0.382	1.618
14	0.802	0.235	3.407	0.329	1.671	0.981	0.414	1.548	0.9453	0.406	1.594
15	0.775	0.223	3.472	0.348	1.652	0.982	0.434	1.530	0.9490	0.428	1.572
16	0.750	0.212	3.532	0.364	1.636	0.984	0.454	1.514	0.9523	0.448	1.552
17	0.728	0.203	3.588	0.379	1.621	0.984	0.469	1.499	0.9551	0.466	1.534
18	0.707	0.194	3.640	0.392	1.608	0.986	0.486	1.486	0.9576	0.482	1.518
19	0.688	0.187	3.689	0.404	1.596	0.986	0.500	1.472	0.9599	0.497	1.503
20	0.671	0.180	3.735	0.414	1.586	0.987	0.513	1.461	0.9619	0.510	1.490
21	0.655	0.173	3.778	0.425	1.575	0.988	0.525	1.451	0.9638	0.523	1.477
22	0.640	0.167	3.819	0.434	1.566	0.988	0.536	1.440	0.9655	0.534	1.466
23	0.626	0.162	3.858	0.443	1.557	0.989	0.546	1.432	0.9670	0.545	1.455
24	0.612	0.157	3.895	0.452	1.548	0.989	0.556	1.422	0.9864	0.555	1.445
25	0.600	0.153	3.931	0.459	1.541	0.990	0.566	1.414	0.9696	0.565	1.435

From Bolz, R.E. and Tuve, G.L., Mathematical and statistical tables, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 935.

Number Systems and Change of Base

Positional Notation

In our ordinary system of writing numbers, the value of any digit depends on its position in the number. The value of a digit in any position is ten times the value of the same digit one position to the right, or one-tenth the value of the same digit one position to the left. For example,

$$173.246 = 1\times 10^2 + 7\times 10^1 + 3 + 2\times\frac{1}{10} + 4\times\frac{1}{10^2} + 6\times\frac{1}{10^3}$$

There is no reason that a number other than 10 cannot be used as the *base*, or *radix*, of the number system. In fact, bases of 2, 8, and 16 are commonly used in working with digital computers. When the base used is not clear from the context, it is usually indicated as a parenthesized subscript or merely as a subscript. Thus

$$743_{(8)} = 7\times 8^2 + 4\times 8 + 3 = 7\times 64 + 4\times 8 + 3 = 448 + 32 + 3 = 483_{(10)}$$

$$1011.101_{(2)} = 1\times 2^3 + 0\times 2^2 + 1\times 2 + 1 + 1\times\frac{1}{2} + 0\times\frac{1}{4} + 1\times\frac{1}{8} = 11.625_{(10)}$$

Change of Base

In this section it is assumed that all calculations will be performed in base 10, since this is the only base in which most people can easily compute. However, there is no logical reason that some other base could not be used for the computations.

To convert a number from another base into base 10:

Simply write down the digits of the number, with each one multiplied by its appropriate positional value. Then perform the indicated computations in base 10, and write down the answer.

To convert a number from base 10 into another base:

The part of the number to the left of the point and the part to the right must be operated on separately.

For the integer part (the part to the left of the point):

a. Divide the number by the new base, getting an integer quotient and remainder.
b. Write the remainder as the last digit of the number in the new base.
c. Using the quotient from the last division in place of the original number, repeat the above two steps until the quotient becomes zero.

For the fractional part (the part to the right of the point):

a. Multiply the number by the new base.
b. Write down the integral part of the product as the first digit of the fractional part in the new base.
c. Using the fractional part of the last product in place of the original number, repeat the above two steps until the product becomes an integer, or until the desired number of places have been computed.

Examples:

These examples show a convenient method of arranging the computations.

1. *Convert* $103.118_{(10)}$ *to base 8.*

8	103	7
8	12	4
	1	

.118
8
.944
8
7.552
8
4.416
8
3.328
8
2.624
8
4.992

147.074324…

The calculation of the fractional part could be carried out as far as desired. It is a non-terminating fraction that will eventually repeat itself.

$$103.118_{(10)} = 147.074324\ldots_{(8)}$$

The calculations may be further shortened by not writing the multiplier and divisor at each step of the algorithm, as shown in the next example.

Number Systems and Change of Base (continued)

2. *Convert 275.824$_{(10)}$ to base 5.*

5	275	0		.824
	55	0		4.120
	11	1		0.600
	2			3.000

$$275.824_{(10)} = 2100.403_{(5)}$$

To convert from one base to another (neither of which is 10):

The easiest procedure is usually to convert first to base 10, and then to the desired base. However, there are two exceptions to this:

1. If computational facility is possessed in either of the bases, it may be used instead of base 10, and the appropriate one of the above methods applied.
2. If the two bases are different powers of the same number, the conversion may be done digit-by-digit to the base that is the common root of both bases, and then digit-by-digit back to the other base.

Example: Convert 127.653$_{(8)}$ to base 16. (For base 16, the letters A–F are used for the digits 10$_{(10)}$–15$_{(10)}$.)

The first step is to convert the number to base 2, simply by converting each digit to its binary equivalent:

$$127.653_{(8)} = 001\ 010\ 111 \cdot 110\ 101\ 011_{(2)}$$

Now by simply regrouping the binary number into groups of four binary digits, starting at the point, we convert to base 16:

$$127.653_{(16)} = 101\ 0111 \cdot 1101\ 0101\ 1_{(2)} = 57.D58_{(16)}$$

From Bolz, R.E. and Tuve, G.L., Number systems and logic, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 949–950.

Binary, Octal, and Decimal Numbers

$10^{\pm n}$ IN OCTAL SCALE

10^n	n	10^{-n}	10^n	n	10^{-n}
1	0	1.000 000 000 000 000	112 402 762 000	10	0.000 000 000 006 676
12	1	0.063 146 314 631 463	1 351 035 564 000	11	0.000 000 000 000 537
144	2	0.005 075 341 217 270	16 432 451 210 000	12	0.000 000 000 000 043
1 750	3	0.000 406 111 564 570	221 441 634 520 000	13	0.000 000 000 000 003
23 420	4	0.000 032 155 613 530	2 657 142 036 440 000	14	0.000 000 000 000 000
303 240	5	0.000 002 476 132 610	34 327 724 461 500 000	15	0.000 000 000 000 000
3 641 100	6	0.000 000 206 157 364	434 157 115 760 200 000	16	0.000 000 000 000 000
46 113 200	7	0.000 000 015 327 745	5 432 127 413 542 400 000	17	0.000 000 000 000 000
575 360 400	8	0.000 000 001 257 143	67 405 553 164 731 000 000	18	0.000 000 000 000 000
7 346 545 000	9	0.000 000 000 104 560			

2^n IN DECIMAL SCALE

n	2^n	n	2^n	n	2^n
0.001	1.00069 33874 62581	0.01	1.00695 55500 56719	0.1	1.07177 34625 36293
0.002	1.00138 72557 11335	0.02	1.01395 94797 90029	0.2	1.14869 83549 97035
0.003	1.00208 16050 79633	0.03	1.02101 21257 07193	0.3	1.23114 44133 44916
0.004	1.00277 64359 01078	0.04	1.02811 38266 56067	0.4	1.31950 79107 72894
0.005	1.00347 17485 09503	0.05	1.03526 49238 41377	0.5	1.41421 35623 73095
0.006	1.00416 75432 38973	0.06	1.04246 57608 41121	0.6	1.51571 65665 10398
0.007	1.00486 38204 23785	0.07	1.04971 66836 23067	0.7	1.62450 47927 12471
0.008	1.00556 05803 98468	0.08	1.05701 80405 61380	0.8	1.74110 11265 92248
0.009	1.00625 78234 97782	0.09	1.06437 01824 53360	0.9	1.86606 59830 73615

$n \log_{10} 2$, $n \log_2 10$ IN DECIMAL SCALE

n	$n \log_{10} 2$	$n \log_2 10$	n	$n \log_{10} 2$	$n \log_2 10$
1	0.30102 99957	3.32192 80949	6	1.80617 99740	19.93156 85693
2	0.60205 99913	6.64385 61898	7	2.10720 99696	23.25349 66642
3	0.90308 99870	9.96578 42847	8	2.40823 99653	26.57542 47591
4	1.20411 99827	13.28771 23795	9	2.70926 99610	29.89735 28540
5	1.50514 99783	16.60964 04744	10	3.01029 99566	33.21928 09489

ADDITION AND MULTIPLICATION TABLES

Binary Scale

Addition	Multiplication
$0 + 0 = 0$	$0 \times 0 = 0$
$0 + 1 = 1 + 0 = 1$	$0 \times 1 = 1 \times 0 = 0$
$1 + 1 = 10$	$1 \times 1 = 1$

Octal Scale

Addition

0	01	02	03	04	05	06	07
1	02	03	04	05	06	07	10
2	03	04	05	06	07	10	11
3	04	05	06	07	10	11	12
4	05	06	07	10	11	12	13
5	06	07	10	11	12	13	14
6	07	10	11	12	13	14	15
7	10	11	12	13	14	15	16

Multiplication

1	02	03	04	05	06	07
2	04	06	10	12	14	16
3	06	11	14	17	22	25
4	10	14	20	24	30	34
5	12	17	24	31	36	43
6	14	22	30	36	44	52
7	16	25	34	43	52	61

Binary, Octal, and Decimal Numbers (continued)

MATHEMATICAL CONSTANTS IN OCTAL SCALE

$\pi =$	$(3.11037\ 555421)_{(8)}$	$e =$	$(2.55760\ 521305)_{(8)}$	$\gamma =$	$(0.44742\ 147707)_{(8)}$
$\pi^{-1} =$	$(0.24276\ 301556)_{(8)}$	$e^{-1} =$	$(0.27426\ 530661)_{(8)}$	$\log_e \gamma =$	$-(0.43127\ 233602)_{(8)}$
$\sqrt{\pi} =$	$(1.61337\ 611067)_{(8)}$	$\sqrt{e} =$	$(1.511411\ 230704)_{(8)}$	$\log_2 \gamma =$	$-(0.62573\ 030645)_{(8)}$
$\log_e \pi =$	$(1.11206\ 404435)_{(8)}$	$\log_{10} e =$	$(0.33626\ 754251)_{(8)}$	$\sqrt{2} =$	$(1.32404\ 746320)_{(8)}$
$\log_2 \pi =$	$(1.51544\ 163223)_{(8)}$	$\log_2 e =$	$(1.34252\ 166245)_{(8)}$	$\log_e 2 =$	$(0.54271\ 027760)_{(8)}$
$\sqrt{10} =$	$(3.12305\ 407267)_{(8)}$	$\log_2 10 =$	$(3.24464\ 741136)_{(8)}$	$\log_e 10 =$	$(2.23273\ 067355)_{(8)}$

From Bolz, R.E. and Tuve, G.L., Number systems and logic, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 951.

Octal-Decimal Integer Conversion

	0	1	2	3	4	5	6	7
0000	0000	0001	0002	0003	0004	0005	0006	0007
0010	0008	0009	0010	0011	0012	0013	0014	0015
0020	0016	0017	0018	0019	0020	0021	0022	0023
0030	0024	0025	0026	0027	0028	0029	0030	0031
0040	0032	0033	0034	0035	0036	0037	0038	0039
0050	0040	0041	0042	0043	0044	0045	0046	0047
0060	0048	0049	0050	0051	0052	0053	0054	0055
0070	0056	0057	0058	0059	0060	0061	0062	0063
1100	0064	0065	0066	0067	0068	0069	0070	0071
0110	0072	0073	0074	0075	0076	0077	0078	0079
0120	0080	0081	0082	0083	0084	0085	0086	0087
0130	0088	0089	0090	0091	0092	0093	0094	0095
0140	0096	0097	0098	0099	0100	0101	0102	0103
0150	0104	0105	0106	0107	0108	0109	0110	0111
0160	0112	0113	0114	0115	0116	0117	0118	0119
0170	0120	0121	0122	0123	0124	0125	0126	0127
0200	0128	0129	0130	0131	0132	0133	0134	0135
0210	0136	0137	0138	0139	0140	0141	0142	0143
0220	0144	0145	0146	0147	0148	0149	0150	0151
0230	0152	0153	0154	0155	0156	0157	0158	0159
0240	0160	0161	0162	0163	0164	0165	0166	0167
0250	0168	0169	0170	0171	0172	0173	0174	0175
0260	0176	0177	0178	0179	0180	0181	0182	0183
0270	0184	0185	0186	0187	0188	0189	0190	0191
0300	0192	0193	0194	0195	0196	0197	0198	0199
0310	0200	0201	0202	0203	0204	0205	0206	0207
0320	0208	0209	0210	0211	0212	0213	0214	0215
0330	0216	0217	0218	0219	0220	0221	0222	0223
0340	0224	0225	0226	0227	0228	0229	0230	0231
0350	0232	0233	0234	0235	0236	0237	0238	0239
0360	0240	0241	0242	0243	0244	0245	0246	0247
0370	0248	0249	0250	0251	0252	0253	0254	0255

	0	1	2	3	4	5	6	7
0400	0256	0257	0258	0259	0260	0261	0262	0263
0410	0264	0265	0266	0267	0268	0269	0270	0271
0420	0272	0273	0274	0275	0276	0277	0278	0279
0430	0280	0281	0282	0283	0284	0285	0286	0287
0440	0288	0289	0290	0291	0292	0293	0294	0295
0450	0296	0297	0298	0299	0300	0301	0302	0303
0460	0304	0305	0306	0307	0308	0309	0310	0311
0470	0312	0313	0314	0315	0316	0317	0318	0319
0500	0320	0321	0322	0323	0324	0325	0326	0327
0510	0328	0329	0330	0331	0332	0333	0334	0335
0520	0336	0337	0338	0339	0340	0341	0342	0343
0530	0344	0345	0346	0347	0348	0349	0350	0351
0540	0352	0353	0354	0355	0356	0357	0358	0359
0550	0360	0361	0362	0363	0364	0365	0366	0367
0560	0368	0369	0370	0371	0372	0373	0374	0375
0570	0376	0377	0378	0379	0380	0381	0382	0383
0600	0384	0385	0386	0387	0388	0389	0390	0391
0610	0392	0393	0394	0395	0396	0397	0398	0399
0620	0400	0401	0402	0403	0404	0405	0406	0407
0630	0408	0409	0410	0411	0412	0413	0414	0415
0640	0416	0417	0418	0419	0420	0421	0422	0423
0650	0424	0425	0426	0427	0428	0429	0430	0431
0660	0432	0433	0434	0435	0436	0437	0438	0439
0670	0440	0441	0442	0443	0444	0445	0446	0447
0700	0448	0449	0450	0451	0452	0453	0454	0455
0710	0456	0457	0458	0459	0460	0461	0462	0463
0720	0464	0465	0466	0467	0468	0469	0470	0471
0730	0472	0473	0474	0475	0476	0477	0478	0479
0740	0480	0481	0482	0483	0484	0485	0486	0487
0750	0488	0489	0490	0491	0492	0493	0494	0495
0760	0496	0497	0498	0499	0500	0501	0502	0503
0770	0504	0505	0506	0507	0508	0509	0510	0511

0000 to 0777 (Octal) — 0000 to 0511 (Decimal)

Octal	Decimal
10000-	4096
20000-	8192
30000-	12288
40000-	16384
50000-	20480
60000-	24576
70000-	28672

	0	1	2	3	4	5	6	7
1000	0512	0513	0514	0515	0516	0517	0518	0519
1010	0520	0521	0522	0523	0524	0525	0526	0527
1020	0528	0529	0530	0531	0532	0533	0534	0535
1030	0536	0537	0538	0539	0540	0541	0542	0543
1040	0544	0545	0546	0547	0548	0549	0550	0551
1050	0552	0553	0554	0555	0556	0557	0558	0559
1060	0560	0561	0562	0563	0564	0565	0566	0567
1070	0568	0569	0570	0571	0572	0573	0574	0575
1100	0576	0577	0578	0579	0580	0581	0582	0583
1110	0584	0585	0586	0587	0588	0589	0590	0591
1120	0592	0593	0594	0595	0596	0597	0598	0599
1130	0600	0601	0602	0603	0604	0605	0606	0607
1140	0608	0609	0610	0611	0612	0613	0614	0615
1150	0616	0617	0618	0619	0620	0621	0622	0623
1160	0624	0625	0626	0627	0628	0629	0630	0631
1170	0632	0633	0634	0635	0636	0637	0638	0639
1200	0640	0641	0642	0643	0644	0645	0646	0647
1210	0648	0649	0650	0651	0652	0653	0654	0655
1220	0656	0657	0658	0659	0660	0661	0662	0663
1230	0664	0665	0666	0667	0668	0669	0670	0671
1240	0672	0673	0674	0675	0676	0677	0678	0679
1250	0680	0681	0682	0683	0684	0685	0686	0687
1260	0688	0689	0690	0691	0692	0693	0694	0695
1270	0696	0697	0698	0699	0700	0701	0702	0703
1300	0704	0705	0706	0707	0708	0709	0710	0711
1310	0712	0713	0714	0715	0716	0717	0718	0719
1320	0720	0721	0722	0723	0724	0725	0726	0727
1330	0728	0729	0730	0731	0732	0733	0734	0735

	0	1	2	3	4	5	6	7
1400	0768	0769	0770	0771	0772	0773	0774	0775
1410	0776	0777	0778	0779	0780	0781	0782	0783
1420	0784	0785	0786	0787	0788	0789	0790	0791
1430	0792	0793	0794	0795	0796	0797	0798	0799
1440	0800	0801	0802	0803	0804	0805	0806	0807
1450	0808	0809	0810	0811	0812	0813	0814	0815
1460	0816	0817	0818	0819	0820	0821	0822	0823
1470	0824	0825	0826	0827	0828	0829	0830	0831
1500	0832	0833	0834	0835	0836	0837	0838	0839
1510	0840	0841	0842	0843	0844	0845	0846	0847
1520	0848	0849	0850	0851	0852	0853	0854	0855
1530	0856	0857	0858	0859	0860	0861	0862	0863
1540	0864	0865	0866	0867	0868	0869	0870	0871
1550	0872	0873	0874	0875	0876	0877	0878	0879
1560	0880	0881	0882	0883	0884	0885	0886	0887
1570	0888	0889	0890	0891	0892	0893	0894	0895
1600	0896	0897	0898	0899	0900	0901	0902	0903
1610	0904	0905	0906	0907	0908	0909	0910	0911
1620	0912	0913	0914	0915	0916	0917	0918	0919
1630	0920	0921	0922	0923	0924	0925	0926	0927
1640	0928	0929	0930	0931	0932	0933	0934	0935
1650	0936	0937	0938	0939	0940	0941	0942	0943
1660	0944	0945	0946	0947	0948	0949	0950	0951
1670	0952	0953	0954	0955	0956	0957	0958	0959
1700	0960	0961	0962	0963	0964	0965	0966	0967
1710	0968	0969	0970	0971	0972	0973	0974	0975
1720	0976	0977	0978	0979	0980	0981	0982	0983
1730	0984	0985	0986	0987	0988	0989	0990	0991

1000 to 1777 (Octal) — 0512 to 1023 (Decimal)

Octal-Decimal Integer Conversion (continued)

1340	0736	0737	0738	0739	0740	0741	0742	0743	1740	0992	0993	0994	0995	0996	0997	0998	0999
1350	0744	0745	0746	0747	0748	0749	0750	0751	1750	1000	1001	1002	1003	1004	1005	1006	1007
1360	0752	0753	0754	0755	0756	0757	0758	0759	1760	1008	1009	1010	1011	1012	1013	1014	1015
1370	0760	0761	0762	0763	0764	0765	0766	0767	1770	1016	1017	1018	1019	1020	1021	1022	1023

2000 to 2777 (Octal) — 1024 to 1535 (Decimal)

Octal	Decimal
10000-	4096
20000-	8192
30000-	12288
40000-	16384
50000-	20480
60000-	24576
70000-	28672

	0	1	2	3	4	5	6	7		0	1	2	3	4	5	6	7
2000	1024	1025	1026	1027	1028	1029	1030	1031	2400	1280	1281	1282	1283	1284	1285	1286	1287
2010	1032	1033	1034	1035	1036	1037	1038	1039	2410	1288	1289	1290	1291	1292	1293	1294	1295
2020	1040	1041	1042	1043	1044	1045	1046	1047	2420	1296	1297	1298	1299	1300	1301	1302	1303
2030	1048	1049	1050	1051	1052	1053	1054	1055	2430	1304	1305	1306	1307	1308	1309	1310	1311
2040	1056	1057	1058	1059	1060	1061	1062	1063	2440	1312	1313	1314	1315	1316	1317	1318	1319
2050	1064	1065	1066	1067	1068	1069	1070	1071	2450	1320	1321	1322	1323	1324	1325	1326	1327
2060	1072	1073	1074	1075	1076	1077	1078	1079	2460	1328	1329	1330	1331	1332	1333	1334	1335
2070	1080	1081	1082	1083	1084	1085	1086	1087	2470	1336	1337	1338	1339	1340	1341	1342	1343
2100	1088	1089	1090	1091	1092	1093	1094	1095	2500	1344	1345	1346	1347	1348	1349	1350	1351
2110	1096	1097	1098	1099	1100	1101	1102	1103	2510	1352	1353	1354	1355	1356	1357	1358	1359
2120	1104	1105	1106	1107	1108	1109	1110	1111	2520	1360	1361	1362	1363	1364	1365	1366	1367
2130	1112	1113	1114	1115	1116	1117	1118	1119	2530	1368	1369	1370	1371	1372	1373	1374	1375
2140	1120	1121	1122	1123	1124	1125	1126	1127	2540	1376	1377	1378	1379	1380	1381	1382	1383
2150	1128	1129	1130	1131	1132	1133	1134	1135	2550	1384	1385	1386	1387	1388	1389	1390	1391
2160	1136	1137	1138	1139	1140	1141	1142	1143	2560	1392	1393	1394	1395	1396	1397	1398	1399
2170	1144	1145	1146	1147	1148	1149	1150	1151	2570	1400	1401	1402	1403	1404	1405	1406	1407
2200	1152	1153	1154	1155	1156	1157	1158	1159	2600	1408	1409	1410	1411	1412	1413	1414	1415
2210	1160	1161	1162	1163	1164	1165	1166	1167	2610	1416	1417	1418	1419	1420	1421	1422	1423
2220	1168	1169	1170	1171	1172	1173	1174	1175	2620	1424	1425	1426	1427	1428	1429	1430	1431
2230	1176	1177	1178	1179	1180	1181	1182	1183	2630	1432	1433	1434	1435	1436	1437	1438	1439
2240	1184	1185	1186	1187	1188	1189	1190	1191	2640	1440	1441	1442	1443	1444	1445	1446	1447
2250	1192	1193	1194	1195	1196	1197	1198	1199	2650	1448	1449	1450	1451	1452	1453	1454	1455
2260	1200	1201	1202	1203	1204	1205	1206	1207	2660	1456	1457	1458	1459	1460	1461	1462	1463
2270	1208	1209	1210	1211	1212	1213	1214	1215	2670	1464	1465	1466	1467	1468	1469	1470	1471
2300	1216	1217	1218	1219	1220	1221	1222	1223	2700	1472	1473	1474	1475	1476	1477	1478	1479
2310	1224	1225	1226	1227	1228	1229	1230	1231	2710	1480	1481	1482	1483	1484	1485	1486	1487
2320	1232	1233	1234	1235	1236	1237	1238	1239	2720	1488	1489	1490	1491	1492	1493	1494	1495
2330	1240	1241	1242	1243	1244	1245	1246	1247	2730	1496	1497	1498	1499	1500	1501	1502	1503
2340	1248	1249	1250	1251	1252	1253	1254	1255	2740	1504	1505	1506	1507	1508	1509	1510	1511
2350	1256	1257	1258	1259	1260	1261	1262	1263	2750	1512	1513	1514	1515	1516	1517	1518	1519
2360	1264	1265	1266	1267	1268	1269	1270	1271	2760	1520	1521	1522	1523	1524	1525	1526	1527
2370	1272	1273	1274	1275	1276	1277	1278	1279	2770	1528	1529	1530	1531	1532	1533	1534	1535

3000 to 3777 (Octal) — 1536 to 2047 (Decimal)

	0	1	2	3	4	5	6	7		0	1	2	3	4	5	6	7
3000	1536	1537	1538	1539	1540	1541	1542	1543	3400	1792	1793	1794	1795	1796	1797	1798	1799
3010	1544	1545	1546	1547	1548	1549	1550	1551	3410	1800	1801	1802	1803	1804	1805	1806	1807
3020	1552	1553	1554	1555	1556	1557	1558	1559	3420	1808	1809	1810	1811	1812	1813	1814	1815
3030	1560	1561	1562	1563	1564	1565	1566	1567	3430	1816	1817	1818	1819	1820	1821	1822	1823
3040	1568	1569	1570	1571	1572	1573	1574	1575	3440	1824	1825	1826	1827	1828	1829	1830	1831
3050	1576	1577	1578	1579	1580	1581	1582	1583	3450	1832	1833	1834	1835	1836	1837	1838	1839
3060	1584	1585	1586	1587	1588	1589	1590	1591	3460	1840	1841	1842	1843	1844	1845	1846	1847
3070	1592	1593	1594	1595	1596	1597	1598	1599	3470	1848	1849	1850	1851	1852	1853	1854	1855
3100	1600	1601	1602	1603	1604	1605	1606	1607	3500	1856	1857	1858	1859	1860	1861	1862	1863
3110	1608	1609	1610	1611	1612	1613	1614	1615	3510	1864	1865	1866	1867	1868	1869	1870	1871
3120	1616	1617	1618	1619	1620	1621	1622	1623	3520	1872	1873	1874	1875	1876	1877	1878	1879
3130	1624	1625	1626	1627	1628	1629	1630	1631	3530	1880	1881	1882	1883	1884	1885	1886	1887
3140	1632	1633	1634	1635	1636	1637	1638	1639	3540	1888	1889	1890	1891	1892	1893	1894	1895
3150	1640	1641	1642	1643	1644	1645	1646	1647	3550	1896	1897	1898	1899	1900	1901	1902	1903
3160	1648	1649	1650	1651	1652	1653	1654	1655	3560	1904	1905	1906	1907	1908	1909	1910	1911
3170	1656	1657	1658	1659	1660	1661	1662	1663	3570	1912	1913	1914	1915	1916	1917	1918	1919
3200	1664	1665	1666	1667	1668	1669	1670	1671	3600	1920	1921	1922	1923	1924	1925	1926	1927
3210	1672	1673	1674	1675	1676	1677	1678	1679	3610	1928	1929	1930	1931	1932	1933	1934	1935
3220	1680	1681	1682	1683	1684	1685	1686	1687	3620	1936	1937	1938	1939	1940	1941	1942	1943
3230	1688	1689	1690	1691	1692	1693	1694	1695	3630	1944	1945	1946	1947	1948	1949	1950	1951
3240	1696	1697	1698	1699	1700	1701	1702	1703	3640	1952	1953	1954	1955	1956	1957	1958	1959
3250	1704	1705	1706	1707	1708	1709	1710	1711	3650	1960	1961	1962	1963	1964	1965	1966	1967
3260	1712	1713	1714	1715	1716	1717	1718	1719	3660	1968	1969	1970	1971	1972	1973	1974	1975
3270	1720	1721	1722	1723	1724	1725	1726	1727	3670	1976	1977	1978	1979	1980	1981	1982	1983
3300	1728	1729	1730	1731	1732	1733	1734	1735	3700	1984	1985	1986	1987	1988	1989	1990	1991

Octal-Decimal Integer Conversion (continued)

3310	1736	1737	1738	1739	1740	1741	1742	1743	3710	1992	1993	1994	1995	1996	1997	1998	1999
3320	1744	1745	1746	1747	1748	1749	1750	1751	3720	2000	2001	2002	2003	2004	2005	2006	2007
3330	1752	1753	1754	1755	1756	1757	1758	1759	3730	2008	2009	2010	2011	2012	2013	2014	2015
3340	1760	1761	1762	1763	1764	1765	1766	1767	3740	2016	2017	2018	2019	2020	2021	2022	2023
3350	1768	1769	1770	1771	1772	1773	1774	1775	3750	2024	2025	2026	2027	2028	2029	2030	2031
3360	1776	1777	1778	1779	1780	1781	1782	1783	3760	2032	2033	2034	2035	2036	2037	2038	2039
3370	1784	1785	1786	1787	1788	1789	1790	1791	3770	2040	2041	2042	2043	2044	2045	2046	2047

	0	1	2	3	4	5	6	7		0	1	2	3	4	5	6	7
4000	2048	2049	2050	2051	2052	2053	2054	2055	4400	2304	2305	2306	2307	2308	2309	2310	2311
4010	2056	2057	2058	2059	2060	2061	2062	2063	4410	2312	2313	2314	2315	2316	2317	2318	2319
4020	2064	2065	2066	2067	2068	2069	2070	2071	4420	2320	2321	2322	2323	2324	2325	2326	2327
4030	2072	2073	2074	2075	2076	2077	2078	2079	4430	2328	2329	2330	2331	2332	2333	2334	2335
4040	2080	2081	2082	2083	2084	2085	2086	2087	4440	2336	2337	2338	2339	2340	2341	2343	2343
4050	2088	2089	2090	2091	2092	2093	2094	2095	4450	2344	2345	2346	2347	2348	2349	2350	2351
4060	2096	2097	2098	2099	2100	2101	2102	2103	4460	2352	2353	2354	2355	2356	2357	2358	2359
4070	2104	2105	2106	2107	2108	2109	2110	2111	4470	2360	2361	2362	2363	2364	2365	2366	2367
4100	2112	2113	2114	2115	2116	2117	2118	2119	4500	2368	2369	2370	2371	2372	2373	2374	2375
4110	2120	2121	2122	2123	2124	2125	2126	2127	4510	2376	2377	2378	2379	2380	2381	2382	2383
4120	2128	2129	2130	2131	2132	2133	2134	2135	4520	2384	2385	2386	2387	2388	2389	2390	2391
4130	2136	2137	2138	2139	2140	2141	2142	2143	4530	2392	2393	2394	2395	2396	2397	2398	2399
4140	2144	2145	2146	2147	2148	2149	2150	2151	4540	2400	2401	2402	2403	2404	2405	2406	2407
4150	2152	2153	2154	2155	2156	2157	2158	2159	4550	2408	2409	2410	2411	2412	2413	2414	2415
4160	2160	2161	2162	2163	2164	2165	2166	2167	4560	2416	2417	2418	2419	2420	2421	2422	2423
4170	2168	2169	2170	2171	2172	2173	2174	2175	4570	2424	2425	2426	2427	2428	2429	2430	2431
4200	2176	2177	2178	2179	2180	2181	2182	2183	4600	2432	2433	2434	2435	2436	2437	2438	2439
4210	2184	2185	2186	2187	2188	2189	2190	2191	4610	2440	2441	2442	2443	2444	2445	2446	2447
4220	2192	2193	2194	2195	2196	2197	2198	2199	4620	2448	2449	2450	2451	2452	2453	2454	2455
4230	2200	2201	2202	2203	2204	2205	2206	2207	4630	2456	2457	2458	2459	2460	2461	2462	2463
4240	2208	2209	2210	2211	2212	2213	2214	2215	4640	2464	2465	2466	2467	2468	2469	2470	2471
4250	2216	2217	2218	2219	2220	2221	2222	2223	4650	2472	2473	2474	2475	2476	2477	2478	2479
4260	2224	2225	2226	2227	2228	2229	2230	2231	4660	2480	2481	2482	2483	2484	2485	2486	2487
4270	2232	2233	2234	2235	2236	2237	2238	2239	4670	2488	2489	2490	2491	2492	2493	2494	2495
4300	2240	2241	2242	2243	2244	2245	2246	2247	4700	2496	2497	2498	2499	2500	2501	2502	2503
4310	2248	2249	2250	2251	2252	2253	2254	2255	4710	2504	2505	2506	2507	2508	2509	2510	2511
4320	2256	2257	2258	2259	2260	2261	2262	2263	4720	2512	2513	2514	2515	2516	2517	2518	2519
4330	2264	2265	2266	2267	2268	2269	2270	2271	4730	2520	2521	2522	2523	2524	2525	2526	2527
4340	2272	2273	2274	2275	2276	2277	2278	2279	4740	2528	2529	2530	2531	2532	2533	2534	2535
4350	2280	2281	2282	2283	2284	2285	2286	2287	4750	2536	2537	2538	2539	2540	2541	2542	2543
4360	2288	2289	2290	2291	2292	2293	2294	2295	4760	2544	2545	2546	2547	2548	2549	2550	2551
4370	2296	2297	2298	2299	2300	2301	2302	2303	4770	2552	2553	2554	2555	2556	2557	2558	2559

4000 to 4777 (Octal) — 2048 to 2559 (Decimal)

Octal	Decimal
10000-	4096
20000-	8192
30000-	12288
40000-	16384
50000-	20480
60000-	24576
70000-	28672

	0	1	2	3	4	5	6	7		0	1	2	3	4	5	6	7
5000	2560	2561	2562	2563	2564	2565	2566	2567	5400	2816	2817	2818	2819	2820	2821	2822	2823
5010	2568	2569	2570	2571	2572	2572	2574	2575	5410	2824	2825	2826	2827	2828	2829	2830	2831
5020	2576	2577	2578	2579	2580	2581	2582	2583	5420	2832	2833	2834	2835	2836	2837	2838	2839
5030	2584	2585	2586	2587	2588	2589	2590	2591	5430	2840	2841	2842	2843	2844	2845	2846	2847
5040	2592	2593	2594	2595	2596	2597	2598	2599	5440	2848	2849	2850	2851	2852	2853	2854	2855
5050	2600	2601	2602	2603	2604	2605	2606	2607	5450	2856	2857	2858	2859	2860	2861	2862	2863
5060	2608	2609	2610	2611	2612	2613	2614	2615	5460	2864	2865	2866	2867	2868	2869	2870	2871
5070	2616	2617	2618	2619	2620	2621	2622	2623	5470	2872	2873	2874	2875	2876	2877	2878	2879
5100	2624	2625	2626	2627	2628	2629	2630	2631	5500	2880	2881	2882	2883	2884	2885	2886	2887
5110	2632	2633	2634	2635	2636	2637	2638	2639	5510	2888	2889	2890	2891	2892	2893	2894	2895
5120	2640	2641	2642	2643	2644	2645	2646	2647	5520	2896	2897	2898	2899	2900	2901	2902	2903
5130	2648	2649	2650	2651	2652	2653	2654	2655	5530	2904	2905	2906	2907	2908	2909	2910	2911
5140	2656	2657	2658	2659	2660	2661	2662	2663	5540	2912	2913	2914	2915	296	2917	2918	2919
5150	2664	2665	2666	2667	2668	2669	2670	2671	5550	2920	2921	2922	2923	2924	2925	2926	2927
5160	2672	2673	2674	2675	2676	2677	2678	2679	5560	2928	2929	2930	2931	2932	2933	2934	2935
5170	2680	2681	2682	2683	2684	2685	2686	2687	5570	2936	2937	2938	2939	2940	2941	2942	2943
5200	2688	2689	2690	2691	2692	2693	2694	2695	5600	2944	2945	2946	2947	2948	2949	2950	2951
5210	2696	2697	2698	2699	2700	2701	2702	2703	5610	2952	2953	2954	2955	2956	2957	2958	2959
5220	2704	2705	2706	2707	2708	2709	2710	2711	5620	2960	2961	2962	2963	2964	2965	2966	2967
5230	2712	2713	2714	2715	2716	2717	2718	2719	5630	2968	2969	2970	2971	2972	2973	2974	2975
5240	2720	2721	2722	2723	2724	2725	2726	2727	5640	2976	2977	2978	2979	2980	2981	2982	2983

5000 to 5777 (Octal) — 2560 to 3071 (Decimal)

Octal-Decimal Integer Conversion (continued)

5250	2728	2729	2730	2731	2732	2733	2734	2735	5650	2984	2985	2986	2987	2988	2989	2990	2991
5260	2736	2737	2738	2739	2740	2741	2742	2743	5660	2992	2993	2994	2995	2996	2997	2998	2999
5270	2744	2745	2746	2747	2748	2749	2750	2751	5670	3000	3001	3002	3003	3004	3005	3006	3007
5300	2752	2753	2754	2755	2756	2757	2758	2759	5700	3008	3009	3010	3011	3012	3013	3014	3015
5310	2760	2761	2762	2763	2764	2765	2766	2767	5710	3016	3017	3018	3019	3020	3021	3022	3023
5320	2768	2769	2770	2771	2772	2773	2774	2775	5720	3024	3025	3026	3027	3028	3029	3030	3031
5330	2776	2777	2778	2779	2780	2781	2782	2783	5730	3032	3033	3034	3035	3036	3037	3038	3039
5340	2784	2785	2786	2787	2788	2789	2790	2791	5740	3040	3041	3042	3043	3044	3045	3046	3047
5350	2792	2793	2794	2795	2796	2797	2798	2799	5750	3048	3049	3050	3051	3052	3053	3054	3055
5360	2800	2801	2802	2803	2804	2805	2806	2807	5760	3056	3057	3058	3059	3060	3061	3062	3063
5370	2808	2809	2810	2811	2812	2813	2814	2815	5770	3064	3065	3066	3067	3068	3069	3070	3071

6000 to 6777 (Octal) 3072 to 3583 (Decimal)

Octal	Decimal
10000-	4096
20000-	8192
30000-	12288
40000-	16384
50000-	20480
60000-	24576
70000-	28672

	0	1	2	3	4	5	6	7		0	1	2	3	4	5	6	7
6000	3072	3073	3074	3075	3076	3077	3078	3079	6400	3328	3329	3330	3331	3332	3333	3334	3335
6010	3080	3081	3082	3083	3084	3085	3086	3087	6410	3336	3337	3338	3339	3340	3341	3342	3343
6020	3088	3089	3090	3091	3092	3093	3094	3095	6420	3344	3345	3346	3347	3348	3349	3350	3351
6030	3096	3097	3098	3099	3100	3101	3102	3103	6430	3352	3353	3354	3355	3356	3357	3358	3359
6040	3104	3105	3106	3107	3108	3109	3110	3111	6440	3360	3361	3362	3363	3364	3365	3366	3367
6050	3112	3113	3114	3115	3116	3117	3118	3119	6450	3368	3369	3370	3371	3372	3373	3374	3375
6060	3120	3121	3122	3123	3124	3125	3126	3127	6460	3376	3377	3378	3379	3380	3381	3382	3383
6070	3128	3129	3139	3131	3132	3133	3134	3135	6470	3384	3385	3386	3387	3388	3389	3390	3391
6100	3136	3137	3138	3139	3140	3141	3142	3143	6500	3392	3393	3394	3395	3396	3397	3398	3399
6110	3144	3145	3146	3147	3148	3149	3150	3151	6510	3400	3401	3402	3403	3404	3405	3406	3407
6120	3152	3153	3154	3155	3156	3157	3158	3159	6520	3408	3409	3410	3411	3412	3413	3414	3415
6130	3160	3161	3162	3163	3164	3165	3166	3167	6530	3416	3417	3418	3419	3420	3421	3422	3423
6140	3168	3169	3170	3171	3172	3173	3174	3175	6540	3424	3425	3426	3427	3428	3429	3430	3431
6150	3176	3177	3178	3179	3180	3181	3182	3183	6550	3432	3433	3434	3435	3436	3437	3438	3439
6160	3184	3185	3186	3187	3188	3189	3190	3191	6560	3440	3441	3442	3443	3444	3445	3446	3447
6170	3192	3193	3194	3195	3196	3197	3198	3199	6570	3448	3449	3450	3451	3452	3453	3454	3455
6200	3200	3201	3202	3203	3204	3205	3206	3207	6600	3456	3457	3458	3459	3460	3461	3462	3463
6210	3208	3209	3210	3211	3212	3213	3214	3215	6610	3464	3465	3466	3467	3468	3469	3470	3471
6220	3216	3217	3218	3219	3220	3221	3222	3223	6620	3472	3473	3474	3475	3476	3477	3478	3479
6230	3224	3225	3226	3227	3228	3229	3230	3231	6630	3480	3481	3482	3483	3484	3485	3486	3487
6240	3232	3233	3234	3235	3236	3237	3238	3239	6640	3488	3489	3490	3491	3492	3493	3494	3495
6250	3240	3241	3242	3243	3244	3245	3246	3247	6650	3496	3497	3498	3499	3500	3501	3502	3503
6260	3248	3249	3250	3251	3252	3253	3254	3255	6660	3504	3505	3506	3507	3508	3509	3510	3511
6270	3256	3267	3258	3259	3260	3261	3262	3263	6670	3512	3513	3514	3515	3516	3517	3518	3519
6300	3264	3265	3266	3267	3268	3269	3270	3271	6700	3520	3521	3522	3523	3524	3525	3526	3527
6310	3272	3273	3274	3275	3276	3277	3278	3279	6710	3528	3529	3530	3531	3532	3533	3534	3535
6320	3280	3281	3282	3283	3284	3285	3286	3287	6720	3536	3537	3538	3539	3540	3541	3542	3543
6330	3288	3289	3290	3291	3292	3293	3294	3295	6730	3544	3545	3546	3547	3548	3549	3550	3551
6340	3296	3297	3298	3299	3300	3301	3302	3303	6740	3552	3553	3554	3555	3556	3557	3558	3559
6350	3304	3305	3306	3307	3308	3309	3310	3311	6750	3560	3561	3562	3563	3564	3565	3566	3567
6360	3312	3313	3314	3315	3316	3317	3318	3319	6760	3568	3569	3570	3571	3572	3573	3574	3575
6370	3320	3321	3322	3323	3324	3325	3326	3327	6770	3576	3577	3578	3579	3580	3581	3582	3583

7000 to 7777 (Octal) 3584 to 4095 (Decimal)

	0	1	2	3	4	5	6	7		0	1	2	3	4	5	6	7
7000	3584	3585	3586	3587	3588	3589	3590	3591	7400	3840	3841	3842	3843	3844	3845	3846	3847
7010	3592	3593	3594	3595	3596	3597	3598	3599	7410	3848	3849	3850	3851	3852	3853	3854	3855
7020	3600	3601	3602	3603	3604	3605	3606	3607	7420	3856	3857	3858	3859	3860	3861	3862	3863
7030	3608	3609	3610	3611	3612	3613	3614	3615	7430	3864	3865	3866	3867	3868	3869	3870	3871
7040	3616	3617	3618	3619	3620	3621	3622	3623	7440	3872	3873	3874	3875	3876	3877	3878	3879
7050	3624	3625	3626	3627	3628	3629	3630	3631	7450	3880	3881	3882	3883	3884	3885	3886	3887
7060	3632	3633	3634	3635	3636	3637	3638	3639	7460	3888	3889	3890	3891	3892	3893	3894	3895
7070	3640	3641	3642	3643	3644	3645	3646	3647	7470	3896	3897	3898	3899	3900	3901	3902	3903
7100	3648	3649	3650	3651	3652	3653	3654	3655	7500	3904	3905	3906	3907	3908	3909	3910	3911
7110	3656	3657	3658	3659	3660	3661	3662	3663	7510	3912	3913	3914	3915	3916	3917	3918	3919
7120	3664	3665	3666	3667	3668	3669	3670	3671	7520	3920	3921	3922	3923	3924	3925	3926	3927
7130	3672	3673	3674	3675	3676	3677	3678	3679	7530	3928	3929	3930	3931	3932	3933	3934	3935
7140	3680	3681	3682	3683	3684	3685	3686	3687	7540	3936	3937	3938	3939	3940	3941	3942	3943
7150	3688	3689	3690	3691	3692	3693	3694	3695	7550	3944	3945	3946	3947	3948	3949	3950	3951
7160	3696	3697	3698	3699	3700	3701	3702	3703	7560	3952	3953	3954	3955	3956	3957	3958	3959
7170	3704	3705	3706	3707	3708	3709	3710	3711	7570	3960	3961	3962	3963	3964	3965	3966	3967

Octal-Decimal Integer Conversion (continued)

7200	3712	3713	3714	3715	3716	3717	3718	3719	7600	3968	3969	3970	3971	3972	3973	3974	3975
7210	3720	3721	3722	3723	3724	3725	3726	3727	7610	3976	3977	3978	3979	3980	3981	3982	3983
7220	3728	3729	3730	3731	3732	3733	3734	3735	7620	3984	3985	3986	3987	3988	3989	3990	3991
7230	3736	3737	3738	3739	3740	3741	3742	3743	7630	3992	3993	3994	3995	3996	3997	3998	3999
7240	3744	3745	3746	3747	3748	3749	3750	3751	7640	4000	4001	4002	4003	4004	4005	4006	4007
7250	3752	3753	3754	3755	3756	3757	3758	3759	7650	4008	4009	4010	4011	4012	4013	4014	4015
7260	3760	3761	3762	3763	3764	3765	3766	3767	7660	4016	4017	4018	4019	4020	4021	4022	4023
7270	3768	3769	3770	3771	3772	3773	3774	3775	7670	4024	4025	4026	4027	4028	4029	4030	4031
7300	3776	3777	3778	3779	3780	3781	3782	3783	7700	4032	4033	4034	4035	4036	4037	4038	4039
7310	3784	3785	3786	3787	3788	3789	3790	3791	7710	4040	4041	4042	4043	4044	4045	4046	4047
7320	3792	3793	3794	3795	3796	3797	3798	3799	7720	4048	4049	4050	4051	4052	4053	4054	4055
7330	3800	3801	3802	3803	3804	3805	3806	3807	7730	4056	4057	4058	4059	4060	4061	4062	4063
7340	3808	3809	3810	3811	3812	3813	3814	3815	7740	4064	4065	4066	4067	4068	4069	4070	4071
7350	3816	3817	3818	3819	3820	3821	3822	3823	7750	4072	4073	4074	4075	4076	4077	4078	4079
7360	3824	3825	3826	3827	3828	3829	3830	3831	7760	4080	4081	4082	4083	4084	4085	4086	4087
7360	3832	3833	3834	3835	3836	3837	3838	3839	7770	4088	4089	4090	4091	4092	4093	4094	4095

From Bolz, R.E. and Tuve, G.L., Number systems and logic, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 952–955.

Boolean Theorems

$A + 0 = A$	$\overline{AB} = \overline{A} + \overline{B}$
$A \cdot 1 = A$	$(A + B) + C = A + (B + C)$
$A + A = A$	$(AB)C = A(BC)$
$A \cdot A = A$	$A + \overline{A}B = A + B$
$A + 1 = 1$	$A(\overline{A} + B) = AB$
$A \cdot 0 = 0$	$(A + B)(\overline{A} + C) = AC + \overline{A}B$
$A + AB = A$	$(\overline{AC + BC}) = \overline{A}C + \overline{B}\,\overline{C}$
$\overline{\overline{A}} = A$	$(A + C)(B + \overline{C}) = (\overline{A} + C)(\overline{B} + \overline{C})$
$\overline{A + B} = \overline{A}\,\overline{B}$	

EXPLANATION:

These Boolean theorems (sometimes called switching theorems) are used in problems involving binary states. The two states may be considered as functional propositions, true or false (hence the alternate name "propositional calculus"). But in physical devices, such as switches, controls, or computers, the two states may be on or off, short circuit or open circuit, high voltage or low voltage, or presence or absence of a hole in a card or tape, and the digits 1 and 0 are arbitrarily used.

In these theorems each of the variables can represent an arbitrary function. One method for manipulating forms in switching algebra is to use a map.

Since the use of symbols in Boolean algebra has not yet been fully standardized, the following is a detailed explanation of the symbols used in the above table.

SYMBOLS:

A, B, and C are variables.

The bar above the variable indicates the negation of the variable, e.g., $\overline{A}$ means "not A".

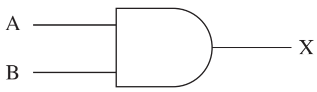
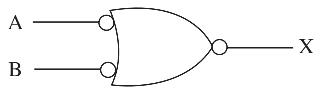
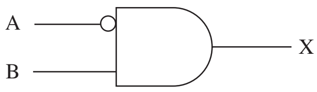
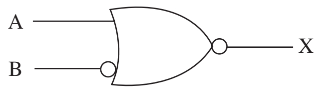
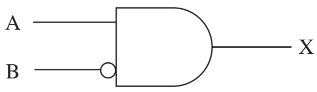
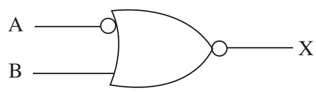
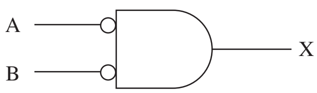
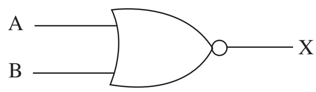
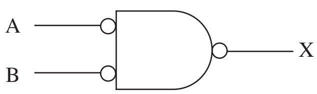
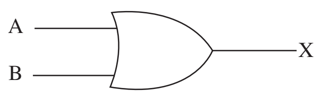
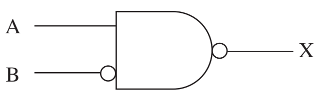
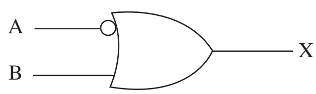
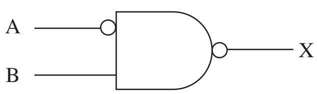
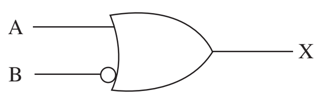
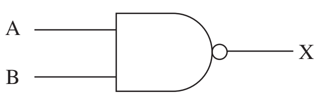
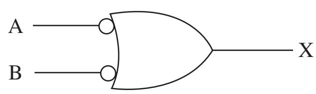
The plus sign, +, is used for the *or* function. This function does not obey the conventional arithmetical rules for sums.

The multiplication sign, ·, is used for the *and* function, sometimes called conjunction. This function obeys the conventional arithmetical rules for products. Thus if the binary values are taken arithmetically as one and zero, $1 \cdot 1 = 1$, and $1 \cdot 0 = 0$. But, in Boolean notation, $1 + 1 = 1$, which is not correct by arithmetical notation.

If a variable (e.g., a switch) can have only two sates, designated as 1 or 0, it follows that $\overline{1}$ is equivalent to 0, and $\overline{0}$ is equivalent to 1.

From Bolz, R.E. and Tuve, G.L., Number systems and logic, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 967.

Applications and Functions of Two Variables

Table of Combinations				
AND	OR	A	B	X
		H H L L	H L H L	H L L L
		H H L L	H L H L	L L H L
		H H L L	H L H L	L H L L
		H H L L	H L H L	L L L H
		H H L L	H L H L	H H H L
		H H L L	H L H L	H L H H
		H H L L	H L H L	H H L H
		H H L L	H L H L	L H H H

From Bolz, R.E. and Tuve, G.L., Number systems and logic, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 968, Originally from MIL-STD 806B, February 1962.