CRC MATERIALS SCIENCE AND ENGINEERING HANDBOOK

FOURTH EDITION

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Preface

This fourth edition of the *CRC Materials Science and Engineering Handbook* builds on the previous edition that provided a comprehensive, single-volume source of data on a wide range of engineering materials. In this regard, we are indebted to Dr. William Alexander who was a coeditor of each of the first three editions and Dr. Jun Park who was a coeditor for the second edition. Those previous editions featured data verified through major professional societies in the materials field, such as ASM International and the American Ceramic Society. The third edition is the basis of Section I (Traditional Materials) of this fourth edition. While the third edition was organized according to categories of properties, this edition has been organized according to categories of materials: metals, ceramics, glasses, polymers, composites, and semiconductors. For each of these material types, properties have been sorted according to two broad categories: physical and chemical. The correspondence between these two categories and the more detailed list of properties found in the third edition is as follows:

Physical Properties:

Structure of Materials
Thermal Properties of Materials
Mechanical Properties of Materials
Electrical Properties of Materials
Optical Properties of Materials

Chemical Properties:

Composition of Materials
Thermodynamic and Kinetic Data
Water Absorption and Corrosion

This edition provides a new Section II (Advanced Materials) corresponding to some of the most actively studied constituents in contemporary materials research: low-dimensional carbons, two-dimensional nanomaterials, MAX phases, and amorphous metals. These tables were generated by the coeditors from Pusan National University and Yeungnam University in Korea, who also wish to acknowledge the considerable effort of their students:

Pusan National University:

Ms Zhixin Wan, Graduate School of Convergence Science
Mr Woo-Jae Lee, Graduate School of Convergence Science
Mr Seung-Il Jang, Graduate School of Convergence Science
Ms Eun-Young Yun, Graduate School, School of Materials Science and Engineering
Ms Ha-Jin Lee, Graduate School, School of Materials Science and Engineering
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Yeungnam University:

Mr Duk-Yeon Kim, Graduate School, School of Materials Science and Engineering
Mr Jae Hui Jeon, Graduate School, School of Materials Science and Engineering

As appropriate for the Advanced Materials section, the sources of the data in the contemporary research literature are detailed, including extensive reference sections at the end of Chapters 8 and 9. It is the editors' hope that the Advanced Materials section will be useful to the research community and facilitate further development and applications of these materials.

Finally, the editors are grateful to CRC editor Allison Shatkin for her encouragement and support throughout the production of this new edition. She and the entire CRC team could not have been more helpful.

Authors

James F. Shackelford earned BS and MS in ceramic engineering from the University of Washington, Seattle, Washington and a PhD in materials science and engineering from the University of California (UC), Berkeley, California. Following a postdoctoral fellowship at McMaster University in Canada, he joined the University of California (UC), Davis, where he is currently distinguished professor emeritus in the Department of Chemical Engineering and Materials Science. For many years, he served as the associate dean for undergraduate studies in the College of Engineering and later as the director of the University Honors Program that serves students from a wide spectrum of majors. Dr. Shackelford also served as associate director for education for the National Science Foundation-funded Center for Biophotonics Science and Technology and as faculty assistant to the director of the McClellan Nuclear Research Center of UC Davis. He teaches and conducts research in the structural characterization and processing of materials, focusing on glasses and biomaterials. His current focus in teaching is using online technologies. A member of the American Ceramic Society and ASM International, he was named a Fellow of the American Ceramic Society in 1992 and a Fellow of ASM International in 2011. Dr. Shackelford received the Outstanding Educator Award of the American Ceramic Society in 1996. In 2003, he received a Distinguished Teaching Award from the Academic Senate of the University of California, Davis. In 2012, he received the Outstanding Teaching Award of the College of Engineering at UC Davis and, in 2014, an Outstanding Service Award from UC Davis Extension. He has published well over 100 archived papers and books, including *Introduction to Materials Science for Engineers* now in its 8th edition and which has been translated into Chinese, German, Italian, Japanese, Korean, Portuguese, and Spanish.

Young-Hwan Han earned BS and MS degrees in metallurgical engineering from the Sung Kyun Kwan University in Korea and MS and PhD degrees in materials science and engineering from the University of Nevada, Reno, Nevada. He is currently a foreign professor in the School of Materials Science and Engineering at Yeungnam University, Korea. For many years, he worked as a postdoctoral research associate at UC Davis and UC Berkeley. Dr. Han also worked as an invited professor and research professor at Sung Kyun Kwan University, Keimyung University, and Pusan National University in Korea. He teaches materials science courses and conducts research in the structural characterization and processing of materials, focusing on nanoceramics. He has published over 60 technical papers and translated books into Korean, including *Introduction to Materials Science for Engineers*, Seventh Edition by James F. Shackelford.

Sukyoung Kim earned a BS in ceramic engineering from the Inha University, Korea and an MS in ceramic engineering at the Seoul National University, Korea and at the New York State College of Ceramics at Alfred University, New York. He earned a PhD in materials science and engineering at the University of Vermont, Burlington, Vermont in 1990. After graduation, he was a postdoctoral fellow at the University of Vermont Hospital, where he was involved in the development and characterization of surface hard coatings on ceramics and wear studies on ceramic hip and knee joint implants. In 1991, he joined the biomaterials group in the Center for Biomaterials at the University of Toronto, Ontario, Canada. At that time, he was involved in a project for the development of biodegradable ceramic–polymer composite materials for orthopedic and dental applications with Dr. Pilliar and Dr. Smith. In 1994, Dr. Kim joined the faculty of the School of Materials Science and Engineering at Yeungnam University, Korea. Dr. Kim is a member of several associations/societies such as the American Society for Biomaterials, Canadian Society for Biomaterials, Korean Society for Biomaterials, Korean Ceramic Society, Korean Tissue Engineering and Regenerative Medicine Society, and the International Society for Ceramics in Medicine. In addition, Dr. Kim served as a chairman, organizing the *Bioceramics 22* meeting in 2009 in Daegu, Korea. In 2012, he organized the *29th International Korea–Japan Seminar on Ceramics*, also in Daegu, Korea. Currently, he is an international executive committee member of the International Society of Ceramics in Medicine (ISCM). His research interests include the synthesis of biodegradable bioceramics and the development of porous ceramics for biodegradable ceramic bone substitutes, drug delivery, and peptide loading. He is also studying bioceramic coatings on dental and orthopedic metallic implants for improving osseointegration.

Se-Hun Kwon earned BS, MS, and PhD degrees and served as a postdoctoral associate in materials science and engineering at the Korea Advanced Institute of Science and Technology (KAIST). In 2009, he joined the Pusan National University (PNU), Korea, where he is currently associate professor in the School of Materials Science and Engineering. Dr. Kwon also worked as an adjunct professor of the School of Convergence Science at PNU. He is a member of several societies including the American Ceramic Society (ACerS), Electrochemical Society (ECS), American Vacuum Society (AVS), Material Research Society of Korea (MRS-K), the Korean Vacuum Society (KVS), the Korean Institute of Metals and Materials (KIM), and the Korean Institute of Surface Engineering (KISE). His research group, "Surface Materials Laboratory," focuses on the design and synthesis of multifunctional surfaces and interfacial layers using atomic layer deposition (ALD) techniques and on the fabrication of highly ordered nanostructures for semiconductors, photovoltaic devices, and nano-devices by utilizing hybrid bottom-up and top-down fabrication approaches. Dr. Kwon has published over 70 archived papers and over 20 published patents.

I

Traditional Materials

1

Metals

Physical Properties

TABLE 1.1 Electronic Structure of Selected Elements

At.			Electronic Configuration																	
No.	Element	Sym	1s	2s	2p	3s	3p	3d	4s	4p	4d	4f	5s	5p	5d	5f	6s	6p	6d	7s
1	Hydrogen	H	1																	
2	Helium	He	2																	
3	Lithium	Li	.	1																
4	Beryllium	Be	.	2																
5	Boron	B	.	2	1															
6	Carbon	C	.	2	2															
7	Nitrogen	N	.	2	3															
8	Oxygen	O	.	2	4															
9	Fluorine	F	.	2	5															
10	Neon	N	.	2	6															
11	Sodium	Na	.	.	.	1														
12	Magnesium	Mg	.	.	.	2														
13	Aluminum	Al	.	.	.	2	1													
14	Silicon	Si	.	.	.	2	2													
15	Phosphorus	P	.	.	.	2	3													
16	Sulfur	S	.	.	.	2	4													
17	Chlorine	Cl	.	.	.	2	5													
18	Argon	Ar	.	.	.	2	6													
19	Potassium	K	.	.	.	.	.		1											
20	Calcium	Ca	.	.	.	.	.		2											
21	Scandium	Sc	.	.	.	.	.	1	2											
22	Titanium	Ti	.	.	.	.	.	2	2											
23	Vanadium	V	.	.	.	.	.	3	2											
24	Chromium	Cr	.	.	.	.	.	5	1											
25	Manganese	Mn	.	.	.	.	.	5	2											
26	Iron	Fe	.	.	.	.	.	6	2											
27	Cobalt	Co	.	.	.	.	.	7	2											
28	Nickel	Ni	.	.	.	.	.	8	2											
29	Copper	Cu	.	.	.	.	.	10	1											

(*Continued*)

TABLE 1.1 (*Continued*) Electronic Structure of Selected Elements

At.			Electronic Configuration																	
No.	Element	Sym	1s	2s	2p	3s	3p	3d	4s	4p	4d	4f	5s	5p	5d	5f	6s	6p	6d	7s
30	Zinc	Zn	.	.	.	.	.	10	2											
31	Gallium	Ga	.	.	.	.	.	10	2	1										
32	Germanium	Ge	.	.	.	.	.	10	2	2										
33	Arsenic	As	.	.	.	.	.	10	2	3										
34	Selenium	Se	.	.	.	.	.	10	2	4										
35	Bromine	Br	.	.	.	.	.	10	2	5										
36	Krypton	Kr	.	.	.	.	.	10	2	6										
37	Rubidium	Rb	.	.	.	.	.	.	.	.			1							
38	Strontium	Sr	.	.	.	.	.	.	.	.			2							
39	Yttrium	Y	.	.	.	.	.	.	.	.	1		2							
40	Zirconium	Zr	.	.	.	.	.	.	.	.	2		2							
41	Niobium	Nb	.	.	.	.	.	.	.	.	4		1							
42	Molybdenum	Mo	.	.	.	.	.	.	.	.	5		1							
43	Technetium	Tc	.	.	.	.	.	.	.	.	6		1							
44	Ruthenium	Ru	.	.	.	.	.	.	.	.	7		1							
45	Rhodium	Rh	.	.	.	.	.	.	.	.	8		1							
46	Palladium	Pd	.	.	.	.	.	.	.	.	10									
47	Silver	Ag	.	.	.	.	.	.	.	.	10		1							
48	Cadmium	Cd	.	.	.	.	.	.	.	.	10		2							
49	Indium	In	.	.	.	.	.	.	.	.	10		2	1						
50	Tin	Sn	.	.	.	.	.	.	.	.	10		2	2						
51	Antimony	Sb	.	.	.	.	.	.	.	.	10		2	3						
52	Tellurium	Te	.	.	.	.	.	.	.	.	10		2	5						
53	Iodine	I	.	.	.	.	.	.	.	.	10		2	5						
54	Xenon	Xe	.	.	.	.	.	.	.	.	10		2	6						
55	Cesium	Ce	.	.	.	.	.	.	.	.	.		.	.			1			
56	Barium	Ba	.	.	.	.	.	.	.	.	.		.	.			2			
57	Lanthanum	La	.	.	.	.	.	.	.	.	.		.	.	1		2			
58	Cerium	Ce	.	.	.	.	.	.	.	.	.	2	.	.			2			
59	Praseodymium	Pr	.	.	.	.	.	.	.	.	.	3	.	.			2			
60	Neodymium	Nd	.	.	.	.	.	.	.	.	.	4	.	.			2			
61	Promethium	Pm	.	.	.	.	.	.	.	.	.	5	.	.			2			
62	Samarium	Sm	.	.	.	.	.	.	.	.	.	6	.	.			2			
63	Europium	Eu	.	.	.	.	.	.	.	.	.	7	.	.			2			
64	Gadolinium	Gd	.	.	.	.	.	.	.	.	.	7	.	.	1		2			
65	Terbium	Tb	.	.	.	.	.	.	.	.	.	9	.	.			2			
66	Dysprosium	Dy	.	.	.	.	.	.	.	.	.	10	.	.			2			
67	Holmium	Ho	.	.	.	.	.	.	.	.	.	11	.	.			2			
68	Erbium	Er	.	.	.	.	.	.	.	.	.	12	.	.			2			
69	Thulium	Tm	.	.	.	.	.	.	.	.	.	13	.	.			2			
70	Ytterbium	Yb	.	.	.	.	.	.	.	.	.	14	.	.			2			
71	Lutetium	Lu	.	.	.	.	.	.	.	.	.	14	.	.	1		2			
72	Hafnium	Hf	.	.	.	.	.	.	.	.	.	14	.	.	2		2			
73	Tantalum	Ta	.	.	.	.	.	.	.	.	.	14	.	.	3		2			
74	Tungsten	W	.	.	.	.	.	.	.	.	.	14	.	.	4		2			

(*Continued*)

TABLE 1.1 (*Continued*) Electronic Structure of Selected Elements

At. No.	Element	Sym	Electronic Configuration																	
			1s	2s	2p	3s	3p	3d	4s	4p	4d	4f	5s	5p	5d	5f	6s	6p	6d	7s
75	Rhenium	Re	.	.	.	.	.	.	.	.	.	14	.	.	5		2			
76	Osmium	Os	.	.	.	.	.	.	.	.	.	14	.	.	6		2			
77	Iridium	Ir	.	.	.	.	.	.	.	.	.	14	.	.	9					
78	Platinum	Pt	.	.	.	.	.	.	.	.	.	14	.	.	9		1			
79	Gold	Au	.	.	.	.	.	.	.	.	.	14	.	.	10		1			
80	Mercury	Hg	.	.	.	.	.	.	.	.	.	14	.	.	10		2			
81	Thallium	Tl	.	.	.	.	.	.	.	.	.	14	.	.	10		2	1		
82	Lead	Pb	.	.	.	.	.	.	.	.	.	14	.	.	10		2	2		
83	Bismuth	Bi	.	.	.	.	.	.	.	.	.	14	.	.	10		2	3		
84	Polonium	Po	.	.	.	.	.	.	.	.	.	14	.	.	10		2	4		
85	Asatine	At	.	.	.	.	.	.	.	.	.	14	.	.	10		2	5		
86	Radon	Rn	.	.	.	.	.	.	.	.	.	14	.	.	10		2	6		
87	Francium	Fr	.	.	.	.	.	.	.	.	.	.	.	.	.		.	.		1
88	Radium	Ra	.	.	.	.	.	.	.	.	.	.	.	.	.		.	.		2
89	Actinium	Ac	.	.	.	.	.	.	.	.	.	.	.	.	.		.	.	1	2
90	Thorium	Th	.	.	.	.	.	.	.	.	.	.	.	.	.		.	.	2	2
91	Protoactinium	Pa	.	.	.	.	.	.	.	.	.	.	.	.	.	2	.	.	1	2
92	Uranium	U	.	.	.	.	.	.	.	.	.	.	.	.	.	3	.	.	1	2
93	Neptunium	Np	.	.	.	.	.	.	.	.	.	.	.	.	.	4	.	.	1	2
94	Plutonium	Pu	.	.	.	.	.	.	.	.	.	.	.	.	.	6	.	.		2
95	Americium	Am	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.		2
96	Curium	Cm	.	.	.	.	.	.	.	.	.	.	.	.	.	7	.	.	1	2
97	Berkelium	Bk	.	.	.	.	.	.	.	.	.	.	.	.	.	9	.	.		2
98	Californium	Cf	.	.	.	.	.	.	.	.	.	.	.	.	.	10	.	.		2
99	Einsteinium	Es	.	.	.	.	.	.	.	.	.	.	.	.	.	11	.	.		2
100	Fermium	Fm	.	.	.	.	.	.	.	.	.	.	.	.	.	12	.	.		2
101	Mendelevium	Md	.	.	.	.	.	.	.	.	.	.	.	.	.	13	.	.		2
102	Nobelium	No	.	.	.	.	.	.	.	.	.	.	.	.	.	14	.	.		2
103	Lawrencium	Lw	.	.	.	.	.	.	.	.	.	.	.	.	.	14	.	.	1	2

TABLE 1.2 Available Stable Isotopes of the Elements

Element	Mass No.	Natural Abundance (%)
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	98.89
	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

(*Continued*)

TABLE 1.2 (*Continued*) Available Stable Isotopes of the Elements

Element	Mass No.	Natural Abundance (%)
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	26.23
	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

(*Continued*)

TABLE 1.2 (*Continued*) Available Stable Isotopes of the Elements

Element	Mass No.	Natural Abundance (%)
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
Strontium	84	0.56
	86	9.86
	87	7.02
	88	82.56
Yttrium	89	100.0
Zirconium	90	51.46
	91	11.23
	92	17.11
	94	17.40
	96	2.80
Niobium	93	100.0
Molybdenum	92	15.84
	94	9.04
	95	15.72
	96	16.53
	97	9.46
	98	23.78
	100	9.63

(*Continued*)

TABLE 1.2 (*Continued*) Available Stable Isotopes of the Elements

Element	Mass No.	Natural Abundance (%)
Ruthenium	96	5.51
	98	1.87
	99	12.72
	100	12.62
	101	17.07
	102	31.61
	104	18.60
Rhodium	103	100.0
Palladium	102	0.96
	104	10.97
	105	22.23
	106	27.33
	108	26.71
	110	11.81
Silver	107	51.82
	109	48.18
Cadmium	106	1.22
	108	0.88
	110	12.39
	111	12.75
	112	24.07
	113	12.26
	114	28.86
	116	7.58
Indium	113	4.28
	115[c]	95.72
Tin	112	0.96
	114	0.66
	115	0.35
	116	14.30
	117	7.61
	118	24.03
	119	8.58
	120	32.85
	122	4.72
	124	5.94
Antimony	121	57.25
	123	42.75
Tellurium	120	0.09
	122	2.46
	123	0.87
	124	4.61

(*Continued*)

TABLE 1.2 (*Continued*) Available Stable Isotopes of the Elements

Element	Mass No.	Natural Abundance (%)
	125	6.99
	126	18.71
	128	31.79
	130	34.48
Iodine	127	100.0
Xenon	124	0.096
	126	0.090
	128	1.92
	129	26.44
	130	4.08
	131	21.18
	132	26.89
	134	10.44
	136	8.87
Cesium	133	100.0
Barium	130	0.101
	132	0.097
	134	2.42
	135	6.59
	136	7.81
	137	11.30
	138	71.66
Lanthanum	138	0.09
	139	99.91
Cerium	136	0.193
	138	0.250
	140	88.48
	142[d]	11.07
Praseodymium	141	100.0
Neodymium	142	27.11
	143	12.17
	144	23.85
	146	17.22
	148	5.73
	150	5.62
Samarium	144	3.09
	147[e]	14.97
	148[f]	11.24
	149[g]	13.83
	150	7.44
	152	26.72
	154	22.71

(*Continued*)

TABLE 1.2 (*Continued*) Available Stable Isotopes of the Elements

Element	Mass No.	Natural Abundance (%)
Europium	151	47.82
	153	52.18
Gadolinium	152[h]	0.20
	154	2.15
	155	14.73
	156	20.47
	157	15.68
	158	24.87
	160	21.90
Terbium	159	100.0
Dysprosium	156[i]	0.052
	158	0.090
	160	2.29
	161	18.88
	162	25.53
	163	24.97
	164	28.18
Holmium	165	100.0
Erbium	162	0.136
	164	1.56
	166	33.41
	167	22.94
	168	27.07
	170	14.88
	186	1.59
Thulium	169	100.0
Ytterbium	168	0.135
	170	3.03
	171	14.31
	172	21.82
	173	16.13
	174	31.84
	176	12.73
Lutetium	175	97.40
	176[j]	2.60
Hafnium	174[k]	0.18
	176	5.20
	177	18.50
	178	27.14
	179	13.75
	180	35.24

(*Continued*)

TABLE 1.2 (*Continued*) Available Stable Isotopes of the Elements

Element	Mass No.	Natural Abundance (%)
Tantalum	180	0.012
	181	99.988
Tungsten	180	0.14
	182	26.41
	183	14.40
	184	30.64
	186	28.41
Rhenium	185	37.07
	187[l]	62.93
Osmium	184	0.018
	187	1.64
	188	13.3
	190	26.4
	192	41.0
Iridium	191	37.3
	193	62.7
Platinum	190[m]	0.013
	192	0.78
	194	32.9
	195	33.8
	196	25.3
	198	7.2
Gold	197	100.0
Mercury	196	0.146
	198	10.02
	199	16.84
	200	23.13
	201	13.22
	202	29.80
	204	6.85
Thallium	203	29.50
	205	70.50
Lead	204	1.48
	206	23.6
	207	22.6
	208	52.3
Bismuth	209	100.0
Thorium	232[nr]	100.0

(*Continued*)

TABLE 1.2 (*Continued*) Available Stable Isotopes of the Elements

Element	Mass No.	Natural Abundance (%)
Uranium	234[o,r]	0.0006
	235[p,r]	0.72
	238[q,r]	99.27

Source: Wang, Y. (Ed.), *Handbook of Radioactive Nuclides*, The Chemical Rubber Co., Cleveland, 1969, p. 25.

[a] Half-life = 1.3×10^9 year.
[b] Half-life $>10^{15}$ year.
[c] Half-life = 5×10^{14} year.
[d] Half-life = 5×10^{14} year.
[e] Half-life = 1.06×10^{11} year.
[f] Half-life = 1.2×10^{13} year.
[g] Half-life = 4×10^{14} year.
[h] Half-life = 1.1×10^{14} year.
[i] Half-life = 2×10^{14} year.
[j] Half-life = 2.2×10^{10} year.
[k] Half-life = 4.3×10^{15} year.
[l] Half-life = 4×10^{10} year.
[m] Half-life = 6×10^{11} year.
[n] Half-life = 1.4×10^{10} year.
[o] Half-life = 2.5×10^5 year.
[p] Half-life = 7.1×10^8 year.
[q] Half-life = 4.5×10^9 year.
[r] Naturally occurring.

TABLE 1.3 Periodic Table of the Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA																	VIIA
1 H	IIA											IIIA	IVA	VA	VIA	VIIA	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg	IIIB	IVB	VB	VIB	VIIB	-----	VIII	-----	IB	IIB	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

TABLE 1.4 Periodic Table of Elements in Metallic Materials

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA																	VIIA
	IIA											IIIA	IVA	VA	VIA	VIIA	
3 Li	4 Be											5 B					
11 Na	12 Mg	IIIB	IVB	VB	VIB	VIIB	-----	VIII	-----	IB	IIB	13 Al					
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga					
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb			
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi			
87 Fr	88 Ra																

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

TABLE 1.5 Periodic Table of Elements in Superconducting Metals

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA																	VIIA
	IIA											IIIA	IVA	VA	VIA	VIIA	
	4 Be																
		IIIB	IVB	VB	VIB	VIIB	-----	VIII	-----	IB	IIB	13 Al					
			22 Ti	23 V							30 Zn	31 Ga					
			40 Zr	41 Nb	42 Mo	43 Tc	44 Ru				48 Cd	49 In	50 Sn	51 Sb			
				73 Ta	74 W	75 Re	76 Os	77 Ir			80 Hg		82 Pb				

57 La														
	90 Th	91 Pa												

TABLE 1.6 Atomic and Ionic Radii of the Elements

Atomic Number	Symbol	Atomic Radius (nm)	Ion	Ionic Radius (nm)
1	H	0.046	H^-	0.154
2	He	–	–	–
3	Li	0.152	Li^+	0.078
4	Be	0.114	Be^{2+}	0.054
5	B	0.097	B^{3+}	0.02
6	C	0.077	C^{4+}	<0.02
7	N	0.071	N^{5+}	0.01–0.2
8	O	0.060	0^{2-}	0.132
9	F	–	F^-	0.133
10	Ne	0.160	–	–
11	Na	0.186	Na^+	0.098
12	Mg	0.160	Mg^{2+}	0.078
13	Al	0.143	Al^{3+}	0.057
14	Si	0.117	Si^{4-}	0.198
·			Si^{4+}	0.039
15	P	0.109	P^{5+}	0.03–0.04
16	S	0.106	S^{2-}	0.174
17	Cl	0.107	Cl^-	0.181
18	Ar	0.192	–	–
19	K	0.231	K^+	0.133
20	Ca	0.197	Ca^{2+}	0.106
21	Sc	0.160	Sc^{2+}	0.083
22	Ti	0.147	Ti^{2+}	0.076
			Ti^{3+}	0.069
			Ti^{4+}	0.064
23	V	0.132	V^{3+}	0.065
			V^{4+}	0.061
			V^{5+}	0.04
24	Cr	0.125	Cr^{3+}	0.064
			Cr^{6+}	0.03–0.04
25	Mn	0.112	Mn^{2+}	0.091
			Mn^{3+}	0.070
			Mn^{4+}	0.052
26	Fe	0.124	Fe^{2+}	0.087
			Fe^{2+}	0.067
27	Co	0.125	Co^{2+}	0.082
			Co^{3+}	0.065
28	Ni	0.125	Ni^{2+}	0.078
29	Cu	0.128	Cu^+	0.096
30	Zn	0.133	Zn^{2+}	0.083
31	Ga	0.135	Ga^{3+}	0.062

(*Continued*)

TABLE 1.6 (*Continued*) Atomic and Ionic Radii of the Elements

Atomic Number	Symbol	Atomic Radius (nm)	Ion	Ionic Radius (nm)
32	Ge	0.122	Ge^{4+}	0.044
33	As	0.125	As^{3+}	0.069
			As^{5+}	~0.04
34	Se	0.116	Se^{2-}	0.191
			Se^{6+}	0.03–0.04
35	Br	0.119	Br^{-}	0.196
36	Kr	0.197	–	–
37	Rb	0.251	Rb^{+}	0.149
38	Sr	0.215	Sr^{2+}	0.127
39	Y	0.181	Y^{3+}	0.106
40	Zr	0.158	Zr^{4+}	0.087
41	Nb	0.143	Nb^{4+}	0.074
			Nb^{5+}	0.069
42	Mo	0.136	Mo^{4+}	0.068
			Mo^{6+}	0.065
43	Tc	–	–	–
44	Ru	0.134	Ru^{4+}	0.065
45	Rh	0.134	Rh^{3+}	0.068
			Rh^{4+}	0.065
46	Pd	0.137	Pd^{2+}	0.050
47	Ag	0.144	Ag^{+}	0.113
48	Cd	0.150	Cd^{2+}	0.103
49	In	0.157	In^{3+}	0.091
50	Sn	0.158	Sn^{4-}	0.215
			Sn^{4+}	0.074
51	Sb	0.161	Sb^{3+}	0.090
52	Te	0.143	Te^{2-}	0.211
			Te^{4-}	0.089
53	I	0.136	I^{-}	0.220
			I^{5+}	0.094
54	Xe	0.218	–	–
55	Cs	0.265	Cs^{+}	0.165
56	Ba	0.217	Ba^{2+}	0.13
57	La	0.187	La^{3+}	0.122
58	Ce	0.182	Ce^{3+}	0.118
			Ce^{4+}	0.102
59	Pr	0.183	Pr^{3+}	0.116
			Pr^{4+}	0.100
60	Nd	0.182	Nd^{3+}	0.115
61	Pm	–	Pm^{3+}	0.106

(*Continued*)

TABLE 1.6 (*Continued*) Atomic and Ionic Radii of the Elements

Atomic Number	Symbol	Atomic Radius (nm)	Ion	Ionic Radius (nm)
62	Sm	0.181	Sm^{3+}	0.113
63	Eu	0.204	Eu^{3+}	0.113
64	Gd	0.180	Gd^{3+}	0.111
65	Tb	0.177	Tb^{3+}	0.109
			Tb^{4+}	0.089
66	Dy	0.177	Dy^{3+}	0.107
67	Ho	0.176	Ho^{3+}	0.105
68	Er	0.175	Er^{3+}	0.104
69	Tm	0.174	Tm^{3+}	0.104
70	Yb	0.193	Yb^{3+}	0.100
71	Lu	0.173	Lu^{3+}	0.099
72	Hf	0.159	Hf^{4+}	0.084
73	Ta	0.147	Ta^{5+}	0.068
74	W	0.137	W^{4+}	0.068
			W^{6+}	0.065
75	Re	0.138	Re^{4+}	0.072
76	Os	0.135	Os^{4+}	0.067
77	Ir	0.135	Ir^{4+}	0.066
78	Pt	0.138	Pt^{2+}	0.052
			Pt^{4+}	0.055
79	Au	0.144	Au^{+}	0.137
80	Hg	0.150	Hg^{2+}	0.112
81	Tl	0.171	Tl^{+}	0.149
			Tl^{3+}	0.106
82	Pb	0.175	Pb^{4-}	0.215
			Pb^{2+}	0.132
			Pb^{4+}	0.084
83	Bi	0.182	Bi^{3+}	0.120
84	Po	0.140	Po^{6+}	0.067
85	At	–	At^{7+}	0.062
86	Rn	–	–	-
87	Fr	–	Fr^{+}	0.180
88	Ra	–	Ra^{+}	0.152
89	Ac	–	Ac^{3+}	0.118
90	Th	0.180	Th^{4+}	0.110
91	Pa	–	–	–
92	U	0.138	U^{4+}	0.105

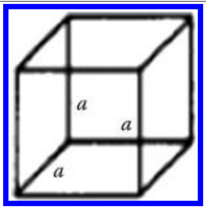
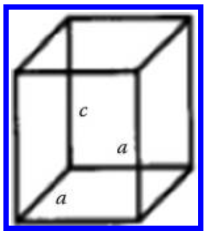
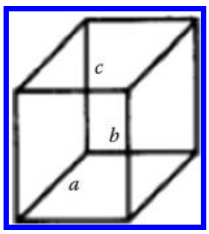
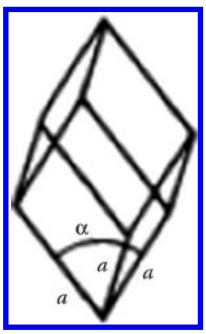
Source: Data from R. A. Flinn and P. K. Trojan, *Engineering Materials and Their Applications*, Houghton Mifflin Company, Boston, 1975.

Note: The ionic radii are based on the calculations of V. M. Goldschmidt, who assigned radii based on known interatomic distances in various ionic crystals.

TABLE 1.7 Key to Tables of Crystal Structure of the Elements

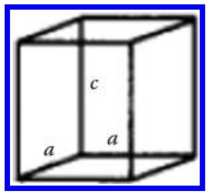
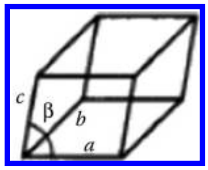
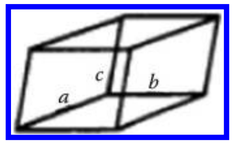
Table Title	Table Number
The Seven Crystal Systems	Table 1.8
The 14 Bravais Lattices	Table 1.9
Periodic Table of the Body Centered Cubic Elements	Table 1.10
Periodic Table of the Face Centered Cubic Elements	Table 1.11
Periodic Table of the Hexagonal Close Packed Elements	Table 1.12
Periodic Table of the Hexagonal Elements	Table 1.13

TABLE 1.8 The Seven Crystal Systems

System	Axial Lengths and Angles	Unit Cell Geometry
Cubic	$a = b = c, \alpha = \beta = \gamma = 90°$	
Tetragonal	$a = b \neq c, \alpha = \beta = \gamma = 90°$	
Orthorhombic	$a \neq b \neq c, \alpha = \beta = \gamma = 90°$	
Rhombohedral	$a = b = c, \alpha = \beta = \gamma \neq 90°$	

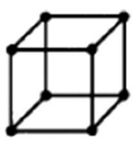
(*Continued*)

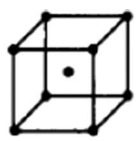
TABLE 1.8 (*Continued*) The Seven Crystal Systems

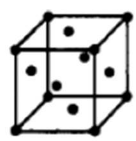
System	Axial Lengths and Angles	Unit Cell Geometry
Hexagonal	$a = b \neq c$, $\alpha = \beta = 90°$, $\gamma = 120°$	
Monoclinic	$a \neq b \neq c$, $\alpha = \gamma = 90° \neq \beta$	
Triclinic	$a \neq b \neq c$, $\alpha \neq \beta \neq \gamma \neq 90°$	

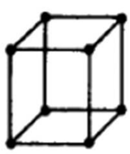
Source: Data from J. F. Shackelford, *Introduction to Materials Science for Engineers*, 4th Edn., Prentice-Hall, Upper Saddle River, NJ, 1996.

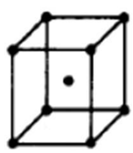
TABLE 1.9 The 14 Bravais Lattices

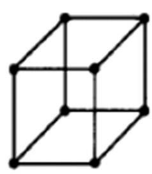

Simple cubic

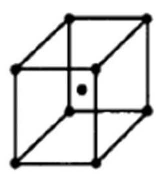

Body-centered cubic


Face-centered cubic


Simple tetragonal

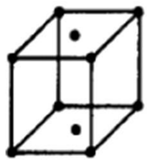

Body-centered tetragonal


Simple orthorhombic

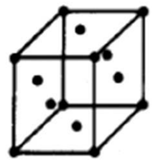

Body-centered orthorhombic

(*Continued*)

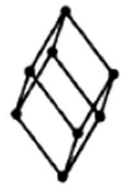
TABLE 1.9 (*Continued*) The 14 Bravais Lattices



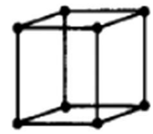
Base-centered orthorhombic



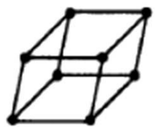
Face-centered orthorhombic



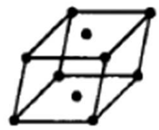
Rhombohedral



Hexagonal



Simple monoclinic



Base-centered monoclinic

Triclinic

Source: Data from J. F. Shackelford, *Introduction to Materials Science for Engineers*, 4th Edn., Prentice-Hall, Upper Saddle River, NJ, 1996.

TABLE 1.10 Periodic Table of the Body-Centered Cubic Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA																	VIIA
	IIA											IIIA	IVA	VA	VIA	VII A	
3 Li																	
11 Na		IIB	IVB	VB	VIB	VIIB	-----	VIII	-----	IB	IIB						
19 K				23 V	24 Cr	25 Mn	26 Fe										
37 Rb				41 Nb	42 Mo												
55 Cs	56 Ba			73 Ta	74 W												
87 Fr	88 Ra																

						63 Eu								

TABLE 1.11 Periodic Table of the Face-Centered Cubic Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA	IIA	IIB	IVB	VB	VIB	VIIB	-----	VIII	-----	IB	IIB	IIIA	IVA	VA	VIA	VII A	VIIA
																	10 Ne
												13 Al	14 Si				18 Ar
	20 Ca									28 Ni	29 Cu		32 Ge				36 Kr
	38 Sr								45 Rh	46 Pd	47 Ag						54 Xe
									77 Ir	78 Pt	79 Au		82 Pb				86 Rn

57 La														
89 Ac														

TABLE 1.12 Periodic Table of the Hexagonal Close Packed Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA	IIA	IIIB	IVB	VB	VIB	VIIB	-----	VIII	-----	IB	IIB	IIIA	IVA	VA	VIA	VII A	VIIA
	4 Be																
	12 Mg																
			22 Ti					27 Co			30 Zn						
		39 Y	40 Zr			43 Tc	44 Ru				48 Cd						
			72 Hf			75 Re	76 Os					81 Tl					

							64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm		71 Lu

TABLE 1.13 Periodic Table of the Hexagonal Elements

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 -----	9 VIII	10 -----	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VII A	18 VIIA
													6 C				
															34 Se		
															52 Te		

57 La		59 Pr	60 Nd	61 Pm										
						95 Am	96 Cm	97 Bk						

TABLE 1.14 Atomic Mass of Selected Elements

Atomic Number	Element	Symbol	Atomic Mass
1	Hydrogen	H	1.008
2	Helium	He	4.003
3	Lithium	Li	6.941
4	Beryllium	Be	9.012
5	Boron	B	10.81
6	Carbon	C	12.01
7	Nitrogen	N	14.01
8	Oxygen	O	16.00
9	Fluorine	F	19.00
10	Neon	N	20.18
11	Sodium	Na	22.99
12	Magnesium	Mg	24.31
13	Aluminum	Al	26.98
14	Silicon	Si	28.09
15	Phosphorus (White)	P	30.97
16	Sulfur	S	32.06
17	Chlorine	Cl	35.45
18	Argon	Ar	39.95
19	Potassium	K	39.1
20	Calcium	Ca	40.08
21	Scandium	Sc	44.96
22	Titanium	Ti	47.9
23	Vanadium	V	50.94
24	Chromium	Cr	52.00
25	Manganese	Mn	54.94

(*Continued*)

TABLE 1.14 (*Continued*) Atomic Mass of Selected Elements

Atomic Number	Element	Symbol	Atomic Mass
26	Iron	Fe	55.85
27	Cobalt	Co	58.93
28	Nickel	Ni	58.71
29	Copper	Cu	63.55
30	Zinc	Zn	65.38
31	Gallium	Ga	69.72
32	Germanium	Ge	72.59
33	Arsenic	As	74.92
34	Selenium	Se	78.96
35	Bromine	Br	79.9
36	Krypton	Kr	83.8
37	Rubidium	Rb	85.47
38	Strontium	Sr	87.62
39	Yttrium	Y	88.91
40	Zirconium	Zr	91.22
41	Niobium	Nb	92.91
42	Molybdenum	Mo	95.94
43	Technetium	Tc	98.91
44	Ruthenium	Ru	101.07
45	Rhodium	Rh	102.91
46	Palladium	Pd	106.4
47	Silver	Ag	107.87
48	Cadmium	Cd	112.4
49	Indium	In	114.82
50	Tin	Sn	118.69
51	Antimony	Sb	121.75
52	Tellurium	Te	127.6
53	Iodine	I	126.9
54	Xenon	Xe	131.3
55	Cesium (–10°)	Ce	132.91
56	Barium	Ba	137.33
57	Lanthanum	La	138.91
58	Cerium	Ce	140.12
59	Praseodymium	Pr	140.91
60	Neodymium	Nd	144.24
61	Promethium	Pm	(145)
62	Samarium	Sm	150.4
63	Europium	Eu	151.96
64	Gadolinium	Gd	157.25
65	Terbium	Tb	158.93
66	Dysprosium	Dy	162.5
67	Holmium	Ho	164.93

(*Continued*)

TABLE 1.14 (*Continued*) Atomic Mass of Selected Elements

Atomic Number	Element	Symbol	Atomic Mass
68	Erbium	Er	167.26
69	Thulium	Tm	168.93
70	Ytterbium	Yb	173.04
71	Lutetium	Lu	174.97
72	Hafnium	Hf	178.49
73	Tantalum	Ta	180.95
74	Tungsten	W	183.85
75	Rhenium	Re	186.2
76	Osmium	Os	190.2
77	Iridium	Ir	192.22
78	Platinum	Pt	195.09
79	Gold	Au	196.97
80	Mercury	Hg	200.59
81	Thallium	Tl	204.37
82	Lead	Pb	207.2
83	Bismuth	Bi	208.98
84	Polonium	Po	(~210)
85	Astatine	At	(210)
86	Radon	Rn	(222)
87	Francium	Fr	(223)
88	Radium	Ra	226.03
89	Actinium	Ac	(227)
90	Thorium	Th	232.04
91	Protactinium	Pa	231.04
92	Uranium	U	238.03
93	Neptunium	Np	237.05
94	Plutonium	Pu	(244)
95	Americium	Am	(243)
96	Curium	Cm	(247)
97	Berkelium	Bk	(247)
98	Californium	Cf	(251)
99	Einsteinium	Es	(254)
100	Fermium	Fm	(257)
101	Mendelevium	Md	(258)
102	Nobelium	No	(259)
103	Lawrencium	Lw	(260)

Source: Data from J. F. Shackelford, *Introduction to Materials Science for Engineers*, Second Edn., Macmillan Publishing Company, New York, 1988, pp. 686–688.

TABLE 1.15 Solid Density of Selected Elements

Atomic Number	Element	Symbol	Solid Density (Mg/m³)
3	Lithium	Li	0.533
4	Beryllium	Be	1.85
5	Boron	B	2.47
6	Carbon	C	2.27
11	Sodium	Na	0.966
12	Magnesium	Mg	1.74
13	Aluminum	Al	2.7
14	Silicon	Si	2.33
15	Phosphorus (White)	P	1.82
16	Sulfur	S	2.09
19	Potassium	K	0.862
20	Calcium	Ca	1.53
21	Scandium	Sc	2.99
22	Titanium	Ti	4.51
23	Vanadium	V	6.09
24	Chromium	Cr	7.19
25	Manganese	Mn	7.47
26	Iron	Fe	7.87
27	Cobalt	Co	8.8
28	Nickel	Ni	8.91
29	Copper	Cu	8.93
30	Zinc	Zn	7.13
31	Gallium	Ga	5.91
32	Germanium	Ge	5.32
33	Arsenic	As	5.78
34	Selenium	Se	4.81
37	Rubidium	Rb	1.53
38	Strontium	Sr	2.58
39	Yttrium	Y	4.48
40	Zirconium	Zr	6.51
41	Niobium	Nb	8.58
42	Molybdenum	Mo	10.22
43	Technetium	Tc	11.5
44	Ruthenium	Ru	12.36
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

(*Continued*)

TABLE 1.15 (*Continued*) Solid Density of Selected Elements

Atomic Number	Element	Symbol	Solid Density (Mg/m^3)
51	Antimony	Sb	6.69
52	Tellurium	Te	6.25
53	Iodine	I	4.95
55	Cesium (–10°)	Ce	1.91
56	Barium	Ba	3.59
57	Lanthanum	La	6.17
58	Cerium	Ce	6.77
59	Praseodymium	Pr	6.78
60	Neodymium	Nd	7.00
62	Samarium	Sm	7.54
63	Europium	Eu	5.25
64	Gadolinium	Gd	7.87
65	Terbium	Tb	8.27
66	Dysprosium	Dy	8.53
67	Holmium	Ho	8.80
68	Erbium	Er	9.04
69	Thulium	Tm	9.33
70	Ytterbium	Yb	6.97
71	Lutetium	Lu	9.84
72	Hafnium	Hf	13.28
73	Tantalum	Ta	16.67
74	Tungsten	W	19.25
75	Rhenium	Re	21.02
76	Osmium	Os	22.58
77	Iridium	Ir	22.55
78	Platinum	Pt	21.44
79	Gold	Au	19.28
81	Thallium	Tl	11.87
82	Lead	Pb	11.34
83	Bismuth	Bi	9.80
84	Polonium	Po	9.2
90	Thorium	Th	11.72
92	Uranium	U	19.05
94	Plutonium	Pu	19.81

Source: Data from J. F. Shackelford, *Introduction to Materials Science for Engineers*, Second Edn., Macmillan Publishing Company, New York, 1988, pp. 686–688.

TABLE 1.16 Density of Iron and Iron Alloys

Class	Metal or Alloy	Density (Mg/m^3)
Iron and iron alloys	Pure iron	7.874
	Ingot iron	7.866
	Wrought iron	7.7
	Gray cast iron	7.15
	Malleable iron	7.27
	0.06% C steel	7.871
	0.23% C steel	7.859
	0.435% C steel	7.844
	1.22% C steel	7.830
Low-carbon chromium–molybdenum steels	0.5% Mo steel	7.86
	1Cr–0.5Mo steel	7.86
	1.25Cr–0.5Mo steel	7.86
	2.25Cr–1.0Mo steel	7.86
	5Cr–0.5Mo steel	7.78
	7Cr–0.5Mo steel	7.78
	9Cr–1Mo steel	7.67
Medium-carbon alloy steels	1Cr–0.35Mo–0.25V steel	7.86
	H11 die steel (5Cr–1.5Mo–0.4V)	7.79
Other iron-base alloys	A-286	7.94
	16-25-6 alloy	8.08
	RA-330	8.03
	Incoloy	8.02
	Incoloy T	7.98
	Incoloy 901	8.23
	T1 tool steel	8.67
	M2 tool steel	8.16
	H41 tool steel	7.88
	20W–4Cr–2V–12Co steel	8.89
	Invar (36% Ni)	8.00
	Hipernik (50% Ni)	8.25
	4% Si	7.6
	10.27% Si	6.97

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 152.

TABLE 1.17 Density of Wrought Stainless Steels[a]

Type	UNS Designation	Density (Mg/m^3)
201	S20100	7.8
202	S20200	7.8
205	S20500	7.8
301	S30100	8.0
302	S30200	8.0
302B	S30215	8.0
303	S30300	8.0
304	S30400	8.0
304L	S30403	8.0
S30430	S30430	8.0
304N	S30451	8.0
305	S30500	8.0
308	S30800	8.0
309	S30900	8.0
310	S31000	8.0
314	S31400	7.8
316	S31600	8.0
316L	S31603	8.0
316N	S31651	8.0
317	S31700	8.0
317L	S31703	8.0
321	S32100	8.0
329	S32900	7.8
330	N08330	8.0
347	S34700	8.0
384	S38400	8.0
405	S40500	7.8
409	S40900	7.8
410	S41000	7.8
414	S41400	7.8
416	S41600	7.8
420	S42000	7.8
422	S42200	7.8
429	S42900	7.8
430	S43000	7.8
430F	S43020	7.8
431	S43100	7.8
434	S43400	7.8
436	S43600	7.8
440A	S44002	7.8
440C	S44004	7.8
444	S44400	7.8

(*Continued*)

TABLE 1.17 (*Continued*) Density of Wrought Stainless Steels[a]

Type	UNS Designation	Density (Mg/m^3)
446	S44600	7.5
PH 13–8 Mo	S13800	7.8
15–5 PH	S15500	7.8
17–4 PH	S17400	7.8
17–7 PH	S17700	7.8

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 360.
[a] Annealed condition.

TABLE 1.18 Density of Stainless Steels and Heat-Resistant Alloys

Class	Metal or Alloy	Density (Mg/m^3)
Corrosion-resistant steel castings	CA-15	7.612
	CA-40	7.612
	CB-30	7.53
	CC-50	7.53
	CE-30	7.67
	CF-8	7.75
	CF-20	7.75
	CF-8M, CF-12M	7.75
	CF-8C	7.75
	CF-16F	7.75
	CH-20	7.72
	CK-20	7.75
	CN-7M	8.00
Heat-resistant alloy castings	HA	7.72
	HC	7.53
	HD	7.58
	HE	7.67
	HF	7.75
	HH	7.72
	HI	7.72
	HK	7.75
	HL	7.72
	HN	7.83
	HT	7.92
	HU	8.04
	HW	8.14
	HX	8.14
Wrought stainless and heat-resisting steels	Type 301	7.9
	Type 302	7.9
	Type 302B	8.0
	Type 303	7.9
	Type 304	7.9
	Type 305	8.0

(*Continued*)

TABLE 1.18 (*Continued*) Density of Stainless Steels and Heat-Resistant Alloys

Class	Metal or Alloy	Density (Mg/m³)
	Type 308	8.0
	Type 309	7.9
	Type 310	7.9
	Type 314	7.72
	Type 316	8.0
	Type 317	8.0
	Type 321	7.9
	Type 347	8.0
	Type 403	7.7
	Type 405	7.7
	Type 410	7.7
	Type 416	7.7
	Type 420	7.7
	Type 430	7.7
	Type 430F	7.7
	Type 431	7.7
	Types 440A, 440B, 440C	7.7
	Type 446	7.6
	Type 501	7.7
	Type 502	7.8
	19-9DL	7.97
Precipitation-hardening stainless steels	PH15-7 Mo	7.804
	17-4 PH	7.8
	17-7 PH	7.81
Nickel-base alloys	D-979	8.27
	Nimonic 80A	8.25
	Nimonic 90	8.27
	M-252	8.27
	Inconel	8.51
	Inconel "x" 550	8.30
	Inconel 700	8.17
	Inconel "713C"	7.913
	Waspaloy	8.23
	René 41	8.27
	Hastelloy alloy B	9.24
	Hastelloy alloy C	8.94
	Hastelloy alloy X	8.23
	Udimet 500	8.07
	GMR-235	8.03
Cobalt–chromium–nickel-base alloys	N-155 (HS-95)	8.23
	S-590	8.36

(*Continued*)

TABLE 1.18 (*Continued*) Density of Stainless Steels and Heat-Resistant Alloys

Class	Metal or Alloy	Density (Mg/m³)
Cobalt-base alloys	S-816	8.68
	V-36	8.60
	HS-25	9.13
	HS-36	9.04
	HS-31	8.61
	HS-21	8.30
Molybdenum-base alloy	Mo-0.5Ti	10.2

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 152–153.

TABLE 1.19 Density of Aluminum Alloys

Class	Metal or Alloy	Density (Mg/m³)
Pure aluminum	Aluminum (99.996%)	2.6989
Wrought alloys	EC, 1060 alloys	2.70
	1100	2.71
	2011	2.82
	2014	2.80
	2024	2.77
	2218	2.81
	3003	2.73
	4032	2.69
	5005	2.70
	5050	2.69
	5052	2.68
	5056	2.64
	5083	2.66
	5086	2.65
	5154	2.66
	5357	2.70
	5456	2.66
	6061, 6063	2.70
	6101, 6151	2.70
	7075	2.80
	7079	2.74
	7178	2.82
Casting alloys	A13	2.66
	43	2.69
	108, A108	2.79
	A132	2.72
	D132	2.76

(*Continued*)

TABLE 1.19 (*Continued*) Density of Aluminum Alloys

Class	Metal or Alloy	Density (Mg/m³)
	F132	2.74
	138	2.95
	142	2.81
	195, B195	2.81
	214	2.65
	220	2.57
	319	2.79
	355	2.71
	356	2.68
	360	2.64
	380	2.71
	750	2.88
	40E	2.81

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 152.

TABLE 1.20 Density of Copper and Copper Alloys

Class	Metal or Alloy	Density (Mg/m³)
Wrought coppers	Pure copper	8.96
	Electrolytic tough pitch copper (ETP)	8.89
	Deoxidized copper, high residual phosphorus (DHP)	8.94
	Free-machining copper, 0.5% Te	8.94
	Free-machining copper, 1.0% Pb	8.94
Wrought alloys	Gilding, 95%	8.86
	Commercial bronze, 90%	8.80
	Jewelry bronze, 87.5%	8.78
	Red brass, 85%	8.75
	Low brass, 80%	8.67
	Cartridge brass, 70%	8.53
	Yellow brass	8.47
	Muntz metal	8.39
	Leaded commercial bronze	8.83
	Low-leaded brass (tube)	8.50
	Medium-leaded brass	8.47
	High-leaded brass (tube)	8.53
	High-leaded brass	8.50
	Extra-high-leaded brass	8.50
	Free-cutting brass	8.50
	Leaded Muntz metal	8.41
	Forging brass	8.44
	Architectural bronze	8.47
	Inhibited admiralty	8.53

(*Continued*)

TABLE 1.20 (*Continued*) Density of Copper and Copper Alloys

Class	Metal or Alloy	Density (Mg/m^3)
	Naval brass	8.41
	Leaded naval brass	8.44
	Manganese bronze	8.36
	Phosphor bronze, 5%	8.86
	Phosphor bronze, 8%	8.80
	Phosphor bronze, 10%	8.78
	Phosphor bronze, 1.25%	8.89
	Free-cutting phosphor bronze	8.89
	Cupro-nickel, 30%	8.94
	Cupro-nickel, 10%	8.94
	Nickel silver, 65–18	8.73
	Nickel silver, 55–18	8.70
	High-silicon bronze	8.53
	Low-silicon bronze	8.75
	Aluminum bronze, 5% Al	8.17
	Aluminum–silicon bronze	7.69
	Aluminum bronze	7.78
	Aluminum bronze	7.58
	Beryllium copper	8.23
Casting alloys	Chromium copper (1% Cr)	8.7
	88Cu–10Sn–2Z	8.7
	88Cu–8Sn–4Zn	8.8
	89Cu–11Sn	8.78
	88Cu–6Sn–1.5Pb–4.5Zn	8.7
	87Cu–8Sn–1Pb–4Zn	8.8
	87Cu–10Sn–1Pb–2Zn	8.8
	80Cu–10Sn–10Pb	8.95
	83Cu–7Sn–7Pb–3Zn	8.93
	85Cu–5Sn–9Pb–1Zn	8.87
	78Cu–7Sn–15Pb	9.25
	70Cu–SSn–2SPb	9.30
	85Cu–5Sn–SPb–SZn	8.80
	83Cu–4Sn–6Pb–7Zn	8.6
	81Cu–3Sn–7Pb–9Zn	8.7
	76Cu–2.5Sn–6.5Pb–15Zn	8.77
	72Cu–1Sn–3Pb–24Zn	8.50
	67Cu–1Sn–3Pb–29Zn	8.45
	61Cu–1Sn–1Pb–37Zn	8.40
	Manganese bronze, 60 ksi	8.2
	Manganese bronze, 65 ksi	8.3
	Manganese bronze, 90 ksi	7.9
	Manganese bronze, 110 ksi	7.7

(*Continued*)

TABLE 1.20 (*Continued*) Density of Copper and Copper Alloys

Class	Metal or Alloy	Density (Mg/m^3)
	Aluminum bronze, alloy 9A	7.8
	Aluminum bronze, alloy 9B	7.55
	Aluminum bronze, alloy 9C	7.5
	Aluminum bronze, alloy 9D	7.7
	Nickel silver, 12% Ni	8.95
	Nickel silver, 16% Ni	8.95
	Nickel silver, 20% Ni	8.85
	Nickel silver, 25% Ni	8.8
	Silicon bronze	8.30
	Silicon brass	8.30

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 152.

TABLE 1.21 Density of Magnesium and Magnesium Alloys

Class	Metal or Alloy	Density (Mg/m^3)
Pure magnesium	Magnesium (99.8%)	1.738
Casting alloys	AM100A	1.81
	AZ63A	1.84
	AZ81A	1.80
	AZ9lA, B, C	1.81
	AZ92A	1.82
	HK31A	1.79
	HZ32A	1.83
	ZH42, ZH62A	1.86
	ZK51A	1.81
	ZE41A	1.82
	EZ33A	1.83
	EK30A	1.79
	EK41A	1.81
Wrought alloys	M1A	1.76
	A3A	1.77
	AZ31B	1.77
	PE	1.76
	AZ61A	1.80
	AZ80A	1.80
	ZK60A, B	1.83
	ZE10A	1.76
	HM21A	1.78
	HM31A	1.81

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 153.

TABLE 1.22 Density of Nickel and Nickel Alloys

Class	Metal or Alloy	Density (Mg/m³)
Pure	Nickel (99.95% Ni+Co)	8.902
	"A" Nickel	8.885
	"D" Nickel	8.78
	Duranickel	8.26
	Cast nickel	8.34
	Monel	8.84
	"K" Monel	8.47
	Monel (cast)	8.63
	"H" Monel (cast)	8.5
	"S" Monel (cast)	8.36
	Inconel	8.51
	Inconel (cast)	8.3
	Ni-o-nel	7.86
Nickel–molybdenum–chromium–iron alloys	Hastelloy B	9.24
	Hastelloy C	8.94
	Hastelloy D	7.8
	Hastelloy F	8.17
	Hastelloy N	8.79
	Hastelloy W	9.03
	Hastelloy X	8.23
Nickel–chromium–molybdenum–copper alloys	Illium G	8.58
	Illium R	8.58
Electrical resistance alloys	80Ni–20Cr	8.4
	60Ni–24Fe–16Cr	8.147
	35Ni–4SFe–20Cr	7.95
	Constantan	8.9

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 153.

TABLE 1.23 Density of Lead and Lead Alloys

Class	Metal or Alloy	Density (Mg/m^3)
Lead alloys	Chemical lead (99.90 + % Pb)	11.34
	Corroding lead (99.73 + % Pb)	11.36
	Arsenical lead	11.34
	Calcium lead	11.34
	5–95 solder	11.0
	20–80 solder	10.2
	50–50 solder	8.89
Antimonial lead alloys	1% antimonial lead	11.27
	Hard lead (96Pb–4Sb)	11.04
	Hard lead (94Pb–6Sb)	10.88
	8% antimonial lead	10.74
	9% antimonial lead	10.66
Lead-base babbitt alloys	Lead-base babbitt, SAE 13	10.24
	Lead-base babbitt, SAE 14	9.73
	Lead-base babbitt, Alloy 8	10.04
	Arsenical lead, babbitt (SAE 15)	10.1
	Arsenical lead, "G" babbitt	10.1

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 153.

TABLE 1.24 Density of Tin and Tin Alloys

Metal or Alloy	Density (Mg/m^3)
Pure tin	7.3
Soft solder (30% Pb)	8.32
Soft solder (37% Pb)	8.42
Tin babbitt, Alloy 1	7.34
Tin babbitt, Alloy 2	7.39
Tin babbitt, Alloy 3	7.46
Tin babbitt, Alloy 4	7.53
Tin babbitt, Alloy 5	7.75
White metal	7.28
Pewter	7.28

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 153.

TABLE 1.25 Density of Wrought Titanium Alloys

Class	Metal or Alloy	Density (Mg/m^3)
Commercially pure	99.5Ti	4.51
	99.2Ti	4.51
	99.1Ti	4.51
	99.0Ti	4.51
	99.2 Ti–0.2Pd	4.51
	Ti–0.8Ni–0.3Mo	4.54
Alpha alloys	Ti–5Al–2.5Sn	4.48
	Ti–5Al–2.5Sn (low O_2)	4.48
Near alpha alloys	Ti–8Al–1Mo–1V	4.37
	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	4.82
	Ti–6Al–2Sn–4Zr–2Mo	4.54
	Ti–5Al–5Sn–2Zr–2Mo–0.25Si	4.51
	Ti–6Al–2Nb–1Ta–1Mo	4.48
Alpha–beta alloys	Ti–8Mn	4.73
	Ti–3Al–2.5V	4.48
	Ti–6Al–4V	4.43
	Ti–6Al–4V (low O_2)	4.43
	Ti–6Al–6V–2Sn	4.54
	Ti–7Al–4Mo	4.48
	Ti–6Al–2Sn–4Zr–6Mo	4.65
	Ti–6Al–2Sn–2Zr–2Mo–2Cr–0.25Si	4.57
	Ti–10V–2Fe–3Al	4.65
Beta alloys	Ti–13V–11Cr–3Al	4.84
	Ti–8Mo–8V–2Fe–3Al	4.84
	Ti–3Al–8V–6Cr–4Mo–4Zr	4.82

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 511.

TABLE 1.26 Density of Titanium and Titanium Alloys

Metal or Alloy	Density (Mg/m^3)
99.9% Ti	4.507
99.2% Ti	4.507
99.0% Ti	4.52
Ti–6Al–4V	4.43
Ti–5Al–2.5Sn	4.46
Ti–2Fe–2Cr–2Mo	4.65
Ti–8Mn	4.71
Ti–7Al–4Mo	4.48
Ti–4Al–4Mn	4.52
Ti–4AI–3Mo–1V	4.507
Ti–2.5Al–16V	4.65

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 153.

TABLE 1.27 Density of Zinc and Zinc Alloys

Metal or Alloy	Density (Mg/m³)
Pure zinc	7.133
AG40A alloy	6.6
AC41A alloy	6.7
Commercial rolled zinc 0.08% Pb	7.14
Commercial rolled zinc 0.06 Pb, 0.06 Cd	7.14
Commercial rolled zinc 0.3 Pb, 0.3 Cd	7.14
Copper-hardened, rolled zinc (1% Cu)	7.18
Rolled zinc alloy (1Cu–0.010 Mg)	7.18
Zn–Cu–Ti alloy (0.8Cu, 0.15Ti)	7.18

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 153–154.

TABLE 1.28 Density of Permanent Magnet Materials

Metal or Alloy	Density (Mg/m³)
Cunico	8.30
Cunife	8.61
Comol	8.16
Alnico I	6.89
Alnico II	7.09
Alnico III	6.89
Alnico IV	7.00
Alnico V	7.31
Alnico VI	7.42

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 154.

TABLE 1.29 Density of Precious Metals

Metal or Alloy	Density (Mg/m³)
Silver	10.49
Gold	19.32
70Au–30Pt	19.92
Platinum	21.45
Pt–3.5Rh	20.9
Pt–5Rb	20.65
Pt–10Rh	19.97
Pt–20Rb	18.74
Pt–30Rh	17.62
Pt–40Rb	16.63
Pt–5Ir	21.49
Pt–10Ir	21.53

(*Continued*)

TABLE 1.29 (*Continued*) Density of Precious Metals

Metal or Alloy	Density (Mg/m³)
Pt–15Ir	21.57
Pt–20Ir	21.61
Pt–25Ir	21.66
Pt–30Ir	21.70
Pt–35Ir	21.79
Pt–5Ru	20.67
Pt–10Ru	19.94
Palladium	12.02
60Pd–40Cu	10.6
95.5Pd–4.5Ru	12.07
95.5Pd-45Ru	11.62

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 154.

TABLE 1.30 Density of Superalloys

Class	Alloy	Density (Mg/m³)
Iron-base alloys	Carpenter 20-Cb3	8.055
	Haynes 556	8.23
	Incoloy 800	7.94
	Incoloy 801	7.94
Cobalt-base alloys	Haynes 25(L-605)	9.13
	Haynes 188	9.13
	Stellite 6B	8.38
	UMCo 50	8.05
Nickel-base alloys	Hastelloy B–2	9.21
	Hastelloy C4	8.64
	Hastelloy C–276	8.90
	Hastelloy N	8.93
	Hastelloy S	8.76
	Hastelloy W	9.03
	Hastelloy X	8.23
	Inconel 600	8.42
	Inconel 625	8.44
	Inconel X-750	8.25
	René 41	8.25
	Udimet 500	8.14
	Udimet 700	7.92
	Waspaloy	8.20

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 386.

TABLE 1.31 Specific Heat of the Elements at 25°C

Element	C_p (cal/g · K)
Aluminum	0.215
Antimony	0.049
Argon	0.124
Arsenic	0.0785
Barium	0.046
Beryllium	0.436
Bismuth	0.0296
Boron	0.245
Bromine (Br_2)	0.113
Cadmium	0.0555
Calcium	0.156
Carbon, diamond	0.124
Carbon, graphite	0.170
Cerium	0.049
Cesium	0.057
Chlorine (Cl_2)	0.114
Chromium	0.107
Cobalt	0.109
Columbium (see Niobium)	
Copper	0.092
Dysprosium	0.0414
Erbium	0.0401
Europium	0.0421
Fluorine (F_2)	0.197
Gadolinium	0.055
Gallium	0.089
Germanium	0.077
Gold	0.0308
Hafnium	0.035
Helium	1.24
Holmium	0.0393
Hydrogen (H_2)	3.41
Indium	0.056
Iodine (I_2)	0.102
Iridium	0.0317
Iron (α)	0.106
Krypton	0.059
Lanthanum	0.047
Lead	0.038
Lithium	0.85
Lutetium	0.037
Magnesium	0.243
Manganese, α	0.114
Manganese, β	1.119

(*Continued*)

TABLE 1.31 (*Continued*) Specific Heat of the Elements at 25°C

Element	C_p (cal/g · K)
Mercury	0.0331
Molybdenum	0.599
Neodymium	0.049
Neon	0.246
Nickel	0.106
Niobium	0.064
Nitrogen (N_2)	0.249
Osmium	0.03127
Oxygen (O_2)	0.219
Palladium	0.0584
Phosphorus, white	0.181
Phosphorus, red, triclinic	0.160
Platinum	0.0317
Polonium	0.030
Potassium	0.180
Praseodymium	0.046
Promethium	0.0442
Protactinium	0.029
Radium	0.0288
Radon	0.0224
Rhenium	0.0329
Rhodium	0.0583
Rubidium	0.0861
Ruthenium	0.057
Samarium	0.043
Scandium	0.133
Selenium (Se_2)	0.0767
Silicon	0.168
Silver	0.0566
Sodium	0.293
Strontium	0.0719
Sulfur, yellow	0.175
Tantalum	0.0334
Technetium	0.058
Tellurium	0.0481
Terbium	0.0437
Thallium	0.0307
Thorium	0.0271
Thulium	0.0382
Tin (α)	0.0510
Tin (β)	0.0530
Titanium	0.125
Tungsten	0.0317

(*Continued*)

TABLE 1.31 (*Continued*) Specific Heat of the Elements at 25°C

Element	C_p (cal/g · K)
Uranium	0.0276
Vanadium	0.116
Xenon	0.0378
Ytterbium	0.0346
Yttrium	0.068
Zinc	0.0928
Zirconium	0.0671

Source: Data from R. C. Weast (Ed.), *Handbook of Chemistry and Physics*, 55th Edn., CRC Press, Cleveland, 1974, D-144; K. K. Kelly, *Bulletin 592*, Bureau of Mines, Washington, DC, 1961; and R. Hultgren, et al. *Selected Values of Thermodynamic Properties of Metals and Alloys*, 1963. Copyright Wiley-VCH Verlag GmbH & Co. KGaA.

TABLE 1.32 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

(*Continued*)

TABLE 1.32 (*Continued*) Thermal Conductivity of Metals (Part 1)

T (K)	Aluminum	Cadmium	Chromium	Copper	Gold
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		

Source: Data from C. Y. Ho, R. W. Powell, and P. E. Liley, *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.

Note: Values in parentheses are for liquid state.
Values are in watt/cm K.
These data apply only to metals of purity of at least 99.9%.
The third significant figure may not be accurate.

TABLE 1.33 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

(*Continued*)

TABLE 1.33 (*Continued*) Thermal Conductivity of Metals (Part 2)

T (K)	Iron	Lead	Magnesium	Mercury	Molybdenum
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

Source: Data from C. Y. Ho, R. W. Powell, and P. E. Liley, *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.

Note: Values are in watt/cm K.
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.

TABLE 1.34 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
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

(*Continued*)

TABLE 1.34 (*Continued*) Thermal Conductivity of Metals (Part 3)

T (K)	Nickel	Niobium	Platinum	Silver	Tantalum
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

Source: Data from C. Y. Ho, R. W. Powell, and P. E. Liley, *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.

Note: Values in parentheses are for liquid state Values are in watt/cm K.
These data apply only to metals of purity of at least 99.9%.
The third significant figure may not be accurate.

TABLE 1.35 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

(*Continued*)

TABLE 1.35 (*Continued*) Thermal Conductivity of Metals (Part 4)

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		

Source: Data from C. Y. Ho, R. W. Powell, and P. E. Liley, *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.

Note: Values in parentheses are for liquid state. Values are in watt/cm K.
These data apply only to metals of purity of at least 99.9%.
The third significant figure may not be accurate.

TABLE 1.36 Thermal Conductivity of Alloy Cast Irons

Description	Description	Thermal Conductivity W/(m · K)
Abrasion-resistant white irons	Low-C white iron	22
	Martensitic nickel–chromium iron	30
Corrosion-resistant irons	High-nickel gray iron	38–40
	High-nickel ductile iron	13.4
Heat-resistant gray irons	Medium-silicon iron	37
	High-chromium iron	20
	High-nickel iron	37–40
	Nickel–chromium–silicon iron	30
Heat-resistant ductile iron	High-nickel ductile (20 Ni)	13

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 172.

TABLE 1.37 Thermal Conductivity of Iron and Iron Alloys

Metal or Alloy	Thermal Conductivity Near Room Temperature ($cal/cm^2 \cdot cm \cdot s \cdot °C$)
Pure iron	0.178
Cast iron (3.16C, 1.54Si, 0.57Mn)	0.112
Carbon steel (0.23C, 0.64Mn)	0.124
Carbon steel (1.22C, 0.35Mn)	0.108
Alloy steel (0.34C, 0.55Mn, 0.78Cr, 3.53Ni, 0.39Mo, 0.05Cu)	0.079
Type 410	0.057
Type 304	0.036
T1 tool steel	0.058

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 156.

TABLE 1.38 Thermal Conductivity of Aluminum and Aluminum Alloys

Metal or Alloy	Designation	Thermal Conductivity Near Room Temperature ($cal/cm^2 \cdot cm \cdot s \cdot °C$)
Wrought alloys	EC(O)	0.57
	1060(O)	0.56
	1100	0.53
	2011(T3)	0.34
	2014(O)	0.46
	2024(O)	0.45
	2218(T72)	0.37
	3003(O)	0.46
	4032(O)	0.37
	5005	0.48
	5050(O)	0.46
	5052(O)	0.33
	5056(O)	0.28
	5083	0.28
	5086	0.30
	5154	0.30
	5357	0.40
	5456	0.28
	6061(O)	0.41
	6063(O)	0.52
	6101(T6)	0.52
	6151(O)	0.49
	7075(T6)	0.29
	7079(T6)	0.29
	7178	0.29
Casting alloys	A13	0.29
	43(F)	0.34

(*Continued*)

TABLE 1.38 (*Continued*) Thermal Conductivity of Aluminum and Aluminum Alloys

Metal or alloy	Designation	Thermal Conductivity Near Room Temperature (cal/cm² · cm · s · °C)
	108(F)	0.29
	A108	0.34
	A132(T551)	0.28
	D132(T5)	0.25
	F132	0.25
	138	0.24
	142 (T21, sand)	0.40
	195 (T4, T62)	0.33
	B195 (T4, T6)	0.31
	214	0.33
	200(T4)	0.21
	319	0.26
	355(T51, sand)	0.40
	356(T51, sand)	0.40
	360	0.35
	380	0.23
	750	0.44
	40E	0.33

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 156.

TABLE 1.39 Thermal Conductivity of Copper and Copper Alloys

Metal or Alloy	Designation	Thermal Conductivity Near Room Temperature (cal/cm² · cm · s · °C)
Wrought coppers	Pure copper	0.941
	Electrolytic tough pitch copper (ETP)	0.934
	Deoxidized copper high residual phosphorus (DHP)	0.81
	Free-machining copper (0.5% Te)	0.88
	Free-machining copper (1% Pb)	0.92
Wrought alloys	Gilding, 95%	0.56
	Commercial bronze, 90%	0.45
	Jewelry bronze, 87.5%	0.41
	Red brass, 85%	0.38
	Low brass, 80%	0.33
	Cartridge brass, 70%	0.29
	Yellow brass	0.28
	Muntz metal	0.29
	Leaded commercial bronze	0.43
	Low-leaded brass (tube)	0.28
	Medium-leaded brass	0.28
	High-leaded brass (tube)	0.28

(*Continued*)

TABLE 1.39 (*Continued*) Thermal Conductivity of Copper and Copper Alloys

Metal or Alloy	Designation	Thermal Conductivity Near Room Temperature (cal/cm^2 · cm · s · °C)
	High-leaded brass	0.28
	Extra-high-leaded brass	0.28
	Leaded Muntz metal	0.29
	Forging brass	0.28
	Architectural bronze	0.29
	Inhibited admiralty	0.26
	Naval brass	0.28
	Leaded naval brass	0.28
	Manganese bronze	0.26
	Phosphor bronze, 5%	0.17
	Phosphor bronze, 8%	0.15
	Phosphor bronze, 10%	0.12
	Phosphor bronze, 1.25%	0.49
	Free-cutting phosphor bronze	0.18
	Cupro-nickel, 30%	0.07
	Cupro-nickel, 10%	0.095
	Nickel silver, 65–18	0.08
	Nickel silver, 55–18	0.07
	Nickel silver, 65–12	0.10
	High-silicon bronze	0.09
	Low-silicon bronze	0.14
	Aluminum bronze, 5% Al	0.198
	Aluminum bronze	0.18
	Aluminum–silicon bronze	0.108
	Aluminum bronze	0.144
	Aluminum bronze	0.091
	Beryllium copper	0.20
Casting alloys	Chromium copper (1% Cr)	0.4
	89cu–11Sn	0.121
	88Cu–6Sn–1.5Pb–4.5Zn	18% of Cu
	87Cu–8Sn–1Pb–4Zn	12% of Cu
	87Cu–10Sn–1Pb–2Zn	12% of Cu
	80Cu–10Sn–10Pb	12% of Cu
	Manganese bronze, 110 ksi	9.05% of Cu
	Aluminum bronze, Alloy 9A	15% of Cu
	Aluminum bronze, Alloy 9B	16% of Cu
	Aluminum bronze, Alloy 9C	18% of Cu
	Aluminum bronze, Alloy 9D	12% of Cu
	Propeller bronze	11% of Cu
	Nickel silver, 12% Ni	7% of Cu
	Nickel silver, 16% Ni	7% of Cu
	Nickel silver, 20% Ni	6% of Cu
	Nickel silver. 25% Ni	6.5% of Cu
	Silicon bronze	7% of Cu

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 156.

TABLE 1.40 Thermal Conductivity of Magnesium and Magnesium Alloys

Metal or Alloy	Designation	Thermal Conductivity Near Room Temperature (cal/cm^2 · cm · s · °C)
Pure	Magnesium (99.8%)	0.367
Casting alloys	AM100A	0.17
	AZ63A	0.18
	AZ81A (T4)	0.12
	AZ91A, B, C	0.17
	AZ92A	0.17
	HK31A (T6, sand cast)	0.22
	HZ32A	0.26
	ZH42	0.27
	ZH62A	0.26
	ZK51A	0.26
	ZE41A (T5)	0.27
	EZ33A	0.24
	EK30A	0.26
	EK41A (T5)	0.24
Wrought alloys	M1A	0.33
	AZ31B	0.23
	AZ61A	0.19
	AZ80A	0.18
	ZK60A,B (F)	0.28
	ZE10A (O)	0.33
	HM21A (O)	0.33
	HM31A	0.25

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 156.

TABLE 1.41 Thermal Conductivity of Nickel and Nickel Alloys

Metal or Alloy	Thermal Conductivity Near Room Temperature (cal/cm^2 · cm · s · °C)
Nickel (99.95% Ni+Co)	0.22
"A" nickel	0.145
"D" nickel	0.115
Monel	0.062
"K" Monel	0.045
Inconel	0.036
Hastelloy B	0.027
Hastelloy C	0.03
Hastelloy D	0.05
Illium G	0.029
Illium R	0.031

(*Continued*)

TABLE 1.41 (*Continued*) Thermal Conductivity of Nickel and Nickel Alloys

Metal or Alloy	Thermal Conductivity Near Room Temperature (cal/cm² · cm · s · °C)
60Ni–24Fe–16Cr	0.032
35Ni–45Fe–20Cr	0.031
Constantan	0.051

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 156.

TABLE 1.42 Thermal Conductivity of Lead and Lead Alloys

Metal or Alloy	Thermal Conductivity Near Room Temperature (cal/cm² · cm · s · °C)
Corroding lead (99.73 + % Pb)	0.083
5–95 solder	0.085
20–80 solder	0.089
50–50 solder	0.111
1% antimonial lead	0.080
Hard lead (96Pb–4Sb)	0.073
Hard lead (94Pb–6Sb)	0.069
8% antimonial lead	0.065
9% antimonial lead	0.064
Lead-base babbitt (SAE 14)	0.057
Lead-base babbitt (alloy 8)	0.058

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 156.

TABLE 1.43 Thermal Conductivity of Tin, Titanium, Zinc, and their Alloys

Metal or Alloy	Designation	Thermal Conductivity Near Room Temperature (cal/cm² · cm · s · °C)
Tin and tin alloys	Pure tin	0.15
	Soft solder (63Sn–37Pb)	0.12
	Tin foil (92Sn–8Zn)	0.14
Titanium and titanium alloys	Titanium (99.0%)	0.043
	Ti–5Al–2.5Sn	0.019
	Ti–2Fe–2Cr–2Mo	0.028
	Ti–8Mn	0.026
Zinc and zinc alloys	Pure zinc	0.27
	AG40A alloy	0.27
	AC41A alloy	0.26
	Commercial rolled zinc 0.08 Pb	0.257
	Commercial rolled zinc 0.06 Pb, 0.06 Cd	0.257
	Rolled zinc alloy (1 CU, 0.010 Mg)	0.25
	Zn–Cu–Ti alloy (0.8 Cu, 0.15 Ti)	0.25

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 156.

TABLE 1.44 Thermal Conductivity of Pure Metals

Metal	Thermal Conductivity Near Room Temperature (cal/cm^2 · cm · s · °C)
Beryllium	0.35
Cadmium	0.22
Chromium	0.16
Cobalt	0.165
Germanium	0.14
Gold	0.71
Indium	0.057
Iridium	0.14
Lithium	0.17
Molybdenum	0.34
Niobium	0.13
Palladium	0.168
Platinum	0.165
Plutonium	0.020
Rhenium	0.17
Rhodium	0.21
Silicon	0.20
Silver	1.0
Sodium	0.32
Tantalum	0.130
Thallium	0.093
Thorium	0.090
Tungsten	0.397
Uranium	0.071
Vanadium	0.074
Yttrium	0.035

Source: Data from Michael Bauccio (Ed.,) *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 156.

TABLE 1.45 Thermal Expansion of Wrought Stainless Steels[a]

		Coefficient of Thermal Expansion (μm/m · °C)		
Type	UNS Designation	0–100°C	100–315°C	0–538°C
201	S20100	15.7	17.5	18.4
202	S20200	17.5	18.4	19.2
205	S20500	–	17.9	19.1
301	S30100	17.0	17.2	18.2
302	S30200	17.2	17.8	18.4
302B	S30215	16.2	18.0	19.4
303	S30300	17.2	17.8	18.4
304	S30400	17.2	17.8	18.4
S30430	S30430	17.2	17.8	–
305	S30500	17.2	17.8	18.4
308	S30800	17.2	17.8	18.4
309	S30900	15.0	16.6	17.2
310	S31000	15.9	16.2	17.0
314	S31400	–	15.1	–
316	S31600	15.9	16.2	17.5
317	S31700	15.9	16.2	17.5
317L	S31703	16.5	–	18.1
321	S32100	16.6	17.2	18.6
330	N08330	14.4	16.0	16.7
347	S34700	16.6	17.2	18.6
384	S38400	17.2	17.8	18.4
405	S40500	10.8	11.6	12.1
409	S40900	11.7	–	–
410	S41000	9.9	11.4	11.6
414	S41400	10.4	11.0	12.1
416	S41600	9.9	11.0	11.6
420	S42000	10.3	10.8	11.7
422	S42200	11.2	11.4	11.9
429	S42900	10.3	–	–
430	S43000	10.4	11.0	11.4
430F	S43020	10.4	11.0	11.4
431	S43100	10.2	12.1	–
434	S43400	10.4	11.0	11.4
436	S43600	9.3	–	–
440A	S44002	10.2	–	–
440C	S44004	10.2	–	–
444	S44400	10.0	10.6	11.4
446	S44600	10.4	10.8	11.2
PH 13–8 Mo	S13800	10.6	11.2	11.9
15–5 PH	S15500	10.8	11.4	–
17–4 PH	S17400	10.8	11.6	–
17–7 PH	S17700	11.0	11.6	–

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 360.

[a] Annealed condition.

TABLE 1.46 Thermal Expansion of Wrought Titanium Alloys

		Coefficient of Linear Thermal Expansion (μm/m · K)						
Class	Metal or Alloy	20–100°C	20–205°C	20–315°C	20–425°C	20–540°C	20–650°C	20–815°C
Commercially pure	99.5Ti	8.6	–	9.2	–	9.7	10.1	10.1
	99.2Ti	8.6	–	9.2	–	9.7	10.1	10.1
	99.1Ti	8.6	–	9.2	–	9.7	10.1	10.1
	99.0Ti	8.6	–	9.2	–	9.7	10.1	10.1
	99.2 Ti–0.2Pd	8.6	–	9.2	–	9.7	10.1	10.1
Alpha alloys	Ti–5Al–2.5Sn	9.4	–	9.5	–	9.5	9.7	10.1
	Ti–5Al–2.5Sn (low O_2)	9.4	–	9.5	–	9.7	9.9	10.1
Near alpha alloys	Ti–8Al–1Mo–1V	8.5	–	9.0	–	10.1	10.3	–
	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	8.5	–	9.2	–	9.4	–	–
	Ti–6Al–2Sn–4Zr–2Mo	7.7	–	8.1	–	8.1	–	–
	Ti–5Al–5Sn–2Zr–2Mo–0.25Si	–	–	–	–	–	–	10.3
	Ti–6Al–2Nb–1Ta–1Mo	–	–	–	–	–	9.0	–
Alpha–beta alloys	Ti–8Mn	8.6	9.2	9.7	10.3	10.8	11.7	12.6
	Ti–3Al–2.5V	9.5	–	9.9	–	9.9	–	–
	Ti–6Al–4V	8.6	9.0	9.2	9.4	9.5	9.7	–
	Ti–6Al–4V (low O_2)	8.6	9.0	9.2	9.4	9.5	9.7	–
	Ti–6Al–6V–2Sn	9.0	–	9.4	–	9.5	–	–
	Ti–7Al–4Mo	9.0	9.2	9.4	9.7	10.1	10.4	11.2
	Ti–6Al–2Sn–4Zr–6Mo	9.0	9.2	9.4	9.5	9.5	–	–
	Ti–6Al–2Sn–2Zr–2Mo–2Cr–0.25Si	–	–	9.2	–	–	–	–
Beta alloys	Ti–13V–11Cr–3Al	9.4	–	10.1	–	10.6	–	–
	Ti–8Mo–8V–2Fe–3Al	–	–	–	–	–	–	–
	Ti–3Al–8V–6Cr–4Mo–4Zr	–	–	–	9.68 (to 900°F)	–	–	–

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 511.

TABLE 1.47 Linear Thermal Expansion of Metals and Alloys

Class	Metal or Alloy	Temperature (°C)	Coefficient of Thermal Expansion (μm/m·°C)
Aluminum and aluminum alloys	Aluminum (99.996%)	20–100	23.6
Wrought alloys	EC, 1060, 1100	20–100	23.6
	2011, 2014	20–100	23.0
	2024	20–100	22.8
	2218	20–100	22.3
	3003	20–100	23.2
	4032	20–100	19.4
	5005, 5050, 5052	20– 100	23.8
	5056	20–100	24.1
	5083	20–100	23.4
	5086	60–300	23.9
	5154	20–100	23.9
	5357	20–100	23.7
	5456	20–100	23.9
	6061, 6063	20–100	23.4
	6101, 6151	20–100	23.0
	7075	20–100	23.2
	7079, 7178	20–100	23.4
Casting alloys	A13	20–100	20.4
	43 and 108	20–100	22.0
	A108	20–100	21.5
	A132	20–100	19.0
	D132	20–100	20.05
	F132	20–100	20.7
	138	20–100	21.4
	142	20–100	22.5
	195	20–100	23.0
	B195	20–100	22.0
	214	20–100	24.0
	220	20–100	25.0
	319	20–100	21.5
	355	20–100	22.0
	356	20–100	21.5
	360	20–100	21.0
	750	20–100	23.1
	40E	21–93	24.7
Copper and copper alloys			
Wrought coppers	Pure copper	20	16.5
	Electrolytic tough pitch copper (ETP)	20–100	16.8

(*Continued*)

TABLE 1.47 (*Continued*) Linear Thermal Expansion of Metals and Alloys

Class	Metal or Alloy	Temperature (°C)	Coefficient of Thermal Expansion (μm/m·°C)
	Deoxidized copper, high residual phosphorus (DHP)	20–300	17.7
	Oxygen-free copper	20–300	17.7
	Free-machining copper, 0.5% Te or 1% Pb	20–300	17.7
Wrought alloys	Gilding, 95%	20–300	18.1
	Commercial bronze, 90%	20–300	18.4
	Jewelry bronze, 87.5%	20–300	18.6
	Red brass, 85%	20–300	18.7
	Low brass, 80%	20–300	19.1
	Cartridge brass, 70%	20–300	19.9
	Yellow brass	20–300	20.3
	Muntz metal	20–300	20.8
	Leaded commercial bronze	20–300	18.4
	Low-leaded brass	20–300	20.2
	Medium-leaded brass	20–300	20.3
	High-leaded brass	20–300	20.3
	Extra-high-leaded brass	20–300	20.5
	Free-cutting brass	20–300	20.5
	Leaded Muntz metal	20–300	20.8
	Forging brass	20–300	20.7
	Architectural bronze	20–300	20.9
	Inhibited admiralty	20–300	20.2
	Naval brass	20–300	21.2
	Leaded naval brass	20–300	21.2
	Manganese bronze (longitudinal)	20–300	21.2
	Manganese bronze (transverse)	20–300	23.4
	Phosphor bronze, 5% (longitudinal)	20–300	17.8
	Phosphor bronze, 5% (transverse)	20–300	23.4
	Phosphor bronze, 8% (longitudinal)	20–300	18.2
	Phosphor bronze, 8% (transverse)	20–300	19.4
	Phosphor bronze, 10% (longitudinal)	20–300	18.4
	Phosphor bronze, 1.25%	20–300	17.8
	Free-cutting phosphor bronze	20–300	17.3
	Cupro-nickel, 30%	20–300	16.2
	Cupro-nickel, 10%	20–300	17.1
	Nickel silver, 65–18	20–300	16.2
	Nickel silver, 55–18	20–300	16.7
	Nickel silver, 65–12	20–300	16.2
	High-silicon bronze (longitudinal)	20–300	18.0
	High-silicon bronze (transverse)	20–300	23.4
	Low-silicon bronze (longitudinal)	20–300	17.9

(*Continued*)

TABLE 1.47 (*Continued*) Linear Thermal Expansion of Metals and Alloys

Class	Metal or Alloy	Temperature (°C)	Coefficient of Thermal Expansion (μm/m · °C)
	Low-silicon bronze (transverse)	20–300	21.1
	Aluminum bronze	20–300	16.4
	Aluminum–silicon bronze	20–300	18.0
	Aluminum bronze	20–300	16.8
	Beryllium copper	20–300	17.8
Casting alloys	88Cu–8Sn–4Zn	21–177	18.0
	89Cu–11Sn	20–300	18.4
	88Cu–6Sn–1.5Pb–4.5Zn	21–260	18.5
	87Cu–8Sn–1Pb–4Zn	21–177	18.0
	87Cu–10Sn–1Pb–2Zn	21–177	18.0
	80Cu–10Sn–10Pb	21–204	18.5
	78Cu–7Sn–15Pb	21–204	18.5
	85Cu–5Sn–5Pb– 5Zn	21–204	18.1
	72Cu–1Sn–3Pb–24Zn	21–93	20.7
	67Cu–1Sn–3Pb–29Zn	21–93	20.2
	61Cu–1Sn–1Pb–37Zn	21–260	21.6
Manganese bronze	Manganese bronze, 60 ksi	21–204	20.5
	Manganese bronze, 65 ksi	21–93	21.6
	Manganese bronze, 110 ksi	21–260	19.8
Iron and iron alloys	Pure iron	20	11.7
	Fe–C alloy 0.06% C	20–100	11.7
	Fe–C alloy 0.22% C	20–100	11.7
	Fe–C alloy 0.40% C	20–100	11.3
	Fe–C alloy 0.56% C	20–100	11.0
	Fe–C alloy 1.08% C	20–100	10.8
	Fe–C alloy 1.45% C	20–100	10.1
	Invar (36% Ni)	20	0–2
	13Mn–1.2C	20	18.0
	13Cr–0.35C	20–100	10.0
	12.3Cr–0.4Ni–0.09C	20–100	9.8
	17.7Cr–9.6Ni–0.06C	20–100	16.5
	18W–4Cr–1V	0–100	11.2
	Gray cast iron	0–100	10.5
	Malleable iron (pearlitic)	20–400	12
Lead and lead alloys	Corroding lead (99.73 + % Pb)	17–100	29.3
	5–95 solder	15–110	28.7
	20–80 solder	15–110	26.5
	50–50 solder	15–110	23.4
	1% antimonial lead	20–100	28.8
	8% antimonial lead	20–100	26.7

(*Continued*)

TABLE 1.47 (*Continued*) Linear Thermal Expansion of Metals and Alloys

Class	Metal or Alloy	Temperature (°C)	Coefficient of Thermal Expansion (μm/m·°C)
	9% antimonial lead	20–100	26.4
	Hard lead (96Pb–4Sb)	20–100	27.8
	Hard lead (94Pb–6Sb)	20–100	27.2
	Lead-base babbitt SAE 14	20–100	19.6
	Lead-base babbitt Alloy 8	20–100	24.0
Magnesium and magnesium alloys	Magnesium (99.8%)	20	25.2
Magnesium casting alloys	AM100A	18–100	25.2
	AZ63A	20–100	26.1
	AZ91A,B,C	20–100	26
	AZ92A	18–100	25.2
	HZ32A	20–200	26.7
	ZH42	20–200	27
	ZH62A	20–200	27.1
	ZK51A	20	26.1
	EZ33A	20–100	26.1
	EK30A, EK41A	20–100	26.1
Magnesium wrought alloys	M1A, A3A	20–100	26
	AZ31B,PE	20–100	26
	AZ61A, Z80A	20–100	26
	ZK60A, B	20–100	26
	HM31A	20–93	26.1
Nickel and nickel alloys	Nickel (99.95% Ni + Co)	0–100	13.3
	Duranickel	0–100	13.0
	Monel	0–100	14.0
	Monel (cast)	25–100	12.9
	Inconel	20–100	11.5
	Ni-o-nel	27–93	12.9
	Hastelloy B	0–100	10.0
	Hastelloy C	0–100	11.3
	Hastelloy D	0–100	11.0
	Hastelloy F	20–100	14.2
	Hastelloy N	21–204	10.4
	Hastelloy W	23–100	11.3
	Hastelloy X	26–100	13.8
	Illium G	0–100	12.19
	Illium R	0–100	12.02
	80Ni–20Cr	20–1000	17.3
	60Ni–24Fe–l6Cr	20–1000	17.0
	35Ni–45Fe–20Cr	20–500	15.8
	Constantan	20–1000	18.8

(*Continued*)

TABLE 1.47 (*Continued*) Linear Thermal Expansion of Metals and Alloys

Class	Metal or Alloy	Temperature (°C)	Coefficient of Thermal Expansion (μm/m·°C)
Tin and tin alloys	Pure tin	0–100	23
	Solder (70Sn–30Pb)	15–110	21.6
	Solder (63Sn–37Pb)	15–110	24.7
Titanium and titanium alloys	99.9% Ti	20	8.41
	99.0% Ti	93	8.55
	Ti–5Al–2.5Sn	93	9.36
	Ti–8Mn	93	8.64
Zinc and zinc alloys	Pure zinc	20–250	39.7
	AG40A alloy	20–100	27.4
	AC41A alloy	20–100	27.4
	Commercial rolled zinc 0.08 Pb	20–40	32.5
	Commercial rolled zinc 0.3 Pb, 0.3 Cd	20–98	33.9
	Rolled zinc alloy (1Cu, 0.010 Mg)	20–100	34.8
	Zn–Cu–Ti alloy (0.8Cu, 0.15Ti)	20–100	24.9
Pure metals	Beryllium	25–100	11.6
	Cadmium	20	29.8
	Calcium	0–400	22.3
	Chromium	20	6.2
	Cobalt	20	13.8
	Gold	20	14.2
	Iridium	20	6.8
	Lithium	20	56
	Manganese	0–100	22
	Palladium	20	11.76
	Platinum	20	8.9
	Rhenium	20–500	6.7
	Rhodium	20–100	8.3
	Ruthenium	20	9.1
	Silicon	0–1400	5
	Silver	0–100	19.68
	Tungsten	27	4.6
	Vanadium	23–100	8.3
	Zirconium	–	5.85

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 154–155.

TABLE 1.48 ASTM B 601 Temper Designation Codes for Copper and Copper Alloys

Class	Temper Designation	Temper Name or Material Condition
Cold-worked tempers[a]	H00	1/8 hard
	H01	1/4 hard
	H02	1/2 hard
	H03	3/4 hard
	H04	Hard
	H06	Extra hard
	H08	Spring
	H10	Extra spring
	H12	Special Spring
	H13	Ultra Spring
	H14	Super Spring
Cold-worked tempers[b]	H50	Extruded and drawn
	H52	Pierced and drawn
	H55	Light drawn, light cold rolled
	H58	Drawn general purpose
	H60	Cold heading; forming
	H63	Rivet
	H64	Screw
	H66	Bolt
	H70	Bending
	H80	Hard drawn
	H85	Medium hard-drawn electrical wire
	H86	Hard-drawn electrical wire
	H90	As-finned
Cold-worked and stress-relieved tempers	HR01	H01 and stress relieved
	HR02	H02 and stress relieved
	HR04	H04 and stress relieved
	HR08	H08 and stress relieved
	HR10	H10 and stress relieved
	HR20	As-finned
	HR50	Drawn and stress relieved
Cold-rolled and order-strengthened tempers[c]	HT04	H04 and order heat treated
	HT08	H08 and order heat treated

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 439.

[a] Cold-worked tempers to meet standard requirements based on cold rolling or cold drawing.

[b] Cold-worked tempers to meet standard requirements based on temper names applicable to specific processes.

[c] Tempers produced by controlled amounts of cold work following by thermal treatment to produce order strengthening.

TABLE 1.49 Temper Designation System for Aluminum Alloys

Temper	Definition
F	As fabricated
O	Annealed
H1	Strain-hardened only
H2	Strain-hardened and partially annealed
H3	Strain-hardened and stabilized (mechanical properties stabilized by low-temperature thermal treatment)
T1	Cooled from an elevated temperature shaping process and naturally aged to a substantially stable condition
T2	Cooled from an elevated temperature shaping process, cold-worked, and naturally aged to a substantially stable condition
T3	Solution heat-treated, cold-worked, and naturally aged to a substantially stable condition
T4	Solution heat-treated and naturally aged to a substantially stable condition
T5	Cooled from an elevated temperature shaping process and artificially aged
T6	Solution heat-treated and artificially aged
T7	Solution heat-treated and stabilized
T8	Solution heat-treated, cold-worked, and artificially aged
T9	Solution heat-treated, artificially aged, and cold-worked
T10	Cooled from an elevated temperature shaping process, cold-worked, and artificially aged

Source: Data from *Metals Handbook,* 9th Edn., Vol. 2, American Society for Metals, Metals Park, OH, 1979, pp. 24–27.

TABLE 1.50 Tool Steel Softening after 100 h

Type	Original Hardness (HRC)	Hardness (HRC) after 100 h at					
		480°C	540°C	600°C	650°C	700°C	760°C
H13	60.2	48.7	46.3	29.0	22.7	20.1	13.9
	41.7	38.6	39.3	27.7	23.7	20.2	13.2
H21	49.2	48.7	47.6	37.2	27.4	19.8	16.2
	36.7	34.8	34.9	32.6	27.1	19.8	14.9
H23	40.8	40.0	40.6	40.8	38.6	33.2	26.8
	38.9	38.9	38.0	38.0	37.1	32.6	26.6
H26	61.0	60.6	60.3	47.1	38.4	26.9	21.3
	42.9	42.4	42.3	41.3	34.9	26.4	21.1

Source: Data from *ASM Metals Reference Book*, Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 426.

TABLE 1.51 Tensile Strength of Tool Steels

Type	Condition	Tensile Strength (MPa)
L2	Annealed	710
	Oil quenched from 855°C and single tempered at	
	205°C	2000
	315°C	1790
	425°C	1550
	540°C	1275
	650°C	930
L6	Annealed	655
	Oil quenched from 845°C and single tempered at	
	315°C	2000
	425°C	1585
	540°C	1345
	650°C	965
S1	Annealed	690
	Oil quenched from 930°C and single tempered at	
	205°C	2070
	315°C	2030
	425°C	1790
	540°C	1680
	650°C	1345
S5	Annealed	725
	Oil quenched from 870°C and single tempered at	
	205°C	2345
	315°C	2240
	425°C	1895
	540°C	1520
	650°C	1035
S7	Annealed	640
	Fan cooled from 940°C and single tempered at	
	205°C	2170
	315°C	1965
	425°C	1895
	540°C	1820
	650°C	1240

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 241.

TABLE 1.52 Tensile Strength of Gray Cast Irons

SAE Grade	Maximum Tensile Strength (MPa)
G1800	118
G2500	173
G2500a	173
G3000	207
C3500	241
G3500b	1241
G3500c	1241
G4000	276
G4000d	1276

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 166–167.

TABLE 1.53 Tensile Strength of Gray Cast Iron Bars

ASTM Class	Tensile Strength (MPa)
20	152
25	179
30	214
35	252
40	293
50	362
60	431

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 166–167.

TABLE 1.54 Tensile Strength of Ductile Irons

Specification Number	Grade or Class	Tensile Strength (MPa)
ASTM A395–76, ASME SA395	60–40–18	414
ASTM A476–70(d); SAE AMS5316	80–60–03	552
ASTM A536–72, MIL–1–11466B(MR)	60–40–18	414
	65–45–12	448
	80–55–06	552
	100–70–03	689
	120–90–02	827
SAE J434c	D4018	414
	D4512	448
	D5506	552
	D7003	689
MIL–I–24137(Ships)	Class A	414
	Class B	379
	Class C	345

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 169.

TABLE 1.55 Tensile Strength of Malleable Iron Castings

Specification Number	Grade or Class	Tensile Strength (MPa)
Ferritic ASTM A47, A338; ANSI G48.1;		
FED QQ–I–666c	32510	345
	35018	365
ASTM A197		276
Pearlitic and martensitic ASTM A220; ANSI C48.2;		
MIL–I–11444B	40010	414
	45008	448
	45006	448
	50005	483
	60004	552
	70003	586
	80002	655
	90001	724
Automotive		
ASTM A602; SAE J158	M3210	345
	M4504[a]	448
	M5003[a]	517
	M5503[b]	517
	M7002[b]	621
	M8501[b]	724

Source: Data from *ASM Metals Reference Book*, Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 171.
[a] Air quenched and tempered.
[b] Liquid quenched and tempered.

TABLE 1.56 Tensile Strength of Austenitic Stainless Steels

Type	Form	Condition	ASTM Specification	Tensile Strength (MPa)
Type 301 (UNS S30100)	Bar, wire, plate, sheet, strip	Annealed	A167	515
Type 302 (UNS S30200)	Bar	Hot finished and annealed	A276	515
		Cold finished and annealed[a]	A276	620
		Cold finished and annealed[b]	A276	515
Type 302B (UNS S30215)	Bar	Hot finished and annealed	A276	515
		Cold finished and annealed[a]	A276	620
		Cold finished and annealed[b]	A276	515
Type 302Cu (UNS S30430)	Bar	Annealed	A493	450–585
Types 303 (UNS S30300) and 303Se (UNS S30323)	Bar	Annealed	A581	585
	Wire	Annealed	A581	585–860
		Cold worked	A581	790–1000
Type 304 (UNS S30400)	Bar	Hot finished and annealed	A276	515
		Cold finished and annealed[a]	A276	620
		Cold finished and annealed[b]	A276	515

(*Continued*)

TABLE 1.56 (*Continued*) Tensile Strength of Austenitic Stainless Steels

Type	Form	Condition	ASTM Specification	Tensile Strength (MPa)
Type 304L (UNS S30403)	Bar	Hot finished and annealed	A276	480
		Cold finished and annealed[a]	A276	620
		Cold finished and annealed[b]	A276	480
Types 304N (UNS S30451) and 316N (UNS S31651)	Bar	Annealed	A276	550
Type 304LN	Bar	Annealed	–	515
Type 305 (UNS S30500)	Bar	Hot finished and annealed	A276	515
		Cold finished and annealed[a]	A276	260
		Cold finished and annealed[b]	A276	515
Types 308 (UNS S30800), 321 (UNS S32100), 347 (UNS34700) and 348 (UNS S34800)	Bar	Hot finished and annealed	A276	515
		Cold finished and annealed[a]	A276	620
		Cold finished and annealed[b]	A276	515
Type 308L	Bar	Annealed	–	550
Types 309 (UNS S30900), 309S (UNS S30908), 310 (UNS S31000) and 310S (UNS S31008)	Bar	Hot finished and annealed	A276	515
		Cold finished and annealed[a]	A276	620
		Cold finished and annealed[b]	A276	515
Type 312 Weld metal	–		MIL–E–19933	655
Type 314 (UNS S31400)	Bar	Hot finished and annealed	A276	515
		Cold finished and annealed[a]	A276	620
		Cold finished and annealed[b]	A276	515
Type 316 (UNS S31600)	Bar	Hot finished and annealed	A276	515
		Cold finished and annealed[a]	A276	620
		Cold finished and annealed[b]	A276	515
Type 316F (UNS S31620)	Bar	Annealed	–	585
Type 316L (UNS S31603)	Bar	Hot finished and annealed	A276	480
		Cold finished and annealed[a]	A276	620
		Cold finished and annealed[b]	A276	480
Type 316LN	Bar	Annealed	–	515
Type 317 (UNS S31700)	Bar	Hot finished and annealed	A276	515
		Cold finished and annealed[a]	A276	620
		Cold finished and annealed[b]	A276	515
Type 317L (UNS S31703)	Bar	Annealed	–	585
Type 317LM	Bar, plate, sheet, strip	Annealed	–	515
Type 329 (UNS S32900)	Bar	Annealed	–	724
Type 330 (UNS N08330)	Bar	Annealed	B511	480
Type 330HC	Bar, wire, strip	Annealed	–	585
Types 384 (UNS S38400)	Bar	Annealed	A493	415–550
Types 385 (UNS38500)	Bar	Annealed	A493	415–550

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 364–366.

[a] Up to 13 mm thick.

[b] Over 13 mm thick.

TABLE 1.57 Tensile Strength of Ferritic Stainless Steels

Type	ASTM Specification	Form	Condition	Tensile Strength (MPa)
Type 405 (UNS S40500)	A580	Wire	Annealed	480
	A580		Annealed, cold finished	480
Type 409 (UNS S40900)	–	Bar	Annealed	450[a]
Type 429 (UNS S42900)	–	Bar	Annealed	490[a]
Type 430 (UNS S43000)	A276	Bar	Annealed, hot finished	480
	A276		Annealed, cold finished	480
Type 430F (UNS S43020)	A581	Wire	Annealed	585–860
Type 430Ti (UNS S43036)	–	Bar	Annealed	515[a]
Type 434 (UNS S43400)	–	Wire	Annealed	545[a]
Type 436 (UNS S43600)	–	Sheet, Strip	Annealed	530[a]
Type 442 (UNS S44200)	–	Bar	Annealed	550[a]
Type 444 (UNS S44400)	A176	Plate, sheet, strip	Annealed	415
Type 446 (UNS S44600)	A276	Bar	Annealed, hot finished	480
	A276		Annealed, cold finished	480

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 368.

[a] Typical values.

TABLE 1.58 Tensile Strength of Precipitation-Hardening Austenitic Stainless Steels

Type	Form	Condition	Tensile Strength (MPa)
PH 13–8 Mo (UNS S13800)	Bar, plate, sheet, strip	H950	1520
		H1000	1380
15–5 PH (UNS S15500) and 17–4 PH (UNS S17400)	Bar, plate, sheet, strip	H900	1310
		H925	1170
		H1025	1070
		H1075	1000
		H1100	965
		H1150	930
		H1150M	795
17–7 PH (UNS S17700)	Bar	RH950	1275
		TH1050	1170

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 371.

TABLE 1.59 Tensile Strength of High-Nitrogen Austenitic Stainless Steels

Type	ASTM Specification	Form	Condition	Tensile Strength (MPa)
Type 201 (UNS S20100)	A276	Bar	Annealed	515
Type 202 (UNS S20200)	A276	Bar	Annealed	515
Type 205 (UNS S20500)	–	Plate	Annealed[a]	830
Type 304N (UNS S30451)	A276	Bar	Annealed	550
Type 304HN (UNS S30452)	–	Bar	Annealed	620
Type 316N (UNS S31651)	A276	Bar	Annealed	550

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 367.

[a] Typical values.

TABLE 1.60 Tensile Strength of Martensitic Stainless Steels

Type	STM Specification	Form	Condition	Tensile Strength (MPa)
Type 403 (UNS S40300)	A276	Bar	Annealed, hot finished	485
	A276		Annealed, cold finished	485
	A276		Intermediate temper, hot finished	690
	A276		Intermediate temper, cold finished	690
	A276		Hard temper, hot finished	825
	A276		Hard temper, cold finished	825
Type 410 (UNS S41000)	A276	Bar	Annealed, hot finished	485
	A276		Annealed, cold finished	485
	A276		Intermediate temper, hot finished	690
	A276		Intermediate temper, cold finished	690
	A276		Hard temper, hot finished	825
	A276		Hard temper, cold finished	825
Type 410S (UNS S41008)	A176	Plate, sheet, strip	Annealed	415
Type 410Cb (UNS S41040)	A276	Bar	Annealed, hot finished	485
	A276		Annealed, cold finished	485
	A276		Intermediate temper, hot finished	860
	A276		Intermediate temper, cold finished	860
Type 414 (UNS S41400)	A276	Bar	Intermediate temper, hot finished	795
	A276		Intermediate temper, cold finished	795
Type 414L	–	Bar	Annealed	795
Types 416 (UNS S41600) and 416Se (UNS S41623)	A581	Wire	Annealed	585–860
	A581		Intermediate temper	795–1000
	A581		Hard temper	965–1210
Type 420 (UNS S42000)	–	Bar	Tempered 205°C	1720
	A580	Wire	Annealed, cold finished	860 max
Type 422 (UNS S42200)	A565	Bar	Intermediate and hard tempers[a]	965

(*Continued*)

TABLE 1.60 (*Continued*) Tensile Strength of Martensitic Stainless Steels

Type	STM Specification	Form	Condition	Tensile Strength (MPa)
Type 431 (UNS S43100)	–	Bar	Tempered 260°C	1370
	–		Tempered 595°C	965
Type 440A (UNS S44002)	–	Bar	Annealed	725
	–		Tempered 315°C	1790
Type 440B (UNS S44003)	–	Bar	Annealed	740
	–		Tempered 315°C	1930
Type 440C (UNS S44004)	–	Bar	Annealed	760
	–		Tempered 315°C	1970
Type 501 (UNS S50100)	–	Bar, plate	Annealed	485
	–		Tempered 540°C	1210
Type 502 (UNS S50200)	–	Bar, plate	Annealed	485

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 369–370.

[a] Heat treated for high-temperature service.

TABLE 1.61 Tensile Strength of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Tensile Strength (MPa)
C10100 Oxygen-free electronic	99.99 Cu	F, R, W, T, P, S	221–455
C10200 Oxygen-free copper	99.95 Cu	F, R, W, T, P, S	221–455
C10300 Oxygen-free, extra-low phosphorus	99.95 Cu, 0.003 P	F, R, T, P, S	221–379
C10400, C10500, C10700 Oxygen-free, silver-bearing	99.95 Cu[b]	F, R, W, S	221–455
C10800 Oxygen-free, low phosphorus	99.95 Cu, 0.009 P	F, R, T, P	221–379
CS11000 Electrolytic tough pitch copper	99.90 Cu, 0.04 O	F, R, W, T, P, S	221–455
C11100 Electrolytic tough pitch, anneal resistant	99.90 Cu, 0.04 O, 0.01 Cd	W	455
C11300, C11400, C11500, C11600 Silver-bearing tough pitch copper	99.90 Cu, 0.04 O, Ag[c]	F, R, W, T, S	221–455
C12000, C12100	99.9 Cu[d]	F, T, P	221–393
C12200 Phosphorus deoxidized copper, high residual phosphorus	99.90 Cu, 0.02 P	F, R, T, P	221–379
C12500, C12700, C12800, C12900, C13000 Fire-refined tough pitch with silver	99.88 Cu[e]	F, R, W, S	221–462
C14200 Phosphorus deoxidized, arsenical	99.68 Cu, 0.3 As, 0.02 P	F, R, T	221–379
C19200	98.97 Cu, 1.0 Fe, 0.03 P	F, T	255–531
C14300	99.9 Cu, 0.1 Cd	F	221–400
C14310	99.8 Cu, 0.2 Cd	F	221–400
C14500 Phosphorus deoxidized, tellurium bearing	99.5 Cu, 0.50 Te, 0.008 P	F, R, W, T	221–386
C14700 Sulfur bearing	99.6 Cu, 0.40 S	R, W	221–393
C15000 Zirconium copper	99.8 Cu, 0.15 Zr	R, W	200–524

(*Continued*)

TABLE 1.61 (*Continued*) Tensile Strength of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Tensile Strength (MPa)
C15500	99.75 Cu, 0.06 P, 0.11 Mg, Ag[f]	F	276–552
C15710	99.8 Cu, 0.2 Al_2O_3	R, W	324–724
C15720	99.6 Cu, 0.4 Al_2O_3	F, R	462–614
C15735	99.3 Cu, 0.7 Al_2O_3	R	483–586
C15760	98.9 Cu, 1.1 Al_2O_3	F, R	483–648
C16200 Cadmium copper	99.0 Cu, 1.0 Cd	F, R, W	241–689
C16500	98.6 Cu, 0.8 Cd, 0.6 Sn	F, R, W	276–655
C17000 Beryllium copper	99.5 Cu, 1.7 Be, 0.20 Co	F, R	483–1310
C17200 Beryllium copper	99.5 Cu, 1.9 Be, 0.20 Co	F, R, W, T, P, S	469–1462
C17300 Beryllium copper	99.5 Cu, 1.9 Be, 0.40 Pb	R	469–1479
C17500 Copper–cobalt–beryllium alloy	99.5 Cu, 2.5 Co, 0.6 Be	F, R	310–793
C18200, C18400, C18500 Chromium copper	99.5 Cu[g]	F, W, R, S, T	234–593
C18700 Leaded copper	99.0 Cu, 1.0 Pb	R	221–379
C18900	98.75 Cu, 0.75 Sn, 0.3 Si, 0.20 Mn	R, W	262–655
C19000 Copper–nickel–phosphorus alloy	98.7 Cu, 1.1 Ni, 0.25 P	F, R, W	262–793
C19100 Copper–nickel–phosphorus–tellurium alloy	98.15 Cu, 1.1 Ni, 0.50 Te, 0.25 P	R, F	248–717
C19400	97.5 Cu, 2.4 Fe, 0.13 Zn, 0.03 P	F	310–524
C19500	97.0 Cu, 1.5 Fe, 0.6 Sn, 0.10 P, 0.80 Co	F	552–669
C21000 Gilding, 95%	95.0 Cu, 5.0 Zn	F, W	234–441
C22000 Commercial bronze, 90%	90.0 Cu, 10.0 Zn	F, R, W, T	255–496
C22600 Jewelry bronze, 87.5%	87.5 Cu, 12.5 Zn	F, W	269–669
C23000 Red brass, 85%	85.0 Cu, 15.0 Zn	F, W, T, P	269–724
C24000 Low brass, 80%	80.0 Cu, 20.0 Zn	F, W	290–862
C26000 Cartridge brass, 70%	70.0 Cu, 30.0 Zn	F, R, W, T	303–896
C26800, C27000 Yellow brass	65.0 Cu, 35.0 Zn	F, R, W	317–883
C28000 Muntz metal	60.0 Cu, 40.0 Zn	F, R, T	372–510
C31400 Leaded commercial bronze	89.0 Cu, 1.75 Pb, 9.25 Zn	F, R	255–414
C31600 Leaded commercial bronze, nickel-bearing	89.0 Cu, 1.9 Pb, 1.0 Ni, 8.1 Zn	F, R	255–462
C33000 Low-leaded brass tube	66.0 Cu, 0.5 Pb, 33.5 Zn	T	324–517
C33200 High-leaded brass tube	66.0 Cu, 1.6 Pb, 32.4 Zn	T	359–517
C33500 Low-leaded brass	65.0 Cu, 0.5 Pb, 34.5 Zn	F	317–510
C34000 Medium-leaded brass	65.0 Cu, 1.0 Pb, 34.0 Zn	F, R, W, S	324–607
C34200 High-leaded brass	64.5 Cu, 2.0 Pb, 33.5 Zn	F, R	338–586
C34900	62.2 Cu, 0.35 Pb, 37.45 Zn	R, W	365–469
C35000 Medium-leaded brass	62.5 Cu, 1.1 Pb, 36.4 Zn	F, R	310–655
C35300 High-leaded brass	62.0 Cu, 1.8 Pb, 36.2 Zn	F, R	338–586
C35600 Extra high-leaded brass	63.0 Cu, 2.5 Pb, 34.5 Zn	F	338–510
C36000 Free-cutting brass	61.5 Cu, 3.0 Pb, 35.5 Zn	F, R, S	339–469

(*Continued*)

TABLE 1.61 (*Continued*) Tensile Strength of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Tensile Strength (MPa)
C36500 to C36800 Leaded Muntz metal	60.0 Cu[h], 0.6 Pb, 39.4 Zn	F	372 (as hot rolled)
C37000 Free-cutting Muntz metal	60.0 Cu, 1.0 Pb, 39.0 Zn	T	372–552
C37700 Forging brass	59.0 Cu, 2.0 Pb, 39.0 Zn	R, S	359 (as extruded)
C38500 Architectural bronze	57.0 Cu, 3.0 Pb, 40.0 Zn	R, S	414 (as extruded)
C40500	95 Cu, 1 Sn, 4 Zn	F	269–538
C40800	95 Cu, 2 Sn, 3 Zn	F	290–545
C41100	91 Cu, 0.5 Sn, 8.5 Zn	F, W	269–731
C41300	90.0 Cu, 1.0 Sn, 9.0 Zn	F, R, W	283–724
C41500	91 Cu, 1.8 Sn, 7.2 Zn	F	317–558
C42200	87.5 Cu, 1.1 Sn, 11.4 Zn	F	296–607
C42500	88.5 Cu, 2.0 Sn, 9.5 Zn	F	310–634
C43000	87.0 Cu, 2.2 Sn, 10.8 Zn	F	317–648
C43400	85.0 Cu, 0.7 Sn, 14.3 Zn	F	310–607
C43500	81.0 Cu, 0.9 Sn, 18.1 Zn	F, T	317–552
C44300, C44400, C44500 Inhibited admiralty	71.0 Cu, 28.0 Zn, 1.0 Sn	F, W, T	331–379
C46400 to C46700 Naval brass	60.0 Cu, 39.25 Zn, 0.75 Sn	F, R, T, S	379–607
C48200 Naval brass, medium-leaded	60.5 Cu, 0.7 Pb, 0.8 Sn, 38.0 Zn	F, R, S	386–517
C48500 Leaded naval brass	60.0 Cu, 1.75 Pb, 37.5 Zn, 0.75 Sn	F, R, S	379–531
C50500 Phosphor bronze, 1.25% E	98.75 Cu, 1.25 Sn, trace P	F, W	276–545
C51000 Phosphor bronze, 5% A	95.0 Cu, 5.0 Sn, trace P	F, R, W, T	324–965
C51100	95.6 Cu, 4.2 Sn, 0.2 P	F	317–710
C52100 Phosphor bronze, 8% C	92.0 Cu, 8.0 Sn, trace P	F, R, W	379–965
C52400 Phosphor bronze, 10% D	90.0 Cu, 10.0 Sn, trace P	F, R, W	455–1014
C54400 Free-cutting phosphor bronze	88.0 Cu, 4.0 Pb, 4.0 Zn, 4.0 Sn	F, R	303–517
C60800 Aluminum bronze, 5%	95.0 Cu, 5.0 Al	T	414
C61000	92.0 Cu, 8.0 Al	R, W	483–552
C61300	92.65 Cu, 0.35 Sn, 7.0 Al	F, R, T, P, S	483–586
C61400 Aluminum bronze, D	91.0 Cu, 7.0 Al, 2.0 Fe	F, R, W, T, P, S	524–614
C61500	90.0 Cu, 8.0 Al, 2.0 Ni	F	483–1000
C61800	89.0 Cu, 1.0 Fe, 10.0 Al	R	552–586
C61900	86.5 Cu, 4.0 Fe, 9.5 Al	F	634–1048
C62300	87.0 Cu, 10.0 Al, 3.0 Fe	F, R	517–676
C62400	86.0 Cu, 3.0 Fe, 11.0 Al	F, R	621–724
C62500	82.7 Cu, 4.3 Fe, 13.0 Al	F, R	689
C63000	82.0 Cu, 3.0 Fe, 10.0 Al, 5.0 Ni	F, R	621–814
C63200	82.0 Cu, 4.0 Fe, 9.0 Al, 5.0 Ni	F, R	621–724
C63600	95.5 Cu, 3.5 Al, 1.0 Si	R, W	414–579

(*Continued*)

TABLE 1.61 (*Continued*) Tensile Strength of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Tensile Strength (MPa)
C63800	99.5 Cu, 2.8 Al, 1.8 Si, 0.40 Co	F	565–896
C64200	91.2 Cu, 7.0 Al	F, R	517–703
C65100 Low-silicon bronze, B	98.5 Cu, 1.5 Si	R, W, T	276–655
C65500 High-silicon bronze, A	97.0 Cu, 3.0 Si	F, R, W, T	386–1000
C66700 Manganese brass	70.0 Cu, 28.8 Zn, 1.2 Mn	F, W	315–689
C67400	58.5 Cu, 36.5 Zn, 1.2 Al, 2.8 Mn, 1.0 Sn	F, R	483–634
C67500 Manganese bronze, A	58.5 Cu, 1.4 Fe, 39.0 Zn, 1.0 Sn, 0.1 Mn	R, S	448–579
C68700 Aluminum brass, arsenical	77.5 Cu, 20.5 Zn, 2.0 Al, 0.1 As	T	414
C68800	73.5 Cu, 22.7 Zn, 3.4 Al, 0.40 Co	F	565–889
C69000	73.3 Cu, 3.4 Al, 0.6 Ni, 22.7 Zn	F	496–896
C69400 Silicon red brass	81.5 Cu, 14.5 Zn, 4.0 Si	R	552–689
C70400	92.4 Cu, 1.5 Fe, 5.5 Ni, 0.6 Mn	F, T	262–531
C70600 Copper nickel, 10%	88.7 Cu, 1.3 Fe, 10.0 Ni	F, T	303–414
C71000 Copper nickel, 20%	79.00 Cu, 21.0 Ni	F, W, T	338–655
C71500 Copper nickel, 30%	70.0 Cu, 30.0 Ni	F, R, T	372–517
C71700	67.8 Cu, 0.7 Fe, 31.0 Ni, 0.5 Be	F, R, W	483–1379
C72500	88.20 Cu, 9.5 Ni, 2.3 Sn	F, R, W, T	379–827
C73500	72.0 Cu, 18.0 Ni, 10.0 Zn	F, R, W, T	345–758
C74500 Nickel silver, 65–10	65.0 Cu, 25.0 Zn, 10.0 Ni	F, W	338–896
C75200 Nickel silver, 65–18	65.0 Cu, 17.0 Zn, 18.0 Ni	F, R, W	386–710
C75400 Nickel silver, 65–15	65.0 Cu, 20.0 Zn, 15.0 Ni	F	365–634
C75700 Nickel silver, 65–12	65.0 Cu, 23.0 Zn, 12.0 Ni	F, W	359–641
C76200	59.0 Cu, 29.0 Zn, 12.0 Ni	F, T	393–841
C77000 Nickel silver, 55–18	55.0 Cu, 27.0 Zn, 18.0 Ni	F, R, W	414–1000
C72200	82.0 Cu, 16.0 Ni, 0.5 Cr, 0.8 Fe, 0.5 Mn	F, T	317–483
C78200 Leaded nickel silver, 65–8–2	65.0 Cu, 2.0 Pb, 25.0 Zn, 8.0 Ni	F	365–627

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 442–454.

[a] F, flat products; R, rod; W, wire; T, tube; P, pipe; S, shapes.

[b] C10400, 8 oz/ton Ag; C10500, 10 oz/ton; C10700, 25 oz/ton.

[c] C11300, 8 oz/ton Ag; C11400, 10 oz/ton; C11500, 16 oz/ton; C11600, 25 oz/ton.

[d] C12000, 0.008 P; C12100, 0.008 P and 4 oz/ton Ag.

[e] C12700, 8 oz/ton Ag; C12800, 10 oz/ton; C12900, 16 oz/ton; C13000, 25 oz/ton.

[f] 8.30 oz/ton Ag.

[g] C18200, 0.9 Cr; C18400, 0.8 Cr; C18500, 0.7 Cr.

[h] Rod, 61.0 Cu min.

TABLE 1.62 Tensile Strength of Aluminum Casting Alloys

Alloy AA No.	Temper	Tensile Strength (MPa)
201.0	T4	365
	T6	485
	T7	460
206.0, A206.0	T7	435
208.0	F	145
242.0	T21	185
	T571	220
	T77	205
	T571	275
	T61	325
295.0	T4	220
	T6	250
	T62	285
296.0	T4	255
	T6	275
	T7	270
308.0	F	195
319.0	F	185
	T6	250
	F	235
	T6	280
336.0	T551	250
	T65	325
354.0	T61	380
355.0	T51	195
	T6	240
	T61	270
	T7	265
	T71	175
	T51	210
	T6	290
	T62	310
	T7	280
	T71	250
356.0	T51	175
	T6	230
	T7	235
	T71	195
	T6	265
	T7	220
357.0, A357.0	T62	360

(*Continued*)

TABLE 1.62 (*Continued*) Tensile Strength of Aluminum Casting Alloys

Alloy AA No.	Temper	Tensile Strength (MPa)
359.0	T61	330
	T62	345
360.0	F	325
A360.0	F	320
380.0	F	330
383.0	F	310
384.0, A384.0	F	330
390.0	F	280
	T5	300
A390.0	F, T5	180
	T6	280
	T7	250
	F, T5	200
	T6	310
	T7	260
413.0	F	300
A413.0	F	290
443.0	F	130
B443.0	F	159
C443.0	F	228
514.0	F	170
518.0	F	310
520.0	T4	330
535.0	F	275
712.0	F	240
713.0	T5	210
	T5	220
771.0	T6	345
850.0	T5	160

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 306–307.

TABLE 1.63 Tensile Strength of Wrought Aluminum Alloys

Alloy	Temper	Tensile Strength (MPa)
1050	0	76
	H14	110
	H16	130
	H18	160
1060	0	69
	H12	83
	H14	97
	H16	110
	H18	130
1100	0	90
	H12	110
	H14	125
	H16	145
	H18	165
1350	0	83
	H12	97
	H14	110
	H16	125
	H19	185
2011	T3	380
	T8	405
2014	0	185
	T4	425
	T6	485
Alclad 2014	0	170
	T3	435
	T4	420
	T6	470
2024	0	185
	T3	485
	T4, T351	470
	T361	495
Alclad 2024	0	180
	T	450
	T4, T351	440
	T361	460
	T81, T851	450
	T861	485
2036	T4	340
2048		455
2124	T851	490
2218	T61	405
	T71	345
	T72	330

(*Continued*)

TABLE 1.63 (*Continued*) Tensile Strength of Wrought Aluminum Alloys

Alloy	Temper	Tensile Strength (MPa)
2219	0	170
	T42	360
	T31, T351	360
	T37	395
	T62	415
	T81, T851	455
	T87	475
2618	All	440
3003 and	0	110
Alclad 3003	H12	130
	H14	150
	H16	180
	H18	200
3004 and	0	180
Alclad 3004	H32	215
	H34	240
	H36	260
	H38	285
3105	0	115
	H12	150
	H14	170
	H16	195
	H18	215
	H25	180
4032	T6	380
4043	0	145
	H18	285
5005	0	125
	H12	140
	H14	160
	H16	180
	H18	200
	H32	140
	H34	160
	H36	180
	H38	200
5050	0	145
	H32	170
	H34	195
	H36	205
	H38	220

(*Continued*)

TABLE 1.63 (*Continued*) Tensile Strength of Wrought Aluminum Alloys

Alloy	Temper	Tensile Strength (MPa)
5052	0	195
	H32	230
	H34	260
	H36	275
	H38	290
5056	0	290
	H18	435
	H38	415
5083	0	290
	H112	305
	H113	315
	H321	315
	H323, H32	325
	H343, H34	345
5086	0	260
	H32, H116, H117	290
	H34	325
	H112	270
5154	0	240
	H32	270
	H34	290
	H36	310
	H38	330
	H112	240
5182	0	275
	H32	315
	H34	340
	H19[a]	420
5252	H25	235
	H28, H38	285
5254	0	240
5254	H32	270
	H34	290
	H36	310
	H38	330
	H112	240
5454	0	250
	H32	275
	H34	305
	H36	340
	H38	370
	H111	260
	H112	250
	H311	260

(*Continued*)

TABLE 1.63 (*Continued*) Tensile Strength of Wrought Aluminum Alloys

Alloy	Temper	Tensile Strength (MPa)
5456	0	310
	H111	325
	H112	310
	H321, H116	350
5457	0	130
	H25	180
	H28, H38	205
5652	0	195
	H32	230
	H34	260
	H36	275
	H38	290
5657	H25	160
	H28, H38	195
6005	T1	170
	T5	260
6009	T4	235
	T6	345
6010	T4	255
6061	0	125
	T4, T451	240
	T6, T651	310
Alclad 6061	0	115
	T4, T451	230
	T6, T651	290
6063	0	90
	T1	150
	T4	170
	T5	185
	T6	240
	T83	255
	T831	205
	T832	290
6066	0	150
	T4, T451	360
	T6, T651	395
6070	0	145
	T4	315
	T6	380
6101	Hlll	97
6151	T6	220
6201	T6	330
	T81	330

(*Continued*)

TABLE 1.63 (*Continued*) Tensile Strength of Wrought Aluminum Alloys

Alloy	Temper	Tensile Strength (MPa)
6205	Tl	260
	T5	310
6262	T9	400
6351	T4	250
	T6	310
6463	Tl	150
	T5	185
	T6	240
7005	0	193
	T53	393
	T6, T63, T6351	372
7050	T736	515
7075	0	230
	T6, T651	570
	T73	505
Alclad 7075	0	220
	T6, T651	525
7175	T66	595
	T736	525
7475	T61	525

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 299–302.

[a] Properties for this temper are those of container end stock 0.25–0.38 mm thick.

TABLE 1.64 Tensile Strength of Cobalt-Base Superalloys

Alloy	Temperature (°C)	Tensile Strength (MPa)
Haynes 25 (L–605) sheet	21	1010
	540	800
	650	710
	760	455
	870	325
Haynes 188, sheet	21	960
	540	740
	650	710
	760	635
	870	420
S-816, bar	21	965
	540	840
	650	765
	760	650
	870	360

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 387.

TABLE 1.65 Tensile Strength of Nickel-Base Superalloys

Alloy	Temperature (°C)	Tensile Strength (MPa)
Astroloy, bar	21	1410
	540	1240
	650	1310
	760	1160
	870	770
D-979, bar	21	1410
	540	1300
	650	1100
	760	7
	870	345
Hastelloy X, sheet	21	785
	540	650
	650	570
	760	435
	870	255
IN-102, bar	21	960
	540	825
	650	710
	760	440
	870	215
Inconel 600, bar	21	620
	540	580
	650	450
	760	185
	870	105
Inconel 601, sheet	21	740
	540	725
	650	525
	760	290
	870	160
Inconel 625, bar	21	855
	540	745
	650	710
	760	505
	870	285
Inconel 706, bar	21	1300
	540	1120
	650	1010
	760	690
Inconel 718, bar	21	1430
	540	1280
	650	1230
	760	950
	870	340

(*Continued*)

TABLE 1.65 (*Continued*) Tensile Strength of Nickel-Base Superalloys

Alloy	Temperature (°C)	Tensile Strength (MPa)
Inconel 718, sheet	21	1280
	540	1140
	650	1030
	760	675
Inconel X-750, bar	21	1120
	540	965
	650	825
	760	485
	870	235
M-252, bar	21	1240
	540	1230
	650	1160
	760	945
	870	510
Nimonic 75, bar	21	750
	540	635
	650	538
	760	290
	870	145
Nimonic 80A, bar	21	1240
	540	1100
	650	1000
	760	760
	870	400
Nimonic 90, bar	21	1240
	540	1100
	650	1030
	760	825
	870	430
Nimonic 105, bar	21	1140
	540	1100
	650	1080
	760	965
	870	605
Nimonic 115, bar	21	1240
	540	1090
	650	1120
	760	1080
	870	825
Pyromet 860, bar	21	1300
	540	1250
	650	1110
	760	910

(*Continued*)

TABLE 1.65 (*Continued*) Tensile Strength of Nickel-Base Superalloys

Alloy	Temperature (°C)	Tensile Strength (MPa)
René 41, bar	21	1420
	540	1400
	650	1340
	760	1100
	870	620
René 95, bar	21	1620
	540	1540
	650	1460
	760	1170
Udimet 500, bar	21	1310
	540	1240
	650	1210
	760	1040
	870	640
Udimet 520, bar	21	1310
	540	1240
	650	1170
	760	725
	870	515
Udimet 700, bar	21	1410
	540	1280
	650	1240
	760	1030
	870	690
Udimet 710, bar	21	1190
	540	1150
	650	1290
	760	1020
	870	705
Unitemp AF2-1DA, bar	21	1290
	540	1340
	650	1360
	760	1150
	870	830
Waspaloy, bar	21	1280
	540	1170
	650	1120
	760	795
	870	525

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 387–389.

TABLE 1.66 Tensile Strength of Wrought Titanium Alloys at Room Temperature

Class	Alloy	Condition	Tensile Strength (MPa)
Commercially pure	99.5 Ti	Annealed	331
	99.2 Ti	Annealed	434
	99.1 Ti	Annealed	517
	99.0 Ti	Annealed	662
	99.2Ti–0.2Pd	Annealed	434
	Ti–0.8Ni–0.3Mo	Annealed	517
Alpha alloys	Ti–5Al–2.5Sn	Annealed	862
	Ti–5Al–2.5Sn (low O_2)	Annealed	807
Near alpha alloys	Ti–8Al–1Mo–1V	Duplex annealed	1000
	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	Duplex annealed	1103
	Ti–6Al–2Sn–4Zr–2Mo	Duplex annealed	979
	Ti–5Al–2Sn–2Zr–2Mo–0.25Si	975°C (1/2 h), AC+595°C (2 h), AC	1048
	Ti–6Al–2Nb–1Ta–1Mo	As rolled 2.5 cm (1 in.) plate	855
	Ti–6Al–2Sn–1.5Zr–1Mo–0.35Bi–0.1Si	Beta forge + duplex anneal	1014
Alpha–beta Alloys	Ti–8Mn	Annealed	945
	Ti–3Al–2.5V	Annealed	689
	Ti–6Al–4V	Annealed	993
		Solution + age	1172
	Ti–6Al–4V (low O_2)	Annealed	896
	Ti–6Al–6V–2Sn	Annealed	1069
		Solution + age	1276
	Ti–7Al–4Mo	Solution + age	1103
	Ti–6Al–2Sn–4Zr–6Mo	Solution + age	1269
	Ti–6Al–2Sn–2Zr–2Mo– 2Cr–0.25Si	Solution + age	1276
	Ti–10V–2Fe–3Al	Solution + age	1276
Beta alloys	Ti–13V–1Cr–3Al	Solution + age	1220
			1276
	Ti–8Mo–8V–2Fe–3Al	Solution + age	1310
	Ti–3Al–8V–6Cr–4Mo–4Zr	Solution + age	1448
		Annealed	883
	Ti–11.5Mo–6Zr–4.5Sn	Solution + age	1386

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 512.

TABLE 1.67 Tensile Strength of Wrought Titanium Alloys at High Temperature

Class	Alloy	Condition	Test Temperature (°C)	Tensile Strength (MPa)
Commercially pure	99.5 Ti	Annealed	315	152
	99.2 Ti	Annealed	315	193
	99.1 Ti	Annealed	315	234
	99.0 Ti	Annealed	315	310
	99.2Ti–0.2Pd	Annealed	315	186
	Ti–0.8Ni–0.3Mo	Annealed	205	345
	Ti–0.8Ni–0.3Mo	Annealed	315	324
Alpha alloys	Ti–5Al–2.5Sn	Annealed	315	565
	Ti–5Al–2.5Sn (low O_2)	Annealed	–195	1241
			–255	1579
Near alpha alloys	Ti-8Al–1Mo–1V	Duplex annealed	315	793
			425	738
			540	621
	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	Duplex annealed	315	896
			425	827
			540	758
	Ti–6Al–2Sn–4Zr–2Mo	Duplex annealed	315	772
			425	703
			540	648
	Ti–5Al–2Sn–2Zr–2Mo–0.25Si	975°C (1/2 h), AC + 595°C (2 h), AC	315	793
			425	779
			540	689
	Ti–6Al–2Nb–1Ta–1Mo	As rolled 2.5 cm (1 in.) plate	315	586
			425	517
			540	483
	Ti–6Al–2Sn–1.5Zr–1Mo–0.35Bi–0.1Si	Beta forge + duplex anneal	480	724
Alpha–beta Alloys	Ti–8Mn	Annealed	315	717
	Ti–3Al–2.5V	Annealed	315	483
	Ti–6Al–4V	Annealed	315	724
		Annealed	425	669
		Annealed	540	531
		Solution + age	315	862
		Solution + age	425	800
		Solution + age	540	655
	Ti–6Al–4V (low O_2)	Annealed	160	1517
	Ti–6Al–6V–2Sn	Annealed	315	931
		Solution + age	315	979
	Ti–7Al–4Mo	Solution + age	315	976
			425	848

(*Continued*)

TABLE 1.67 (*Continued*) Tensile Strength of Wrought Titanium Alloys at High Temperature

Class	Alloy	Condition	Test Temperature (°C)	Tensile Strength (MPa)
	Ti–6Al–2Sn–4Zr–6Mo	Solution + age	315	1020
			425	951
			540	848
	Ti–6Al–2Sn–2Zr–2Mo–2Cr–0.25Si	Solution + age	315	979
	Ti–10V–2Fe–3Al	Solution + age	205	1117
			315	1103
Beta alloys	Ti–13V–1Cr–3Al	Solution + age	315	883
			425	1103
	Ti–8Mo–8V–2Fe–3Al	Solution + age	315	1131
	Ti–3Al–8V–6Cr–4Mo–4Zr	Solution + age	315	1034
			425	938
		Annealed	315	724
	Ti–11.5Mo–6Zr–4.5Sn	Solution + age	315	903

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 512.

TABLE 1.68 Tensile Strength of Refractory Metal Alloys

Class	Alloy	Alloying Additions (%)	Form	Condition	Temperature (°F)	Tensile Strength (ksi)
Niobium and niobium alloys	Pure niobium	–	All	Recrystallized	2000	10
	Nb–1Zr	1 Zr	All	Recrystallized	2000	23
	C103(KbI-3)	10 Hf, 1 Ti 0.7 Zr	All	Recrystallized	2000	27
	SCb291	10 Ta, 10 W	Bar, sheet	Recrystallized	2000	32
	C129	10 W, 10 Hf, 0.1 Y	Sheet	Recrystallized	2400	26
	FS85	28 Ta, 11 W, 0.8 Zr	Sheet	Recrystallized	2400	23
	SU31	17 W, 3.5 Hf, 0.12 C, 0.03 Si	Bar, sheet	Special thermal processing	2400	40
Molybdenum and molybdenum alloys	Pure molybdenum	–	All	Stress-relieved annealed	1800	52
	Doped Mo	K, Si; ppm levels	Wire, sheet	Cold worked	3000	30
	Low C Mo	None	All	Stress-relieved annealed	1800	50
	TZM	0.5 Ti, 0.08 Zr, 0.015 C	All	Stress-relieved annealed	2400	45
	TZC	1.0 Ti, 0.14 Zr, 0.02—0.08 C	All	Stress-relieved annealed	2400	55
	Mo–5Re	5 Re	All	Stress-relieved annealed	3000	2
	Mo–30W	30 W	All	Stress-relieved annealed	2000	50
Tantalum alloys	Unalloyed	None	All	Recrystallized	2400	8.5
	FS61	7.5 W (P/M)	Wire, sheet	Cold worked	75	165
	FS63	2.5 W, 0.15 Nb	All	Recrystallized	200	46
	TA–10W	10 W	All	Recrystallized	2400	50

(*Continued*)

TABLE 1.68 (*Continued*) Tensile Strength of Refractory Metal Alloys

Class	Alloy	Alloying Additions (%)	Form	Condition	Temperature (°F)	Tensile Strength (ksi)
	KBI-40	40 Nb	All	Recrystallized	500	42
Tungsten alloys	Unalloyed	None	Bar, sheet, wire	Stress-relieved annealed	3000	25
	Doped	K, Si, Al; ppm levels	Wire	Cold worked	3000	94
	W–1 ThO_2	1 ThO_2	Bar, sheet, wire	Stress-relieved annealed	3000	37
	W–2 ThO_2	2 ThO_2	Bar, sheet, wire	Stress-relieved annealed	3000	30
	W–3 ThO_2	3 ThO_2	Bar, wire	Stress-relieved annealed	3000	30
	W–4 ThO_2	4 ThO_2	Bar	Stress-relieved annealed	3000	30
	W–15 Mo	15 Mo	Bar, wire	Stress-relieved annealed	3000	36
	W–50 Mo	50 Mo	Bar, wire	Stress-relieved annealed	3000	20
	W–3 Re	3 Re	Wire	Cold worked	–	–
	W–25 Re	25 Re	Bar, sheet, wire	Stress-relieved annealed	3000	33

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 390.

Note: To convert ksi to MPa, multiply by 6.89.

TABLE 1.69 Compressive Strength of Gray Cast Iron Bars

ASTM Class	Compressive Strength (MPa)
20	572
25	669
30	752
35	855
40	965
50	1130
60	1293

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 166–167.

TABLE 1.70 Yield Strength of Tool Steels

Type	Condition	0.2% Yield Strength (MPa)
L2	Annealed	510
	Oil quenched from 855°C and single tempered at	
	205°C	1790
	315°C	1655
	425°C	1380
	540°C	1170
	650°C	760
L6	Annealed	380
	Oil quenched from 845°C and single tempered at	
	315°C	1790
	425°C	1380
	540°C	1100
	650°C	830

(*Continued*)

TABLE 1.70 (*Continued*) Yield Strength of Tool Steels

Type	Condition	0.2% Yield Strength (MPa)
S1	Annealed	415
	Oil quenched from 930°C and single tempered at	
	205°C	1895
	315°C	1860
	425°C	1690
	540°C	1525
	650°C	1240
S5	Annealed	440
	Oil quenched from 870°C and single tempered at	
	205°C	1930
	315°C	1860
	425°C	1690
	540°C	1380
	650°C	1170
S7	Annealed	380
	Fan cooled from 940°C and single tempered at	
	205°C	1450
	315°C	1585
	425°C	1410
	540°C	1380
	650°C	1035

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 241.

TABLE 1.71 Yield Strength of Ductile Irons

Specification Number	Grade or Class	Yield Strength (MPa)
ASTM A395–76; ASME SA395	60–40–18	276
ASTM A476–70(d); SAE AMS5316	80–60–03	414
ASTM A536–72; MIL–1–11466B(MR)	60–40–18	276
	65–45–12	310
	80–55–06	379
	100–70–03	483
	120–90–02	621
SAE J434c	D4018	276
	D4512	310
	D5506	379
	D7003	483
MIL–I–24137(Ships)	Class A	310
	Class B	207
	Class C	172

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 169.

TABLE 1.72 Yield Strength of Malleable Iron Castings

Specification Number	Grade or Class	Yield Strength (MPa)
Ferritic		
ASTM A47, A338; ANSI G48.1;		
FED QQ–I–666c	32510	224
	35018	241
ASTM A197		207
Pearlitic and Martensitic		
ASTM A220; ANSI C48.2;		
MIL–I–11444B	40010	276
	45008	310
	45006	310
	50005	345
	60004	414
	70003	483
	80002	552
	90001	621
Automotive		
ASTM A602; SAE J158	M3210	224
	M4504[a]	310
	M5003[a]	345
	M5503[b]	379
	M7002[b]	483
	M8501[b]	586

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 171.

[a] Air quenched and tempered.

[b] Liquid quenched and tempered.

TABLE 1.73 Yield Strength of Austenitic Stainless Steels

Type	Form	Condition	ASTM Specification	0.2% Yield Strength (MPa)
Type 301 (UNS S30100)	Bar, wire, plate, sheet, strip	Annealed	A167	205
Type 302 (UNS S30200)	Bar	Hot finished and annealed	A276	205
		Cold finished and annealed[a]	A276	310
		Cold finished and annealed[b]	A276	205
Type 302B (UNS S30215)	Bar	Hot finished and annealed	A276	205
		Cold finished and annealed[a]	A276	310
		Cold finished and annealed[b]	A276	205
Types 303 (UNS S30300) and 303Se (UNS S30323)	Bar	Annealed	A581	240
Type 304 (UNS S30400)	Bar	Hot finished and annealed	A276	205
		Cold finished and annealed[a]	A276	310
		Cold finished and annealed[b]	A276	205

(*Continued*)

TABLE 1.73 (*Continued*) Yield Strength of Austenitic Stainless Steels

Type	Form	Condition	ASTM Specification	0.2% Yield Strength (MPa)
Type 304L (UNS S30403)	Bar	Hot finished and annealed	A276	170
		Cold finished and annealed[a]	A276	310
		Cold finished and annealed[b]	A276	170
Types 304N (UNS S30451) and 316N (UNS S31651)	Bar	Annealed	A276	240
Type 304LN	Bar	Annealed	–	205
Type 305 (UNS S30500)	Bar	Hot finished and annealed	A276	205
		Cold finished and annealed[a]	A276	310
		Cold finished and annealed[b]	A276	205
Types 308 (UNS S30800), 321 (UNS S32100), 347 (UNS34700), and 348 (UNS S34800)	Bar	Hot finished and annealed	A276	205
		Cold finished and annealed[a]	A276	310
		Cold finished and annealed[b]	A276	205
Type 308L	Bar	Annealed	–	207
Types 309 (UNS S30900), 309S (UNS S30908), 310 (UNS S31000), and 310S (UNS S31008)	Bar	Hot finished and annealed	A276	205
		Cold finished and annealed[a]	A276	310
		Cold finished and annealed[b]	A276	205
Type 314 (UNS S31400)	Bar	Hot finished and annealed	A276	205
		Cold finished and annealed[a]	A276	310
		Cold finished and annealed[b]	A276	205
Type 316 (UNS S31600)	Bar	Hot finished and annealed	A276	205
		Cold finished and annealed[a]	A276	310
		Cold finished and annealed[b]	A276	205
Type 316F (UNS S31620)	Bar	Annealed	–	240
Type 316L (UNS S31603)	Bar	Hot finished and annealed	A276	170
		Cold finished and annealed[a]	A276	310
		Cold finished and annealed[b]	A276	170
Type 316LN	Bar	Annealed	–	205
Type 317 (UNS S31700)	Bar	Hot finished and annealed	A276	205
		Cold finished and annealed[a]	A276	310
		Cold finished and annealed[b]	A276	205
Type 317L (UNS S31703)	Bar	Annealed	–	240
Type 317LM	Bar, plate, sheet, strip	Annealed	–	205
Type 329 (UNS S32900)	Bar	Annealed	–	550
Type 330 (UNS N08330)	Bar	Annealed	B511	210
Type 330HC	Bar, wire, strip	Annealed	–	290

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 364–366.

[a] Up to 13 mm thick.

[b] Over 13 mm thick.

TABLE 1.74 Yield Strength of Ferritic Stainless Steels

Type	ASTM Specification	Form	Condition	0.2% Yield Strength (MPa)
Type 405 (UNS S40500)	A580	Wire	Annealed	275
	A580		Annealed, cold finished	275
Type 409 (UNS S40900)	–	Bar	Annealed	240[a]
Type 429 (UNS S42900)	–	Bar	Annealed	310[a]
Type 430 (UNS S43000)	A276	Bar	Annealed, hot finished	275
	A276		Annealed, cold finished	275
Type 430Ti (UNS S43036)	–	Bar	Annealed	310[a]
Type 434 (UNS S43400)	–	Wire	Annealed	415[a]
Type 436 (UNS S43600)	–	Sheet, strip	Annealed	365[a]
Type 442 (UNS S44200)	–	Bar	Annealed	310[a]
Type 444 (UNS S44400)	A176	Plate, sheet, strip	Annealed	275
Type 446 (UNS S44600)	A276	Bar	Annealed, hot finished	275
	A276		Annealed, cold finished	275

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 368.
[a] Typical values.

TABLE 1.75 Yield Strength of Martensitic Stainless Steels

Type	ASTM Specification	Form	Condition	0.2% Yield Strength (MPa)
Type 403 (UNS S40300)	A276	Bar	Annealed, hot finished	275
	A276		Annealed, cold finished	275
	A276		Intermediate temper, hot finished	550
	A276		Intermediate temper, cold finished	550
	A276		Hard temper, hot finished	620
	A276		Hard temper, cold finished	620
Type 410 (UNS S41000)	A276	Bar	Annealed, hot finished	275
	A276		Annealed, cold finished	275
	A276		Intermediate temper, hot finished	550
	A276		Intermediate temper, cold finished	550
	A276		Hard temper, hot finished	620
	A276		Hard temper, cold finished	620
Type 410S (UNS S41008)	A176	Plate, sheet, strip	Annealed	205
Type 410Cb (UNS S41040)	A276	Bar	Annealed, hot finished	275
	A276		Annealed, cold finished	275
	A276		Intermediate temper, hot finished	690
	A276		Intermediate temper, cold finished	690
Type 414 (UNS S41400)	A276	Bar	Intermediate temper, hot finished	620
	A276		Intermediate temper, cold finished	620
Type 414L	–	Bar	Annealed	550
Type 420 (UNS S42000)	–	Bar	Tempered 205°C	1480
Type 422 (UNS S42200)	A565	Bar	Intermediate and hard tempers for high-temperature service	760

(*Continued*)

TABLE 1.75 (*Continued*) Yield Strength of Martensitic Stainless Steels

Type	ASTM Specification	Form	Condition	0.2% Yield Strength (MPa)
Type 431 (UNS S43100)	–	Bar	Tempered 260°C	1030
	–		Tempered 595°C	795
Type 440A (UNS S44002)	–	Bar	Annealed	415
	–		Tempered 315°C	1650
Type 440B (UNS S44003)	–	Bar	Annealed	425
	–		Tempered 315°C	1860
Type 440C (UNS S44004)	–	Bar	Annealed	450
	–		Tempered 315°C	1900
Type 501 (UNS S50100)	–	Bar, plate	Annealed	205
	–		Tempered 540°C	965
Type 502 (UNS S50200)	–	Bar, plate	Annealed	205

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 369–370.

TABLE 1.76 Yield Strength of Precipitation-Hardening Austenitic Stainless Steels

Type	Form	Condition	0.2% Yield Strength (MPa)
PH 13–8 Mo (UNS S13800)	Bar, plate, sheet, strip	H950	1410
		H1000	1310
15–5 PH (UNS S15500) and 17–4 PH (UNS S17400)	Bar, plate, sheet, strip	H900	1170
		H925	1070
		H1025	1000
		H1075	860
		H1100	795
		H1150	725
		H1150M	515
17–7 PH (UNS S17700)	Bar	RH950	1030
		TH1050	965

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn, ASM International, Materials Park, OH, 1993, p. 371.

TABLE 1.77 Yield Strength of High-Nitrogen Austenitic Stainless Steels

Type	ASTM Specification	Form	Condition	0.2% Yield Strength (MPa)
Type 201 (UNS S20100)	A276	Bar	Annealed	275
Type 202 (UNS S20200)	A276	Bar	Annealed	275
Type 205 (UNS S20500)	–	Plate	Annealed[a]	475
Type 304N (UNS S30451)	A276	Bar	Annealed	240
Type 304HN (UNS S30452)	–	Bar	Annealed	345
Type 316N (UNS S31651)	A276	Bar	Annealed	240

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 367.

[a] Typical values.

TABLE 1.78 Yield Strength of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Yield Strength (MPa)
C10100 Oxygen-free electronic	99.99 Cu	F, R, W, T, P, S	69–365
C10200 Oxygen-free copper	99.95 Cu	F, R, W, T, P, S	69–365
C10300 Oxygen-free, extra-low phosphorus	99.95 Cu, 0.003 P	F, R, T, P, S	69–345
C10400, C10500, C10700 Oxygen-free, silver-bearing	99.95 Cu[b]	F, R, W, S	69–365
C10800 Oxygen-free, low phosphorus	99.95 Cu, 0.009 P	F, R, T, P	69–345
CS11000 Electrolytic tough pitch copper	99.90 Cu, 0.04 O	F, R, W, T, P, S	69–365
C11300, C11400, C11500, C11600 Silver-bearing tough pitch copper	99.90 Cu, 0.04 O, Ag[c]	F, R, W, T, S	69–365
C12000, C12100	99.9 Cu[d]	F, T, P	69–365
C12200 Phosphorus deoxidized copper, high residual phosphorus	99.90 Cu, 0.02 P	F, R, T, P	69–345
C12500, C12700, C12800, C12900, C13000 Fire-refined tough pitch with silver	99.88 Cu[e]	F, R, W, S	69–365
C14200 Phosphorus deoxidized, arsenical	99.68 Cu, 0.3 As, 0.02 P	F, R, T	69–345
C19200	98.97 Cu, 1.0 Fe, 0.03 P	F, T	76–510
C14300	99.9 Cu, 0.1 Cd	F	76–386
C14310	99.8 Cu, 0.2 Cd	F	76–386
C14500 Phosphorus deoxidized, tellurium bearing	99.5 Cu, 0.50 Te, 0.008 P	F, R, W, T	69–352
C14700 Sulfur bearing	99.6 Cu, 0.40 S	R, W	69–379
C15000 Zirconium copper	99.8 Cu, 0.15 Zr	R, W	41–496
C15500	99.75 Cu, 0.06 P, 0.11 Mg, Ag[f]	F	124–496
C15710	99.8 Cu, 0.2 Al_2O_3	R, W	268–689
C15720	99.6 Cu, 0.4 Al_2O_3	F, R	365–586
C15735	99.3 Cu, 0.7 Al_2O_3	R	414–565
C15760	98.9 Cu, 1.1 Al_2O_3	F, R	386–552
C16200 Cadmium copper	99.0 Cu, 1.0 Cd	F, R, W	48–476
C16500	98.6 Cu, 0.8 Cd, 0.6 Sn	F, R, W	97–490
C17000 Beryllium copper	99.5 Cu, 1.7 Be, 0.20 Co	F, R	221–1172
C17200 Beryllium copper	99.5 Cu, 1.9 Be, 0.20 Co	F, R, W, T, P, S	172–1344
C17300 Beryllium copper	99.5 Cu, 1.9 Be, 0.40 Pb	R	172–1255
C17500 Copper–cobalt–beryllium alloy	99.5 Cu, 2.5 Co, 0.6 Be	F, R	172–758
C18200, C18400, C18500 Chromium copper	99.5 Cu[g]	F, W, R, S, T	97–531
C18700 leaded copper	99.0 Cu, 1.0 Pb	R	69–345
C18900	98.75 Cu, 0.75 Sn, 0.3 Si, 0.20 Mn	R, W	62–359
C19000 Copper–nickel–phosphorus alloy	98.7 Cu, 1.1 Ni, 0.25 P	F, R, W	138–552
C19100 Copper–nickel–phosphorus–tellurium alloy	98.15 Cu, 1.1 Ni, 0.50 Te, 0.25 P	R, F	69–634
C19400	97.5 Cu, 2.4 Fe, 0.13 Zn, 0.03 P	F	165–503
C19500	97.0 Cu, 1.5 Fe, 0.6 Sn, 0.10 P, 0.80 Co	F	448–655

(*Continued*)

TABLE 1.78 (*Continued*) Yield Strength of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Yield Strength (MPa)
C21000 Gilding, 95%	95.0 Cu, 5.0 Zn	F, W	69–400
C22000 Commercial bronze, 90%	90.0 Cu, 10.0 Zn	F, R, W, T	69–427
C22600 Jewelry bronze, 87.5%	87.5 Cu, 12.5 Zn	F, W	76–427
C23000 Red brass, 85%	85.0 Cu, 15.0 Zn	F, W, T, P	69–434
C24000 Low brass, 80%	80.0 Cu, 20.0 Zn	F, W	83–448
C26000 Cartridge brass, 70%	70.0 Cu, 30.0 Zn	F, R, W, T	76–448
C26800, C27000 Yellow brass	65.0 Cu, 35.0 Zn	F, R, W	97–427
C28000 Muntz metal	60.0 Cu, 40.0 Zn	F, R, T	145–379
C31400 Leaded commercial bronze	89.0 Cu, 1.75 Pb, 9.25 Zn	F, R	83–379
C31600 Leaded commercial bronze, nickel-bearing	89.0 Cu, 1.9 Pb, 1.0 Ni, 8.1 Zn	F, R	83–407
C33000 Low-leaded brass tube	66.0 Cu, 0.5 Pb, 33.5 Zn	T	103–414
C33200 High-leaded brass tube	66.0 Cu, 1.6 Pb, 32.4 Zn	T	138–414
C33500 Low-leaded brass	65.0 Cu, 0.5 Pb, 34.5 Zn	F	97–414
C34000 Medium-leaded brass	65.0 Cu, 1.0 Pb, 34.0 Zn	F, R, W, S	103–414
C34200 High-leaded brass	64.5 Cu, 2.0 Pb, 33.5 Zn	F, R	117–427
C34900	62.2 Cu, 0.35 Pb, 37.45 Zn	R, W	110–379
C35000 Medium-leaded brass	62.5 Cu, 1.1 Pb, 36.4 Zn	F, R	90–483
C35300 High-leaded brass	62.0 Cu, 1.8 Pb, 36.2 Zn	F, R	117–427
C35600 Extra-high-leaded brass	63.0 Cu, 2.5 Pb, 34.5 Zn	F	117–414
C36000 Free-cutting brass	61.5 Cu, 3.0 Pb, 35.5 Zn	F, R, S	124–310
C36500 to C36800 Leaded Muntz metal	60.0 Cu[h], 0.6 Pb, 39.4 Zn	F	138
C37000 Free-cutting Muntz metal	60.0 Cu, 1.0 Pb, 39.0 Zn	T	138–414
C37700 Forging brass	59.0 Cu, 2.0 Pb, 39.0 Zn	R, S	138
C38500 Architectural bronze	57.0 Cu, 3.0 Pb, 40.0 Zn	R, S	138
C40500	95 Cu, 1 Sn, 4 Zn	F	83–483
C40800	95 Cu, 2 Sn, 3 Zn	F	90–517
C41100	91 Cu, 0.5 Sn, 8.5 Zn	F, W	76–496
C41300	90.0 Cu, 1.0 Sn, 9.0 Zn	F, R, W	83–565
C41500	91 Cu, 1.8 Sn, 7.2 Zn	F	117–517
C42200	87.5 Cu, 1.1 Sn, 11.4 Zn	F	103–517
C42500	88.5 Cu, 2.0 Sn, 9.5 Zn	F	124–524
C43000	87.0 Cu, 2.2 Sn, 10.8 Zn	F	124–503
C43400	85.0 Cu, 0.7 Sn, 14.3 Zn	F	103–517
C43500	81.0 Cu, 0.9 Sn, 18.1 Zn	F, T	110–469
C44300, C44400, C44500 Inhibited admiralty	71.0 Cu, 28.0 Zn, 1.0 Sn	F, W, T	124–152
C46400 to C46700 Naval brass	60.0 Cu, 39.25 Zn, 0.75 Sn	F, R, T, S	172–455
C48200 Naval brass, medium-leaded	60.5 Cu, 0.7 Pb, 0.8 Sn, 38.0 Zn	F, R, S	172–365
C48500 Leaded naval brass	60.0 Cu, 1.75 Pb, 37.5 Zn, 0.75 Sn	F, R, S	172–365

(*Continued*)

TABLE 1.78 (*Continued*) Yield Strength of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Yield Strength (MPa)
C50500 Phosphor bronze, 1.25% E	98.75 Cu, 1.25 Sn, trace P	F, W	97–345
C51000 Phosphor bronze, 5% A	95.0 Cu, 5.0 Sn, trace P	F, R, W, T	131–552
C51100	95.6 Cu, 4.2 Sn, 0.2 P	F	345–552
C52100 Phosphor bronze, 8% C	92.0 Cu, 8.0 Sn, trace P	F, R, W	165–552
C52400 Phosphor bronze, 10% D	90.0 Cu, 10.0 Sn, trace P	F, R, W	193 (annealed)
C54400 Free-cutting phosphor bronze	88.0 Cu, 4.0 Pb, 4.0 Zn, 4.0 Sn	F, R	131–434
C60800 Aluminum bronze, 5%	95.0 Cu, 5.0 Al	T	186
C61000	92.0 Cu, 8.0 Al	R, W	207–379
C61300	92.65 Cu, 0.35 Sn, 7.0 Al	F, R, T, P, S	207–400
C61400 Aluminum bronze, D	91.0 Cu, 7.0 Al, 2.0 Fe	F, R, W, T, P, S	228–414
C61500	90.0 Cu, 8.0 Al, 2.0 Ni	F	152–965
C61800	89.0 Cu, 1.0 Fe, 10.0 Al	R	269–293
C61900	86.5 Cu, 4.0 Fe, 9.5 Al	F	338–1000
C62300	87.0 Cu, 10.0 Al, 3.0 Fe	F, R	241–359
C62400	86.0 Cu, 3.0 Fe, 11.0 Al	F, R	276–359
C62500	82.7 Cu, 4.3 Fe, 13.0 Al	F, R	379
C63000	82.0 Cu, 3.0 Fe, 10.0 Al, 5.0 Ni	F, R	345–517
C63200	82.0 Cu, 4.0 Fe, 9.0 Al, 5.0 Ni	F, R	310–365
C63800	99.5 Cu, 2.8 Al, 1.8 Si, 0.40 Co	F	372–786
C64200	91.2 Cu, 7.0 Al	F, R	241–469
C65100 Low-silicon bronze, B	98.5 Cu, 1.5 Si	R, W, T	103–476
C65500 High-silicon bronze, A	97.0 Cu, 3.0 Si	F, R, W, T	145–483
C66700 Manganese brass	70.0 Cu, 28.8 Zn, 1.2 Mn	F, W	83–638
C67400	58.5 Cu, 36.5 Zn, 1.2 Al, 2.8 Mn, 1.0 Sn	F, R	234–379
C67500 Manganese bronze, A	58.5 Cu, 1.4 Fe, 39.0 Zn, 1.0 Sn, 0.1 Mn	R, S	207–414
C68700 Aluminum brass, arsenical	77.5 Cu, 20.5 Zn, 2.0 Al, 0.1 As	T	186
C68800	73.5 Cu, 22.7 Zn, 3.4 Al, 0.40 Co	F	379–786
C69000	73.3 Cu, 3.4 Al, 0.6 Ni, 22.7 Zn	F	345–807
C69400 Silicon red brass	81.5 Cu, 14.5 Zn, 4.0 Si	R	276–393
C70400	92.4 Cu, 1.5 Fe, 5.5 Ni, 0.6 Mn	F, T	276–524
C70600 Copper nickel, 10%	88.7 Cu, 1.3 Fe, 10.0 Ni	F, T	110–393
C71000 Copper nickel, 20%	79.00 Cu, 21.0 Ni	F, W, T	90–586
C71500 Copper nickel, 30%	70.0 Cu, 30.0 Ni	F, R, T	138–483
C71700	67.8 Cu, 0.7 Fe, 31.0 Ni, 0.5 Be	F, R, W	207–1241
C72500	88.20 Cu, 9.5 Ni, 2.3 Sn	F, R, W, T	152–745
C73500	72.0 Cu, 18.0 Ni, 10.0 Zn	F, R, W, T	103–579
C74500 Nickel silver, 65–10	65.0 Cu, 25.0 Zn, 10.0 Ni	F, W	124–524
C75200 Nickel silver, 65–18	65.0 Cu, 17.0 Zn, 18.0 Ni	F, R, W	172–621
C75400 Nickel silver, 65–15	65.0 Cu, 20.0 Zn, 15.0 Ni	F	124–545
C75700 Nickel silver, 65–12	65.0 Cu, 23.0 Zn, 12.0 Ni	F, W	124–545

(*Continued*)

TABLE 1.78 (*Continued*) Yield Strength of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Yield Strength (MPa)
C76200	59.0 Cu, 29.0 Zn, 12.0 Ni	F, T	145–758
C77000 Nickel silver, 55–18	55.0 Cu, 27.0 Zn, 18.0 Ni	F, R, W	186–621
C72200	82.0 Cu, 16.0 Ni, 0.5 Cr, 0.8 Fe, 0.5 Mn	F, T	124–455
C78200 Leaded nickel silver, 65–8–2	65.0 Cu, 2.0 Pb, 25.0 Zn, 8.0 Ni	F	159–524

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 442–454.

[a] F, flat products; R, rod; W, wire; T, tube; P, pipe; S, shapes.

[b] C10400, 8 oz/ton Ag; C10500, 10 oz/ton; C10700, 25 oz/ton.

[c] C11300, 8 oz/ton Ag; C11400, 10 oz/ton; C11500, 16 oz/ton; C11600, 25 oz/ton.

[d] C12000, 0.008 P; C12100, 0.008 P and 4 oz/ton Ag.

[e] C12700, 8 oz/ton Ag; C12800, 10 oz/ton; C12900, 16 oz/ton; C13000, 25 oz/ton.

[f] 8.30 oz/ton Ag.

[g] C18200, 0.9 Cr; C18400, 0.8 Cr; C18500, 0.7 Cr.

[h] Rod, 61.0 Cu min.

TABLE 1.79 Yield Strength of Cast Aluminum Alloys

Alloy AA No.	Temper	Yield Strength (MPa)
201.0	T4	215
	T6	435
	T7	415
206.0, A206.0	T7	345
208.0	F	97
242.0	T21	125
	T571	205
	T77	160
	T571	235
	T61	290
295.0	T4	110
	T6	165
	T62	220
296.0	T4	130
	T6	180
	T7	140
308.0	F	110
319.0	F	125
	T6	165
	F	130
	T6	185
336.0	T551	195
	T65	295
354.0	T61	285

(*Continued*)

TABLE 1.79 (*Continued*) Yield Strength of Cast Aluminum Alloys

Alloy AA No.	Temper	Yield Strength (MPa)
355.0	T51	160
	T6	175
	T61	240
	T7	250
	T71	200
	T51	165
	T6	190
	T62	280
	T7	210
	T71	215
356.0	T51	140
	T6	165
	T7	210
	T71	145
	T6	185
	T7	165
357.0, A357.0	T62	290
359.0	T61	255
	T62	290
360.0	F	170
A360.0	F	165
380.0	F	165
383.0	F	150
384.0, A384.0	F	165
390.0	F	240
	T5	260
A390.0	F, T5	180
	T6	280
	T7	250
	F, T5	200
	T6	310
	T7	260
413.0	F	140
A413.0	F	130
443.0	F	55
B443.0	F	62
C443.0	F	110
514.0	F	85
518.0	F	190
520.0	T4	180
535.0	F	140
712.0	F	170
713.0	T5	150
771.0	T6	275
850.0	T5	75

Source: Data from *ASM Metals Reference Book*, Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 306–307.

TABLE 1.80 Yield Strength of Wrought Aluminum Alloys

Alloy	Temper	Yield Strength (MPa)
1050	0	28
	H14	105
	H16	125
	H18	145
1060	0	28
	H12	76
	H14	90
	H16	105
	H18	125
1100	0	34
	H12	105
	H14	115
	H16	140
	H18	150
1350	0	28
	H12	83
	H14	97
	H16	110
	H19	165
2011	T3	295
	T8	310
2014	0	97
	T4	290
	T6	415
Alclad 2014	0	69
	T3	275
	T4	255
	T6	415
2024	0	76
	T3	345
	T4, T351	325
	T361	395
Alclad 2024	0	76
	T	310
	T4, T351	290
	T361	365
	T81, T851	415
	T861	455
2036	T4	195
2048		415
2124	T851	440

(*Continued*)

TABLE 1.80 (*Continued*) Yield Strength of Wrought Aluminum Alloys

Alloy	Temper	Yield Strength (MPa)
2218	T61	305
	T71	275
	T72	255
2219	0	76
	T42	185
	T31, T351	250
	T37	315
	T62	290
	T81, T851	350
	T87	395
2618	All	370
3003 and Alclad 3003	0	42
	H12	125
	H14	145
	H16	170
	H18	185
3004 and Alclad 3004	0	69
	H32	170
	H34	200
	H36	230
	H38	250
3105	0	55
	H12	130
	H14	150
	H16	170
	H18	195
	H25	160
4032	T6	315
4043	0	69
	H18	270
5005	0	41
	H12	130
	H14	150
	H16	170
	H18	195
	H32	115
	H34	140
	H36	165
	H38	185

(*Continued*)

TABLE 1.80 (*Continued*) Yield Strength of Wrought Aluminum Alloys

Alloy	Temper	Yield Strength (MPa)
5050	0	55
	H32	145
	H34	165
	H36	180
	H38	200
5052	0	90
	H32	195
	H34	215
	H36	240
	H38	255
5056	0	150
	H18	405
	H38	345
5083	0	145
	H112	195
	H113	230
	H321	230
	H323, H32	250
	H343, H34	285
5086	0	115
	H32, H116, H117	205
	H34	255
	H112	130
5154	0	115
	H32	205
	H34	230
	H36	250
	H38	270
	H112	115
5182	0	140
	H32	235
	H34	285
	H19[a]	395
5252	H25	170
	H28, H38	240
5254	0	115
	H32	205
	H34	230
	H36	250
	H38	270
	H112	115

(*Continued*)

TABLE 1.80 (*Continued*) Yield Strength of Wrought Aluminum Alloys

Alloy	Temper	Yield Strength (MPa)
5454	0	115
	H32	205
	H34	240
	H36	275
	H38	310
	H111	180
	H112	125
	H311	180
5456	0	160
	H111	230
	H112	165
	H321, H116	255
5457	0	48
	H25	160
	H28, H38	185
5652	0	90
	H32	195
	H34	215
	H36	240
	H38	255
5657	H25	140
	H28, H38	165
6005	T1	105
	T5	240
6009	T4	130
	T6	325
6010	T4	170
6061	0	55
	T4, T451	145
	T6, T651	275
Alclad 6061	0	48
	T4, T451	130
	T6, T651	255
6063	0	48
	T1	90
	T4	90
	T5	145
	T6	215
	T83	240
	T831	185
	T832	270

(*Continued*)

TABLE 1.80 (*Continued*) Yield Strength of Wrought Aluminum Alloys

Alloy	Temper	Yield Strength (MPa)
6066	0	83
	T4, T451	205
	T6, T651	360
6070	0	69
	T4	170
	T6	350
6101	Hill	76
6151	T6	195
6201	T6	300
	T81	310
6205	Tl	140
	T5	290
6262	T9	380
6351	T4	150
	T6	285
6463	Tl	90
	T5	145
	T6	215
7005	0	83
	T53	345
	T6, T63, T6351	315
7050	T736	455
7075	0	105
	T6, T651	505
	T73	435
Alclad 7075	0	95
	T6, T651	460
7175	T66	525
	T736	455
7475	T61	460

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 299–302.

[a] Properties for this temper are those of container end stock 0.25–0.38 mm thick.

TABLE 1.81 Yield Strength of Wrought Titanium Alloys at Room Temperature

Class	Alloy	Condition	Yield Strength (MPa)
Commercially pure	99.5 Ti	Annealed	241
	99.2 Ti	Annealed	345
	99.1 Ti	Annealed	448
	99.0 Ti	Annealed	586
	99.2Ti–0.2Pd	Annealed	345
	Ti–0.8Ni–0.3Mo	Annealed	448
Alpha alloys	Ti–5Al–2.5Sn	Annealed	807
	Ti–5Al–2.5Sn (low O_2)	Annealed	745
Near alpha alloys	Ti–8Al–1Mo–1V	Duplex annealed	951
	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	Duplex annealed	993
	Ti–6Al–2Sn–4Zr–2Mo	Duplex annealed	896
	Ti–5Al–2Sn–2Zr–2Mo–0.25Si	975°C (1/2 h), AC+595°C (2 h), AC	965
	Ti–6Al–2Nb–1Ta–1Mo	As rolled 2.5 cm (1 in.) plate	758
	Ti–6Al–2Sn–1.5Zr–1Mo– 0.35Bi–0.1Si	Beta forge + duplex anneal	945
Alpha–beta alloys	Ti–8Mn	Annealed	862
	Ti–3Al–2.5V	Annealed	586
	Ti–6Al–4V	Annealed	924
		Solution + age	1103
	Ti–6Al–4V (low O_2)	Annealed	827
	Ti–6Al–6V–2Sn	Annealed	1000
		Solution + age	1172
	Ti–7Al–4Mo	Solution + age	1034
	Ti–6Al–2Sn–4Zr–6Mo	Solution + age	1172
	Ti–6Al–2Sn–2Zr–2Mo– 2Cr–0.25Si	Solution + age	1138
	Ti–10V–2Fe–3Al	Solution + age	1200
Beta alloys	Ti–13V–1Cr–3Al	Solution + age	1172
			1207
	Ti–8Mo–8V–2Fe–3Al	Solution + age	1241
	Ti–3Al–8V–6Cr–4Mo–4Zr	Solution + age	1379
		Annealed	834
	Ti–11.5Mo–6Zr–4.5Sn	Solution + age	1317

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 512.

TABLE 1.82 Yield Strength of Wrought Titanium Alloys at High Temperature

Class	Alloy	Condition	Test Temperature (°C)	Yield Strength (MPa)
Commercially pure	99.5 Ti	Annealed	315	97
	99.2 Ti	Annealed	315	117
	99.1 Ti	Annealed	315	138
	99.0 Ti	Annealed	315	172
	99.2Ti–0.2Pd	Annealed	315	110
	Ti–0.8Ni–0.3Mo	Annealed	205	248
	Ti–0.8Ni–0.3Mo	Annealed	315	207
Alpha alloys	Ti–5Al–2.5Sn	Annealed	315	448
	Ti–5Al–2.5Sn (low O_2)	Annealed	–195	1158
			–255	1420
Near alpha alloys	Ti–8Al–1Mo–1V	Duplex annealed	315	621
			425	565
			540	517
Near alpha alloys	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	Duplex annealed	315	758
			425	676
			540	586
	Ti–6Al–2Sn–4Zr–2Mo	Duplex annealed	315	586
			425	586
			540	489
	Ti–5Al–2Sn–2Zr–2Mo–0.25Si	975°C (1/2 h), AC+595°C (2 h), AC	315	565
			425	531
			540	503
	Ti–6Al–2Nb–1Ta–1Mo	As rolled 2.5 cm (1 in.) plate	315	462
			425	414
			540	379
	Ti–6Al–2Sn–1.5Zr–1Mo–0.35Bi–0.1Si	Beta forge + duplex anneal	480	586
Alpha–beta alloys	Ti–8Mn	Annealed	315	565
	Ti–3Al–2.5V	Annealed	315	345
	Ti–6Al–4V	Annealed	315	655
		Annealed	425	572
		Annealed	540	427
		Solution + age	315	703
		Solution + age	425	621
		Solution + age	540	483
	Ti–6Al–4V (low O_2)	Annealed	160	1413
	Ti–6Al–6V–2Sn	Annealed	315	807
		Solution + age	315	896

(*Continued*)

TABLE 1.82 (*Continued*) Yield Strength of Wrought Titanium Alloys at High Temperature

Class	Alloy	Condition	Test Temperature (°C)	Yield Strength (MPa)
	Ti–7Al–4Mo	Solution + age	315	745
			425	717
	Ti–6Al–2Sn–4Zr–6Mo	Solution + age	315	841
			425	758
			540	655
	Ti–6Al–2Sn–2Zr–2Mo–2Cr–0.25Si	Solution + age	315	807
	Ti–10V–2Fe–3Al	Solution + age	205	1048
			315	979
Beta alloys	Ti–13V–1Cr–3Al	Solution + age	315	793
			425	827
	Ti–8Mo–8V–2Fe–3Al	Solution + age	315	979
	Ti–3Al–8V–6Cr–4Mo–4Zr	Solution + age	315	896
			425	758
		Annealed	315	655
	Ti–11.5Mo–6Zr–4.5Sn	Solution + age	315	848

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 512.

TABLE 1.83 Yield Strength of Cobalt-Base Superalloys

Alloy	Temperature (°C)	Yield Strength (MPa)
Haynes 25 (L–605) sheet	21	460
	540	250
	650	240
	760	260
	870	240
Haynes 188, sheet	21	485
	540	305
	650	305
	760	290
	870	260
S-816, Bar	21	385
	540	310
	650	305
	760	285
	870	240

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 387.

TABLE 1.84 Yield Strength of Nickel-Base Superalloys

Alloy	Temperature (°C)	Yield Strength (MPa)
Astroloy, bar	21	1050
	540	965
	650	965
	760	910
	870	690
D-979, bar	21	1010
	540	925
	650	890
	760	655
	870	305
Hastelloy X, sheet	21	360
	540	290
	650	275
	760	260
	870	180
IN–102, bar	21	505
	540	400
	650	400
	760	385
	870	200
Inconel 600, bar	21	250
	540	195
	650	180
	760	115
	870	62
Inconel 601, sheet	21	340
	540	150
	650	180
	760	200
	870	140
Inconel 625, bar	21	490
	540	405
	650	420
	760	420
	870	475
Inconel 706, bar	21	980
	540	895
	650	825
	760	675
Inconel 718, bar	21	1190
	540	1060
	650	1020
	760	740
	870	330

(*Continued*)

TABLE 1.84 (*Continued*) Yield Strength of Nickel-Base Superalloys

Alloy	Temperature (°C)	Yield Strength (MPa)
Inconel 718, sheet	21	1050
	540	945
	650	870
	760	625
Inconel X-750, bar	21	635
	540	580
	650	565
	760	455
	870	165
M-252, bar	21	840
	540	765
	650	745
	760	715
	870	485
Nimonic 80A, bar	21	620
	540	530
	650	550
	760	505
	870	260
Nimonic 90, bar	21	805
	540	725
	650	685
	760	540
	870	260
Nimonic 105, bar	21	815
	540	775
	650	800
	760	655
	870	365
Nimonic 115, bar	21	860
	540	795
	650	815
	760	800
	870	550
Pyromet 860, bar	21	835
	540	840
	650	850
	760	835
René 41, bar	21	1060
	540	1010
	650	1000
	760	940
	870	550

(*Continued*)

TABLE 1.84 (*Continued*) Yield Strength of Nickel-Base Superalloys

Alloy	Temperature (°C)	Yield Strength (MPa)
René 95, bar	21	1310
	540	1250
	650	1220
	760	1100
Udimet 500, bar	21	840
	540	795
	650	760
	760	730
	870	495
Udimet 520, bar	21	860
	540	825
	650	795
	760	725
	870	515
Udimet 700, bar	21	965
	540	895
	650	855
	760	825
	870	635
Udimet 710, bar	21	910
	540	850
	650	860
	760	815
	870	635
Unitemp AF2–1DA, bar	21	1050
	540	1080
	650	1080
	760	1010
	870	715
Waspaloy, bar	21	795
	540	725
	650	690
	760	675
	870	515

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 387–389.

TABLE 1.85 Yield Strength of Commercially Pure Tin

Temperature (°C)	Yield Strength (MPa)
Strained at 0.2 mm/m · min	
–200	36.2
–160	90.3
–120	87.6
–80	38.9
–40	20.1
0	12.5
23	11.0
Strained at 0.4 mm/m · min	
15	14.5
50	12.4
100	11.0
150	7.6
200	4.5

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 488.

TABLE 1.86 Shear Strength of Wrought Aluminum Alloys

Alloy AA No.	Temper	Shear Strength (MPa)
1050	0	62
	H14	69
	H16	76
	H18	83
1060	0	48
	H12	55
	H14	62
	H16	69
	H18	76
1100	0	62
	H12	69
	H14	76
	H16	83
	H18	90
1350	0	55
	H12	62
	H14	69
	H16	76
	H19	105
2011	T3	220
	T8	240

(*Continued*)

TABLE 1.86 (*Continued*) Shear Strength of Wrought Aluminum Alloys

Alloy AA No.	Temper	Shear Strength (MPa)
2014	0	125
	T4	260
	T6	290
Alclad 2014	0	125
	T3	255
	T4	255
	T6	285
2024	0	125
	T3	285
	T4, T351	285
	T361	290
Alclad 2024	0	125
	T	275
	T4, T351	275
	T361	285
	T81, T851	275
	T861	290
2218	T72	205
2618	All	260
3003 and Alclad 3003	0	76
	H12	83
	H14	97
	H16	105
	H18	110
3004 and Alclad 3004	0	110
	H32	115
	H34	125
	H36	140
	H38	145
3105	0	83
	H12	97
	H14	105
	H16	110
	H18	115
	H25	105
4032	T6	260
5005	0	76
	H12	97
	H14	97
	H16	105
	H18	110
	H32	97
	H34	97
	H36	105
	H38	110

(*Continued*)

TABLE 1.86 (*Continued*) Shear Strength of Wrought Aluminum Alloys

Alloy AA No.	Temper	Shear Strength (MPa)
5050	0	105
	H32	115
	H34	125
	H36	130
	H38	140
5052	0	125
	H32	140
	H34	145
	H36	160
	H38	165
5056	0	180
	H18	235
	H38	220
5083	0	170
5086	0	160
	H34	185
5154	0	150
	H32	150
	H34	165
	H36	180
	H38	195
5182	0	150
5252	H25	145
	H28, H38	160
5254	0	150
	H32	150
	H34	165
	H36	180
	H38	195
5454	0	160
	H32	165
	H34	180
	H111	160
	H112	160
	H311	160
5456	H321, H116	205
5457	0	83
	H25	110
	H28, H38	125

(*Continued*)

TABLE 1.86 (*Continued*) Shear Strength of Wrought Aluminum Alloys

Alloy AA No.	Temper	Shear Strength (MPa)
5652	0	125
	H32	140
	H34	145
	H36	160
	H38	165
5657	H25	97
	H28, H38	105
6005	T5	205
6009	T4	150
6061	0	83
	T4, T451	165
	T6, T651	205
Alclad 6061	0	76
	T4, T451	150
	T6, T651	185
6063	0	69
	T1	97
	T5	115
	T6	150
	T83	150
	T831	125
	T832	185
6066	0	97
	T4, T451	200
	T6, T651	235
6070	0	97
	T4	205
	T6	235
6151	T6	140
6205	T5	205
6262	T9	240
6351	T6	200
6463	Tl	97
	T5	115
	T6	150
7005	0	117
	T53	221
	T6,T63,T6351	214
7072	0	55
	H12	62
	H14	69

(*Continued*)

TABLE 1.86 (*Continued*) Shear Strength of Wrought Aluminum Alloys

Alloy AA No.	Temper	Shear Strength (MPa)
7075	0	150
	T6,T651	330
Alclad 7075	0	150
	T6,T651	315
7175	T66	325
	T736	290
7475	T651	295
	T7351	270
	T7651	270

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 299–302.

TABLE 1.87 Torsion Shear Strength of Gray Cast Fe

ASTM Class	Torsional Shear Strength (MPa)
20	179
25	220
30	276
35	334
40	393
50	503
60	610

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 166–167.

TABLE 1.88 Hardness of Gray Cast Irons

SAE grade	Hardness (HB)
G1800	187 max
G2500	170–229
G2500a	170–229
G3000	187–241
C3500	207–255
G3500b	207–255
G3500c	207–255
G4000	217–269
G4000d	241–321

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 166–167.

TABLE 1.89 Hardness of Gray Cast Iron Bars

ASTM Class	Hardness (HB)
20	156
25	174
30	210
35	212
40	235
50	262
60	302

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 166–167.

TABLE 1.90 Hardness of Malleable Iron Castings

Specification Number	Grade or Class	Hardness (HB)
Ferritic ASTM A47, A338; ANSI G48.1;		
FED QQ–I–666c	32510	156 max
	35018	156 max
ASTM A197		156 max
Pearlitic and martensitic ASTM A220; ANSI C48.2;		
MIL–I–11444B	40010	149–197
	45008	156–197
	45006	156–207
	50005	179–229
	60004	197–241
	70003	217–269
	80002	241–285
	90001	269–321
Automotive ASTM A602; SAE J158	M3210	156 max
	M4504[a]	163–217
	M5003[a]	187–241
	M5503[b]	187–241
	M7002[b]	229–269
	M8501[b]	269–302

Source: Data from *ASM Metals Reference Book*, Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 171.

[a] Air quenched and tempered.

[b] Liquid quenched and tempered.

TABLE 1.91 Hardness of Ductile Irons

Specification Number	Grade or Class	Hardness (HB)
ASTM A395–76		
ASME SA395	60–40–18	143–187
ASTM A476–70(d);		
SAE AMS5316	80–60–03	201 min
SAE J434c	D4018	170 max
	D4512	156–217
	D5506	187–255
	D7003	241–302
MlL–I–24137(Ships)	Class A	190 max
	Class B	190 max
	Class C	175 max

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 169.

TABLE 1.92 Hardness of Tool Steels

Type	Condition	Hardness (HRC)
L2	Annealed	96 HRB
	Oil quenched from 855°C and single tempered at	
	205°C	54
	315°C	52
	425°C	47
	540°C	41
	650°C	30
L6	Oil quenched from 845°C and single tempered at	
	315°C	54
	425°C	46
	540°C	42
	650°C	32
S1	Annealed	96 HRB
	Oil quenched from 930°C and single tempered at	
	205°C	57.5
	315°C	54
	425°C	50.5
	540°C	47.5
	650°C	42
S5	Annealed	96 HRB
	Oil quenched from 870°C and single tempered at	
	205°C	59
	315°C	58
	425°C	52
	540°C	48
	650°C	37

(*Continued*)

TABLE 1.92 (*Continued*) Hardness of Tool Steels

Type	Condition	Hardness (HRC)
S7	Annealed	95 HRB
	Fan cooled from 940°C and single tempered at	
	205°C	58
	315°C	55
	425°C	53
	540°C	51
	650°C	39

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 241.

TABLE 1.93 Hardness of Austenitic Stainless Steels

Type	Form	Condition	ASTM Specification	Hardness (HRB)
Type 301 (UNS S30100)	Bar, wire, plate, sheet, strip	Annealed	A167	88 max
Type 317L (UNS S31703)	Bar	Annealed	–	85 max
Type 317LM	Bar, plate, sheet, strip	Annealed	–	95 max

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 364–366.

TABLE 1.94 Hardness of Ferritic Stainless Steels

Type	ASTM Specification	Form	Condition	Hardness (HRB)
Type 409 (UNS S40900)	–	Bar	Annealed	75 max[a]
Type 434 (UNS S43400)	–	Wire	Annealed	90 max[a]
Type 436 (UNS S43600)	–	Sheet, strip	Annealed	83 max[a]
Type 442 (UNS S44200)	–	Bar	Annealed	90 max[a]
Type 444 (UNS S44400)	A176	Plate, sheet, strip	Annealed	95 max

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 368.

[a] Typical values.

TABLE 1.95 Hardness of Martensitic Stainless Steels

Type	ASTM Specification	Form	Condition	Rockwell Hardness
Type 410S (UNS S41008)	A176	Plate, sheet, strip	Annealed	95 HRB max
Type 420 (UNS S42000)	–	Bar	Tempered 205°C	52 HRC
Type 440A (UNS S44002)	–	Bar	Annealed	95 HRB
	–		Tempered 315°C	51 HRC
Type 440B (UNS S44003)	–	Bar	Annealed	96 HRB
	–		Tempered 315°C	55 HRC
Type 440C (UNS S44004)	–	Bar	Annealed	97 HRB
	–		Tempered 315°C	57 HRC

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 369–370.

TABLE 1.96 Hardness of Precipitation-Hardening Austenitic Stainless Steels

Type	Form	Condition	Hardness (HRC)	
			Minimum	Maximum
PH 13–8 Mo (UNS S13800)	Bar, plate, sheet, strip	H950	45	–
		H1000	43	–
15–5 PH (UNS S15500) and 17–4 PH (UNS S17400)	Bar, plate, sheet, strip	H900	40	48
		H925	38	47[a]
		H1025	35[a]	42[a]
		H1075	32[a]	38[a]
		H1100	31[a]	38[a]
		H1150	28[a]	36[a]
		H1150M	24[a]	34[a]
17–7 PH (UNS S17700)	Bar	RH950	41	–
		TH1050	38	–

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 371.

[a] For flat rolled products, value varies with thickness.

TABLE 1.97 Hardness of Wrought Aluminum Alloys

Alloy AA No.	Temper	Hardness (BHN)
1060	0	19
	H12	23
	H14	26
	H16	30
	H18	35
1100	0	23
	H12	28
	H14	32
	H16	38
	H18	44
2011	T3	95
	T8	100
2014	0	45
	T4	105
	T6	135
2024	0	47
	T3	120
	T4, T351	120
	T361	130
2218	T61	115
	T71	105
	T72	95

(*Continued*)

TABLE 1.97 (*Continued*) Hardness of Wrought Aluminum Alloys

Alloy AA No.	Temper	Hardness (BHN)
3003 and	0	28
Alclad 3003	H12	35
	H14	40
	H16	47
	H18	55
3004 and	0	45
Alclad 3004	H32	52
	H34	63
	H36	70
	H38	77
4032	T6	120
5005	0	28
	H32	36
	H34	41
	H36	46
	H38	51
5050	0	36
	H32	46
	H34	53
	H36	58
	H38	63
5052	0	47
	H32	60
	H34	68
	H36	73
	H38	77
5056	0	65
	H18	105
	H38	100
5154	0	58
	H32	67
	H34	73
	H36	78
	H38	80
	H112	63
5182	0	58
5252	H25	68
	H28, H38	75
5254	0	58
	H32	67
	H34	73
	H36	78
	H38	80
	H112	63

(*Continued*)

TABLE 1.97 (*Continued*) Hardness of Wrought Aluminum Alloys

Alloy AA No.	Temper	Hardness (BHN)
5454	0	62
	H32	73
	H34	81
	H111	70
	H112	62
	H311	70
5456	H321, H116	90
5457	0	32
	H25	48
	H28, H38	55
5652	0	47
	H32	60
	H34	68
	H36	73
	H38	77
5657	H25	40
	H28, H38	50
6005	T5	95
6009	T4	70
6010	T4	76
6061	0	30
	T4, T451	65
	T6, T651	95
6063	0	25
	T1	42
	T5	60
	T6	73
	T83	82
	T831	70
	T832	95
6066	0	43
	T4, T451	90
	T6, T651	120
6070	0	35
	T4	90
	T6	120
6151	T6	71
6201	T6	90
6205	T1	65
	T5	95
6262	T9	120

(*Continued*)

TABLE 1.97 (*Continued*) Hardness of Wrought Aluminum Alloys

Alloy AA No.	Temper	Hardness (BHN)
6351	T6	95
6463	T1	42
	T5	60
	T6	74
7049	T73	135
7072	0	20
	H12	28
	H14	32
7075	0	60
	T6, T651	150
7175	T66	150
	T736	145

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 299–302.

TABLE 1.98 Hardness of Wrought Titanium Alloys at Room Temperature

Class	Alloy	Condition	Hardness (HRC)
Commercially pure	99.5 Ti	Annealed	120[a]
	99.2 Ti	Annealed	200[a]
	99.1 Ti	Annealed	225[a]
	99.0 Ti	Annealed	265[a]
	99.2Ti–0.2Pd	Annealed	200[a]
Alpha alloys	Ti–5Al–2.5Sn	Annealed	36
	Ti–5Al–2.5Sn (low O_2)	Annealed	35
Near alpha alloys	Ti–8Al–1Mo–1V	Duplex annealed	35
	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	Duplex annealed	36
	Ti–6Al–2Sn–4Zr–2Mo	Duplex annealed	32
	Ti–6Al–2Nb–1Ta–1Mo	As rolled 2.5 cm plate	30
Alpha–beta alloys	Ti–6Al–4V	Annealed	36
		Solution + age	41
	Ti–6Al–4V (low O_2)	Annealed	35
	Ti–6Al–6V–2Sn	Annealed	38
		Solution + age	42
	Ti–7Al–4Mo	Solution + age	38
Beta alloys	Ti–13V–1C–3Al	Solution + age	40
	Ti–8Mo–8V–2Fe–3Al	Solution + age	40
	Ti–3Al–8V–6Cr–4Mo–4Zr	Solution + age	42

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 512.

[a] Hardness, HB.

TABLE 1.99 Machinability Rating of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Machinability Rating[b]
C10100 Oxygen-free electronic	99.99 Cu	F, R, W, T, P, S	20
C10200 Oxygen-free copper	99.95 Cu	F, R, W, T, P, S	20
C10300 Oxygen-free extra-low phosphorus	99.95 Cu, 0.003 P	F, R, T, P, S	20
C10400, C10500, C10700 Oxygen-free, silver-bearing	99.95 Cu[c]	F, R, W, S	20
C10800 Oxygen-free, low phosphorus	99.95 Cu, 0.009 P	F, R, T, P	20
CS11000 Electrolytic tough pitch copper	99.90 Cu, 0.040 O	F, R, W, T, P, S	20
C11100 Electrolytic tough pitch, anneal resistant	99.90 Cu, 0.04 O, 0.01 Cd	W	20
C11300, C11400, C11500, C11600 Silver-bearing tough pitch copper	99.90 Cu, 0.04 O, Ag[d]	F, R, W, T, S	20
C12000, C12100	99.9 Cu[e]	F, T, P	20
C12200 Phosphorus deoxidized copper, high residual phosphorus	99.90 Cu, 0.02 P	F, R, T, P	20
C12500, C12700, C12800, C12900, C13000 Fire-refined tough pitch with silver	99.88 Cu[f]	F, R, W, S	20
C14200 Phosphorus deoxidized, arsenical	99.68 Cu, 0.3 As, 0.02 P	F, R, T	20
C19200	98.97 Cu, 1.0 Fe, 0.03 P	F, T	20
C14300	99.9 Cu, 0.1 Cd	F	20
C14310	99.8 Cu, 0.2 Cd	F	20
C14500 Phosphorus deoxidized, tellurium bearing	99.5 Cu, 0.50 Te, 0.008 P	F, R, W, T	85
C14700 Sulfur bearing	99.6 Cu, 0.40 S	R, W	85
C15000 Zirconium copper	99.8 Cu, 0.15 Zr	R, W	20
C15500	99.75 Cu, 0.06 P, 0.11 Mg, Ag[g]	F	20
C16200 Cadmium copper	99.0 Cu, 1.0 Cd	F, R, W	20
C16500	98.6 Cu, 0.8 Cd, 0.6 Sn	F, R, W	20
C17000 Beryllium copper	99.5 Cu, 1.7 Be, 0.20 Co	F, R	20
C17200 Beryllium copper	99.5 Cu, 1.9 Be, 0.20 Co	F, R, W, T, P, S	20
C17300 Beryllium copper	99.5 Cu, 1.9 Be, 0.40 Pb	R	50
C18200, C18400, C18500 Chromium copper	99.5 Cu[h]	F, W, R, S, T	20
C18700 Leaded copper	99.0 Cu, 1.0 Pb	R	85
C18900	98.75 Cu, 0.75 Sn, 0.3 Si, 0.20 Mn	R, W	20
C19000 Copper–nickel–phosphorus alloy	98.7 Cu, 1.1 Ni, 0.25 P	F, R, W	30
C19100 Copper–nickel–phosphorus–tellurium alloy	98.15 Cu, 1.1 Ni, 0.50 Te, 0.25 P	R, F	75
C19400	97.5 Cu, 2.4 Fe, 0.13 Zn, 0.03 P	F	20
C19500	97.0 Cu, 1.5 Fe, 0.6 Sn, 0.10 P, 0.80 Co	F	20
C21000 Gilding, 95%	95.0 Cu, 5.0 Zn	F, W	20
C22000 Commercial bronze, 90%	90.0 Cu, 10.0 Zn	F, R, W, T	20
C22600 Jewelry bronze, 87.5%	87.5 Cu, 12.5 Zn	F, W	30

(*Continued*)

TABLE 1.99 (*Continued*) Machinability Rating of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Machinability Rating[b]
C23000 Red brass, 85%	95.0 Cu, 15.0 Zn	F, W, T, P	30
C24000 Low brass, 80%	80.0 Cu, 20.0 Zn	F, W	30
C26000 Cartridge brass, 70%	70.00 Cu, 30.0 Zn	F, R, W, T	30
C26800, C27000 Yellow brass	65.0 Cu, 35.0 Zn	F, R, W	30
C28000 Muntz metal	60.0 Cu, 40.0 Zn	F, R, T	40
C31400 Leaded commercial bronze	89.0 Cu, 1.75 Pb, 9.25 Zn	F, R	80
C31600 Leaded commercial bronze, nickel-bearing	89.0 Cu, 1.9 Pb, 1.0 Ni, 8.1 Zn	F, R	80
C33000 Low-leaded brass tube	66.0 Cu, 0.5 Pb, 33.5 Zn	T	60
C33200 High-leaded brass tube	66.0 Cu, 1.6 Pb, 32.4 Zn	T	80
C33500 Low-leaded brass	65.0 Cu, 0.5 Pb, 34.5 Zn	F	60
C34000 Medium-leaded brass	65.0 Cu, 1.0 Pb, 34.0 Zn	F, R, W, S	70
C34200 High-leaded brass	64.5 Cu, 2.0 Pb, 33.5 Zn	F, R	90
C34900	62.2 Cu, 0.35 Pb, 37.45 Zn	R, W	50
C35000 Medium-leaded brass	62.5 Cu, 1.1 Pb, 36.4 Zn	F, R	70
C35300 High-leaded brass	62.0 Cu, 1.8 Pb, 36.2 Zn	F, R	90
C35600 Extra-high-leaded brass	63.0 Cu, 2.5 Pb, 34.5 Zn	F	100
C36000 Free-cutting brass	61.5 Cu, 3.0 Pb, 35.5 Zn	F, R, S	100
C36500 to C36800 Leaded Muntz metal	60.0 Cu[i], 0.6 Pb, 39.4 Zn	F	60
C37000 Free-cutting Muntz metal	60.0 Cu, 1.0 Pb, 39.0 Zn	T	70
C37700 Forging brass	59.0 Cu, 2.0 Pb, 39.0 Zn	R, S	80
C38500 Architectural bronze	57.0 Cu, 3.0 Pb, 40.0 Zn	R, S	90
C40500	95 Cu, 1 Sn, 4 Zn	F	20
C40800	95 Cu, 2 Sn, 3 Zn	F	20
C41100	91 Cu, 0.5 Sn, 8.5 Zn	F, W	20
C41300	90.0 Cu, 1.0 Sn, 9.0 Zn	F, R, W	20
C41500	91 Cu, 1.8 Sn, 7.2 Zn	F	30
C42200	87.5 Cu, 1.1 Sn, 11.4 Zn	F	30
C42500	88.5 Cu, 2.0 Sn, 9.5 Zn	F	30
C43000	87.0 Cu, 2.2 Sn, 10.8 Zn	F	30
C43400	85.0 Cu, 0.7 Sn, 14.3 Zn	F	30
C43500	81.0 Cu, 0.9 Sn, 18.1 Zn	F, T	30
C44300, C44400, C44500 Inhibited admiralty	71.0 Cu, 28.0 Zn, 1.0 Sn	F, W, T	30
C46400 to C46700 Naval brass	60.0 Cu, 39.25 Zn, 0.75 Sn	F, R, T, S	30
C48200 Naval brass, medium-leaded	60.5 Cu, 0.7 Pb, 0.8 Sn, 38.0 Zn	F, R, S	50
C48500 Leaded naval brass	60.0 Cu, 1.75 Pb, 37.5 Zn, 0.75 Sn	F, R, S	70
C50500 Phosphor bronze, 1.25% E	98.75 Cu, 1.25 Sn, trace P	F, W	20
C51000 Phosphor bronze, 5% A	95.0 Cu, 5.0 Sn, trace P	F, R, W, T	20
C51100	95.6 Cu, 4.2 Sn, 0.2 P	F	20
C52100 Phosphor bronze, 8% C	92.0 Cu, 8.0 Sn, trace P	F, R, W	20
C52400 Phosphor bronze, 10% D	90.0 Cu, 10.0 Sn, trace P	F, R, W	20

(*Continued*)

TABLE 1.99 (*Continued*) Machinability Rating of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Machinability Rating[b]
C54400 Free-cutting phosphor bronze	88.0 Cu, 4.0 Pb, 4.0 Zn, 4.0 Sn	F, R	80
C60800 Aluminum bronze, 5%	95.0 Cu, 5.0 Al	T	20
C61000	92.0 Cu, 8.0 Al	R, W	20
C61300	92.65 Cu, 0.35 Sn, 7.0 Al	F, R, T, P, S	30
C61400 Aluminum bronze, D	91.0 Cu, 7.0 Al, 2.0 Fe	F, R, W, T, P, S	20
C61500	90.0 Cu, 8.0 Al, 2.0 Ni	F	30
C61800	89.0 Cu, 1.0 Fe, 10.0 Al	R	40
C62300	87.0 Cu, 10.0 Al, 3.0 Fe	F, R	50
C62400	86.0 Cu, 3.0 Fe, 11.0 Al	F, R	50
C62500	82.7 Cu, 4.3 Fe, 13.0 Al	F, R	20
C63000	82.0 Cu, 3.0 Fe, 10.0 Al, 5.0 Ni	F, R	30
C63200	82.0 Cu, 4.0 Fe, 9.0 Al, 5.0 Ni	F, R	30
C63600	95.5 Cu, 3.5 Al, 1.0 Si	R, W	40
C64200	91.2 Cu, 7.0 Al	F, R	60
C65100 Low-silicon bronze, B	98.5 Cu, 1.5 Si	R, W, T	30
C65500 High-silicon bronze, A	97.0 Cu, 3.0 Si	F, R, W, T	30
C66700 Manganese brass	70.0 Cu, 28.8 Zn, 1.2 Mn	F, W	30
C67400	58.5 Cu, 36.5 Zn, 1.2 Al, 2.8 Mn, 1.0 Sn	F, R	25
C67500 Manganese bronze, A	58.5 Cu, 1.4 Fe, 39.0 Zn, 1.0 Sn, 0.1 Mn	R, S	30
C68700 Aluminum brass, arsenical	77.5 Cu, 20.5 Zn, 2.0 Al, 0.1 As	T	30
C69400 Silicon red brass	81.5 Cu, 14.5 Zn, 4.0 Si	R	30
C70400	92.4 Cu, 1.5 Fe, 5.5 Ni, 0.6 Mn	F, T	20
C70600 Copper nickel, 10%	88.7 Cu, 1.3 Fe, 10.0 Ni	F, T	20
C71000 Copper nickel, 20%	79.00 Cu, 21.0 Ni	F, W, T	20
C71500 Copper nickel, 30%	70.0 Cu, 30.0 Ni	F, R, T	20
C71700	67.8 Cu, 0.7 Fe, 31.0 Ni, 0.5 Be	F, R, W	20
C72500	88.20 Cu, 9.5 Ni, 2.3 Sn	F, R, W, T	20
C73500	72.0 Cu, 18.0 Ni, 10.0 Zn	F, R, W, T	20
C74500 Nickel silver, 65–10	65.0 Cu, 25.0 Zn, 10.0 Ni	F, W	20
C75200 Nickel silver, 65–18	65.0 Cu, 17.0 Zn, 18.0 Ni	F, R, W	20
C75400 Nickel silver, 65–15	65.0 Cu, 20.0 Zn, 15.0 Ni	F	20
C75700 Nickel silver, 65–12	65.0 Cu, 23.0 Zn, 12.0 Ni	F, W	20
C77000 Nickel silver, 55–18	55.0 Cu, 27.0 Zn, 18.0 Ni	F, R, W	30
C78200 Leaded nickel silver, 65–8–2	65.0 Cu, 2.0 Pb, 25.0 Zn, 8.0 Ni	F	60

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 442–454.

[a] F, flat products; R, rod; W, wire; T, tube; P, pipe; S, shapes.
[b] Based on 100% for C360000.
[c] C10400, 8 oz/ton Ag; C10500, 10 oz/ton; C10700, 25 oz/ton.
[d] C11300, 8 oz/ton Ag; C11400, 10 oz/ton; C11500, 16 oz/ton; C11600, 25 oz/ton.
[e] C12000, 0.008 P; C12100, 0.008 P and 4 oz/ton Ag.
[f] C12700, 8 oz/ton Ag; C12800, 10 oz/ton; C12900, 16 oz/ton; C13000, 25 oz/ton.
[g] 8.30 oz/ton Ag
[h] C18200, 0.9 Cr; C18400, 0.9 Cr; C18500, 0.7 Cr.
[i] Rod, 61.0 Cu min.

TABLE 1.100 Fatigue Strength of Wrought Aluminum Alloys

Alloy AA No.	Temper	Fatigue Strength (MPa)
1060	0	21
	H12	28
	H14	34
	H16	45
	H18	45
1100	0	34
	H12	41
	H14	48
	H16	62
	H18	62
1350	H19	48
2011	T3	125
	T8	125
2014	0	90
	T4	140
	T6	125
2024	0	90
	T3	140
	T4, T351	140
	T361	125
2036	T4	125
2048		220
2219	T62	105
	T81, T851	105
	T87	105
2618	All	125
3003 and	0	48
Alclad 3003	H12	55
	H14	62
	H16	69
	H18	69
3004 and	0	97
Alclad 3004	H32	105
	H34	105
	H36	110
	H38	110
4032	T6	110

(*Continued*)

TABLE 1.100 (*Continued*) Fatigue Strength of Wrought Aluminum Alloys

Alloy AA No.	Temper	Fatigue Strength (MPa)
5050	0	83
	H32	90
	H34	90
	H36	97
	H38	97
5052	0	110
	H32	115
	H34	125
	H36	130
	H38	140
5056	0	140
	H18	150
	H38	150
5083	H321	160
5154	0	115
	H32	125
	H34	130
	H36	140
	H38	145
	H112	115
5182	0	140
5254	0	115
	H32	125
	H34	130
	H36	140
	H38	145
	H112	115
5652	0	110
	H32	115
	H34	125
	H36	130
	H38	140
6005	T1	97
	T5	97
6009	T4	115
6010	T4	115
6061	0	62
	T4, T451	97
	T6, T651	97

(*Continued*)

TABLE 1.100 (*Continued*) Fatigue Strength of Wrought Aluminum Alloys

Alloy AA No.	Temper	Fatigue Strength (MPa)
6063	0	55
	T1	62
	T5	69
	T6	69
6066	T6, T651	110
6070	0	62
	T4	90
	T6	97
6205	T5	105
6262	T9	90
6351	T6	90
6463	T1	69
	T5	69
	T6	69
7005	T53	140
	T6, T63, T6351	125
7049	T73	295
7050	T736	240
7075	T6, T651	160
7175	T66	160
	T736	160
7475	T7351	220

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 299–302.

TABLE 1.101 Reversed Bending Fatigue Limit of Gray Cast Iron Bars

ASTM Class	Reversed Bending Fatigue Limit (MPa)
20	69
25	79
30	97
35	110
40	128
50	148
60	169

Source: Data from ASM *Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 166–167.

TABLE 1.102 Impact Energy Of Tool Steels

Type	Condition	Impact Energy (J)
L2	Oil quenched from 855°C and single tempered at	
	205°C	28[a]
	315°C	19[a]
	425°C	26[a]
	540°C	39[a]
	650°C	125[a]
L6	Annealed	93 HRB
	Oil quenched from 845°C and single tempered at	
	315°C	12[a]
	425°C	18[a]
	540°C	23[a]
	650°C	81[a]
S1	Oil quenched from 930°C and single tempered at	
	205°C	249[b]
	315°C	233[b]
	425°C	203[b]
	540°C	230[b]
S5	Oil quenched from 870°C and single tempered at	
	205°C	206[b]
	315°C	232[b]
	425°C	243[b]
	540°C	188[b]
S7	Fan cooled from 940°C and single tempered at	
	205°C	244[b]
	315°C	309[b]
	425°C	243[b]
	540°C	324[b]
	650°C	358[b]

Source: Data from *ASM Metals Reference Book*, Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 241.

[a] Charpy V-notch.

[b] Charpy unnotched.

TABLE 1.103 Impact Strength of Wrought Titanium Alloys at Room Temperature

Class	Alloy	Condition	Charpy Impact Strength (J)
Commercially pure	99.2Ti	Annealed	43
	99.1Ti	Annealed	38
	99.0Ti	Annealed	20
	99.2Ti–0.2Pd	Annealed	43
Alpha alloys	Ti–5Al–2.5Sn	Annealed	26
	Ti–5Al–2.5Sn (low O_2)	Annealed	27
Near alpha alloys	Ti–8Al–1Mo–1V	Duplex annealed	32
	Ti–6Al–2Nb–1Ta–1Mo	As rolled 2.5 cm plate	31
Alpha–beta alloys	Ti–6Al–4V	Annealed	19
	Ti–6Al–4V (low O_2)	Annealed	24
	Ti–6Al–6V–2Sn	Annealed	18
	Ti–7Al–4Mo	Solution + age	18
Beta alloys	Ti–13V–1Cr–3Al	Solution + age	11
	Ti–3Al–8V–6Cr–4Mo–4Zr	Solution + age	10

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 512.

TABLE 1.104 Tensile Modulus of Gray Cast Irons

ASTM Class	Tensile Modulus (GPa)
20	66–97
25	79–102
30	90–113
35	100–119
40	110–138
50	130–157
60	141–162

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 166–167.

TABLE 1.105 Tension Modulus of Treated Ductile Irons

Treatment	Tension Modulus (MPa)
60–40–18	169
65–45–12	168
80–55–06	168
120–90–02	164

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 169–170.

TABLE 1.106 Elastic Modulus of Wrought Stainless Steels[a]

Type	UNS Designation	Elastic Modulus (GPa)
201	S20100	197
205	S20500	197
301	S30100	193
302	S30200	193
302B	S30215	193
303	S30300	193
304	S30400	193
S30430	S30430	193
304N	S30451	196
305	S30500	193
308	S30800	193
309	S30900	200
310	S31000	200
314	S31400	200
316	S31600	193
316N	S31651	196
317	S31700	193
317L	S31703	200
321	S32100	193
330	N08330	196
347	S34700	193
384	S38400	193
405	S40500	200
410	S41000	200
414	S41400	200
416	S41600	200
420	S42000	200
429	S42900	200
430	S43000	200
430F	S43020	200
431	S43100	200
434	S43400	200
436	S43600	200
440A	S44002	200
440C	S44004	200
444	S44400	200
446	S44600	200
PH 13–8 Mo	S13800	203
15–5 PH	S15500	196
17–4 PH	S17400	196
17–7 PH	S17700	204

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 360.

[a] Annealed condition.

TABLE 1.107 Modulus of Elasticity of Wrought Titanium Alloys

Class	Metal or Alloy	Modulus of Elasticity (GPa)
Commercially pure	99.5Ti	102.7
	99.2Ti	102.7
	99.1Ti	103.4
	99.0Ti	104.1
	99.2Ti–0.2Pd	102.7
Alpha alloys	Ti–5Al–2.5Sn	110.3
	Ti–5Al–2.5Sn (low O_2)	110.3
Near alpha alloys	Ti–8Al–1Mo–1V	124.1
	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	113.8
	Ti–6Al–2Sn–4Zr–2Mo	113.8
	Ti–5Al–5Sn–2Zr–2Mo–0.25Si	113.8
	Ti–6Al–2Nb–1Ta–1Mo	113.8
Alpha–beta alloys	Ti–8Mn	113.1
	Ti–3Al–2.5V	106.9
	Ti–6Al–4V	113.8
	Ti–6Al–4V (low O_2)	113.8
	Ti–6Al–6V–2Sn	110.3
	Ti–7Al–4Mo	113.8
	Ti–6Al–2Sn–4Zr–6Mo	113.8
	Ti–6Al–2Sn–2Zr–2Mo–2Cr–0.25Si	122.0
	Ti–10V–2Fe–3Al	111.7
Beta alloys	Ti–13V–11Cr–3Al	101.4
	Ti–8Mo–8V–2Fe–3Al	106.9
	Ti–3Al–8V–6Cr–4Mo–4Zr	105.5
	Ti–11.5Mo–6Zr–4.5Sn	103.4

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 511.

TABLE 1.108 Compression Modulus of Treated Ductile Irons

Treatment	Compression Modulus (MPa)
60–40–18	164
65–45–12	163
80–55–06	165
120–90–02	164

Source: Data from ASM *Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 169–170.

TABLE 1.109 Torsional Modulus of Gray Cast Irons

ASTM Class	Torsional Modulus (GPa)
20	27–39
25	32–41
30	36–45
35	40–48
40	44–54
50	50–55
60	54–59

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 166–167.

TABLE 1.110 Torsion Modulus of Treated Ductile Irons

Treatment	Torsion Modulus (MPa)
60–40–18	63
65–45–12	64
80–55–06	62
120–90–02	63.4

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 169–170.

TABLE 1.111 Rupture Strength of Refractory Metal Alloys

Class	Alloy	Alloying Additions (%)	Form	Condition	Temperature (°F)	10-h Rupture (ksi)
Niobium and niobium alloys	Pure niobium	–	All	Recrystallized	2000	5.4
	Nb–1Zr	1 Zr	All	Recrystallized	2000	14
	SCb291	10 Ta, 10 W	Bar, sheet	Recrystallized	2000	9
	C129	10 W, 10 Hf, 0.1 Y	Sheet	Recrystallized	2400	15
	FS85	28 Ta, 11 W, 0.8 Zr	Sheet	Recrystallized	2400	12
	SU31	17 W, 3.5 Hf, 0.12 C, 0.03 Si	Bar, sheet	Special thermal processing	2400	22
Molybdenum and molybdenum alloys	Pure molybdenum	–	All	Stress-relieved annealed	1800	25
	Low C Mo	None	All	Stress-relieved annealed	1800	24
	TZM	0.5 Ti, 0.08 Zr, 0.015 C	All	Stress-relieved annealed	2400	23
	TZC	1.0 Ti, 0.14 Zr, 0.02–0.08 C	All	Stress-relieved annealed	2400	28
	Mo–5Re	5 Re	All	Stress-relieved annealed	3000	1
	Mo–30W	30 W	All	Stress-relieved annealed	2000	20
Tantalum alloys	Unalloyed	None	All	Recrystallized	2400	2.5
	TA–10W	10 W	All	Recrystallized	2400	20

(*Continued*)

TABLE 1.111 (*Continued*) Rupture Strength of Refractory Metal Alloys

Class	Alloy	Alloying Additions (%)	Form	Condition	Temperature (°F)	10-h Rupture (ksi)
Tungsten alloys	Unalloyed	None	Bar, sheet, wire	Stress-relieved annealed	3000	6.8
	W–2 ThO_2	2 ThO_2	Bar, sheet, wire	Stress-relieved annealed	3000	18
	W–3 ThO_2	3 ThO_2	Bar, wire	Stress-relieved annealed	3000	18
	W–4 ThO_2	4 ThO_2	Bar	Stress-relieved annealed	3000	18
	W–15 Mo	15 Mo	Bar, wire	Stress-relieved annealed	3000	12
	W–50 Mo	50 Mo	Bar, wire	Stress-relieved annealed	3000	12
	W–25 Re	25 Re	Bar, sheet, wire	Stress-relieved annealed	3000	10

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 106.

Note: To convert ksi to MPa, multiply by 6.89.

TABLE 1.112 Rupture Strength of Superalloys

		Stress Rupture	
Alloy	Temperature (°C)	100 h (MPa)	1000 h (MPa)
Incoloy 800	650	220	145
	760	115	69
	870	45	33
Incoloy 801	650	250	–
	730	145	–
	815	62	–
Incoloy 802	650	240	170
	760	145	105
	870	97	62
Inconel 600	815	55	39
	870	37	24
Inconel 601[a]	540	–	400
	870	48	30
	980	23	14
Inconel 617[b]	815	140	97
	925	62	–
	980	41	–
Inconel 625[a]	650	440	370
	815	130	93
	870	72	48
Inconel 718[c]	540	–	951
	595	860	760
	650	690	585
Inconel 751[d]	815	200	125
	870	120	69
Inconel X-750[e]	540	–	827
	870	83	45
	925	58	21

(*Continued*)

TABLE 1.112 (*Continued*) Rupture Strength of Superalloys

		Stress Rupture	
Alloy	Temperature (°C)	100 h (MPa)	1000 h (MPa)
N-155, bar[f]	650	360	295
	730	195	150
	870	97	66
N-155[g]	650	380	290
N-155, sheet[f]	980	39	20
Nimonic 75[h]	815	38	24
	870	23	15
	925	14	10
	980	–	7.6
Nimonic 80A[i]	540	–	825
	815	185	115
	870	105	–
Nimonic 90[i]	815	240	155
	870	150	69
	925	69	–
Nimonic 105[j]	815	325	225
	870	210	135
Nimonic 115[k]	815	425	315
	870	315	205
	925	205	130
Nimonic 263[l]	815	170	105
	870	93	46
	925	45	–

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book*, Third Edn., ASM International, Materials Park, OH, 1993, p. 391.

[a] Solution treat 1150°C.
[b] Solution treat 1175°C.
[c] Heat treat to 980°C plus 720°C hold for 8 h, furnace cool to 620°C, hold for 8 h.
[d] 730°C hold for 2 h.
[e] Heat treat to 1150°C plus 840°C hold for 24 h, plus 705°C hold for 20 h.
[f] Solution treated and aged.
[g] Stress-relieved forging.
[h] Heat treat to 1050°C hold for 1 h.
[i] Heat treat to 1080°C hold for 8 h, plus 700°C hold for 16 h.
[j] Heat treat to 1150°C hold for 4 h, plus 1050°C hold for 16 h, plus 850°C hold for 16 h.
[k] Heat treat to 1190°C hold for 1.5 h, plus 1100°C hold for 6 h.
[l] Heat treat to 1150°C hold for 2 h, water quench, plus 800°C hold for 8 h.

TABLE 1.113 Poisson's Ratio of Wrought Titanium Alloys

Class	Metal or Alloy	Poisson's Ratio
Commercially Pure	99.5Ti	0.34
	99.2Ti	0.34
	99.1Ti	0.34
	99.0Ti	0.34
	99.2Ti–0.2Pd	0.34
Near alpha alloys	Ti–8Al–1Mo–1V	0.32
	Ti–5Al–5Sn–2Zr–2Mo–0.25Si	0.326
Alpha–beta alloys	Ti–6Al–4V	0.342
	Ti–6Al–4V (low O_2)	0.342
	Ti–6Al–2Sn–2Zr–2Mo–2Cr–0.25Si	0.327
Beta alloys	Ti–13V–11Cr–3Al	0.304

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 511.

TABLE 1.114 Compression Poisson's Ratio of Treated Ductile Irons

Treatment	Compression Poisson's Ratio
60–40–18	0.26
65–45–12	0.31
80–55–06	0.31
120–90–02	0.27

Source: Data from ASM *Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 169–170.

TABLE 1.115 Torsion Poisson's Ratio of Treated Ductile Irons

Treatment	Torsion Poisson's Ratio
60–40–18	0.29
65–45–12	0.29
80–55–06	0.31
120–90–02	0.28

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 169–170.

TABLE 1.116 Elongation of Tool Steels

Type	Condition	Elongation (%)
L2	Annealed	25
	Oil quenched from 855°C and single tempered at	
	205°C	5
	315°C	10
	425°C	12
	540°C	15
	650°C	25
L6	Annealed	25
	Oil quenched from 845°C and single tempered at	
	315°C	4
	425°C	8
	540°C	12
	650°C	20
S1	Annealed	24
	Oil quenched from 930°C and single tempered at	
	205°C	
	315°C	4
	425°C	5
	540°C	9
	650°C	12
S5	Annealed	25
	Oil quenched from 870°C and single tempered at	
	205°C	5
	315°C	7
	425°C	9
	540°C	10
	650°C	15
S7	Annealed	25
	Fan cooled from 940°C and single tempered at	
	205°C	7
	315°C	9
	425°C	10
	540°C	10
	650°C	14

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 241.

TABLE 1.117 Elongation of Ductile Irons

Specification Number	Grade or Class	Elongation (%)
ASTM A395–76		
ASME SA395	60–40–18	18
ASTM A476–70(d);		
SAE AMS5316	80–60–03	3
ASTM A536–72,		
MIL–1–11466B(MR)	60–40–18	18
	65–45–12	12
	80–55–06	6
	100–70–03	3
	120–90–02	2
SAE J434c	D4018	18
	D4512	12
	D5506	6
	D7003	3
MIL–I–24137(Ships)	Class A	15
	Class B	7
	Class C	20

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 169.

TABLE 1.118 Elongation of Malleable Iron Castings

Specification Number	Grade or Class	Elongation (%)
Ferritic		
ASTM A47, A338; ANSI G48.1;		
FED QQ–I–666c	32510	10
	35018	18
ASTM A197		5
Pearlitic and martensitic		
ASTM A220; ANSI C48.2;		
MIL–I–11444B	40010	10
	45008	8
	45006	6
	50005	5
	60004	4
	70003	3
	80002	2
	90001	1
Automotive		
ASTM A602; SAE J158	M3210	10
	M4504[a]	4
	M5003[a]	3
	M5503[b]	3
	M7002[b]	2
	M8501[b]	1

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 171.

[a] Air quenched and tempered.

[b] Liquid quenched and tempered.

TABLE 1.119 Elongation of Ferritic Stainless Steels

Type	ASTM Specification	Form	Condition	Elongation (%)
Type 405 (UNS S40500)	A580	Wire	Annealed	20
	A580		Annealed, cold finished	16
Type 409 (UNS S40900)	–	Bar	Annealed	25[a]
Type 429 (UNS S42900)	–	Bar	Annealed	30[a]
Type 430 (UNS S43000)	A276	Bar	Annealed, hot finished	20
	A276		Annealed, cold finished	16
Type 430Ti (UNS S43036)	–	Bar	Annealed	30[a]
Type 434 (UNS S43400)	–	Wire	Annealed	33[a]
Type 436 (UNS S43600)	–	Sheet, strip	Annealed	23[a]
Type 442 (UNS S44200)	–	Bar	Annealed	20[a]
Type 444 (UNS S44400)	A176	Plate, sheet, strip	Annealed	20
Type 446 (UNS S44600)	A276	Bar	Annealed, hot finished	20
	A276		Annealed, cold finished	16

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 368.

[a] Typical values.

TABLE 1.120 Elongation of Martensitic Stainless Steels

Type	ASTM Specification	Form	Condition	Elongation (%)
Type 403 (UNS S40300)	A276	Bar	Annealed, hot finished	20
	A276		Annealed, cold finished	16
	A276		Intermediate temper, hot finished	15
	A276		Intermediate temper, cold finished	12
	A276		Hard temper, hot finished	12
	A276		Hard temper, cold finished	12
Type 410 (UNS S41000)	A276	Bar	Annealed, hot finished	20
	A276		Annealed, cold finished	16
	A276		Intermediate temper, hot finished	15
	A276		Intermediate temper, cold finished	12
	A276		Hard temper, hot finished	12
	A276		Hard temper, cold finished	12
Type 410S (UNS S41008)	A176	Plate, sheet, strip	Annealed	22
Type 410Cb (UNS S41040)	A276	Bar	Annealed, hot finished	13
	A276		Annealed, cold finished	12
	A276		Intermediate temper, hot finished	13
	A276		Intermediate temper, cold finished	12
Type 414 (UNS S41400)	A276	Bar	Intermediate temper, hot finished	15
	A276		Intermediate temper, cold finished	15
Type 414L	–	Bar	Annealed	20
Type 420 (UNS S42000)	–	Bar	Tempered 205°C	8
Type 422 (UNS S42200)	A565	Bar	Intermediate and hard tempers for high-temperature service	13

(*Continued*)

TABLE 1.120 (*Continued*) Elongation of Martensitic Stainless Steels

Type	ASTM Specification	Form	Condition	Elongation (%)
Type 431 (UNS S43100)	–	Bar	Tempered 260°C	16
	–		Tempered 595°C	19
Type 440A (UNS S44002)	–	Bar	Annealed	20
	–		Tempered 315°C	5
Type 440B (UNS S44003)	–	Bar	Annealed	18
	–		Tempered 315°C	3
Type 440C (UNS S44004)	–	Bar	Annealed	14
	–		Tempered 315°C	2
Type 501 (UNS S50100)	–	Bar, plate	Annealed	28
	–		Tempered 540°C	15
Type 502 (UNS S50200)	–	Bar, plate	Annealed	30

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 369–370.

TABLE 1.121 Elongation of Precipitation-Hardening Austenitic Stainless Steels

Type	Form	Condition	Elongation (%)
PH 13–8 Mo (UNS S13800)	Bar, plate, sheet, strip	H950	6–10
		H1000	6–10
15–5 PH (UNS S15500) and 17–4 PH (UNS S17400)	Bar, plate, sheet, strip	H900	10[a]
		H925	10[a]
		H1025	12[a]
		H1075	13[a]
		H1100	14[a]
		H1150	16[a]
		H1150M	18[a]
17–7 PH (UNS S17700)	Bar	RH950	6
		TH1050	6

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 371.

[a] For flat rolled products, value varies with thickness.

TABLE 1.122 Elongation of High-Nitrogen Austenitic Stainless Steels

Type	ASTM Specification	Form	Condition	Elongation (%)
Type 201 (UNS S20100)	A276	Bar	Annealed	40
Type 202 (UNS S20200)	A276	Bar	Annealed	40
Type 205 (UNS S20500)	–	Plate	Annealed	58[a]
Type 304N (UNS S30451)	A276	Bar	Annealed	30
Type 304HN (UNS S30452)	–	Bar	Annealed	30
Type 316N (UNS S31651)	A276	Bar	Annealed	30

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 367.

[a] Typical value.

TABLE 1.123 Total Elongation of Cast Aluminum Alloys

Alloy AA No.	Temper	Elongation (in 25 mm) (%)
201.0	T4	20
	T6	7
	T7	4.5
206.0, A206.0	T7	11.7
208.0	F	2.5
242.0	T21	1.0
	T571	0.5
	T77	2.0
	T571	1.0
	T61	0.5
295.0	T4	8.5
	T6	5.0
	T62	2.0
296.0	T4	9.0
	T6	5.0
	T7	4.5
308.0	F	2.0
319.0	F	2.0
	T6	2.0
	F	2.5
	T6	3.0
336.0	T551	0.5
	T65	0.5
354.0	T61	6.0
355.0	T51	1.5
	T6	3.0
	T61	1.0
	T7	0.5
	T71	1.5
	T51	2.0
	T6	4.0
	T62	1.5
	T7	2.0
	T71	3.0
356.0	T51	2.0
	T6	3.5
	T7	2.0
	T71	3.5
	T6	5.0
	T7	6.0
357.0, A357.0	T62	8.0

(*Continued*)

TABLE 1.123 (*Continued*) Total Elongation of Cast Aluminum Alloys

Alloy AA No.	Temper	Elongation (in 25 mm) (%)
359.0	T61	6.0
	T62	5.5
360.0	F	3.0
A360.0	F	5.0
380.0	F	3.0
383.0	F	3.5
384.0, A384.0	F	2.5
390.0	F	1.0
	T5	1.0
A390.0	F, T5	<1.0
	T6	<1.0
	T7	<1.0
	F, T5	1.0
	T6	<1.0
	T7	<1.0
413.0	F	2.5
A413.0	F	3.5
443.0	F	8.0
B443.0	F	10.0
C443.0	F	9.0
514.0	F	9.0
518.0	F	5.0–8.0
520.0	T4	16
535.0	F	13
712.0	F	5.0
713.0	T5	3.0
	T5	4.0
771.0	T6	9.0
850.0	T5	10.0

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 306–307.

TABLE 1.124 Elongation of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Elongation (%)
C10100 Oxygen-free electronic	99.99 Cu	F, R, W, T, P, S	55
C10200 Oxygen-free copper	99.95 Cu	F, R, W, T, P, S	55
C10300 Oxygen-free, extra-low phosphorus	99.95 Cu, 0.003 P	F, R, T, P, S	50
C10400, C10500, C10700 Oxygen-free, silver-bearing	99.95 Cu[b]	F, R, W, S	55
C10800 Oxygen-free, low phosphorus	99.95 Cu, 0.009 P	F, R, T, P	50
CS11000 Electrolytic tough pitch copper	99.90 Cu, 0.04 O	F, R, W, T, P, S	55
C11100 Electrolytic tough pitch, anneal resistant	99.90 Cu, 0.04 O, 0.01 Cd	W	60
C11300, C11400, C11500, C11600 Silver-bearing tough pitch copper	99.90 Cu, 0.04 O, Ag[c]	F, R, W, T, S	55
C12000, C12100	99.9 Cu[d]	F, T, P	55
C12200 Phosphorus deoxidized copper, high residual phosphorus	99.90 Cu, 0.02 P	F, R, T, P	45
C12500, C12700, C12800, C12900, C13000 Fire-refined tough pitch with silver	99.88 Cu[e]	F, R, W, S	55
C14200 Phosphorus deoxidized, arsenical	99.68 Cu, 0.3 As, 0.02 P	F, R, T	45
C19200	98.97 Cu, 1.0 Fe, 0.03 P	F, T	40
C14300	99.9 Cu, 0.1 Cd	F	42
C14310	99.8 Cu, 0.2 Cd	F	42
C14500 Phosphorus deoxidized, tellurium bearing	99.5 Cu, 0.50 Te, 0.008 P	F, R, W, T	50
C14700 Sulfur bearing	99.6 Cu, 0.40 S	R, W	52
C15000 Zirconium copper	99.8 Cu, 0.15 Zr	R, W	54
C15500	99.75 Cu, 0.06 P, 0.11 Mg, Ag[f]	F	40
C15710	99.8 Cu, 0.2 Al_2O_3	R, W	20
C15720	99.6 Cu, 0.4 Al_2O_3	F, R	20
C15735	99.3 Cu, 0.7 Al_2O_3	R	16
C15760	98.9 Cu, 1.1 Al_2O_3	F, R	20
C16200 Cadmium copper	99.0 Cu, 1.0 Cd	F, R, W	57
C16500	98.6 Cu, 0.8 Cd, 0.6 Sn	F, R, W	53
C17000 Beryllium copper	99.5 Cu, 1.7 Be, 0.20 Co	F, R	45
C17200 Beryllium copper	99.5 Cu, 1.9 Be, 0.20 Co	F, R, W, T, P, S	48
C17300 Beryllium copper	99.5 Cu, 1.9 Be, 0.40 Pb	R	48
C17500 Copper–cobalt–beryllium alloy	99.5 Cu, 2.5 Co, 0.6 Be	F, R	28
C18200, C18400, C18500 Chromium copper	99.5 Cu[g]	F, W, R, S, T	40

(*Continued*)

TABLE 1.124 (*Continued*) Elongation of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Elongation (%)
C18700 leaded copper	99.0 Cu, 1.0 Pb	R	45
C18900	98.75 Cu, 0.75 Sn, 0.3 Si, 0.20 Mn	R, W	48
C19000 Copper–nickel–phosphorus alloy	98.7 Cu, 1.1 Ni, 0.25 P	F, R, W	50
C19100 Copper–nickel–phosphorus–tellurium alloy	98.15 Cu, 1.1 Ni, 0.50 Te, 0.25 P	R, F	27
C19400	97.5 Cu, 2.4 Fe, 0.13 Zn, 0.03 P	F	32
C19500	97.0 Cu, 1.5 Fe, 0.6 Sn, 0.10 P, 0.80 Co	F	15
C21000 Gilding, 95%	95.0 Cu, 5.0 Zn	F, W	45
C22000 Commercial bronze, 90%	90.0 Cu, 10.0 Zn	F, R, W, T	50
C22600 Jewelry bronze, 87.5%	87.5 Cu, 12.5 Zn	F, W	46
C23000 Red brass, 85%	85.0 Cu, 15.0 Zn	F, W, T, P	55
C24000 Low brass, 80%	80.0 Cu, 20.0 Zn	F, W	55
C26000 Cartridge brass, 70%	70.0 Cu, 30.0 Zn	F, R, W, T	66
C26800, C27000 Yellow brass	65.0 Cu, 35.0 Zn	F, R, W	65
C28000 Muntz metal	60.0 Cu, 40.0 Zn	F, R, T	52
C31400 Leaded commercial bronze	89.0 Cu, 1.75 Pb, 9.25 Zn	F, R	45
C31600 Leaded commercial bronze, nickel-bearing	89.0 Cu, 1.9 Pb, 1.0 Ni, 8.1 Zn	F, R	45
C33000 Low-leaded brass tube	66.0 Cu, 0.5 Pb, 33.5 Zn	T	60
C33200 High-leaded brass tube	66.0 Cu, 1.6 Pb, 32.4 Zn	T	50
C33500 Low-leaded brass	65.0 Cu, 0.5 Pb, 34.5 Zn	F	65
C34000 Medium-leaded brass	65.0 Cu, 1.0 Pb, 34.0 Zn	F, R, W, S	60
C34200 High-leaded brass	64.5 Cu, 2.0 Pb, 33.5 Zn	F, R	52
C34900	62.2 Cu, 0.35 Pb, 37.45 Zn	R, W	72
C35000 Medium-leaded brass	62.5 Cu, 1.1 Pb, 36.4 Zn	F, R	66
C35300 High-leaded brass	62.0 Cu, 1.8 Pb, 36.2 Zn	F, R	52
C35600 Extra-high-leaded brass	63.0 Cu, 2.5 Pb, 34.5 Zn	F	50
C36000 Free-cutting brass	61.5 Cu, 3.0 Pb, 35.5 Zn	F, R, S	53
C36500 to C36800 Leaded Muntz metal	60.0 Cu[h], 0.6 Pb, 39.4 Zn	F	45
C37000 Free-cutting Muntz metal	60.0 Cu, 1.0 Pb, 39.0 Zn	T	40
C37700 Forging brass	59.0 Cu, 2.0 Pb, 39.0 Zn	R, S	45
C38500 Architectural bronze	57.0 Cu, 3.0 Pb, 40.0 Zn	R, S	30
C40500	95 Cu, 1 Sn, 4 Zn	F	49
C40800	95 Cu, 2 Sn, 3 Zn	F	43
C41100	91 Cu, 0.5 Sn, 8.5 Zn	F, W	13
C41300	90.0 Cu, 1.0 Sn, 9.0 Zn	F, R, W	45
C41500	91 Cu, 1.8 Sn, 7.2 Zn	F	44

(*Continued*)

TABLE 1.124 (*Continued*) Elongation of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Elongation (%)
C42200	87.5 Cu, 1.1 Sn, 11.4 Zn	F	46
C42500	88.5 Cu, 2.0 Sn, 9.5 Zn	F	49
C43000	87.0 Cu, 2.2 Sn, 10.8 Zn	F	55
C43400	85.0 Cu, 0.7 Sn, 14.3 Zn	F	49
C43500	81.0 Cu, 0.9 Sn, 18.1 Zn	F, T	46
C44300, C44400, C44500 Inhibited admiralty	71.0 Cu, 28.0 Zn, 1.0 Sn	F, W, T	65
C46400 to C46700 Naval brass	60.0 Cu, 39.25 Zn, 0.75 Sn	F, R, T, S	50
C48200 Naval brass, medium-leaded	60.5 Cu, 0.7 Pb, 0.8 Sn, 38.0 Zn	F, R, S	43
C48500 Leaded naval brass	60.0 Cu, 1.75 Pb, 37.5 Zn, 0.75 Sn	F, R, S	40
C50500 Phosphor bronze, 1.25% E	98.75 Cu, 1.25 Sn, trace P	F, W	48
C51000 Phosphor bronze, 5% A	95.0 Cu, 5.0 Sn, trace P	F, R, W, T	64
C51100	95.6 Cu, 4.2 Sn, 0.2 P	F	48
C52100 Phosphor bronze, 8% C	92.0 Cu, 8.0 Sn, trace P	F, R, W	70
C52400 Phosphor bronze, 10% D	90.0 Cu, 10.0 Sn, trace P	F, R, W	70
C54400 Free-cutting phosphor bronze	88.0 Cu, 4.0 Pb, 4.0 Zn, 4.0 Sn	F, R	50
C60800 Aluminum bronze, 5%	95.0 Cu, 5.0 Al	T	55
C61000	92.0 Cu, 8.0 Al	R, W	65
C61300	92.65 Cu, 0.35 Sn, 7.0 Al	F, R, T, P, S	42
C61400 Aluminum bronze, D	91.0 Cu, 7.0 Al, 2.0 Fe	F, R, W, T, P, S	45
C61500	90.0 Cu, 8.0 Al, 2.0 Ni	F	55
C61800	89.0 Cu, 1.0 Fe, 10.0 Al	R	28
C61900	86.5 Cu, 4.0 Fe, 9.5 Al	F	30
C62300	87.0 Cu, 10.0 Al, 3.0 Fe	F, R	35
C62400	86.0 Cu, 3.0 Fe, 11.0 Al	F, R	18
C62500	82.7 Cu, 4.3 Fe, 13.0 Al	F, R	1
C63000	82.0 Cu, 3.0 Fe, 10.0 Al, 5.0 Ni	F, R	20
C63200	82.0 Cu, 4.0 Fe, 9.0 Al, 5.0 Ni	F, R	25
C63600	95.5 Cu, 3.5 Al, 1.0 Si	R, W	64
C63800	99.5 Cu, 2.8 Al, 1.8 Si, 0.40 Co	F	36
C64200	91.2 Cu, 7.0 Al	F, R	32
C65100 Low-silicon bronze, B	98.5 Cu, 1.5 Si	R, W, T	55
C65500 High-silicon bronze, A	97.0 Cu, 3.0 Si	F, R, W, T	63
C66700 Manganese brass	70.0 Cu, 28.8 Zn, 1.2 Mn	F, W	60
C67400	58.5 Cu, 36.5 Zn, 1.2 Al, 2.8 Mn, 1.0 Sn	F, R	28
C67500 Manganese bronze, A	58.5 Cu, 1.4 Fe, 39.0 Zn, 1.0 Sn, 0.1 Mn	R, S	33
C68700 Aluminum brass, arsenical	77.5 Cu, 20.5 Zn, 2.0 Al, 0.1 As	T	55

(*Continued*)

TABLE 1.124 (*Continued*) Elongation of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Elongation (%)
C68800	73.5 Cu, 22.7 Zn, 3.4 Al, 0.40 Co	F	36
C69000	73.3 Cu, 3.4 Al, 0.6 Ni, 22.7 Zn	F	40
C69400 Silicon red brass	81.5 Cu, 14.5 Zn, 4.0 Si	R	25
C70400	92.4 Cu, 1.5 Fe, 5.5 Ni, 0.6 Mn	F, T	46
C70600 Copper nickel, 10%	88.7 Cu, 1.3 Fe, 10.0 Ni	F, T	42
C71000 Copper nickel, 20%	79.00 Cu, 21.0 Ni	F, W, T	40
C71500 Copper nickel, 30%	70.0 Cu, 30.0 Ni	F, R, T	45
C71700	67.8 Cu, 0.7 Fe, 31.0 Ni, 0.5 Be	F, R, W	40
C72500	88.20 Cu, 9.5 Ni, 2.3 Sn	F, R, W, T	35
C73500	72.0 Cu, 18.0 Ni, 10.0 Zn	F, R, W, T	37
C74500 Nickel silver, 65–10	65.0 Cu, 25.0 Zn, 10.0 Ni	F, W	50
C75200 Nickel silver, 65–18	65.0 Cu, 17.0 Zn, 18.0 Ni	F, R, W	45
C75400 Nickel silver, 65–15	65.0 Cu, 20.0 Zn, 15.0 Ni	F	43
C75700 Nickel silver, 65–12	65.0 Cu, 23.0 Zn, 12.0 Ni	F, W	48
C76200	59.0 Cu, 29.0 Zn, 12.0 Ni	F, T	50
C77000 Nickel silver, 55–18	55.0 Cu, 27.0 Zn, 18.0 Ni	F, R, W	40
C72200	82.0 Cu, 16.0 Ni, 0.5 Cr, 0.8 Fe, 0.5 Mn	F, T	46
C78200 Leaded nickel silver, 65–8–2	65.0 Cu, 2.0 Pb, 25.0 Zn, 8.0 Ni	F	40

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 442–454.

[a] F, flat products; R, rod; W, wire; T, tube; P, pipe; S, shapes.

[b] C10400, 8 oz/ton Ag; C10500, 10 oz/ton; C10700, 25 oz/ton.

[c] C11300, 8 oz/ton Ag; C11400, 10 oz/ton; C11500, 16 oz/ton; C11600, 25 oz/ton.

[d] C12000, 0.008 P; C12100, 0.008 P and 4 oz/ton Ag.

[e] C12700, 8 oz/ton Ag; C12800, 10 oz/ton; C12900, 16 oz/ton; C13000, 25 oz/ton.

[f] 8.30 oz/ton Ag.

[g] C18200, 0.9 Cr; C18400, 0.8 Cr; C18500, 0.7 Cr.

[h] Rod, 61.0 Cu min.

TABLE 1.125 Elongation of Commercially Pure Tin

Temperature (°C)	Elongation in 25 mm (%)
Strained at 0.2 mm/m · min	
–200	6
–160	15
–120	60
–80	89
–40	86
0	64
23	57
Strained at 0.4 mm/m · min	
15	75
50	85
100	55
150	55
200	45

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 488.

TABLE 1.126 Elongation of Cobalt-Base Superalloys

Alloy	Temperature (°C)	Elongation (%)
Haynes 25 (L–605) sheet	21	64
	540	59
	650	35
	760	12
	870	30
Haynes 188, sheet	21	56
	540	70
	650	61
	760	43
	870	73
S-816, bar	21	30
	540	27
	650	25
	760	21
	870	16

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 387.

TABLE 1.127 Elongation of Nickel-Base Superalloys

Alloy	Temperature (°C)	Elongation (%)
Astroloy, bar	21	16
	540	16
	650	18
	760	21
	870	25
D-979, bar	21	15
	540	15
	650	21
	760	17
	870	18
Hastelloy X, sheet	21	43
	540	45
	650	37
	760	37
	870	50
IN-102, bar	21	47
	540	48
	650	64
	760	110
	870	110
Inconel 600, bar	21	47
	540	47
	650	39
	760	46
	870	80
Inconel 601, sheet	21	45
	540	38
	650	45
	760	73
	870	92
Inconel 625, bar	21	50
	540	50
	650	35
	760	42
	870	125
Inconel 706, bar	21	19
	540	19
	650	21
	760	32
Inconel 718, bar	21	21
	540	18
	650	19
	760	25
	870	88

(*Continued*)

TABLE 1.127 (*Continued*) Elongation of Nickel-Base Superalloys

Alloy	Temperature (°C)	Elongation (%)
Inconel 718, sheet	21	22
	540	26
	650	15
	760	8
Inconel X-750, bar	21	24
	540	22
	650	9
	760	9
	870	47
M-252, bar	21	16
	540	15
	650	11
	760	10
	870	18
Nimonic 75, bar	21	41
	540	41
	650	42
	760	70
	870	68
Nimonic 80A, bar	21	24
	540	24
	650	18
	760	20
	870	34
Nimonic 90, bar	21	23
	540	23
	650	20
	760	10
	870	16
Nimonic 105, bar	21	12
	540	18
	650	24
	760	22
	870	25
Nimonic 115, bar	21	25
	540	26
	650	25
	760	22
	870	18
Pyromet 860, bar	21	22
	540	15
	650	17
	760	18

(*Continued*)

TABLE 1.127 (*Continued*) Elongation of Nickel-Base Superalloys

Alloy	Temperature (°C)	Elongation (%)
René 41, bar	21	14
	540	14
	650	14
	760	11
	870	19
René 95, bar	21	15
	540	12
	650	14
	760	15
Udimet 500, bar	21	32
	540	28
	650	28
	760	39
	870	20
Udimet 520, bar	21	21
	540	20
	650	17
	760	15
	870	20
Udimet 700, bar	21	17
	540	16
	650	16
	760	20
	870	27
Udimet 710, bar	21	7
	540	10
	650	15
	760	25
	870	29
Unitemp AF2–1DA, bar	21	10
	540	13
	650	13
	760	8
	870	8
Waspaloy, bar	21	25
	540	23
	650	34
	760	28
	870	35

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book*, Third Edn., ASM International, Materials Park, OH, 1993, pp. 387–389.

TABLE 1.128 Ductility of Refractory Metal Alloys

Class	Alloy	Alloying Additions (%)	Form	Condition	Low Temperature Ductility[a]
Niobium and niobium alloys	Pure niobium	–	All	Recrystallized	A
	Nb–1Zr	1 Zr	All	Recrystallized	A
	C103(KbI–3)	10 Hf, 1 Ti, 0.7 Zr	All	Recrystallized	A
	SCb291	10 Ta, 10 W	Bar, sheet	Recrystallized	A
	C129	10 W, 10 Hf, 0.1 Y	Sheet	Recrystallized	A
	FS85	28 Ta, 11 W, 0.8 Zr	Sheet	Recrystallized	A
	SU31	17 W, 3.5 Hf, 0.12 C, 0.03 Si	Bar, sheet	Special thermal processing	C
Molybdenum and molybdenum alloys	Pure molybdenum	–	All	Stress-relieved annealed	B–C
	Doped Mo	K, Si; ppm levels	Wire, sheet	Cold worked	B
	Low C Mo	None	All	Stress-relieved annealed	B
	TZM	0.5 Ti, 0.08 Zr, 0.015 C	All	Stress-relieved annealed	B–C
	TZC	1.0 Ti, 0.14 Zr, 0.02–0.08 C	All	Stress-relieved annealed	B–C
	Mo–5Re	5 Re	All	Stress-relieved annealed	B
	Mo–30W	30 W	All	Stress-relieved annealed	B–C
Tantalum alloys	Unalloyed	None	All	Recrystallized	A
	FS61	7.5 W(P/M)	Wire, sheet	Cold worked	A
	FS63	2.5 W, 0.15 Nb	All	Recrystallized	A
	TA–10W	10 W	All	Recrystallized	A
	KBI–40	40 Nb	All	Recrystallized	A
Tungsten alloys	Unalloyed	None	Bar, sheet, wire	Stress-relieved annealed	D
	Doped	K, Si, Al; ppm levels	Wire	Cold worked	C
	W–1 ThO_2	1 ThO_2	Bar, sheet, wire	Stress-relieved annealed	D
	W–2 ThO_2	2 ThO_2	Bar, sheet, wire	Stress-relieved annealed	D
	W–3 ThO_2	3 ThO_2	Bar, wire	Stress-relieved annealed	D
	W–4 ThO_2	4 ThO_2	Bar	Stress-relieved annealed	D
	W–15 Mo	15 Mo	Bar, wire	Stress-relieved annealed	D
	W–50 Mo	50 Mo	Bar, wire	Stress-relieved annealed	D
	W–3 Re	3 Re	Wire	Cold worked	C
	W–25 Re	25 Re	Bar, sheet, wire	Stress-relieved annealed	B

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 390.

[a] A—excellent cryogenic ductility; B—excellent room-temperature ductility; C—may have marginal ductility at room temperature; D—normally brittle at room temperature.

TABLE 1.129 Elongation of Wrought Titanium Alloys At Room Temperature

Class	Alloy	Condition	Elongation (%)
Commercially pure	99.5Ti	Annealed	30
	99.2Ti	Annealed	28
	99.1Ti	Annealed	25
	99.0Ti	Annealed	20
	99.2Ti–0.2Pd	Annealed	28
	Ti–0.8Ni–0.3Mo	Annealed	25
Alpha alloys	Ti–5Al–2.5Sn	Annealed	16
	Ti–5Al–2.5Sn (low O_2)	Annealed	16
Near alpha alloys	Ti–8Al–1Mo–1V	Duplex annealed	15
	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	Duplex annealed	15
	Ti–6Al–2Sn–4Zr–2Mo	Duplex annealed	15
	Ti–5Al–2Sn–2Zr–2Mo–0.25Si	975°C (1/2 h), AC + 595°C (2 h), AC	13
	Ti–6Al–2Nb–1Ta–1Mo	As rolled 2.5 cm plate	13
	Ti–6Al–2Sn–1.5Zr–1Mo–0.35Bi–0.1Si	Beta forge + duplex anneal	11
Alpha–beta alloys	Ti–8Mn	Annealed	15
	Ti–3Al–2.5V	Annealed	20
	Ti–6Al–4V	Annealed	14
		Solution + age	10
	Ti–6Al–4V (low O_2)	Annealed	15
	Ti–6Al–6V–2Sn	Annealed	14
		Solution + age	10
	Ti–7Al–4Mo	Solution + age	16
	Ti–6Al–2Sn–4Zr–6Mo	Solution + age	10
	Ti–6Al–2Sn–2Zr–2Mo–2Cr–0.25Si	Solution + age	11
	Ti–10V–2Fe–3Al	Solution + age	10
Beta alloys	Ti–13V–1Cr–3Al	Solution + age	8
	Ti–8Mo–8V–2Fe–3Al	Solution + age	8
	Ti–3Al–8V–6Cr–4Mo–4Zr	Solution + age	7
		Annealed	15
	Ti–11.5Mo–6Zr–4.5Sn	Solution + age	11

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 512.

TABLE 1.130 Elongation of Wrought Titanium Alloys at High Temperature

Class	Alloy	Condition	Test Temperature (°C)	Elongation (%)
Commercially pure	99.5 Ti	Annealed	315	32
	99.2 Ti	Annealed	315	35
	99.1 Ti	Annealed	315	34
	99.0 Ti	Annealed	315	25
	99.2Ti–0.2Pd	Annealed	315	37
	Ti–0.8Ni–0.3Mo	Annealed	205	37
	Ti–0.8Ni–0.3Mo	Annealed	315	32
Alpha alloys	Ti–5Al–2.5Sn	Annealed	315	18
	Ti–5Al–2.5Sn (low O_2)	Annealed	–195	16
			–255	15
Near alpha alloys	Ti–8Al–1Mo–1V	Duplex annealed	315	20
			425	20
			540	25
	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	Duplex annealed	315	20
			425	22
			540	24
	Ti–6Al–2Sn–4Zr–2Mo	Duplex annealed	315	16
			425	21
			540	26
	Ti–5Al–2Sn–2Zr–2Mo–0.25Si	975°C (1/2 h), AC + 595°C (2 h), AC	315	15
			425	17
			540	19
	Ti–6Al–2Nb–1Ta–1Mo	As rolled 2.5 cm plate	315	20
			425	20
			540	20
	Ti–6Al–2Sn–1.5Zr–1Mo–0.35Bi–0.1Si	Beta forge + duplex anneal	480	15
Alpha–beta alloys	Ti–8Mn	Annealed	315	18
	Ti–3Al–2.5V	Annealed	315	25
	Ti–6Al–4V	Annealed	315	14
		Annealed	425	18
		Annealed	540	35
		Solution + age	315	10
		Solution + age	425	12
		Solution + age	540	22
	Ti–6Al–4V (low O_2)	Annealed	160	14
	Ti–6Al–6V–2Sn	Annealed	315	18
		Solution + age	315	12
	Ti–7Al–4Mo	Solution + age	315	18
			425	20
	Ti–6Al–2Sn–4Zr–6Mo	Solution + age	315	18
			425	19
			540	19

(*Continued*)

TABLE 1.130 (*Continued*) Elongation of Wrought Titanium Alloys at High Temperature

Class	Alloy	Condition	Test Temperature (°C)	Elongation (%)
	Ti–6Al–2Sn–2Zr–2Mo–2Cr–0.25Si	Solution + age	315	14
	Ti–10V–2Fe–3Al	Solution + age	205	13
			315	13
Beta alloys	Ti–13V–1Cr–3Al	Solution + age	315	19
			425	12
	Ti–8Mo–8V–2Fe–3Al	Solution + age	315	15
	Ti–3Al–8V–6Cr–4Mo–4Zr	Solution + age	315	20
			425	17
		Annealed	315	22
	Ti–11.5Mo–6Zr–4.5Sn	Solution + age	315	16

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn. ASM International, Materials Park, OH, 1993, p. 512.

TABLE 1.131 Area Reduction of Tool Steels

Type	Condition	Area Reduction[a] (%)
L2	Annealed	50
	Oil quenched from 855°C and single tempered at	
	205°C	15
	315°C	30
	425°C	35
	540°C	45
	650°C	55
L6	Annealed	55
	Oil quenched from 845°C and single tempered at	
	315°C	9
	425°C	20
	540°C	30
	650°C	48
S1	Annealed	52
	Oil quenched from 930°C and single tempered at	
	205°C	
	315°C	12
	425°C	17
	540°C	23
	650°C	37
S5	Annealed	50
	Oil quenched from 870°C and single tempered at	
	205°C	20
	315°C	24
	425°C	28
	540°C	30
	650°C	40

(*Continued*)

TABLE 1.131 (*Continued*) Area Reduction of Tool Steels

Type	Condition	Area Reduction[a] (%)
S7	Annealed	55
	Fan cooled from 940°C and single tempered at	
	205°C	20
	315°C	25
	425°C	29
	540°C	33
	650°C	45

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 241.
[a] Area reduction in 50 mm.

TABLE 1.132 Reduction in Area of Austenitic Stainless Steels

Type	Form	Condition	ASTM Specification	Area Reduction (%)
Type 302 (UNS S30200)	Bar	Hot finished and annealed	A276	50
		Cold finished and annealed[a]	A276	40
		Cold finished and annealed[b]	A276	40
Type 302B (UNS S30215)	Bar	Hot finished and annealed	A276	50
		Cold finished and annealed[a]	A276	40
		Cold finished and annealed[b]	A276	40
Types 303 (UNS S30300) and 303Se (UNS S30323)	Bar	Annealed	A581	55
Type 304 (UNS S30400)	Bar	Hot finished and annealed	A276	50
		Cold finished and annealed[a]	A276	40
		Cold finished and annealed[b]	A276	40
Type 304L (UNS S30403)	Bar	Hot finished and annealed	A276	50
		Cold finished and annealed[a]	A276	40
		Cold finished and annealed[b]	A276	40
Type 305 (UNS S30500)	Bar	Hot finished and annealed	A276	50
		Cold finished and annealed[a]	A276	40
		Cold finished and annealed[b]	A276	40
Types 308 (UNS S30800), 321 (UNS S32100), 347(UNS34700) and 348 (UNS S34800)	Bar	Hot finished and annealed	A276	50
		Cold finished and annealed[a]	A276	40
		Cold finished and annealed[b]	A276	40
Type 308L	Bar	Annealed	–	70
Types 309 (UNS S30900), 309S (UNS S30908), 310 (UNS S31000) and 310S (UNS S31008)	Bar	Hot finished and annealed	A276	50
		Cold finished and annealed[a]	A276	40
		Cold finished and annealed[b]	A276	40
Type 314 (UNS S31400)	Bar	Hot finished and annealed	A276	50
		Cold finished and annealed[a]	A276	40
		Cold finished and annealed[b]	A276	40

(*Continued*)

TABLE 1.132 (*Continued*) Reduction in Area of Austenitic Stainless Steels

Type	Form	Condition	ASTM Specification	Area Reduction (%)
Type 316 (UNS S31600)	Bar	Hot finished and annealed	A276	50
		Cold finished and annealed[a]	A276	40
		Cold finished and annealed[b]	A276	40
Type 316F (UNS S31620)	Bar	Annealed	–	55
Type 316L (UNS S31603)	Bar	Hot finished and annealed	A276	50
		Cold finished and annealed[a]	A276	40
		Cold finished and annealed[b]	A276	40
Type 316LN	Bar	Annealed	–	70
Type 317 (UNS S31700)	Bar	Hot finished and annealed	A276	50
		Cold finished and annealed[a]	A276	40
		Cold finished and annealed[b]	A276	40
Type 317L (UNS S31703)	Bar	Annealed	–	65
Type 317LM	Bar, plate, sheet, strip	Annealed	–	50
Type 329 (UNS S32900)	Bar	Annealed	–	50
Type 330HC	Bar, wire, strip	Annealed	–	65

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 364–366.

[a] Up to 13 mm thick.

[b] Over 13 mm thick.

TABLE 1.133 Reduction in Area of Ferritic Stainless Steels

Type	ASTM Specification	Form	Condition	Area Reduction (%)
Type 405 (UNS S40500)	A580	Wire	Annealed	45
	A580		Annealed, cold finished	45
Type 429 (UNS S42900)	–	Bar	Annealed	65[a]
Type 430 (UNS S43000)	A276	Bar	Annealed, hot finished	45
	A276		Annealed, cold finished	45
Type 430Ti (UNS S43036)	–	Bar	Annealed	65[a]
Type 434 (UNS S43400)	–	Wire	Annealed	78[a]
Type 442 (UNS S44200)	–	Bar	Annealed	40[a]
Type 446 (UNS S44600)	A276	Bar	Annealed, hot finished	45
	A276		Annealed, cold finished	45

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 368.

[a] Typical values.

TABLE 1.134 Reduction in Area of High-Nitrogen Austenitic Stainless Steels

Type	ASTM Specification	Form	Condition	Area Reduction (%)
Type 201 (UNS S20100)	A276	Bar	Annealed	45
Type 205 (UNS S20500)	–	Plate	Annealed	62[a]
Type 304HN (UNS S30452)	–	Bar	Annealed	50

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 367.

[a] Typical value.

TABLE 1.135 Reduction in Area of Precipitation-Hardening Austenitic Stainless Steels

Type	Form	Condition	Area Reduction (%)
PH 13–8 Mo (UNS S13800)	Bar, plate, sheet, strip	H950	45
		H1000	45
15–5 PH (UNS S15500) and 17–4 PH (UNS S17400)	Bar, plate, sheet, strip	H900	35[a]
		H925	38[a]
		H1025	45[a]
		H1075	45[a]
		H1100	45[a]
		H1150	50[a]
		H1150M	55[a]
17–7 PH (UNS S17700)	Bar	RH950	10
		TH1050	25

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 371.

[a] For flat rolled products, value generally lower and varies with thickness.

TABLE 1.136 Reduction in Area of Martensitic Stainless Steels

Type	ASTM Specification	Form	Condition	Area Reduction (%)
Type 403 (UNS S40300)	A276	Bar	Annealed, hot finished	45
	A276		Annealed, cold finished	45
	A276		Intermediate temper, hot finished	45
	A276		Intermediate temper, cold finished	40
	A276		Hard temper, hot finished	40
	A276		Hard temper, cold finished	40
Type 410 (UNS S41000)	A276	Bar	Annealed, hot finished	45
	A276		Annealed, cold finished	45
	A276		Intermediate temper, hot finished	45
	A276		Intermediate temper, cold finished	40
	A276		Hard temper, hot finished	40
	A276		Hard temper, cold finished	40

(*Continued*)

TABLE 1.136 (*Continued*) Reduction in Area of Martensitic Stainless Steels

Type	ASTM Specification	Form	Condition	Area Reduction (%)
Type 410Cb (UNS S41040)	A276	Bar	Annealed, hot finished	45
	A276		Annealed, cold finished	35
	A276		Intermediate temper, hot finished	45
	A276		Intermediate temper, cold finished	35
Type 414 (UNS S41400)	A276	Bar	Intermediate temper, hot finished	45
	A276		Intermediate temper, cold finished	45
Type 414L	–	Bar	Annealed	60
Type 420 (UNS S42000)	–	Bar	Tempered 205°C	25
Type 422 (UNS S42200)	A565	Bar	Intermediate and hard tempers for high-temperature service	30
Type 431 (UNS S43100)	–	Bar	Tempered 260°C	55
	–		Tempered 595°C	57
	–		Tempered 315°C	20
	–		Tempered 315°C	15
	–		Tempered 315°C	10
Type 501 (UNS S50100)	–	Bar, plate	Annealed	65
	–		Tempered 540°C	50
Type 502 (UNS S50200)	–	Bar, plate	Annealed	70

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 369–370.

TABLE 1.137 Reduction in Area of Commercially Pure Tin

Temperature (°C)	Area Reduction (%)
Strained at 0.2 mm/m · min	
–200	6
–160	10
–120	97
–80	100
–40	100
0	100
23	100

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 488.

TABLE 1.138 Area Reduction of Wrought Titanium Alloys at Room Temperature

Class	Alloy	Condition	Area Reduction (%)
Commercially pure	99.5 Ti	Annealed	55
	99.2 Ti	Annealed	50
	99.1 Ti	Annealed	45
	99.0 Ti	Annealed	40
	99.2Ti–0.2Pd	Annealed	50
	Ti–0.8Ni–0.3Mo	Annealed	42
Alpha alloys	Ti–5Al–2.5Sn	Annealed	40
Near alpha alloys	Ti–8Al–1Mo–1V	Duplex annealed	28
	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	Duplex annealed	35
	Ti–6Al–2Sn–4Zr–2Mo	Duplex annealed	35
	Ti–6Al–2Nb–1Ta–1Mo	As rolled 2.5 cm plate	34
Alpha–beta alloys	Ti–8Mn	Annealed	32
	Ti–6Al–4V	Annealed	30
		Solution + age	25
	Ti–6Al–4V (low O_2)	Annealed	35
	Ti–6Al–6V–2Sn	Annealed	30
		Solution + age	20
	Ti–7Al–4Mo	Solution + age	22
	Ti–6Al–2Sn–4Zr–6Mo	Solution + age	23
	Ti–6Al–2Sn–2Zr–2Mo–2Cr–0.25Si	Solution + age	33
	Ti–10V–2Fe–3Al	Solution + age	19

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 512.

TABLE 1.139 Area Reduction of Wrought Titanium Alloys at High Temperature

Class	Alloy	Condition	Test Temperature (°C)	Area Reduction (%)
Commercially pure	99.5 Ti	Annealed	315	80
	99.2 Ti	Annealed	315	75
	99.1 Ti	Annealed	315	75
	99.0 Ti	Annealed	315	70
	99.2Ti–0.2Pd	Annealed	315	75
Alpha alloys	Ti–5Al–2.5Sn	Annealed	315	45
Near alpha alloys	Ti–8Al–1Mo–1V	Duplex annealed	315	38
			425	44
			540	55
	Ti–11Sn–1Mo–2.25Al–5.0Zr–1Mo–0.2Si	Duplex annealed	315	44
			425	48
			540	50
	Ti–6Al–2Sn–4Zr–2Mo	Duplex annealed	315	42
			425	55
			540	60

(*Continued*)

TABLE 1.139 (*Continued*) Area Reduction of Wrought Titanium Alloys at High Temperature

Class	Alloy	Condition	Test Temperature (°C)	Area Reduction (%)
Alpha–beta alloys	Ti–6Al–4V	Annealed	315	35
		Annealed	425	40
		Annealed	540	50
		Solution + age	315	28
		Solution + age	425	35
		Solution + age	540	45
	Ti–6Al–6V–2Sn	Annealed	315	42
		Solution + age	315	28
	Ti–7Al–4Mo	Solution + age	315	50
			425	55
	Ti–6Al–2Sn–4Zr–6Mo	Solution + age	315	55
			425	67
			540	70
	Ti–6Al–2Sn–2Zr–2Mo– 2Cr–0.25Si	Solution + age	315	27
	Ti–10V–2Fe–3Al	Solution + age	205	33
			315	42

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 512.

TABLE 1.140 Surface Tension of Elements at Melting

Element	Purity (wt.%)	σ_{mp} (dyn/cm)	Atmosphere
Ag	99.7	863 ± 25	Ar
	99.99	(785)	vac.
	99.99	860 ± 20	Ar
	99.99	865	vac.
	99.99	(825)	Ar
	99.99	866	He
	99.999	(828)	vac.
	99.999	873	He
	spect. pure	921	
	spect. pure	918	
Au		(754)	vac.
	99.999	1130	He
	99.999	(731)	vac.
B	99.8	1060 ± 50	vac.
Ba	99.5	276	
Bi	99.9	380 ± 10	Ar
	99.98	378	vac., Ar, H_2
	99.98	380 ± 10	Ar
	99.99	376	Vac.
	99.999	380 ± 3	Ar
	99.99995	375	

(*Continued*)

TABLE 1.140 (*Continued*) Surface Tension of Elements at Melting

Element	Purity (wt.%)	σ_{mp} (dyn/cm)	Atmosphere
Ca	p.a.	360	
Cd	99.9	(550 ± 10)	Ar
		(525 ± 30)	H_2
	99.9999	590 ± 5	–
Co	99.99	(1520)	H_2, He
	99.9983	1880	Vac.
Cr	99.9997	1700 ± 50	Ar
Cs	99.995	68.6	He
Cu	99.9	(11802 ± 40)	Ar
	99.9	(1127)	Vac.
	99.98	(1085)	Vac.
	99.98	1270	Vac.
	99.997	1352	Vac.
	99.997	1355	He, H_2
	99.997	1358	Ar
	99.99999	1300	Vac.
Fe	99.69	1760 ± 20	He, H_2
	99.85	(1619)	Vac.
	99.93	(1510)	Vac.
	99.93	1860 ± 40	He
	99.985	(1560)	
	99.99	(1384)	Vac.
	99.99	(1650)	He, H_2
	99.99	(1700)	Vac.
	99.9992	1773	He, H_2
	99.9998	1880	Vac.
Fr	99.9998	718	Vac., Al_2O_3
		650	Vac.
		632 ± 5	N_2, He
Hf	97.5 ± 2.5	1630	Vac.
In	99.95	559	H_2
	99.995	556.0	Ar, He
Ir	99.9980	2250	Vac.
K	99.895	101	Ar
	99.895	110.3 ± 1	–
	99.895	117	Vac.
	99.936	(79.2)	He
	99.936	95 ± 9.5	–
	99.97 ± 0.64	111.35	He
	99.986	116.95	Ar

(*Continued*)

TABLE 1.140 (*Continued*) Surface Tension of Elements at Melting

Element	Purity (wt.%)	σ_{mp} (dyn/cm)	Atmosphere
Mg	99.5	583	–
	99.91	(525 ± 10)	Ar
Mn	99.9985	1100 ± 50	Ar
Mo	99.7	2080	Vac.
	99.98	2049	Vac.
	99.98	2130	Vac.
	99.9996	2250	Vac.
Na	99.96	210.12	Ar
	99.982	187.4	He
	99.995	191	Ar
	99.995	200.2 ± 0.6	–
	99.995	202	Vac.
Nb, Cb	99.99	2020	Vac.
	99.9986	1900	Vac.
Nd		688	Ar
Ni	99.7	1725	Vac.
	99.999	1770 ± 13	Vac.
	99.999	1728 ± 10	Vac.
	99.999	1822 ± 8	Vac.
	99.999	(1670)	Vac.
	99.999	1760	Vac.
	99.999	(1687)	Vac.
	99.99975	(1977)	He
	–	1809 ± 20	H_2, He,
Os	99.9998	2500	Vac.
Pb	99.9	(410 ± 5)	Ar
	99.98	450	He
	99.98	451	Vac.
	99.998	480	H_2
	99.999	470	Ar
	99.9995	470	
Pd	–	1470	Vac.
	99.998	1500	Vac.
	99.998	1460	He
Pt	–	1869	CO_2
	99.84	(1740 ± 20)	Vac.
	99.9980	1865	Vac.
Rb	–	(77 ± 5)	Vac.
	–	99.8	Ar
	99.92	91 17	Ar
	99.997	85.7	He
Re	99.4	2610	Vac.

(*Continued*)

TABLE 1.140 (*Continued*) Surface Tension of Elements at Melting

Element	Purity (wt.%)	σ_{mp} (dyn/cm)	Atmosphere
	99.9999	2700	Vac.
Rh	–	1940	Vac.
	99.9975	2000	Vac.
Ru	99.9980	2250	Vac.
S	–	60.9	Vac.
Sb	99.15	395 ± 20	Ar
	99.5	383	H_2, N_2
	99.99	395 ± 20	Ar
Sn	99.89	543.7	–
	99.89	562	Vac.
	99.9	(526 ± 10)	Ar
	99.96	552	Vac.
	99.96	552	Ar
	99.99	537	Vac.
	99.99	530	He
	99.998	566	H_2
	99.998	610	Vac.
	99.999	590	Vac.
	99.999	555.8 ± 1.9	–
Sr	99.5	303	
Ta	99.9	(1884)	Vac.
	99.9983	2150	Vac.
	–	2360	Vac.
	–	2030	Vac.
	–	1910	Vac.
Te	99.4	186 ± 2	Ar
	–	178	–
Ti	98.7	1510	Vac.
	99.69	1402	Vac.
	99.92	1390	Ar
	99.92	1460	Vac.
	99.9991	1650	Vac.
Tl	–	464.5	Ar
	99.999	467	–
U	99.94	(1294)	Vac.
	–	1500 ± 75	–
	–	1550	Ar
V	99.9977	1950	Vac.
	–	(1760)	Vac.

(*Continued*)

TABLE 1.140 (*Continued*) Surface Tension of Elements at Melting

Element	Purity (wt.%)	σ_{mp} (dyn/cm)	Atmosphere
W	99.8	2220	Vac.
	99.9	(2000)	Vac.
	99.9999	2500	Vac.
	–	2310	Vac.
Zn	99.9	750 ± 20	Ar
	99.99	757.0 ± 5	Vac.
	99.999	761.0	Vac.
	99.9999	767.5	Vac.
Zr	–	1400	Ar
	99.5	1411 ± 70	Vac.
	99.7	(1533)	Vac.
	99.9998	1480	Vac.

Source: Data from Lang, G., in R. C. Weast (Ed), *Handbook of Chemistry and Physics,* 55th Edn., CRC Press, Cleveland, 1974, F–23.

Note: Values in parentheses are less certain.

TABLE 1.141 Surface Tension of Liquid Elements[a]

Element	Purity (wt.%)	σ_t (dyn/cm)	Temperature °C	Atmosphere
Ag	99.7	$\sigma = (863 + 25) - 0.33\,(t - t_{mp})$	Ar	
	99.96	893	1000	H_2
		862	1150	
		849	1250	
		908	1000	Vac.
	99.72	840	950	Vac.
	99.99	890	1000	Ar, H_2
		916	1000	H_2
		$\sigma = 865 - 0.14\,(t - t_{mp})$	Vac.	
		$\sigma = 825 - 0.05\,(T - 993)^b$	Ar	
		$\sigma = 866 - 0.15\,(t - t_{mp})$	He	
	99.995	907	1000	H_2
		894	1100	
		876	1200	
	99.999	905 ± 10	980	Ar
		890 ± 10	1108	
		725	1600	He
		$\sigma = 873 - 0.15\,(t - t_{mp})$		
	Spect. pure	$\sigma = 1136 - 0.174\,T$	(Valid 1300 – 2200 K)	
		$\sigma = 918 - 0.149\,(t - t_{mp})$		
Au	99.999	1130 ± 10	1108	Ar
		1070	1200	He
		1020	1300	

(*Continued*)

TABLE 1.141 (*Continued*) Surface Tension of Liquid Elements[a]

Element	Purity (wt.%)	σ_t (dyn/cm)	Temperature°C	Atmosphere
Ba	–	224	720	Ar
	99.5	$\sigma = 351 - 0.075$ T	(Valid 1410–1880 K)[b]	
Be	99.98	1100	1500	Vac.
Bi	99.9	362	350	Ar
		350	700	Vac.
	99.90	343	800	H_2
		328	1000	
		(382)	450	Vac.
	99.98	380	450	–
		379	300	Vac.
	99.999	$\sigma = 380 - 0.142\ (t - t_{mp})$	(Valid MP to 555°C)	Ar
	99.99995	$\sigma = 423 - 0.088$ T	(Valid 1352–1555 K)[b]	
Ca	–	337	850	Ar
	p.a.	$\sigma = 472 - 0.100$ T	(Valid 1445–1655 K)[b]	
Cd	99.9	604	390	Ar
Co		1836	1550	Ar
	99.99	1800	1520	Vac., Al_2O_3
	99.99	(1630)	1520	He, Al_2O_3
	99.99	(1640)	1520	He, BeO
	99.99	(1560)	1520	He, MgO
	99.99	1780	1520	H, Al_2O_3
	99.99	(1620)	1520	He
	99.99	(1590)	1520	H_2
		1870	1500	Vac.
		1815	1600	Vac.
	99.99	1812	1600	Vac., Al_2O_3
	99.99	1845	1550	H_2, He
	99.99	1780	1550	
Cr	–	1590 ± 50	1950	Vac.
	99.9997			Ar
Cs		68.4	62	Ar
		67.5	62	Ar
		62.9	146	0
	99.95	69.5	39	Ar
		42.8	494	
		34.6	642	
	99.995	$\sigma = 68.6 - 0.047\ (t - t_{mp})$	(Valid 52–1100°C)	He
Cu		1269 ± 20	1120	Ar
		1285 ± 10	1120	Ar
	99.9	1220	1100	Ar
		1370	1150	Vac.
		(1130)	1183	Ar
	99.99	$\sigma = 73.74 - 1.791 \cdot 10^{-2}\ (t - t_{mp})$		
		$-9.610 \cdot 10^{-5}\ (t - t_{mp})^2$		
		$+6.629 \cdot 10^{-8}\ (t - t_{mp})^3$	(Valid 71–1011°C)	Ar

(*Continued*)

TABLE 1.141 (*Continued*) Surface Tension of Liquid Elements[a]

Element	Purity (wt.%)	σ_t (dyn/cm)	Temperature°C	Atmosphere
	99.98	1301	1100	H_2
		1295	1165	
		1287	1255	
		1285	1120	Vac.
		1298	1440	
	99.98	1230	1600	Ar
	99.99	1290	1250	He
	99.99	1300	1250	H_2
	99.997			He, H_2
	99.997	$\sigma = 1352 - 0.17\ (t - t_{mp})$		Vac.
	99.997	$\sigma = 1358 - 0.20\ (t - t_{mp})$		Ar
		1285 ± 10	1120	Ar, He
	99.99	1320	1100	Ar, H_2
	99.99	1265	1550	H_2, He
	99.999	1341	1100	N_2
		1338	1150	
		1335	1200	
	99.99999	1268 ± 60	1130	Vac.
Fe	Armco	1795	1550	Ar, N_2
		1754	1550	Vac.
	99.69	(1727)	1550	He, Al_2O_3
		(1734)	1550	H_2, Al_2O_3
		$\sigma = 1760 - 0.35\ (t - t_{mp})$		He, H_2
	99.94	(1710)	1560	Vac., Al_2O_3
	99.97	1830 ± 6	1550	Vac., BeO
	99.985	1788	1550	Ar, N_2
	99.987	(1730)	1550	Vac.
	99.99	(1610)	1650	He
		(1430)	1650	He
		(1400)	1650	H_2
		1865	1550	Vac., He
		(1430)	1650	He
		(1400)	1650	H
		(1640)	1650	
	99.9992	$\sigma = 773 + 0.65t$	(Valid 1550–1780°C)	He, H_2
Fr	–	58.4	100	
				Ar
	–	718	350	Vac.
	–	559	1500	He, Al_2O_3
	99.9998	$\sigma = 718 - 0.101\ (t - t_{mp})$		Vac., Al_2O_3
		530	1200	Vac.
		650	1000	Vac.

(*Continued*)

TABLE 1.141 (*Continued*) Surface Tension of Liquid Elements[a]

Element	Purity (wt.%)	σ_t (dyn/cm)	Temperature°C	Atmosphere
Hg		(437)	20	
		(350.5)	21	
		476	25	
		472	25	
		(464)	25	
		(516)	25	
		(435)	25	
		488	25	
		(498)	25	
		476	25	
		484 ± 1.5	25	
		484.9 ± 1.8	25	
		449.7	103	
		387.1	350	
		(410)	16	Air
		(435.5)	20	Air
		(454.7)	20	Ar
		(542)	20	H
		473	19	H_2
		476	25	H_2
		472	20	Vac.
		(402)	20	Vac.
		(432)	20	Vac.
		(436)	20	Vac.
		480	20	Vac.
		(420)	20	Vac.
		(410)	20	Vac.
		(455)	20	Vac.
		(465.2)	20	Vac.
		485.5 ± 1.0	20	Vac.
		(468)	22	Vac.
		473	25	Vac.
		$\sigma = 489.5 - 0.20t$		
	99.9			
		487	−10	
		487.3	16.5	
		(500 ± 15)	20	
		484.6 ± 1.3	20	
		482.5 ± 3.0	20	
		484.9 ± 0.3	21.5	
		(465)	22	
		482.8 ± 9.7	23–25	
		483.5 ± 1.0	25	
		485.1	25	

(*Continued*)

TABLE 1.141 (*Continued*) Surface Tension of Liquid Elements[a]

Element	Purity (wt.%)	σ_t (dyn/cm)	Temperature°C	Atmosphere
		485.4 ± 1.2	25	
		480	25	
		$\sigma = 468.7 - 1.61 \cdot 10^{-1}t - 1.815 \cdot 10^{-2} t^2$		
		$\sigma = 485.5 - 0.149t - 2.84 \cdot 10^{-4} t^2$		
	99.99	475	20	
In	99.95	515	600	H_2
		540	623	
	99.995	592	185	Vac.
		514	600	H_2
		541	300	
	99.999	556	200	Ar
		535	400	
		527.8	550	
	99.9994	539	350	Vac.
	99.9999	$\sigma = 568.0 - 0.04\,t - 7.08 \cdot 10^{-5} t^2$		
K	99.895	$\sigma = 117 - 0.66\,(t - t_{mp})$		Vac.
		112	87	Ar
		80	457	
		64.8	677	
	99.986	$\sigma = 116.95 - 6.742 \cdot 10^{-2}\,(t - t_{mp}) - 3.836 \cdot 10^{-5}\,(t - t_{mp})^2 + 3.707 \cdot 10^{-8}\,(t - t_{mp})^3$	(Valid 77–983°C)	Ar
	99.936	$\sigma = 76.8 - 70.3 \cdot 10^{-4}\,(t - 400)$	(Valid 600–1126°C)	He
	99.97 ± 0.64	$\sigma = 115.51 - 0.0653t$	(Valid 70–713°C)	He
Li	99.95	397.5	180	Ar
		380	300	
		351.5	500	
	99.98	386	287	Ar
		275	922	
		253	1077	
Mg	99.5	$\sigma = 721 - 0.149$ T[b]	(Valid 1125–1326°K)	
	99.8	552	670	N_2
		542	700	
		528	740	
	99.9	550 ± 15	700	Ar
Mn	99.94	1030	1550	Vac.
		1010	1550	

(*Continued*)

TABLE 1.141 (*Continued*) Surface Tension of Liquid Elements[a]

Element	Purity (wt.%)	σ_t (dyn/cm)	Temperature°C	Atmosphere
Na	99.982	$\sigma = 144 - 0.108\,(t - 500)$	(Valid 400–1125°C)	
	99.995	198	123	
		198.5	129	
		190	140	
		$\sigma = 202 - 0.092\,(t - t_{mp})$	(Valid 100–1000°C)	Vac.
	99.96	$\sigma = 210.12 – 8.105 \cdot 10^{-2}\,(t - t_{mp}) - 8.064 \cdot 10^{-5}\,(t - t_{mp})^2 + 3.380 \cdot 10^{-8}\,(t - t_{mp})^3$	(Valid 141–992°C)	
	p.a.	144	617	Ar
		130	764	
		120.4	855	
Nd		674	1186	Ar
Ni	99.7	(1615)	1470	He
		(1570)	1470	H_2
		1735	1470	Vac.
		1725	1475	Vac.
		(1934)	1550	Ar
	99.99	(1490)	1470	He
		(1500)	1470	He, BeO
		(1530)	1470	He, MgO
		(1530)	1470	H_2
		(1600)	1520	H_2, Al_2O_3
		(1650)	1530	H_2
		1700	1470	H_2, He
		1720	1500	Vac.
		1705	1640	Vac.
		1740	1520	Vac., Al_2O_3
		1770	1520	He, Ar, Al_2O_3
		1780	1550	Vac., Al_2O_3
		1810	1560	Vac., Al_2O_3
	99.999	1745	1500	He
		$\sigma = 1770 - 0.39\,(t - 1550)$		
	99.99975	$\sigma = 1665 + 0.215t$	(Valid 1475–1650°C)	He
P(white)		69.7	50	
		64.95	68.7	
Pb	99.9	388	1000	H_2
		445	350	Ar
	99.98	448	340	H, N_2
		442	390	
		439	440	
		452	360	Air
		442	340	Vac.
		435	400	

(*Continued*)

TABLE 1.141 (*Continued*) Surface Tension of Liquid Elements[a]

Element	Purity (wt.%)	σ_t (dyn/cm)	Temperature°C	Atmosphere
		440	425	
		450	350–450	
	99.998	428	700	Vac.
		474	623	H_2
		455	362	Vac.
	99.999	456	390	He
		310	1600	
		$\sigma = 470 - 0.164\,(t - t_{mp})$	(Valid mp to 535°C)	Ar
	99.9994	438	450	Vac.
	99.9995	$\sigma = 538 - 0.114\,T^b$	(Valid 1440–1970°K)	
Pt	99.999	(1699 ± 20)	1800	Ar
Rb		84	52	Ar
		55	477	
		46.8	632	
	99.92	$\sigma = 91.17 - 9.189\,10^{-2}\,(t - t_{mp}) + 7.228 \cdot 10^{-5}\,(t - t_{mp})^2 - 3.830 \cdot 10^{-8}\,(t - t_{mp})^3$	(Valid 1104–1006°C)	Ar
	99.997	$\sigma = 85.7 - 0.054\,(t - t_{mp})$	(Valid 53–1115°C)	He
S	–	51.1	250	Vac.
Sb		349	640	H_2
		349	700	
		368	750	
		361	900	
		342	974	
		348	1100	
		367.9	640	Vac.
		364.9	762	
	99.5	384	675	H_2, N_2
		380	800	
	99.995	350.2	650	Ar
		347.6	700	
		345.0	800	
	99.999	359	800	N_2
		351	1000	
		345	1100	
		320	1600	He
Se	–	88.0 ± 5	230–250	Ar
Si		725	1450	He
		720	1550	Vac.
	99.99	750	1550	Vac.
	99.9999	825	1500	Ar

(*Continued*)

TABLE 1.141 (*Continued*) Surface Tension of Liquid Elements[a]

Element	Purity (wt.%)	σ_t (dyn/cm)	Temperature°C	Atmosphere
Sn	99.9	600	290	Vac.
	99.93	549	250	Vac.
		539	400	
		526	600	
	99.96	470	1000	Vac.
		$\sigma = 552 - 0.167\,(t - t_{mp})$	(Valid MP to 500°C)	Ar
	99.965	508	740	H_2
		489.5	950	
		479.5	1115	
	99.89	554	300	Vac.
	99.99	524	500	Vac.
		508	600	
		543	489	H_2
		528	572	
		503	692	
		536	250	
		530	450	
		545	250	
		530	600	H_2, He
	99.998	559	623	H_2
		500	800	Vac.
		538	300	–
		546	290	–
	99.999	(520)	290	H_2
		(524)	290	Vac.
		$\sigma = 566.84 - 4.76 \cdot 10^{-2}t$		
	99.9994	537	350	Vac.
	99.9999	552.7	246	H_2
Sr		288	775	Ar
		282	830	
		282	893	
	99.5	$\sigma = 392 - 0.085\,T$	(Valid 1152–1602 K)	
Te	99.4	178 ± 1.5	460	Vac.
	–	(162)	475	Vac.
		$\sigma = 178 - 0.024\,(t - t_{mp})$		
Ti	99.0	1576	1680	Vac.
	99.99999	1588	1680	Vac.
Tl	–	450	450	Vac.
	99.999	450	450	Vac.
		$\sigma = 536 - 0.119\,T^b$	(Valid 1270–1695°K)	

Source: Data from Lang, G., in R. C. Weast (Ed), *Handbook of Chemistry and Physics,* 55th Edn., CRC Press, Cleveland, 1974, F–23.

[a] The data are a compilation of several studies and measurements were obtained from the "sessile drop," "maximum bubble pressure," and "pendant drop" methods. The accuracy varies with both method and study.

[b] T in Kelvin (t in °C). Values in parentheses are less certain.

TABLE 1.142 Electrical Conductivity of Metals

Class	Metal or Alloy	Electrical Conductivity (%IACS)
Aluminum and aluminum alloys	Aluminum (99.996%)	64.95
	EC (O, H19)	62
	5052 (O, H38)	35
	5056 (H38)	27
	6101 (T6)	56
Copper and copper alloys: wrought copper	Pure copper	103.06
	Electrolytic (ETP)	101
	Oxygen-free copper (OF)	101
	Free-machining copper 0.5% Te	95
	Free-machining copper 1.0% Pb	98
Wrought alloys	Cartridge brass, 70%	28
	Yellow brass	27
	Leaded commercial bronze	42
	Phosphor bronze, 1.25%	48
	Nickel silver, 55–18	5.5
	Low-silicon bronze (B)	12
	Beryllium copper	22–30
Copper and copper alloys: casting alloys	Chromium copper (1% Cr)	80–90
	88Cu–8Sn–4Zn	11
	87Cu–10Sn–1Pb–2Zn	11
Electrical contact materials: copper alloys	0.04 Oxide	100
	1.25 Sn + P	48
	5 Sn + P	18
	8 Sn + P	13
	15 Zn	37
	20 Zn	32
	35 Zn	27
	2 Be + Ni or Co	17–21
Electrical contact materials: silver and silver alloys	Fine silver	106
	92.5Ag–7.5Cu	85
	90Ag–10Cu	85
	72Ag–28Cu	87
	72Ag–26Cu–2Ni	60
	85Ag–15Cd	35
	97Ag–3Pt	50
	97Ag–3Pd	60
	90Ag–10Pd	30
	90Ag–10Au	40
	60Ag–40Pd	8
	70Ag–30Pd	12
Electrical contact materials: platinum and platinum alloys	Platinum	16
	95Pt–5Ir	9
	90Pt–10Ir	7
	85Pt–15Ir	6

(*Continued*)

TABLE 1.142 (*Continued*) Electrical Conductivity of Metals

Class	Metal or Alloy	Electrical Conductivity (%IACS)
	80Pt–20Ir	5.6
	75Pt–25Ir	5.5
	70Pt–30Ir	5
	65Pt–35Ir	5
	95Pt–5Ru	5.5
	90Pt–10Ru	4
	89Pt–11Ru	4
	86Pt–14Ru	3.5
	96Pt–4W	5
Electrical contact materials: palladium and palladium alloys	Palladium	16
	95.5Pd–4.5Ru	7
	90Pd–10Ru	6.5
	70Pd–30Ag	4.3
	60Pd 40Ag	4.0
	50Pd–50Ag	5.5
	72Pd–26Ag–2Ni	4
	60Pd–40Cu	5
	45Pd–30Ag–20Au–5Pt	4.5
	35Pd–30Ag–14Cu–l0Pt–l0Au–1Zn	5
Electrical contact materials: gold and gold alloys	Gold	75
	90Au–10Cu	16
	75Au–25Ag	16
	72.5Au–14Cu–8.5Pt–4Ag–1Zn	10
	69Au–25Ag–6Pt	11
	41.7Au–32.5Cu–18.8Ni–7Zn	4.5
Electrical heating alloys: Ni–Cr and Ni–Cr–Fe alloys	78.5Ni–20Cr–1.5Si (80–20)	1.6
	73.5Ni–20Cr–5Al–1.5Si	1.2
	68Ni–20Cr–8.5Fe–2Si	1.5
	60Ni–16Cr–22.5Fe–1.5Si	1.5
	35Ni–20Cr–43.5Fe–1.5Si	1.7
Electrical heating alloys:Fe–Cr–Al alloys	72Fe–23Cr–5Al	1.3
	55Fe–37.5Cr–75Al	1.2
Pure metals	Molybdenum	34
	Platinum	16
	Tantalum	13.9
	Tungsten	30
Nonmetallic heating element materials	Silicon carbide, SiC	1–1.7
	Molybdenum disilicide, $MoSi_2$	4.5
Instrument and control alloys: Cu–Ni alloys	98Cu–2Ni	35
	94Cu–6Ni	17
	89Cu–11Ni	11
	78Cu–22Ni	5.7
	55Cu–45Ni (constantan)	3.5

(*Continued*)

TABLE 1.142 (*Continued*) Electrical Conductivity of Metals

Class	Metal or Alloy	Electrical Conductivity (%IACS)
Instrument and control alloys:	87Cu–13Mn (manganin)	3.5
Cu–Mn–Ni alloys	83Cu–13Mn 4Ni (manganin)	3.5
	85Cu–10Mn–4Ni (shunt manganin)	45
	70Cu–20Ni–10Mn	3.6
	67Cu–5Ni–27Mn	1.8
Instrument and control alloys:	99.8 Ni	23
Ni-base alloys	71Ni–29Fe	9
	80Ni–20Cr	1.5
	75Ni–20Cr–3Al + Cu or Fe	1.3
	76Ni–17Cr–4Si–3Mn	1.3
	60Ni–16Cr–24Fe	1.5
	35Ni–20Cr–45Fe	1.7
Instrument and control alloys:	72Fe–23Cr–5Al–0.5Co	1.3
Fe–Cr–Al alloy		
Instrument and control alloys:		
Pure metals	Iron (99.99%)	17.75
Thermostat metals	75Fe–22Ni–3Cr	3
	72Mn–18Cu–10Ni	1.5
	67Ni–30Cu–1.4Fe–1Mn	3.5
	75Fe–22Ni–3Cr	12
	66.5Fe–22Ni–8.5Cr	3.3
Permanent magnet materials:	Carbon steel (0.65%)	9.5
Steels	Carbon steel (1% C)	8
	Chromium steel (3.5% Cr)	6.1
	Tungsten steel (6% W)	6
	Cobalt steel (17% Co)	6.3
	Cobalt steel (36% Co)	6.5
Permanent magnet materials:		
Intermediate alloys	Cunico	7.5
	Cunife	9.5
	Comol	3.6
Permanent magnet materials:	Alnico I	3.3
Alnico alloys	Alnico II	3.3
	Alnico III	3.3
	Alnico IV	3.3
	Alnico V	3.5
	Alnico VI	3.5
Magnetically soft materials:		
Electrical steel sheet	M–50	9.5
	M–43	6–9
	M–36	5.5–7.5
	M–27	3.5–5.5
	M–22	3.5–5
	M–19	3.5–5
	M–17	3–3.5

(*Continued*)

TABLE 1.142 (*Continued*) Electrical Conductivity of Metals

Class	Metal or Alloy	Electrical Conductivity (%IACS)
	M–15	3–3.5
	M–14	3–3.5
	M–7	3–3.5
	M–6	3–3.5
	M–5	3–3.5
Moderately high-permeability materials	Thermenol	0.5
	16 Alfenol	0.7
	Sinimax	2
	Monimax	2.5
	Supermalloy	3
	4–79 Moly Pemalloy, Hymu 80	3
	Mumetal	3
	1040 alloy	3
	High Permalloy 49, A–L 4750, Armco 48	3.6
	45 Permalloy	3.6
High-permeability materials	Supermendur	4.5
	2V Pamendur	4.5
	35% Co, 1% Cr	9
	Ingot iron	17.5
	0.5% Si steel	6
	1.75% Si steel	4.6
	3.0% Si steel	3.6
	Grain-oriented 3.0% Si steel	3.5
	Grain–oriented 50% Ni iron	3.6
	50% Ni iron	3.5
Relay steels and alloys after annealing		
Low-carbon iron and steel	Low-carbon iron	17.5
	1010 Steel	14.5
Silicon steels	1% Si	7.5
	2.5% Si	4
	3% Si	3.5
	3% Si, grain-oriented	3.5
	4% Si	3
Stainless steels	Type 410	3
	Type 416	3
	Type 430	3
	Type 443	3
	Type 446	3
Nickel irons	50% Ni	3.5
	78% Ni	11
	77% Ni (Cu, Cr)	3
	79% Ni (Mo)	3
Stainless and heat resisting alloys	Type 302	3

(*Continued*)

TABLE 1.142 (*Continued*) Electrical Conductivity of Metals

Class	Metal or Alloy	Electrical Conductivity (%IACS)
	Type 309	2.5
	Type 316	2.5
	Type 317	2.5
	Type 347	2.5
	Type 403	3
	Type 405	3
	Type 501	4.5
	HH	2.5
	HK	2
	HT	1.7

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 157–158.

TABLE 1.143 Electrical Resistivity of Metals

Class	Metal or Alloy	Electrical Resistivity (μΩ · cm)
Aluminum and aluminum alloys	Aluminum (99.996%)	2.65
	EC (O, H19)	2.8
	5052 (O, H38)	4.93
	5056 (H38)	6.4
	6101 (T6)	3.1
Copper and copper alloys:		
Wrought copper	Pure copper	1.67
	Electrolytic (ETP)	1.71
	Oxygen-free copper (OF)	1.71
	Free-machining copper 0.5% Te	1.82
	Free-machining copper 1.0% Pb	1.76
Wrought alloys	Cartridge brass, 70%	6.2
	Yellow brass	6.4
	Leaded commercial bronze	4.1
	Phosphor bronze, 1.25%	3.6
	Nickel silver, 55–18	31
	Low-silicon bronze (B)	14.3
	Beryllium copper	5.7–7.8
Copper and copper alloys:		
Casting alloys	Chromium copper (1% Cr)	2.10
	88Cu–8Sn–4Zn	15
	87Cu–10Sn–1Pb–2Zn	15
Electrical contact materials:		
Copper alloys	0.04 Oxide	1.72
	1.25 Sn + P	3.6
	5 Sn + P	11

(*Continued*)

TABLE 1.143 (*Continued*) Electrical Resistivity of Metals

Class	Metal or Alloy	Electrical Resistivity (μΩ · cm)
	8 Sn + P	13
	15 Zn	4.7
	20 Zn	5.4
	35 Zn	6.4
	2 Be + Ni or Co	9.6–11.5
Electrical contact materials:		
Silver and silver alloys	Fine silver	1.59
	92.5Ag–7.5Cu	2
	90Ag–10Cu	2
	72Ag–28Cu	2
	72Ag–26Cu–2Ni	2.9
	85Ag–15Cd	4.93
	97Ag–3Pt	3.5
	97Ag–3Pd	2.9
	90Ag–10Pd	5.3
	90Ag–10Au	4.2
	60Ag–40Pd	23
	70Ag–30Pd	14.3
Electrical contact materials:		
Platinum and platinum alloys	Platinum	10.6
	95Pt–5Ir	19
	90Pt–10Ir	25
	85Pt–15Ir	28.5
	80Pt–20Ir	31
	75Pt–25Ir	33
	70Pt–30Ir	35
	65Pt–35Ir	36
	95Pt–5Ru	31.5
	90Pt–10Ru	43
	89Pt–11Ru	43
	86Pt–14Ru	46
	96Pt–4W	36
Electrical contact materials:		
Palladium and palladium alloys	Palladium	10.8
	95.5Pd–4.5Ru	24.2
	90Pd–10Ru	27
	70Pd–30Ag	40
	60Pd–40Ag	43
	50Pd–50Ag	31.5
	72Pd–26Ag–2Ni	43
	60Pd–40Cu	35
	45Pd–30Ag–20Au–5Pt	39

(*Continued*)

TABLE 1.143 (*Continued*) Electrical Resistivity of Metals

Class	Metal or Alloy	Electrical Resistivity (μΩ · cm)
	35Pd–30Ag–14Cu–l0Pt–10Au–1Zn	35
Electrical contact materials:		
Gold and gold alloys	Gold	2.35
	90Au–10Cu	10.8
	75Au–25Ag	10.8
	72.5Au–14Cu–8.5Pt–4Ag–1Zn	17
	69Au–25Ag–6Pt	15
	41.7Au–32.5Cu–18.8Ni–7Zn	39
Electrical heating alloys:		
Ni–Cr and Ni–Cr–Fe alloys	78.5Ni–20Cr–1.5Si (80–20)	108.05
	73.5Ni–20Cr–5Al–1.5Si	137.97
	68Ni–20Cr–8.5Fe–2Si	116.36
	60Ni–16Cr–22.5Fe–1.5Si	112.20
	35Ni–20Cr–43.5Fe–1.5Si	101.4
Electrical heating alloys:		
Fe–Cr–Al Alloys	72Fe–23Cr–5Al	138.8
	55Fe–37.5Cr–7.5Al	166.23
Pure metals	Molybdenum	5.2
	Platinum	10.64
	Tantalum	12.45
	Tungsten	5.65
Nonmetallic heating element materials	Silicon carbide, SiC	100–200
	Molybdenum disilicide, $MoSi_2$	37.24
	Graphite	910.1
Instrument and control alloys:		
Cu–Ni Alloys	98Cu–2Ni	4.99
	94Cu–6Ni	9.93
	89Cu–11Ni	14.96
	78Cu–22Ni	29.92
	55Cu–45Ni (constantan)	49.87
Instrument and control alloys:		
Cu–Mn–Ni Alloys	87Cu–13Mn (manganin)	48.21
	83Cu–13Mn–4Ni (manganin)	48.21
	85Cu–10Mn–4Ni (shunt manganin)	38.23
	70Cu–20Ni–10Mn	48.88
	67Cu–5Ni–27Mn	99.74
Instrument and control alloys:		
Ni-base Alloys	99.8 Ni	7.98

(*Continued*)

TABLE 1.143 (*Continued*) Electrical Resistivity of Metals

Class	Metal or Alloy	Electrical Resistivity (μΩ · cm)
	71Ni–29Fe	19.95
	80Ni–20Cr	112.2
	75Ni–20Cr–3Al + Cu or Fe	132.98
	76Ni–17Cr–4Si–3Mn	132.98
	60Ni–16Cr–24Fe	112.2
	35Ni–20Cr–45Fe	101.4
Instrument and control alloys:		
Fe–Cr–Al alloy	72Fe–23Cr–5Al–0.5Co	135.48
Instrument and control alloys:		
Pure metals	Iron (99.99%)	9.71
Thermostat metals	75Fe–22Ni–3Cr	78.13
	72Mn–18Cu–10Ni	112.2
	67Ni–30Cu–1.4Fe–1Mn	56.52
	75Fe–22Ni–3Cr	15.79
	66.5Fe–22Ni–8.5Cr	58.18
Permanent magnet materials:		
Steels	Carbon steel (0.65%)	18
	Carbon steel (1% C)	20
	Chromium steel (3.5% Cr)	29
	Tungsten steel (6% W)	30
	Cobalt steel (17% Co)	28
	Cobalt steel (36% Co)	27
Permanent magnet materials:		
Intermediate alloys	Cunico	24
	Cunife	18
	Comol	45
Permanent magnet materials:		
Alnico alloys	Alnico I	75
	Alnico II	65
	Alnico III	60
	Alnico IV	75
	Alnico V	47
	Alnico VI	50
Magnetically soft materials:		
Electrical steel sheet	M–50	18
	M–43	20–28
	M–36	24–33
	M–27	32–47
	M–22	41–52
	M–19	41–56

(*Continued*)

TABLE 1.143 (*Continued*) Electrical Resistivity of Metals

Class	Metal or Alloy	Electrical Resistivity (μΩ · cm)
	M–17	45–58
	M–15	45–69
	M–14	58–69
	M–7	45–52
	M–6	45–52
	M–5	45–52
Moderately high-permeability materials	Thermenol	162
	16 Alfenol	153
	Sinimax	90
	Monimax	80
	Supermalloy	65
	4–79 Moly Pemalloy, Hymu 80	58
	Mumetal	60
	1040 alloy	56
	High Permalloy 49, A–L 4750, Armco 48	48
	45 Permalloy	45
High-permeability materials	Supermendur	40
	2V Pamendur	40
	35% Co, 1% Cr	20
	Ingot iron	10
	0.5% Si steel	28
	1.75% Si steel	37
	3.0% Si steel	47
	Grain-oriented 3.0% Si steel	50
	Grain-oriented 50% Ni iron	45
	50% Ni iron	50
Relay steels and alloys after annealing		
Low-carbon iron and steel	Low-carbon iron	10
	1010 Steel	12
Silicon steels	1% Si	23
	2.5% Si	41
	3% Si	48
	3% Si, grain-oriented	48
	4% Si	59
Stainless steels	Type 410	57
	Type 416	57
	Type 430	60
	Type 443	68
	Type 446	61

(*Continued*)

TABLE 1.143 (*Continued*) Electrical Resistivity of Metals

Class	Metal or Alloy	Electrical Resistivity (μΩ · cm)
Nickel irons	50% Ni	48
	78% Ni	16
	77% Ni (Cu, Cr)	60
	79% Ni (Mo)	58
Stainless and heat resisting alloys	Type 302	72
	Type 309	78
	Type 316	74
	Type 317	74
	Type 347	73
	Type 403	57
	Type 405	60
	Type 501	40
	HH	80
	HK	90
	HT	100

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 157–158.

TABLE 1.144 Electrical Resistivity of Alloy Cast Irons

Class	Description	Electrical Resistivity (μΩ · m)
Abrasion-resistant white irons	Low-C white iron	0.53
	Martensitic nickel–chromium iron	0.80
Corrosion-resistant irons	High-silicon iron	0.50
	High-nickel gray iron	1.0[a]
	High-nickel ductile iron	1.0[a]
Heat-resistant gray irons	High-nickel iron	1.4–1.7
	Nickel–chromium–silicon iron	1.5–1.7
	High-aluminum iron	2.4
Heat-resistant ductile irons	Medium-silicon ductile iron	0.58–0.87
	High-nickel ductile (20 Ni)	1.02
	High-nickel ductile (23 Ni)	1.0[a]

Source: Ddata from *ASM Metals Reference Book*, Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 172.

[a] Estimated

TABLE 1.145 Critical Temperature of Superconductive Elements

Element	T_c (K)
Al	1.175
Be	0.026
Cd	0.518–0.52
Ga	1.0833
Ga (β)	5.90–6.2
Ga (γ)	7.62
Ga (δ)	7.85
Hg (α)	4.154
Hg (β)	3.949
In	3.405
Ir	0.11–0.14
La (α)	4.88
La (β)	6.00
Mo	0.916
Nb	9.25
Os	0.655
Pa	1.4
Pb	7.23
Re	1.697
Ru	0.493
Sb	2.6–2.7[a]
Sn	3.721
Ta	4.47
Tc	7.73–7.78
Th	1.39
Ti	0.39
Tl	2.332–2.39
V	5.43–5.31
W	0.0154
Zn	0.875
Zr	0.53
Zr (ω)	0.65

Source: Data from Roberts, B. W., *Properties of Selected Superconductive Materials—1974 Supplement*, NBS Technical Note 825, National Bureau of Standards, U.S. Government Printing Office, Washington, DC, 1974, p. 10.

[a] Metastable.

TABLE 1.146 Composition Limits of Tool Steels

	Designations			Compositions (%)								
	AISI	SAE	UNS	C	Mn	Si	Cr	Ni	Mo	W	V	Co
Molybdenum high-speed steels												
	M2	M2	T11302	0.78–0.88	0.15–0.40	0.20–0.45	3.75–4.50	0.30 max	4.50–5.50	5.50–6.75	1.75–2.20	
Tungsten high-speed steels												
	T1	T1	T12001	0.65–0.80	0.10–0.40	0.20–0.40	3.75–4.00	0.30 max		17.25–18.75	0.90–1.30	
	T15		T12015	1.50–1.60	0.15–0.40	0.15–0.40	3.75–5.00	0.30 max	1.00 max	11.75–13.00	4.50–5.25	4.75–5.25
Chromium hot work steels												
	H11	H11	T20811	0.33–0.43	0.20–0.50	0.80–1.20	4.75–5.50	0.30 max	1.10–1.60		0.30–0.60	
	H13	H13	T20813	0.32–0.45	0.20–0.50	0.80–1.20	4.75–5.50	0.30 max	1.10–1.75		0.80–1.20	
Tungsten hot work steels												
	H21	H21	T20821	0.26–0.36	0.15–0.40	0.15–0.50	3.00–3.75	0.30 max		8.50–10.00	0.30–0.60	
	H26		T20826	0.45–0.55	0.15–0.40	0.15–0.40	3.75–4.50	0.30 max		17.25–19.00	0.75–1.25	
Air-hardening medium-alloy cold work steels												
	A2	A2	T30102	0.95–1.05	1.00 max	0.50 max	4.75–5.50	0.30 max	0.90–1.40		0.15–0.50	
	A3		T30103	1.20–1.30	0.40–0.60	0.50 max	4.75–5.50	0.30 max	0.90–1.40		0.80–1.40	
Shock-resisting steels												
	S1	S1	T41901	0.40–0.55	0.10–0.40	0.15–1.20	1.00–1.80	0.30 max	0.50 max	1.50–3.00	0.15–0.30	
	S2	S5	T41905	0.50–0.65	0.60–1.00	1.75–2.25	0.35 max		0.20–1.35		0.35 max	
	S7		T41907	0.45–0.55	0.20–0.80	0.20–1.00	3.00–3.50		1.30–1.80		0.20–0.30	
Low-alloy special-purpose tool steels												
	L2		T61202	0.45–1.00	0.10–0.90	0.50 max	0.70–1.20		0.25 max		0.10–0.30	
	L6	L6	T61206	0.62–0.75	0.25–0.80	0.50 max	0.60–1.20	1.25–2.00	0.50 max		0.20–0.30	
Water-hardening tool steels												
	W1	W108	T72301	0.70–1.50	0.10–0.40	0.10–0.40	0.15 max	0.20 max	0.10 max	0.15 max	0.10 max	
		W109										
		W110										
		W112										

Source: Data from *ASM Metals Reference Book*, Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 239.

TABLE 1.147 Composition Limits of Gray Cast Irons

		Composition Limits (%)				
UNS	SAE Grade	TC	Mn	Si	P	S
F10004	G1800	3.40–3.70	0.50–0.80	2.80–2.30	0.15	0.15
F10005	G2500	3.20–3.50	0.60–0.90	2.40–2.00	0.12	0.15
F10009	G2500	3.40 min	0.60–0.90	1.60–2.10	0.12	0.12
F10006	G3000	3.10–3.40	0.60–0.90	2.30–1.90	0.10	0.16
F10007	G3500	3.00–3.30	0.60–0.90	2.20–1.80	0.08	0.16
F10010	G3500	3.40 min	0.60–0.90	1.30–1.80	0.08	0.12
F10011	G3500	3.50 min	0.60–0.90	1.30–1.80	0.08	0.12
F10008	G4000	3.00–3.30	0.70–1.00	2.10–1.80	0.07	0.16
F10012	G4000	3.10–3.60	0.60–0.90	1.95–2.40	0.07	0.12

Source: Data from *ASM Metals Reference Book*, Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 166.

TABLE 1.148 Composition Limits of Ductile Irons

Specification No.		Composition (%)				
Grade or Class	UNS	TC	Si	Mn	P	S
ASTM A395						
ASME SA395						
60–40–18	F32800	3.00 min	2.50 max	0.08 max		
ASTM A476						
SAE AM55316						
80–60–03	F34100	3.00 min	3.0 max	0.08 max		
SAE J434c						
D4018	F32800	3.20–4.10	1.80–3.00	0.10–1.00	0.015–0.10	0.005–0.035
MIL–1–24137						
(Ships)						
Class A	F33101	3.0 min	2.50 max	0.08 max		
Class B	F43020	2.40–3.00	1.80–3.20	0.80–1.50	0.20 max	
Class C	F43021	2.70–3.10	2.00–3.00	1.90–2.50	0.15 max	

Source: Data from *ASM Metals Reference Book*, Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 168–169.

TABLE 1.149 Composition Ranges for Malleable Irons

	Composition (%)				
Type	TC	Mn	Si	P	S
Ferritic					
Grade 32510	2.30–2.70	0.25–0.55	1.00–1.75	0.05 max	0.03–0.18
Grade 35018	2.00–2.45	0.25–0.55	1.00–1.35	0.05 max	0.03–0.18
Pearlitic	2.00–2.70	0.25–1.25	1.00–1.75	0.05 max	0.03–0.18

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 170.

TABLE 1.150 Composition Ranges for Carbon Steels

		Composition Range (%)	
AISI–SAE Designation	UNS Designation	C	Mn
1015	G10150	0.12–0.18	0.30–0.60
1020	G10200	0.17–0.23	0.30–0.60
1022	G10220	0.17–0.23	0.70–1.00
1030	G10900	0.27–0.34	0.60–0.90
1040	G10400	0.36–0.44	0.60–0.90
1050	G10500	0.47–0.55	0.60–0.90
1060	G10600	0.55–0.66	0.60–0.90
1080	G10800	0.74–0.88	0.60–0.90
1095	G10950	0.90–1.04	0.30–0.50

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 184.

TABLE 1.151 Composition Ranges for Resulfurized Carbon Steels

		Composition Range (%)		
AISI–SAE Designation	UNS Designation	C	Mn	S
1118	G11180	0.14–0.20	1.30–1.60	0.08–0.13
1137	G11370	0.32–0.39	1.35–1.65	0.08–0.13
1141	G11410	0.37–0.45	1.35–1.65	0.08–0.13
1144	G11440	0.40–0.48	1.35–1.65	0.24–0.33

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 185.

TABLE 1.152 Composition Ranges for Alloy Steels

AISI–SAE Designation	UNS Designation	Composition Range (%)							
		C	Mn	P (max)	S (max)	Si	Cr	Ni	Mo
1330	G13300	0.28–0.33	1.60–1.90	0.035	0.040	0.15–0.30			
1340	G13400	0.38–0.43	1.60–1.90	0.035	0.040	0.15–0.30			
3140		0.38–0.43	0.70–0.90	0.040	0.040	0.20–0.35	0.55–0.75	1.10–1.40	
4037	G40370	0.35–0.40	0.70–0.90	0.035	0.040	0.15–0.30	0.20–0.30		
4042	G40420	0.40–0.45	0.70–0.90	0.035	0.040	0.15–0.30	0.20–0.30		
4130	G41300	0.28–0.33	0.40–0.60	0.035	0.040	0.15–0.30	0.80–1.10		0.15–0.25
4140	G41400	0.38–0.43	0.75–1.00	0.035	0.040	0.15–0.30	0.80–1.10		0.15–0.25
4150	G41500	0.48–0.53	0.75–1.00	0.035	0.040	0.15–0.30	0.80–1.10		0.15–0.25
4320	G43200	0.17–0.22	0.45–0.65	0.035	0.040	0.15–0.30	0.40–0.60	1.65–2.00	0.20–0.30
4340	G43400	0.38–0.43	0.60–0.80	0.035	0.040	0.15–0.30	0.70–0.90	1.65–2.00	0.20–0.30
4620	G46200	0.17–0.22	0.45–0.65	0.035	0.040	0.15–0.30	1.65–2.00		0.20–0.30
4820	G48200	0.18–0.23	0.50–0.70	0.035	0.040	0.15–0.30	3.25–3.75		0.20–0.30
5046	G50460	0.43–0.48	0.75–1.00	0.035	0.040	0.15–0.30	0.20–0.35		
50B46	G50461	0.44–0.49	0.75–1.00	0.035	0.040	0.15–0.30	0.20–0.35		
5060	G50600	0.56–0.64	0.75–1.00	0.035	0.040	0.15–0.30	0.40–0.60		
50B60	G50461	0.56–0.64	0.75–1.00	0.035	0.040	0.15–0.30	0.40–0.60		
5130	G51300	0.28–0.33	0.70–0.90	0.035	0.040	0.15–0.30	0.80–1.10		
5140	G51400	0.38–0.43	0.70–0.90	0.035	0.040	0.15–0.30	0.70–0.90		
5150	G51500	0.48–0.53	0.70–0.90	0.035	0.040	0.15–0.30	0.70–0.90		
5160	G51600	0.56–0.64	0.75–1.00	0.035	0.040	0.15–0.30	0.70–0.90		
51B60	G51601	0.56–0.64	0.75–1.00	0.035	0.040	0.15–0.30	0.70–0.90		
6150[a]	G61500	0.48–0.53	0.70–0.90	0.035	0.040	0.15–0.30	0.80–1.10		
81B45	G81451	0.43–0.48	0.75–1.00	0.035	0.040	0.15–0.30	0.35–0.55	0.20–0.40	0.08–0.15
8620	G86200	0.18–0.23	0.70–0.90	0.035	0.040	0.15–0.30	0.40–0.60	0.40–0.70	0.15–0.25
8630	G86300	0.28–0.33	0.70–0.90	0.035	0.040	0.15–0.30	0.40–0.60	0.40–0.70	0.15–0.25
8640	G86400	0.38–0.43	0.75–1.00	0.035	0.040	0.15–0.30	0.40–0.60	0.40–0.70	0.15–0.25
86B45	G86451	0.43–0.48	0.75–1.00	0.035	0.040	0.15–0.30	0.40–0.60	0.40–0.70	0.15–0.25
8650	G86500	0.48–0.53	0.75–1.00	0.035	0.040	0.15–0.30	0.40–0.60	0.40–0.70	0.15–0.25
8660	G86600	0.56–0.64	0.75–1.00	0.035	0.040	0.15–0.30	0.40–0.60	0.40–0.70	0.15–0.25
8740	G87400	0.38–0.43	0.75–1.00	0.035	0.040	0.15–0.30	0.40–0.60	0.40–0.70	0.20–0.30
9255	G92550	0.51–0.59	0.70–0.95	0.035	0.040	1.80–2.20			
9260	G92600	0.56–0.64	0.75–1.00	0.035	0.040	1.80–2.20			
9310	G93106	0.08–0.13	0.45–0.65	0.025	0.025	0.15–0.30	1.00–1.40	3.00–3.50	0.08–0.15
94B30	G94301	0.28–0.33	0.75–1.00	0.035	0.040	0.15–0.30	0.30–0.50	0.30–0.60	0.08–0.15

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, pp. 186–193.

[a] Contains 0.15% min vanadium.

TABLE 1.153 Composition of Stainless Steels

		Composition[a] (%)							
Type	UNS Number	C	Mn	Si	Cr	Ni[b]	P	S	Others
Austenitic									
201	S20100	0.15	5.5–7.5	1.00	16.0–18.0	3.5–5.5	0.06	0.03	0.25 N
202	S20200	0.15	7.5–10.0	1.00	17.0–19.0	4.0–6.0	0.06	0.03	0.25 N
205	S20500	0.12–0.25	14.0–15.5	1.00	16.5–18.0	1.0–1.75	0.06	0.03	0.32–0.40 N
301	S30100	0.15	2.00	1.00	16.0–18.0	6.0–8.0	0.045	0.03	–
302	S30200	0.15	2.00	1.00	17.0–19.0	8.0–10.0	0.045	0.03	–
302B	S30215	0.15	2.00	2.0–3.0	17.0–19.0	8.0–10.0	0.045	0.03	–
303	S30300	0.15	2.00	1.00	17.0–19.0	8.0–10.0	0.20	0.15 min	0.6 Mo[c]
303Se	S30323	0.15	2.00	1.00	17.0–19.0	8.0–10.0	0.20	0.06	0.15 Se min
304	S30400	0.08	2.00	1.00	18.0–20.0	8.0–10.5	0.045	0.03	
304H	S30409	0.04–0.10	2.00	1.00	18.0–20.0	8.0–10.5	0.045	0.03	–
304L	S30403	0.03	2.00	1.00	18.0–20.0	8.0–12.0	0.045	0.03	–
304LN	–	0.03	2.00	1.00	18.0–20.0	8.0–10.5	0.045	0.03	0.10–0.15 N
S30430	S30430	0.08	2.00	1.00	17.0–19.0	8.0–10.0	0.045	0.03	3.0–4.0 Cu
304N	S30451	0.08	2.00	1.00	18.0–20.0	8.0–10.5	0.045	0.03	0.10–0.16 N
30S	S30500	0.12	2.00	1.00	17.0–19.0	10.S–13.0	0.045	0.03	–
308	S30800	0.08	2.00	1.00	19.0–21.0	10.0–12.0	0.045	0.03	–
309	S30900	0.20	2.00	1.00	22.0–24.0	12.0 15.0	0.045	0.03	–
309S	S30908	0.08	2.00	1.00	22.0–24.0	12.0–15.0	0.045	0.03	–
310	S31000	0.25	2.00	1.50	24.0–26.0	19.0–22.0	0.045	0.03	–
310S	S31008	0.08	2.00	1.50	24.0–26.0	19.0–22.0	0.045	0.03	–
314	S31400	0.25	2.00	1.5–3.0	23.0–26.0	19.0–22.0	0.045	0.03	–
316	S31600	0.08	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.03	2.0–3.0 Mo
316F	S31620	0.08	2.00	1.00	16.0–18.0	10.0–14.0	0.20	0.10 min	1.75–2.5 Mo
316H	S31609	0.04–0.10	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.03	2.0–3.0 Mo
316L	S31603	0.03	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.03	2.0–3.0 Mo
316LN	—	0.03	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.03	2.0–3.0 Mo; 0.10–0.30 N

(*Continued*)

TABLE 1.153 (*Continued*) Composition of Stainless Steels

Type	UNS Number	Composition[a] (%)							
		C	Mn	Si	Cr	Ni[b]	P	S	Others
316N	S31651	0.08	2.00	1.00	16.0–18.0	10.0–14.0	0.045	0.03	2.0–3.0 Mo; 0.10–0.16 N
317	S31700	0.08	2.00	1.00	18.0–20.0	11.0–15.0	0.045	0.03	3.0–4.0 Mo
317L	S31703	0.03	2.00	1.00	18.0–20.0	11.0–15.0	0.045	0.03	3.0–4.0 Mo
321	S32100	0.08	2.00	1.00	17.0–19.0	9.0–12.0	0.045	0.03	5 × %C Ti min
321H	S32109	0.04–0.10	2.00	1.00	17.0–19.0	9.0–12.0	0.045	0.03	5 × %C Ti min
329	S32900	0.10	2.00	1.00	25.0–30.0	3.0–6.0	0.045	0.03	1.0–2.0 Mo
330	N08330	0.08	2.00	0.75–1.5	17.0–20.0	34.0–37.0	0.04	0.03	–
347	S34700	0.08	2.00	1.00	17.0–19.0	9.0–13.0	0.045	0.03	10 × %C Nb + Ta[d] min
347H	S34709	0.04–0.10	2.00	1.00	17.0–19.0	9.0–13.0	0.045	0.03	10 × %C Nb + Ta min
348	S34800	0.08	2.00	1.00	17.0–19.0	9.0–13.0	0.045	0.03	0.2 Cu; 10 × %C Nb + Ta[d] min
348H	S34809	0.04–0.10	2.00	1.00	17.0–19.0	9.0–13.0	0.045	0.03	0.2 Cu; 10 × %C Nb + Ta[d] min
384	S38400	0.08	2.00	1.00	15.0–17.0	17.0–19.0	0.045	0.03	–
Ferritic									
405	S40500	0.08	1.00	1.00	11.5–14.5	–	0.04	0.03	0.10–0.30 Al
409	S40900	0.08	1.00	1.00	10.5–11.75	–	0.045	0.045	6 × %C Ti[e] min
429	S42900	0.12	1.00	1.00	14.0–16.0	–	0.04	0.03	–
430	S43000	0.12	1.00	1.00	16.0–18.0	–	0.04	0.03	–
430F	S43020	0.12	1.25	1.00	16.0–18.0	–	0.06	0.15	0.6 Mo[c]
430FSe	S43023	0.12	1.25	1.00	16.0–18.0	–	0.06	0.06	0.15 Se min
434	S43400	0.12	1.00	1.00	16.0–18.0	–	0.04	0.03	0.75–1.25 Mo
436	S43600	0.12	1.00	1.00	16.0–18.0	–	0.04	0.03	0.75–1.25 Mo; 5 × %C Nb + Ta[f] min
442	S44200	0.20	1.00	1.00	18.0–23.0	–	0.04	0.03	–
446	S44600	0.20	1.50	1.00	23.0–27.0	–	0.04	0.03	0.25 N
Martensitic									
403	S40300	0.15	1.00	0.50	11.5–13.0	–	0.04	0.03	–
410	S41000	0.15	1.00	1.00	11.5–13.0	–	0.04	0.03	
414	S41400	0.15	1.00	1.00	11.5–13.5	1.25–2.50	0.04	0.03	–

(*Continued*)

TABLE 1.153 (*Continued*) Composition of Stainless Steels

		Composition[a] (%)							
Type	UNS Number	C	Mn	Si	Cr	Ni[b]	P	S	Others
416	S41600	0.15	1.25	1.00	12.0–14.0	–	0.04	0.03	0.6 Mo[c]
416Se	S41623	0.15	1.25	1.00	12.0–14.0	–	0.06	0.06	0.15 Se min
420	S42000	0.15 min	1.00	1.00	12.0–14.0	–	0.04	0.03	–
420F	S42020	0.15 min	1.25	1.00	12.0–14.0	–	0.06	0.15 min	0.6Mo[c]
422	S42200	0.2–0.25	1.00	0.75	11.0–13.0	0.5–1.0	0.025	0.025	0.75–1.25 Mo; 0.75–1.25 W; 0.15–0.3 V
431	S43100	0.20	1.00	1.00	15.0–17.0	1.25–2.50	0.04	0.03	–
440A	S44002	0.60–0.75	1.00	1.00	16.0–18.0	–	0.04	0.03	0.75 Mo
440B	S44003	0.75–0.95	1.00	1.00	16.0–18.0	–	0.04	0.03	0.75 Mo
440C	S44004	0.95–1.20	1.00	1.00	16.0–18.0	–	0.04	0.03	0.75 Mo
501	S50100	0.10 min	1.00	1.00	4.0–6.0	–	0.04	0.03	0.40–0.65 Mo
501A	S50300	0.15	0.30–0.60	0.50–1.00	6.0–8.0	–	0.03	0.03	0.45–0.65 Mo
501B	S50400	0.15	0.30–0.60	0.50–1.00	8.0–10.0	–	0.03	0.03	0.9–1.1 Mo
502	S50200	0.10	1.00	1.00	4.0–6.0	–	0.04	0.03	0.40–4.65Mo
503	S50300	0.15	1.00	1.00	6.0–8.0	–	0.04	0.04	0.45–0.65Mo
504	S50400	0.15	1.00	1.00	8.0–10.0	–	0.04	0.04	0.9–1.1 Mo
Precipitation-hardening									
PH 13–8 Mo	S13800	0.05	0.10	0.10	12.25–13.25	7.5–8.5	0.01	0.008	2.0–2.5 Mo; 0.90–1.35 Al; 0.01 N
15–5 PH	S15500	0.07	1.00	1.00	14.0–15.5	3.5–5.5	0.04	0.03	2.5–4.5 Cu; 0.15–0.45 Nb + Ta
17–4 PH	S17400	0.07	1.00	1.00	15.5–17.5	3.0–5.0	0.04	0.03	3.0–5.0 Cu; 0.15–0.45 Nb + Ta
17–7 PH	S17700	0.09	1.00	1.00	16.0–18.0	6.5–7.75	0.04	0.03	0.75–1.5 Al

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 357–358.

[a] Single values are maximum values unless otherwise indicated.

[b] For some tube making processes, the nickel content of certain austenitic types may be slightly higher than shown.

[c] Optional.

[d] 0.10% Ta max.

[e] 0.75% max.

[f] 0.70% max.

TABLE 1.154 Composition of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]
C10100 Oxygen-free electronic	99.99 Cu	F, R, W, T, P, S
C10200 Oxygen-free copper	99.95 Cu	F, R, W, T, P, S
C10300 Oxygen-free extra-low phosphorus	99.95 Cu, 0.003 P	F, R, T, P, S
C10400, C10500, C10700 Oxygen-free, silver-bearing	99.95 Cu[b]	F, R, W, S
C10800 Oxygen-free, low phosphorus	99.95 Cu, 0.009 P	F, R, T, P
CS11000 Electrolytic tough pitch copper	99.90 Cu, 0.04 O	F, R, W, T, P, S
C11100 Electrolytic tough pitch, anneal resistant	99.90 Cu, 0.04 O, 0.01 Cd	W
C11300, C11400, C11500, C11600 Silver-bearing tough pitch copper	99.90 Cu, 0.04 O, Ag[c]	F, R, W, T, S
C12000, C12100	99.9 Cu[d]	F, T, P
C12200 Phosphorus deoxidized copper, high residual phosphorus	99.90 Cu, 0.02 P	F, R, T, P
C12500, C12700, C12800, C12900, C13000 Fire-refined tough pitch with silver	99.88 Cu[e]	F, R, W, S
C14200 Phosphorus deoxidized, arsenical	99.68 Cu, 0.3 As, 0.02 P	F, R, T
C19200	98.97 Cu, 1.0 Fe, 0.03 P	F, T
C14300	99.9 Cu, 0.1 Cd	F
C14310	99.8 Cu, 0.2 Cd	F
C14500 Phosphorus deoxidized, tellurium bearing	99.5 Cu, 0.50 Te, 0.008 P	F, R, W, T
C14700 Sulfur bearing	99.6 Cu, 0.40 S	R, W
C15000 Zirconium copper	99.8 Cu, 0.15 Zr	R, W
C15500	99.75 Cu, 0.06 P, 0.11 Mg, Ag[f]	F
C15710	99.8 Cu, 0.2 Al_2O_3	R, W
C15720	99.6 Cu, 0.4 Al_2O_3	F, R
C15735	99.3 Cu, 0.7 Al_2O_3	R
C15760	98.9 Cu, 1.1 Al_2O_3	F, R
C16200 Cadmium copper	99.0 Cu, 1.0 Cd	F, R, W
C16500	98.6 Cu, 0.8 Cd, 0.6 Sn	F, R, W
C17000 Beryllium copper	99.5 Cu, 1.7 Be, 0.20 Co	F, R
C17200 Beryllium copper	99.5 Cu, 1.9 Be, 0.20 Co	F, R, W, T, P, S
C17300 Beryllium copper	99.5 Cu, 1.9 Be, 0.40 Pb	R
C17500 Copper–cobalt–beryllium alloy	99.5 Cu, 2.5 Co, 0.6 Be	F, R
C18200, C18400, C18500 Chromium copper	99.5 Cu[g]	F, W, R, S, T
C18700 Leaded copper	99.0 Cu, 1.0 Pb	R
C18900	98.75 Cu, 0.75 Sn, 0.3 Si, 0.20 Mn	R, W
C19000 Copper–nickel–phosphorus alloy	98.7 Cu, 1.1 Ni, 0.25 P	F, R, W
C19100 Copper–nickel–phosphorus–tellurium alloy	98.15 Cu, 1.1 Ni, 0.50 Te, 0.25 P	R, F
C19400	97.5 Cu, 2.4 Fe, 0.13 Zn, 0.03 P	F
C19500	97.0 Cu, 1.5 Fe, 0.6 Sn, 0.10 P, 0.80 Co	F
C21000 Gilding, 95%	95.0 Cu, 5.0 Zn	F, W
C22000 Commercial bronze, 90%	90.0 Cu, 10.0 Zn	F, R, W, T

(*Continued*)

TABLE 1.154 (*Continued*) Composition of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]
C22600 Jewelry bronze, 87.5%	87.5 Cu, 12.5 Zn	F, W
C23000 Red brass, 85%	85.0 Cu, 15.0 Zn	F, W, T, P
C24000 Low brass, 80%	80.0 Cu, 20.0 Zn	F, W
C26000 Cartridge brass, 70%	70.0 Cu, 30.0 Zn	F, R, W, T
C26800, C27000 Yellow brass	65.0 Cu, 35.0 Zn	F, R, W
C28000 Muntz metal	60.0 Cu, 40.0 Zn	F, R, T
C31400 Leaded commercial bronze	89.0 Cu, 1.75 Pb, 9.25 Zn	F, R
C31600 Leaded commercial bronze, nickel-bearing	89.0 Cu, 1.9 Pb, 1.0 Ni, 8.1 Zn	F, R
C33000 Low-leaded brass tube	66.0 Cu, 0.5 Pb, 33.5 Zn	T
C33200 High-leaded brass tube	66.0 Cu, 1.6 Pb, 32.4 Zn	T
C33500 Low-leaded brass	65.0 Cu, 0.5 Pb, 34.5 Zn	F
C34000 Medium-leaded brass	65.0 Cu, 1.0 Pb, 34.0 Zn	F, R, W, S
C34200 High-leaded brass	64.5 Cu, 2.0 Pb, 33.5 Zn	F, R
C34900	62.2 Cu, 0.35 Pb, 37.45 Zn	R, W
C35000 Medium-leaded brass	62.5 Cu, 1.1 Pb, 36.4 Zn	F, R
C35300 High-leaded brass	62.0 Cu, 1.8 Pb, 36.2 Zn	F, R
C35600 Extra-high-leaded brass	63.0 Cu, 2.5 Pb, 34.5 Zn	F
C36000 Free-cutting brass	61.5 Cu, 3.0 Pb, 35.5 Zn	F, R, S
C36500 to C36800 Leaded Muntz metal	60.0 Cu[h], 0.6 Pb, 39.4 Zn	F
C37000 Free-cutting Muntz metal	60.0 Cu, 1.0 Pb, 39.0 Zn	T
C37700 Forging brass	59.0 Cu, 2.0 Pb, 39.0 Zn	R, S
C38500 Architectural bronze	57.0 Cu, 3.0 Pb, 40.0 Zn	R, S
C40500	95 Cu, 1 Sn, 4 Zn	F
C40800	95 Cu, 2 Sn, 3 Zn	F
C41100	91 Cu, 0.5 Sn, 8.5 Zn	F, W
C41300	90.0 Cu, 1.0 Sn, 9.0 Zn	F, R, W
C41500	91 Cu, 1.8 Sn, 7.2 Zn	F
C42200	87.5 Cu, 1.1 Sn, 11.4 Zn	F
C42500	88.5 Cu, 2.0 Sn, 9.5 Zn	F
C43000	87.0 Cu, 2.2 Sn, 10.8 Zn	F
C43400	85.0 Cu, 0.7 Sn, 14.3 Zn	F
C43500	81.0 Cu, 0.9 Sn, 18.1 Zn	F, T
C44300, C44400, C44500 Inhibited admiralty	71.0 Cu, 28.0 Zn, 1.0 Sn	F, W, T
C46400 to C46700 Naval brass	60.0 Cu, 39.25 Zn, 0.75 Sn	F, R, T, S
C48200 Naval brass, medium-leaded	60.5 Cu, 0.7 Pb, 0.8 Sn, 38.0 Zn	F, R, S
C48500 Leaded naval brass	60.0 Cu, 1.75 Pb, 37.5 Zn, 0.75 Sn	F, R, S
C50500 Phosphor bronze, 1.25% E	98.75 Cu, 1.25 Sn, trace P	F, W
C51000 Phosphor bronze, 5% A	95.0 Cu, 5.0 Sn, trace P	F, R, W, T
C51100	95.6 Cu, 4.2 Sn, 0.2 P	F
C52100 Phosphor bronze, 8% C	92.0 Cu, 8.0 Sn, trace P	F, R, W
C52400 Phosphor bronze, 10% D	90.0 Cu, 10.0 Sn, trace P	F, R, W
C54400 Free-cutting phosphor bronze	88.0 Cu, 4.0 Pb, 4.0 Zn, 4.0 Sn	F, R
C60800 Aluminum bronze, 5%	95.0 Cu, 5.0 Al	T

(*Continued*)

TABLE 1.154 (*Continued*) Composition of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]
C61000	92.0 Cu, 8.0 Al	R, W
C61300	92.65 Cu, 0.35 Sn, 7.0 Al	F, R, T, P, S
C61400 Aluminum bronze, D	91.0 Cu, 7.0 Al, 2.0 Fe	F, R, W, T, P, S
C61500	90.0 Cu, 8.0 Al, 2.0 Ni	F
C61800	89.0 Cu, 1.0 Fe, 10.0 Al	R
C61900	86.5 Cu, 4.0 Fe, 9.5 Al	F
C62300	87.0 Cu, 10.0 Al, 3.0 Fe	F, R
C62400	86.0 Cu, 3.0 Fe, 11.0 Al	F, R
C62500	82.7 Cu, 4.3 Fe, 13.0 Al	F, R
C63000	82.0 Cu, 3.0 Fe, 10.0 Al, 5.0 Ni	F, R
C63200	82.0 Cu, 4.0 Fe, 9.0 Al, 5.0 Ni	F, R
C63600	95.5 Cu, 3.5 Al, 1.0 Si	R, W
C63800	99.5 Cu, 2.8 Al, 1.8 Si, 0.40 Co	F
C64200	91.2 Cu, 7.0 Al	F, R
C65100 Low-silicon bronze, B	98.5 Cu, 1.5 Si	R, W, T
C65500 High-silicon bronze, A	97.0 Cu, 3.0 Si	F, R, W, T
C66700 Manganese brass	70.0 Cu, 28.8 Zn, 1.2 Mn	F, W
C67400	58.5 Cu, 36.5 Zn, 1.2 Al, 2.8 Mn, 1.0 Sn	F, R
C67500 Manganese bronze, A	58.5 Cu, 1.4 Fe, 39.0 Zn, 1.0 Sn, 0.1 Mn	R, S
C68700 Aluminum brass, arsenical	77.5 Cu, 20.5 Zn, 2.0 Al, 0.1 As	T
C68800	73.5 Cu, 22.7 Zn, 3.4 Al, 0.40 Co	F
C69000	73.3 Cu, 3.4 Al, 0.6 Ni, 22.7 Zn	F
C69400 Silicon red brass	81.5 Cu, 14.5 Zn, 4.0 Si	R
C70400	92.4 Cu, 1.5 Fe, 5.5 Ni, 0.6 Mn	F, T
C70600 Copper nickel, 10%	88.7 Cu, 1.3 Fe, 10.0 Ni	F, T
C71000 Copper nickel, 20%	79.0 Cu, 21.0 Ni	F, W, T
C71500 Copper nickel, 30%	70.0 Cu, 30.0 Ni	F, R, T
C71700	67.8 Cu, 0.7 Fe, 31.0 Ni, 0.5 Be	F, R, W
C72500	88.20 Cu, 9.5 Ni, 2.3 Sn	F, R, W, T
C73500	72.0 Cu, 18.0 Ni, 10.0 Zn	F, R, W, T
C74500 Nickel silver, 65–10	65.0 Cu, 25.0 Zn, 10.0 Ni	F, W
C75200 Nickel silver, 65–18	65.0 Cu, 17.0 Zn, 18.0 Ni	F, R, W
C75400 Nickel silver, 65–15	65.0 Cu, 20.0 Zn, 15.0 Ni	F
C75700 Nickel silver, 65–12	65.0 Cu, 23.0 Zn, 12.0 Ni	F, W
C76200	59.0 Cu, 29.0 Zn, 12.0 Ni	F, T
C77000 Nickel silver, 55–18	55.0 Cu, 27.0 Zn, 18.0 Ni	F, R, W
C72200	82.0 Cu, 16.0 Ni, 0.5 Cr, 0.8 Fe, 0.5 Mn	F, T
C78200 Leaded nickel silver, 65–8–2	65.0 Cu, 2.0 Pb, 25.0 Zn, 8.0 Ni	F

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 442–454.

[a] F, flat products; R, rod; W, wire; T, tube; P, pipe; S, shapes.

[b] C10400, 8 oz/ton Ag; C10500, 10 oz/ton; C10700, 25 oz/ton.

[c] C11300, 8 oz/ton Ag; C11400, 10 oz/ton; C11500, 16 oz/ton; C11600, 25 oz/ton.

[d] C12000, 0.008 P; C12100, 0.008 P, and 4 oz/ton Ag.

[e] C12700, 8 oz/ton Ag; C12800, 10 oz/ton; C12900, 16 oz/ton; C13000, 25 oz/ton.

[f] 8.30 oz/ton Ag.

[h] Rod, 61.0 Cu min.

TABLE 1.155 Classification of Copper and Copper Alloys

Family	Wrought Alloys UNS Numbers	Principal Alloying Element
Coppers, high copper alloys	C10000	<8 at. %
Brasses	C20000, C30000, C40000, C66400 to C69800	Zn
Phosphor bronzes	C50000	Sn
Aluminum bronzes	C60600 to C64200	Al
Silicon bronzes	C64700 to C66100	Si
Copper nickels, nickel silvers	C70000	Ni

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 439.

TABLE 1.156 Composition Ranges for Cast Aluminum Alloys

	Composition (%)				
AA Number	Cu	Mg	Mn	Si	Others
201.0	4.6	0.35	0.35	–	0.7 Ag, 0.25 Ti
206.0	4.6	0.25	0.35	0.10 (max)	0.22 Ti, 0.15 Fe (max)
A206.0	4.6	0.25	0.35	0.05 (max)	0.22 Ti, 0.10 Fe (max)
208.0	4.0	–	–	3.0	–
242.0	4.0	1.5	–		2.0 Ni
295.0	4.5	–	–	0.8	–
296.0	4.5	–	–	2.5	–
308.0	4.5	–	–	5.5	–
319.0	3.5	–	–	6.0	–
336.0	1.0	1.0		12.0	2.5 Ni
354.0	1.8	0.50	–	9.0	–
355.0	1.2	0.50	0.50 (max)	5.0	0.6 Fe (max), 0.35 Zn (max)
C355.0	1.2	0.50	0.10 (max)	5.0	0.20 Fe (max), 0.10 Zn (max)
356.0	0.25 (max)	0.32	0.35 (max)	7.0	0.6 Fe (max), 0.35 Zn (max)
A356.0	0.20 (max)	0.35	0.10 (max)	7.0	0.20 Fe (max), 0.10 Zn (max)
357.0	–	0.50	–	7.0	–
A357.0	–	0.6	–	7.0	0.15 Ti, 0.005 Be
359.0	–	0.6	–	9.0	–
360.0	–	0.50	–	9.5	2.0 Fe (max)
A360.0	–	0.50		9.5	1.3 Fe (max)
380.0	3.5	–	–	8.5	2.0 Fe (max)
A380.0	3.5	–	–	8.5	1.3 Fe (max)
383.0	2.5	–	–	10.5	–
384.0	3.8		–	11.2	3.0 Zn (max)
A384.0	3.8	–	–	11.2	1.0 Zn (max)
390.0	4.5	0.6	–	17.0	1.3 Zn (max)
A390.0	4.5	0.6	–	17.0	0.5 Zn (max)
413.0	–	–	–	12.0	2.0 Fe (max)
A413.0	–	–	–	12.0	1.3 Fe (max)
443.0	0.6 (max)	–	–	5.2	–
A443.0	0.30 (max)	–	–	5.2	–

(*Continued*)

TABLE 1.156 (*Continued*) Composition Ranges for Cast Aluminum Alloys

	Composition (%)				
AA Number	Cu	Mg	Mn	Si	Others
B443.0	0.15 (max)	–	–	5.2	–
C443.0	0.6 (max)	–	–	5.2	2.0 Fe (max)
514.0	–	4.0	–	–	–
518.0	–	8.0	–		
520.0	–	10.0	–	–	–
535.0	–	6.8	0.18	–	0.18 Ti
A535.0		7.0	0.18	–	–
B535.0	–	7.0	–	–	0.18 Ti
712.0	–	0.6	–	–	5.8 Zn, 0.5 Cr, 0.20 Ti
713.0	0.7	0.35	–	–	7.5 Zn, 0.7 Cu
771.0	–	0.9	–	–	7.0 Zn, 0.13 Cr, 0.15 Ti
850.0	1.0	–	–	–	6.2 Sn, 1.0 Ni

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 303.

TABLE 1.157 Composition Ranges for Wrought Aluminum Alloys

	Composition (%)							
AA Number	Al	Si	Cu	Mn	Mg	Cr	Zn	Other
1060	99.60 min	–	–	–	–	–	–	–
1100	99.00 min	–	0.12	–	–	–	–	–
2011	93.7	–	5.5	–	–	–	–	0.4 Bi; 0.4 Pb
2014	93.5	0.8	4.4	0.8	0.5	–	–	–
2024	93.5	–	4.4	0.6	1.5	–	–	–
2219	93.0	–	6.3	0.3	–	–	–	0.06 Ti; 0.10 V; 0.18 Zr
2319	93.0	–	6.3	0.3	–	–	–	0.18 Zn, 0.15 Ti; 0.10 V
2618	93.7	0.18	2.3	–	1.6	–	–	1.1 Fe; 1.0 Ni; 0.07 Ti
3003	98.6	–	–	0.12	1.2	–	–	–
3004	97.8	–	–	1.2	1.0	–	–	–
3105	99.0	–	0.55	0.50	–	–	–	–
4032	85.0	12.2	0.9		1.0	–	–	0.9 Ni
4043	94.8	5.2	–	–	–	–	–	–
5005	99.2	–	–	–	0.8	–	–	–
5050	98.6	–	–	–	1.4	–	–	–
5052	97.2	–	–	–	2.5	0.25	–	–
5056	95.0	–	–	0.12	5.0	0.12	–	–
5083	94.7	–	–	0.7	4.4	0.15	–	–
5086	95.4	–	–	0.4	4.0	0.15	–	–
5154	96.2	–	–	–	3.5	0.25	–	–
5182	95.2	–	–	0.35	4.5	–	–	–
5252	97.5	–	–	–	2.5	–	–	–

(*Continued*)

TABLE 1.157 (*Continued*) Composition Ranges for Wrought Aluminum Alloys

	Composition (%)							
AA Number	Al	Si	Cu	Mn	Mg	Cr	Zn	Other
5254	96.2	–	–	–	3.5	0.25	–	–
5356	94.6	–	–	0.12	5.0	0.12	–	0.13 Ti
5454	96.3		–	0.8	2.7	0.12	–	–
5456	93.9	–	–	0.8	5.1	0.12	–	–
5457	98.7	–	–	0.3	1.0	–	–	–
5652	97.2	–	–	–	2.5	0.25	–	–
5657	99.2	–	–	–	0.8	–	–	–
6005	98.7	0.8	–	–	0.5	–	–	–
6009	97.7	0.8	0.35	0.5	0.6	–	–	–
6010	97.3	1.0	0.35	0.5	0.8	–	–	–
6061	97.9	0.6	0.28	–	1.0	0.2	–	–
6063	98.9	0.4	–	–	0.7	–	–	–
6066	95.7	1.4	1.0	0.8	1.1	–	–	–
6070	96.8	1.4	0.28	0.7	0.8	–	–	–
6101	98.9	0.5	–	–	0.6	–	–	–
6151	98.2	0.9	–	–	0.6	0.25	–	–
6201	98.5	0.7	–	–	0.8	–	–	–
6205	98.4	0.8	–	0.1	0.5	0.1	–	0.1 Zr
7049	88.2	–	1.5	–	2.5	0.15	7.6	–
7075	90.0	–	1.6	–	2.5	0.23	5.6	–

Source: Data from *ASM Metals Reference Book,* Second Edn., American Society for Metals, Metals Park, OH, 1984, p. 292.

TABLE 1.158 Composition of Tin and Tin Alloys

Grade			Composition (% max)										
ASTM B339	Designation	Class	Sn	Sb	As	Bi	Cd	Cu	Fe	Pb	Ni + Co	S	Zn
AAA	Electrolytic	Extra-high purity	99.98	0.008	0.0005	0.001	0.001	0.002	0.005	0.010	0.005	0.002	0.001
AA	Electrolytic	High purity	99.95	0.02	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.005
A	A. Straits	High purity; commercial	99.80	0.04	0.05	0.015	0.001	0.04	0.015	0.05	0.01	0.01	0.005
B	B	General purpose	99.80	–	0.05	–	–	–	–	–	–	–	–
C	C	Intermediate grade	99.65	–	–	–	–	–	–	–	–	–	–
D	D	Lower intermediate grade	99.50	–	–	–	–	–	–	–	–	–	–
E	E	Common	99.00	–	–	–	–	–	–	–	–	–	–

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 488.

TABLE 1.159 Compositions of ACI Heat-Resistant Casting Alloys

ACI Designation	UNS Number	ASTM Specification[a]	Composition[b] (%) C	Cr	Ni	Si (Max)	Mn	P & S (Max)	Mo (Max)	Other
HC	J92605	A297, A608	0.50 max	26–30	4 max	2.00	1	0.04	0.5	
HD	J93005	A297, A608	0.50 max	26–30	4–7	2.00	1.5	0.04	0.5	
HE	J93403	A297, A608	0.20–0.50	26–30	8–11	2.00	2	0.04	0.5	
HF	J92603	A297, A608	0.20–0.40	19–23	9–12	2.00	2	0.04	0.5	
HH	J93503	A297, A608	0.20–0.50	24–28	11–14	2.00	2	0.04	0.5	0.2 N max
HI	J94003	A297, A567, A608	0.20–0.50	26–30	14–18	2.00	2	0.04	0.5	
HK	J94224	A297, A351, A567, A608	0.20–0.60	24–28	18–22	2.00	2	0.04	0.5	
HL	J94604	A297, A608	0.20–0.60	28–32	18–22	2.00	2	0.04	0.5	
HN	J94213	A297, A608	0.20–0.50	19–32	23–27	2.00	2	0.04	0.5	
HP	–	A297	0.35–0.75	24–28	33–37	2.00	2	0.04	0.5	
HT	J94605	A297, A351, A567, A608	0.35–0.75	13–17	33–37	2.50	2	0.04	0.5	
HU	–	A297, A608	0.35–0.75	17–21	37–41	2.50	2	0.04	0.5	
HW	–	A297, A608	0.35–0.75	10–14	58–62	2.50	2	0.04	0.5	
HX	–	A297, A608	0.35–0.75	15–19	64–68	2.50	2	0.04	0.5	

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 384.

[a] ASTM designations are same as ACI designations.

[b] Remainder is Fe in all compositions.

TABLE 1.160 Composition of Zinc Die Casting Alloys

Alloy	Form	Composition (% Max) Cu	Al	Mg	Pb	Cd	Sn	Fe	Others	Zn
AG40A	Ingot	0.10	3.9–4.3	0.025–0.05	0.004	0.003	0.002	0.075	Ni 0.02, Cr 0.02, Si 0.035, Mn 0.5	Rem
AC41A	Die castings	0.25–0.75	3.5–4.3	0.020–0.05[a]	0.005	0.004	0.003	0.100	Ni 0.02, Cr 0.02, Si 0.035, Mn 0.5	Rem
Alloy 7	Ingot	0.75–1.25	3.9–4.3	0.03–0.06	0.004	0.003	0.002	0.075	Ni 0.02, Cr 0.02, Si 0.035, Mn 0.5	Rem
ILZRO 16	Die castings	0.75–1.25	3.5–4.3	0.03–0.08[a]	0.005	0.004	0.003	0.100	Ni 0.02, Cr 0.02, Si 0.035, Mn 0.5	Rem
	Die castings	0.25	3.5–4.3	0.010–0.02	0.0020	0.0020	0.0010	0.050	–	Rem
	Die castings	1.0–1.5	0.01–0.04	–	–	–	–		Ti 0.15–0.25, Cr 0.10–0.20, Ti + Cr 0.30–0.40	Rem

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 490.

[a] Magnesium content may be as low as 0.015% provided that lead, cadmium, and tin contents do not exceed 0.003. 0.003, and 0.001%, respectively.

TABLE 1.161 Compositions of Wrought Superalloys

Alloy	UNS Number	Composition (%)										
		Cr	Ni	Co	Mo	W	Nb	Ti	Al	Fe	C	Other
Astroloy	–	15.0	56.5	15.0	5.25	–	–	3.5	4.4	<0.3	0.06	0.03 B; 0.06 Zr
D-979	N09979	15.0	45.0	–	4.0	4.0	–	3.0	1.0	27.0	0.05	0.01 B
IN 102	N06102	15.0	67.0	–	2.9	3.0	2.9	0.5	0.5	7.0	0.06	0.005 B; 0.02 Mg; 0.03 Zr
Inconel 706	N09706	16.0	41.5	–	–	–	–	1.75	0.2	37.5	0.03	2.9(Nb + Ta); 0.15 Cu max
Inconel 718	N07718	19.0	52.5	–	3.0	–	5.1	0.9	0.5	18.5	0.08 max	0.15 Cu max
Inconel 751	–	15.5	72.5	–	–	–	1.0	2.3	1.2	7.0	0.05	0.25 Cu max
Inconel X-750	N07750	15.5	73.0	–	–	–	1.0	2.5	0.7	7.0	0.04	0.25 Cu max
M252	N07252	19.0	56.5	10.0	10.0	–	–	2.6	1.0	<0.75	0.15	0.005 B
Nimonic 80A	N07080	19.5	73.0	1.0	–	–	–	2.25	1.4	1.5	0.05	0.10 Cu max
Nimonic 90	N07090	19.5	55.5	18.0	–	–	–	2.4	1.4	1.5	0.06	–
Nimonic 95	–	19.5	53.5	18.0	–	–	–	2.9	2.0	5.0 max	0.15 max	+B; +Zr
Nimonic 100	–	11.0	56.0	20.0	5.0	–	–	1.5	5.0	2.0 max	0.30 max	+B; +Zr
Nimonic 105	–	15.0	54.0	20.0	5.0	–	–	1.2	4.7	–	0.08	0.005 B
Nimonic 115	–	15.0	55.0	15.0	4.0	–	–	4.0	5.0	1.0	0.20	0.04 Zr
Nimonic 263	–	20.0	51.0	20.0	5.9	–	–	2.1	0.45	0.7 max	0.06	–
Pyromet 860	–	13.0	44.0	4.0	6.0	–	–	3.0	1.0	28.9	0.05	0.01 B
René 41	N07041	19.0	55.0	11.0	10.0	–	–	3.1	1.5	<0.3	0.09	0.01 B
René 95	–	14.0	61.0	8.0	3.5	3.5	3.5	2.5	3.5	<0.3	0.16	0.01 B; 0.05 Zr
Udimet 500	N07500	19.0	48.0	19.0	4.0	–	–	3.0	3.0	4.0 max	0.08	0.005 B
Udimet 520	–	19.0	57.0	12.0	6.0	1.0	–	3.0	2.0	–	0.08	0.005 B
Udimet 700	–	15.09	53.0	18.5	5.0	–	–	3.4	4.3	<1.0	0.07	0.03 B
Udimet 710	–	18.0	55.0	14.8	3.0	1.5	–	5.0	2.5	–	0.07	0.01 B
Unitemp AF2–1DA	–	12.0	59.0	10.0	3.0	6.0	–	3.0	4.6	<0.5	0.35	1.5 Ta; 0.015 B; 0.1 Zr
Waspaloy	N07001	19.5	57.0	13.5	4.3	–	–	3.0	1.4	2.0 max	0.07	0.006 B; 0.09 Zr

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, pp. 382–383.

TABLE 1.162 Solubility of Copper and Copper Alloys

Family	Wrought Alloys UNS Numbers	Principal Alloying Element	Solid Solubility at 20°C (at.%)
Brasses	C20000, C30000, C40000, C66400 to C69800	Zn	37
Phosphor bronzes	C50000	Sn	9
Aluminum bronzes	C60600 to C64200	Al	19
Silicon bronzes	C64700 to C66100	Si	8
Copper nickels, nickel silvers	C70000	Ni	100

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 439.

TABLE 1.163 Phase Change Thermodynamic Properties for the Elements

Element	Phase	Transition Temperature (K)	Heat of Transition (kcal/g · mol)	Entropy of Transition (e.u.)
Ac	Solid	(1090)	(2.5)	(2.3)
	Liquid	(2750)	(70)	(25)
Ag	Solid	1234	2.855	2.313
	Liquid	2485	60.72	24.43
Al	Solid	931.7	2.57	2.76
	Liquid	2600	67.9	26
Am	Solid	(1200)	(2.4)	(2.0)
	Liquid	2733	51.7	18.9
As	Solid	883	3.25	35.25
Au	Solid	1336.16	3.03	2.27
	Liquid	2933	74.21	25.30
B	Solid	2313	(3.8)	(1.6)
	Liquid	2800	75	27
Ba	Solid, α	648	0.14	0.22
	Solid, β	977	1.83	1.87
	Liquid	1911	35.665	18.63
Be	Solid	1556	2.919	1.501
	Liquid	–		
Bi	Solid	544.2	2.63	4.83
	Liquid	1900	41.1	21.6
C	Solid	–	–	–
Ca	Solid, α	723	0.24	0.33
	Solid, β	1123	2.2	1.96
	Liquid	1755	38.6	22.0
Cd	Solid	594.1	1.46	2.46
	Liquid	1040	23.86	22.94
Ce	Solid	1048	2.1	2.0
	Liquid	2800	73	26
Cl_2	Gas	–	–	–
Co	Solid, α	723	0.005	0.007
	Solid, β	1398	0.095	0.068
	Solid, γ	1766	3.7	2.1
	Liquid	3370	93	28
Cr	Solid	2173	3.5	1.6
	Liquid	2495	72.97	29.25
Cs	Solid	301.9	0.50	1.7
	Liquid	963	16.32	17.0
Cu	Solid	1356.2	3.11	2.29
	Liquid	2868	72.8	25.4
F_2	Gas	–	–	–

(*Continued*)

TABLE 1.163 (*Continued*) Phase Change Thermodynamic Properties for the Elements

Element	Phase	Transition Temperature (K)	Heat of Transition (kcal/g · mol)	Entropy of Transition (e.u.)
Fe	Solid, α	1033	0.410	0.397
	Solid, β	1180	0.217	0.184
	Solid, γ	1673	0.15	0.084
	Solid, δ	1808	3.86	2.14
	Liquid	3008	84.62	28.1
Ga	Solid	302.94	1.335	4.407
	Liquid	2700	–	–
Ge	Solid	1232	8.3	6.7
	Liquid	2980	68	23
H_2	Gas	–	–	–
Hf	Solid	(2600)	(6.0)	(2.3)
Hg	Liquid	629.73	13.985	22.208
In	Solid	430	0.775	1.80
	Liquid	2440	53.8	22.0
Ir	Solid	2727	6.6	2.4
K	Solid	336.4	0.5575	1.657
	Liquid	1052	18.88	17.95
La	Solid	1153	(2.3)	(2.0)
	Liquid	3000	80	27
Li	Solid	459	0.69	1.5
	Liquid	1640	32.48	19.81
Mg	Solid	923	2.2	2.4
	Liquid	1393	31.5	22.6
Mn	Solid, α	1000	0.535	0.535
	Solid, β	1374	0.545	0.397
	Solid, γ	1410	0.430	0.305
	Solid, δ	1517	3.5	2.31
	Liquid	2368	53.7	22.7
Mo	Solid	2883	(5.8)	(2.0)
N_2	Gas	–	–	–
Na	Solid	371	0.63	1.7
	Liquid	1187	23.4	20.1
Nb	Solid	2760	(5.8)	(2.1)
Nd	Solid	1297	(2.55)	(197)
	Liquid	(2750)	(61)	(22)
Ni	Solid, α	626	0.092	0.15
	Solid, β	1728	4.21	2.44
	Liquid	3110	90.48	29.0
Np	Solid	913	(2.3)	(2.5)
	Liquid	(2525)	(55)	(22)
O_2	Gas	–	–	–

(*Continued*)

TABLE 1.163 (*Continued*) Phase Change Thermodynamic Properties for the Elements

Element	Phase	Transition Temperature (K)	Heat of Transition (kcal/g · mol)	Entropy of Transition (e.u.)
Os	Solid	2970	(6.4)	(2.2)
P_4	Solid, white	317.4	0.601	1.89
	Liquid	553	11.9	21.5
Pa	Solid	(18.25)	(4.0)	(2.2)
	Liquid	(4500)	(115)	(26)
Pb	Solid	600.6	1.141	1.900
	Liquid	2023	42.5	21.0
Pd	Solid	1828	4.12	2.25
	Liquid	3440	89	26
Po	Solid	525	(2.4)	(4.6)
	Liquid	(1235)	(24.6)	(19.9)
Pr	Solid	1205	(25)	(2.1)
	Liquid	3563	–	–
Pt	Solid	2042.5	5.2	25
	Liquid	4100	122	29.8
Pu	Solid	913	(2.26)	(2.48)
	Liquid	–		
Ra	Solid	1233	(2.3)	(1.9)
	Liquid	(1700)	(35)	(21)
Rb	Solid	312.0	0.525	1.68
	Liquid	952	18.11	19.0
Re	Solid	3440	(7.9)	(2.3)
Rh	Solid	2240	(5.2)	(2.3)
	Liquid	4150	127	30.7
Ru	Solid, α	1308	0.034	0.026
	Solid, β	1473	0	–
	Solid, γ	1773	0.23	0.13
	Solid, δ	2700	(6.1)	(2.3)
S	Solid, α	368.6	0.088	0.24
	Solid, β	392	0.293	0.747
	Liquid	717.76	2.5	3.5
Sb	Solid (α, β, γ)	903.7	4.8	5.3
	Liquid	1713	46.665	27.3
Sc	Solid	1670	(4.0)	(2.4)
	Liquid	3000	80	27
Se	Solid	490.6	1.25	2.55
	Liquid	1000	14.27	14.27
Si	Solid	1683	11.1	6.60
	Liquid	2750	71	26
Sm	Solid	1623	3.7	2.3
	Liquid	(2800)	(70)	(25)

(*Continued*)

TABLE 1.163 (*Continued*) Phase Change Thermodynamic Properties for the Elements

Element	Phase	Transition Temperature (K)	Heat of Transition (kcal/g · mol)	Entropy of Transition (e.u.)
Sn	Solid, α, β	505.1	1.69	335
	Liquid	2473	(55)	(22)
Sr	Solid	1043	2.2	2.1
	Liquid	1657	33.61	20.28
Ta	Solid	3250	7.5	2.3
Tc	Solid	(2400)	(5.5)	(2.3)
	Liquid	(3800)	(120)	(32)
Te	Solid, α	621	0.13	0.21
	Solid, β	723	4.28	5.92
	Liquid	1360	11.9	8.75
Th	Solid	2173	(4.6)	(2.1)
	Liquid	4500	(130)	(29)
Ti	Solid, α	1155	0.950	0.822
	Solid, β	2000	(4.6)	(23)
	Liquid	3550	(101)	(28)
Tl	Solid, α	508.3	0.082	0.16
	Solid, β	576.8	1.03	1.79
	Liquid	1730	38.81	22.4
U	Solid, α	938	0.665	0.709
	Solid, β	1049	1.165	1.111
	Solid, γ	1405	(3.0)	(2.1)
	Liquid	3800	–	–
V	Solid	2003	(4.0)	(2.0)
	Liquid	3800	–	–
W	Solid	3650	8.42	2.3
Y	Solid	1750	(4.0)	(2.3)
	Liquid	3500	(90)	(26)
Zn	Solid	692.7	1.595	2.303
	Liquid	1180	27.43	23.24
Zr	Solid, α	1135	0.920	0.811
	Solid, β	2125	(4.9)	(2.3)
	Liquid	(3900)	(100)	(26)

Source: Data from R. C. Weast (Ed.), *Handbook of Chemistry and Physics,* 69th Edn., CRC Press, Boca Raton, FL, 1988, D44.

TABLE 1.164 Melting Points of the Elements

At. No.	Element	Symbol	Melting Point (°C)
1	Hydrogen	H	–259.14
2	Helium	He	–272.2
3	Lithium	Li	180.54
4	Beryllium	Be	1278
5	Boron	B	2300
6	Carbon	C	~3550
7	Nitrogen	N	–209.86
8	Oxygen	O	–218.4
9	Fluorine	F	–219.62
10	Neon	N	–248.67
11	Sodium	Na	97.81
12	Magnesium	Mg	648.8
13	Aluminum	Al	660.37
14	Silicon	Si	1410
15	Phosphorus (white)	P	44.1
16	Sulfur	S	112.8
17	Chlorine	Cl	–100.98
18	Argon	Ar	–189.2
19	Potassium	K	63.65
20	Calcium	Ca	839
21	Scandium	Sc	1539
22	Titanium	Ti	1660
23	Vanadium	V	1890
24	Chromium	Cr	1857
25	Manganese	Mn	1244
26	Iron	Fe	1535
27	Cobalt	Co	1495
28	Nickel	Ni	1453
29	Copper	Cu	1083.4
30	Zinc	Zn	419.58
31	Gallium	Ga	29.78
32	Germanium	Ge	937.4
33	Arsenic	As	817
34	Selenium	Se	217
35	Bromine	Br	–7.2
36	Krypton	Kr	–156.6
37	Rubidium	Rb	38.89
38	Strontium	Sr	769
39	Yttrium	Y	1523
40	Zirconium	Zr	1852
41	Niobium	Nb	2408
42	Molybdenum	Mo	2617
43	Technetium	Tc	2172

(*Continued*)

TABLE 1.164 (*Continued*) Melting Points of the Elements

At. No.	Element	Symbol	Melting Point (°C)
44	Ruthenium	Ru	2310
45	Rhodium	Rh	1966
46	Palladium	Pd	1552
47	Silver	Ag	961.93
48	Cadmium	Cd	320.9
49	Indium	In	156.61
50	Tin	Sn	231.9681
51	Antimony	Sb	630.74
52	Tellurium	Te	449.5
53	Iodine	I	113.5
54	Xenon	Xe	–111.9
55	Cesium (–10°)	Ce	28.4
56	Barium	Ba	7.25
57	Lanthanum	La	920
58	Cerium	Ce	798
59	Praseodymium	Pr	931
60	Neodymium	Nd	1010
61	Promethium	Pm	~1080
62	Samarium	Sm	1072
63	Europium	Eu	822
64	Gadolinium	Gd	1311
65	Terbium	Tb	1360
66	Dysprosium	Dy	1409
67	Holmium	Ho	1470
68	Erbium	Er	1522
69	Thulium	Tm	1545
70	Ytterbium	Yb	824
71	Lutetium	Lu	1659
72	Hafnium	Hf	2227
73	Tantalum	Ta	2996
74	Tungsten	W	3410
75	Rhenium	Re	3180
76	Osmium	Os	3045
77	Iridium	Ir	2410
78	Platinum	Pt	1772
79	Gold	Au	1064.43
80	Mercury	Hg	–38.87
81	Thallium	Tl	303.5
82	Lead	Pb	327.502
83	Bismuth	Bi	271.3
84	Polonium	Po	254
85	Astatine	At	302
86	Radon	Rn	–71

(*Continued*)

TABLE 1.164 (*Continued*) Melting Points of the Elements

At. No.	Element	Symbol	Melting Point (°C)
87	Francium	Fr	~27
88	Radium	Ra	700
89	Actinium	Ac	1050
90	Thorium	Th	1750
91	Protactinium	Pa	<1600
92	Uranium	U	1132
93	Neptunium	Np	640
94	Plutonium	Pu	641
95	Americium	Am	994
96	Curium	Cm	1340

Source: Data from J. F. Shackelford, *Introduction to Materials Science for Engineers,* Second Edn., Macmillan Publishing Company, New York, 1988, pp. 686–688.

TABLE 1.165 Key to Tables of Thermodynamic Coefficients

Thermodynamic calculations over a wide range of temperatures are generally made with the aid of algebraic equations representing the characteristic properties of the substances being considered. The necessary integrations and differentiations, or other mathematical manipulations, are then most easily effected. The most convenient starting point in making such calculations for a given substance is the heat capacity at constant pressure. From this quantity and knowledge of the properties of any phase transitions, the other thermodynamic properties may be computed by the well-known equations given in standard texts on thermodynamics. Please note that the units for a, b, c, and d are cal/g mol, whereas those for A are kcal/g mol. The necessary adjustment must be made when the data are substituted into the equations. Empirical heat capacity equations are generated in the form of a power series, with the absolute temperature T as the independent variable

$$C_p = a' + (b' \times 10^{-3})T + (c' \times 10^{-6})T^2$$

or

$$C_p = a'' + (b'' \times 10^{-3})T + \frac{d \times 10^5}{T^2}$$

Since both forms are used in the following, let

$$C_p = a + (b \times 10^{-3})T + (c \times 10^{-6})T^2 + \frac{d \times 10^5}{T^2}$$

The constants a, b, c, and d are to be determined either experimentally or by some theoretical or semi-empirical approach. The heat content, or enthalpy (H), is determined from the heat capacity by a simple integration of the range of temperatures for which the formula for c_p is valid. Thus, if 298 K is taken as a reference temperature, then

$$\begin{aligned} H_T - H_{298} &= \int_{298}^{T} C_p dT \\ &= a(T - 298) + \frac{1}{2}(b \times 10^{-3})(T^2 - 298^2) + \frac{1}{3}(c \times 10^{-6})(T^3 - 298^3) - (d \times 10^5)\left(\frac{1}{T} - \frac{1}{298}\right) \\ &= aT + \frac{1}{2}(b \times 10^{-3})T^2 + \frac{1}{3}(c \times 10^{-6})T^3 - \frac{d \times 10^5}{T} - A \end{aligned}$$

where all the constants on the right-hand side of the equation have been incorporated in the term $-A$.

In general, the enthalpy is given by a sum of terms for each phase of the substance involved in the temperature range considered plus terms that represent the heats of transitions

$$H_T - H_{298} = \sum \int_{T_1}^{T_2} C_p dT + \sum \Delta H_{tr.}$$

(*Continued*)

TABLE 1.165 (*Continued*) Key to Tables of Thermodynamic Coefficients

In a similar manner, the entropy S is obtained by performing the integration

$$S_T - S_{298} = \int_{298}^{T} (C_p/T)dt$$

$$= a\ln(T/298) + (b \times 10^{-3})(T - 298) + \frac{1}{2}(c \times 10^{-6})(T^2 - 298^2) - \frac{1}{2}(d \times 10^5)\left(\frac{1}{T^2} - \frac{1}{298^2}\right)$$

$$= \text{a} \ln T + (b \times 10^{-3})T + \frac{1}{2}(c \times 10^{-6})T^2 - \frac{\frac{1}{2}(d \times 10^5)}{T^2} - B'$$

or

$$S_T = 2.303\, a \log T + (b \times 10^{-3})T + \frac{1}{2}(c \times 10^{-6})T^2 - \frac{\frac{1}{2}(d \times 10^5)}{T^2} - B$$

where

$$B = B' - S_{298}$$

From the definition of free energy (F):

$$F = H - TS$$

the quantity

$$F_T - H_{298} = (H_T - H_{298}) - TS_T$$

may be written as

$$F_T - H_{298} = -2.303aT \log T - \frac{1}{2}(b \times 10^{-3})T^2 - \frac{1}{6}(c \times 10^{-6})T^3 - \frac{\frac{1}{2}(d \times 10^5)}{T} + (B + a)T - A$$

and also the free energy function

$$\frac{F_T - H_{298}}{T} = -2.303a \log T - \frac{1}{2}(b \times 10^{-3})T - \frac{1}{6}(c \times 10^{-6})T^2 - \frac{\frac{1}{2}(d \times 10^5)}{T^2} + (B + a) - \frac{A}{T}$$

Values of these thermodynamic coefficients are given in Tables 1.166 and 2.26. The first column in each table lists the material. The second column gives the phase to which the coefficients are applicable. The remaining columns list the values of the constants a, b, c, d, A, and B required in the thermodynamic equations. All values that represent estimates are enclosed in parentheses. The heat capacities at temperatures beyond the range of experimental determination were estimated by extrapolation. Where no experimental values were found, analogy with compounds of neighboring elements in the periodic table was used.

TABLE 1.166 Thermodynamic Coefficients for Selected Elements[a]

Element	Phase	*a*	*b*	*c* (cal/g · mol)	*d*	*A* (kcal/g · mol)	*B* (e.u.)
Ac	Solid	(5.4)	(3.0)	–	–	(1.743)	(18.7)
	Liquid	(8)	–	–	–	(0.295)	(31.3)
Ag	Solid	5.09	1.02	–	0.36	1.488	19.21
	Liquid	7.30	–	–	–	0.164	30.12
	Gas	(4.97)	–	–	–	(–66.34)	(–12.52)
Al	Solid	4.94	2.96	–	–	1.604	22.26
	Liquid	7.0	–	–	–	0.33	30.83
Am	Solid	(4.9)	(4.4)	–	–	(1.657)	(16.2)
	Liquid	(8.5)	–	–	–	(0.409)	(34.5)
As	Solid	5.17	2.34	–	–	1.646	21.8
Au	Solid	6.14	–0.175	0.92	–	1.831	23.65
	Liquid	7.00	–	–	–	–0.631	26.99
B	Solid	1.54	4.40	–	–	0.655	8.67
	Liquid	(6.0)	–	–	–	(–4.599)	(31.4)
Ba	Solid, α	5.55	4.50	–	–	1.722	16.1
	Solid, β	5.55	1.50	–	–	1.582	15.9
	Liquid	(7.4)	–	–	–	(0.843)	(25.3)
	Gas	(497)	–	–	–	(–39.65)	(–11.7)
Be	Solid	5.07	1.21	–	–1.15	1.951	27.62
	Liquid	5.27	–	–	–	–1.611	25.68
Bi	Solid	5.38	2.60	–	–	1.720	17.8
	Liquid	7.60	–	–	–	–0.087	25.6
	Gas	(4.97)	–	–	–	(–46.19)	(–15.9)
C	Solid	4.10	1.02	–	–2.10	1.972	23.484
Ca	Solid, α	5.24	3.50	–	–	1.718	2095
	Solid, β	6.29	1.40	–	–	1.689	26.01
	Liquid	7.4	–	–	–	–0.147	30.28
	Gas	(4.97)	–	–	–	(–43.015)	(–9.88)
Cd	Solid	5.31	2.94	–	–	1.714	18.8
	Liquid	7.10	–	–	–	0.798	26.1
	Gas	(4.97)	–	–	–	(–25.28)	(–11.7)
Ce	Solid	4.40	6.0	–	–	1.579	13.1
	Liquid	(7.9)	–	–	–	(–0.148)	(29.1)
Cl_2	Gas	8.76	0.27	–	–0.65	2.845	–2.929
Co	Solid, α	4.72	4.30	–	–	1.598	21.4
	Solid, β	3.30	5.86	–	–	0.974	3.1
	Solid, γ	9.60	–	–	–	3.961	50.5
	Liquid	8.30	–	–	–	–2.034	38.7
Cr	Solid	5.35	2.36	–	–0.44	1.848	25.75
	Liquid	9.40	–	–	–	1.556	50.13
	Gas	(4.97)	–	–	–	(–82.47)	(–13.8)

(*Continued*)

TABLE 1.166 (*Continued*) Thermodynamic Coefficients for Selected Elements[a]

Element	Phase	*a*	*b*	*c* (cal/g · mol)	*d*	*A* (kcal/g · mol)	*B* (e.u.)
Cs	Solid	7.42	–	–	–	2.212	22.5
	Liquid	8.00	–	–	–	1.887	24.1
	Gas	(4.97)	–	–	–	(–17.35)	(–13.6)
Cu	Solid	5.41	1.50	–	–	1.680	23.30
	Liquid	7.50	–	–	–	0.024	34.05
F_2	Gas	8.29	0.44	–	–0.80	2.760	–0.76
Fe	Solid, α	3.37	7.10	–	0.43	1.176	14.59
	Solid, β	10.40	–	–	–	4.281	55.66
	Solid, γ	4.85	3.00	–	–	0.396	19.76
	Solid, δ	10.30	–	–	–	4.382	55.11
	Liquid	10.00	–	–	–	–0.021	50.73
Ga	Solid	5.237	3.33	–	–	1.710	21.01
	Liquid	(6.645)	–	–	–	(0.648)	(23.64)
Ge	Solid	5.90	1.13	–	–	1.764	23.8
	Liquid	(7.3)	–	–	–	(–5.668)	(25.7)
H_2	Gas	6.62	0.81	–	–	2.010	6.75
Hf	Solid	(6.00)	(0.52)	–	–	(1.812)	(21.2)
Hg	Liquid	6.61	–	–	–	1.971	19.20
	Gas	4.969	–	–	–	–13.048	–13.54
In	Solid	5.81	2.50	–	–	1.844	19.97
	Liquid	7.50	–	–	–	1.564	27.34
	Gas	(4.97)	–	–	–	(–58.42)	(–14.46)
Ir	Solid	5.56	1.42	–	–	1.721	23.4
K	Solid	1.3264	19.405	–	–	1.258	–1.86
	Liquid	8.8825	4.565	2.9369	–	1.923	32.55
	Gas	(4.97)	–	–	–	(–19.689)	(–9.46)
La	Solid	6.17	1.60	–	–	1.911	21.9
	Liquid	(7.3)	–	–	–	(–0.15)	(26.0)
Li	Solid	3.05	8.60	–	–	1.292	12.92
	Liquid	7.0	–	–	–	1.509	32.00
	Gas	(4.97)	–	–	–	(–34.30)	(–2.84)
Mg	Solid	5.33	2.45	–	–0.103	1.733	23.39
	Liquid	(8.0)	–	–	–	0.942	36.967
	Gas	(4.97)	–	–	–	(–34.78)	(–7.60)
Mn	Solid, α	6.70	3.38	–	–0.37	1.974	26.11
	Solid, β	8.33	0.66	–	–	2.672	41.02
	Solid, γ	10.70	–	–	–	4.760	56.84
	Solid, δ	11.30	–	–	–	5.176	60.88
	Liquid	11.00	–	–	–	1.221	56.38
	Gas	6.26	–			–63.704	–3.13
Mo	Solid	5.48	1.30	–	–	1.692	24.78
N_2	Gas	6.76	0.606	0.13	–	2.044	–7.064

(*Continued*)

TABLE 1.166 (*Continued*) Thermodynamic Coefficients for Selected Elements[a]

Element	Phase	*a*	*b*	*c* (cal/g · mol)	*d*	*A* (kcal/g · mol)	*B* (e.u.)
Na	Solid	5.657	3.252	0.5785	–	1.836	20.92
	Liquid	8.954	−4.577	2.540	–	1.924	36.0
		(4.97)	–	–	–	(−24.40)	(−8.7)
Nb	Solid	5.66	0.96	–	–	1.730	24.24
Nd	Solid	5.61	5.34	–	–	1.910	19.7
	Liquid	(9.1)	–	–	–	(−0.606)	35.8
Ni	Solid, α	4.06	7.04	–	–	1.523	18.095
	Solid, β	6.00	1.80	–	–	1.619	27.16
	Liquid	9.20	–	–	–	0.251	45.47
Np	Solid	(5.3)	(3.4)	–	–	(1.731)	(17.9)
	Liquid	(9.0)	–	–	–	(1.392)	(37.5)
O_2	Gas	8.27	0.258	–	−1.877	3.007	−0.750
Os	Solid	5.69	0.88	–	–	1.736	24.9
P_4	Solid, white	13.62	28.72	–	–	5.338	43.8
	Liquid	19.23	0.51	–	−2.98	6.035	66.7
	Gas	(19.5)	(−0.4)	(1.3)	–	(−6.32)	(46.1)
Pa	Solid	(5.2)	(4.0)	–	–	(1.728)	(17.3)
	Liquid	(8.0)	–	–	–	(−3.823)	(28.8)
Pb	Solid	5.64	2.30	–	–	1.784	17.33
	Liquid	7.75	−0.73	–	–	1.362	27.11
	Gas	(4.97)	–	–	–	(−45.25)	(−13.6)
Pd	Solid	5.80	1.38	–	–	1.791	24.6
	Liquid	(9.0)	–	–	–	(1.215)	(43.8)
Po	Solid	(5.2)	(3.2)	–	–	(1.693)	(17.6)
	Liquid	(9.0)	–	–	–	(0.847)	(35.2)
	Gas	(4.97)	–	–	–	(−28.73)	(−13.5)
Pr	Solid	(5.0)	(4.6)	–	–	(1.705)	(16.4)
	Liquid	(8.0)	–	–	–	(−0.519)	(30.0)
Pt	Solid	5.74	1.34	–	0.10	1.737	23.0
	Liquid	(9.0)	–	–	–	(0.406)	(42.6)
Pu	Solid	(5.2)	(3.6)	–	–	(1.710)	(17.7)
	Liquid	(8.0)	–	–	–	(0.506)	(31.0)
Ra	Solid	(5.8)	(1.2)	–	–	(1.783)	(16.4)
	Liquid	(8.0)	–	–	–	(1.284)	(28.6)
	Gas	(4.97)	–	–	–	(−38.87)	(−14.5)
Rb	Solid	3.27	13.1	–	–	1.557	5.9
	Liquid	7.85	–	–	–	1.814	26.5
	Gas	(4.97)	–	–	–	(−19.04)	(−12.3)
Re	Solid	(5.85)	(0.8)	–	–	(1.780)	(24.7)
Rh	Solid	5.40	2.19	–	–	1.707	23.8
	Liquid	(9.0)	–	–	–	(−0.923)	(44.4)

(*Continued*)

TABLE 1.166 (*Continued*) Thermodynamic Coefficients for Selected Elements[a]

Element	Phase	*a*	*b*	*c* (cal/g · mol)	*d*	*A* (kcal/g · mol)	*B* (e.u.)
Ru	Solid, α	5.25	1.50	–	–	1.632	23.5
	Solid, β	7.20	–	–	–	2.867	35.5
	Solid, γ	7.20	–	–	–	2.867	35.5
	Solid, δ	7.50	–	–	–	3.169	37.6
S	Solid, α	3.58	6.24	–	–	1.345	14.64
	Solid, β	3.56	6.95	–	–	1.298	14.54
	Liquid	5.4	5.0	–	–	1.576	24.02
1/2 S_2	Gas	(4.25)	(0.15)	–	(–1.0)	(–2.859)	(9.57)
Sb	Solid, α, β, γ	5.51	1.74	–	–	1.720	21.4
	Liquid	7.50	–	–	–	1.992	28.1
1/2 Sb_2	Gas	4.47	–	–	–0.11	–53.876	–21.7
Sc	Solid	(5.13)	(3.0)	–	–	1.663	21.1
	Liquid	(7.50)	–			(–2.563)	31.3
Se	Solid	3.30	8.80	–	–	1.375	11.28
	Liquid	7.0	–	–	–	0.881	27.34
Si	Solid	5.70	1.02	–	–1.06	2.100	28.88
	Liquid	7.4	–			7.646	33.17
Sm	Solid	(6.7)	(3.4)	–	–	(2.149)	(24.2)
	Liquid	(9.0)	–	–	–	(–2.296)	(33.4)
Sn	Solid, α, β	4.42	6.30	–	–	1.598	14.8
	Liquid	7.30	–	–	–	0.559	26.2
	Gas	(4.97)	–	–	–	(60.21)	(–14.3)
Sr	Solid	(5.60)	(1.37)	–	–	(1.731)	(19.3)
	Liquid	(7.7)	–	–	–	(0.976)	(30.4)
	Gas	(4.97)	–	–	–	(37.16)	(–10.2)
Ta	Solid	5.82	0.78	–	–	1.770	23.4
Tc	Solid	(5.6)	(2.0)	–	–	(1.759)	(24.5)
	Liquid	–	–	–	–	(3.459)	(59.4)
Te	Solid, α	4.58	5.25	–	–	1.599	15.78
	Solid, β	4.58	5.25	–	–	1.469	15.57
	Liquid	9.0	–	–	–	–0.988	34.96
1/2 Te_2	Gas	4.47	–	–	–0.10	–19.048	–6.47
Th	Solid	8.2	–0.77	2.04	–	2.591	33.64
	Liquid	(8.0)	–	–	–	(–7.602)	(26.84)
Ti	Solid, α	5.25	2.52	–	–	1.677	23.33
	Solid, β	7.50	–	–	–	1.645	35.46
	Liquid	(7.8)	–	–	–	(–2.355)	(35.45)
Tl	Solid, α	5.26	3.46	–	–	1.722	15.6
	Solid, β	7.30	–	–	–	2.230	26.4
	Liquid	7.50	–	–	–	1.315	25.9
	Gas	(4.97)	–	–	–	(–41.88)	(–15.4)

(*Continued*)

TABLE 1.166 (*Continued*) Thermodynamic Coefficients for Selected Elements[a]

Element	Phase	*a*	*b*	*c* (cal/g · mol)	*d*	*A* (kcal/g · mol)	*B* (e.u.)
U	Solid, α	3.25	8.15	–	0.80	1.063	8.47
	Solid, β	10.28	–	–	–	3.493	48.27
	Solid, γ	9.12	–	–	–	1.110	39.09
	Liquid	(8.99)	–	–	–	(–2.073)	36.01
V	Solid	5.57	0.97	–	–	1.704	24.97
	Liquid	(8.6)	–	–	–	1.827	44.06
W	Solid	5.74	0.76	–	–	1.745	24.9
Y	Solid	(5.6)	(2.2)	–	–	(1.767)	(21.6)
	Liquid	(7.5)	–	–	–	(2.277)	(29.6)
Zn	Solid	5.35	2.40	–	–	1.702	21.25
	Liquid	7.50	–	–	–	1.020	31.35
		(4.97)	–	–	–	(−29.407)	(−9.81)
Zr	Solid, α	6.83	1.12	–	−0.87	2.378	30.45
	Solid, β	7.27	–	–	–	1.159	31.43
	Liquid	(8.0)	–	–	–	(–2.190)	(34.7)

Source: Data from R. C. Weast (Ed.), *Handbook of Chemistry and Physics,* 69th Edn., CRC Press, Boca Raton, FL, 1988, D44.

[a] Refer to Table 1.165, "Key to Tables of Thermodynamic Coefficients" for an explanation of the coefficients.

TABLE 1.167 Entropy of the Elements

Element	Phase	Entropy at 298 K (e.u.)
Ac	Solid	(13)
Ag	Solid	10.20
Al	Solid	6.769
Am	Solid	(13)
As	Solid	8.4
Au	Solid	11.32
B	Solid	1.42
Ba	Solid, α	16
Be	Solid	2.28
Bi	Solid	13.6
C	Solid	1.3609
Ca	Solid, α	9.95
Cd	Solid	12.3
Ce	Solid	13.8
Cl_2	Gas	53.286
Co	Solid, α	6.8
Cr	Solid	5.68
Cs	Solid	19.8
Cu	Solid	7.97
F_2	Gas	48.58
Fe	Solid, α	6.491
Ga	Solid	9.82

(*Continued*)

TABLE 1.167 (*Continued*) Entropy of the Elements

Element	Phase	Entropy at 298 K (e.u.)
Ge	Solid	10.1
H_2	Gas	31.211
Hf	Solid	13.1
Hg	Liquid	18.46
In	Solid	13.88
Ir	Solid	8.7
K	Solid	15.2
La	Solid	13.7
Li	Solid	6.70
Mg	Solid	7.77
Mn	Solid, α	7.59
Mo	Solid	6.83
N_2	Gas	45.767
Na	Solid	12.31
Nb	Solid	8.3
Nd	Solid	13.9
Ni	Solid, α	7.137
Np	Solid	(14)
O_2	Gas	49.003
Os	Solid	7.8
P_4	Solid, white	42.4
Pa	Solid	(13.5)
Pb	Solid	15.49
Pd	Solid	8.9
Po	Solid	13
Pr	Solid	(13.5)
Pt	Solid	10.0
Pu	Solid	(13.0)
Ra	Solid	(17)
Rb	Solid	16.6
Re	Solid	(8.89)
Rh	Solid	7.6
Ru	Solid, α	6.9
S	Solid, α	7.62
Sb	Solid (α, β, γ)	10.5
Sc	Solid	(9.0)
Se	Solid	10.144
Si	Solid	4.50
Sm	Solid	(15)
Sn	Solid (α, β)	12.3
Sr	Solid	13.0
Ta	Solid	9.9
Tc	Solid	(8.0)

(*Continued*)

TABLE 1.167 (*Continued*) Entropy of the Elements

Element	Phase	Entropy at 298 K (e.u.)
Te	Solid, α	11.88
Th	Solid	12.76
Ti	Solid, α	7.334
Tl	Solid, α	15.4
U	Solid, α	12.03
V	Solid	7.05
W	Solid	8.0
Y	Solid	(11)
Zn	Solid	9.95
Zr	Solid, α	9.29

Source: Data from R. C. Weast (Ed.), *Handbook of Chemistry and Physics,* 69th Edn., CRC Press, Boca Raton, FL, 1988, D44.

TABLE 1.168 Vapor Pressure of the Elements at Very Low Pressures

Element	Melting Point (°C)	Pressure (mmHg)					
		10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1
Ag	961	767	848	936	1047	1184	1353
Al	660	724	808	889	996	1123	1279
Au	1063	1083	1190	1316	1465	1646	1867
Ba	717	418	476	546	629	730	858
Be	1284	942	1029	1130	1246	1395	1582
Bi	271	474	536	609	698	802	934
C		2129	2288	2471	2681	2926	3214
Cd	321	148	180	220	264	321	
Co	1478	1249	1362	1494	1649	1833	2056
Cr	1900	907	992	1090	1205	1342	1504
Cu	1083	946	1035	1141	1273	1432	1628
Fe	1535	1094	1195	1310	1447	1602	1783
Hg	−38.9	−23.9	−5.5	18.0	48.0	82.0	126
In	157	667	746	840	952	1088	1260
Ir	2454	1993	2154	2340	2556	2811	3118
Mg	651	287	331	383	443	515	605
Mn	1244	717	791	878	980	1103	1251
Mo	2622	1923	2095	2295	2533		
Ni	1455	1157	1257	1371	1510	1679	1884
Os	2697	2101	2264	2451	2667	2920	3221
Pb	328	483	548	625	718	832	975
Pd	1555	1156	1271	1405	1566	1759	2000
Pt	1774	1606	1744	1904	2090	2313	2582
Sb	630	466	525	595	678	779	904

(*Continued*)

TABLE 1.168 (*Continued*) Vapor Pressure of the Elements at Very Low Pressures

Element	Melting Point (°C)	Pressure (mmHg)					
		10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1
Si	1410	1024	1116	1223	1343	1485	1670
Sn	232	823	922	1042	1189	1373	1609
Ta	2996	2407	2599	2820			
W	3382	2554	2767	3016	3309		
Zn	419	211	248	292	343	405	
Zr	2127	1527	1660	1816	2001	2212	2459

Source: Dushman, S., *Scientific Foundations of Vacuum Technique*. 1949. Copyright Wiley-VCH Verlag GmbH & Co. KGaA.

Note: To convert mmHg (torr) to N/m², multiply by 133.3.
To convert atm to MN/m², multiply by 0.1013.
This table lists the temperature in degrees Celsius (Centigrade) at which an element has a vapor pressure indicated by the headings of the columns.
The values given in this table are from a variety of sources that are not always in agreement; for that reason, the table should be used only as a general guide.

TABLE 1.169 Vapor Pressure of the Elements at Moderate Pressures

Element	Symbol	Pressure (mmHg)				
		1	10	100	400	760
Aluminum	Al	1540	1780	2080	2320	2467
Antimony	Sb		960	1280	1570	1750
Arsenic	As	380	440	510	580	610
Barium	Ba	860	1050	1300	1520	1640
Beryllium	Be	1520	1860	2300	2770	2970
Bismuth	Bi		1060	1280	1450	1560
Boron	B	2660	3030	3460	3810	4000
Bromine	Br	–60	–30	+9	39	59
Cadmium	Cd	393	486	610	710	765
Calcium	Ca	800	970	1200	1390	1490
Cesium	Cs		373	513	624	690
Chlorine	Cl	–123	–101	–71	–46	–34
Chromium	Cr	1610	1840	2140	2360	2480
Cobalt	Co	1910	2170	2500	2760	2870
Copper	Cu		1870	2190	2440	2600
Fluorine	F			–203	–193	–188
Gallium	Ca	1350	1570	1850	2060	2180
Germanium	Ge		2080	2440	2710	2830
Gold	Au	1880	2160	2520	2800	2940
Indium	In				1960	2080
Iodine	I	40	72	115	160	185
Iridium	Ir	2830	3170	3630	3960	4130
Iron	Fe	1780	2040	2370	2620	2750

(*Continued*)

TABLE 1.169 (*Continued*) Vapor Pressure of the Elements at Moderate Pressures

		Pressure (mmHg)				
Element	Symbol	1	10	100	400	760
Lanthanum	La				3230	3420
Lead	Pb	970	1160	1420	1630	1740
Lithium	Li	750	890	1080	1240	1310
Magnesium	Mg	620	740	900	1040	1110
Manganese	Mn		1510	1810	2050	2100
Mercury	Hg			260	330	356.9
Molybdenum	Mo	3300	3770	4200	4580	4830
Neodymium	Nd				2870	3100
Nickel	Ni	1800	2090	2370	2620	2730
Palladium	Pd	1470	2290	2670	2950	3140
Phosphorus	P		127	199	253	283
Platinum	Pt	2600	2940	3360	3650	3830
Polonium	Po	472	587	752	890	960
Potassium	K			590	710	770
Rhodium	Rh	2530	2850	3260	3590	3760
Rubidium	Rb		390	527	640	700
Selenium	Se		429	547	640	685
Silver	Ag	1310	1540	1850	2060	2210
Sodium	Na	440	546	700	830	890
Strontium	Sr	740	900	1100	1280	1380
Sulfur	S		246	333	407	445
Tellurium	Te	520	633	792	900	962
Thallium	Tl		1000	1210	1370	1470
Tin	Sn	1610	1890	2270	2580	2750
Titanium	Ti	2180	2480	2860	3100	3260
Tungsten	W	3980	4490	5160	5470	5940
Uranium	U	2450	2800	3270	3620	3800
Vanadium	V	2290	2570	2950	3220	3380
Zinc	Zn		590	730	840	907

Source: Dushman, S., *Scientific Foundations of Vacuum Technique*. 1949. Copyright Wiley-VCH Verlag GmbH & Co. KGaA.

To convert mm Hg (torr) to N/m^2, multiply by 133.3.

To convert atm to MN/m^2, multiply by 0.1013.

This table lists the temperature in degrees Celsius (Centigrade) at which an element has a vapor pressure indicated by the headings of the columns.

The values given in this table are from a variety of sources that are not always in agreement; for that reason, the table should be used only as a general guide.

TABLE 1.170 Vapor Pressure of the Elements at High Pressures

		Pressure (atm)				
Element	Symbol	2	5	10	20	40
Aluminum	Al	2610	2850	3050	3270	3530
Antimony	Sb	1960	2490			
Barium	Ba	1790	2030	2230		
Beryllium	Be	3240	3730	4110	4720	5610
Bismuth	Bi	1660	1850	2000	2180	
Bromine	Br	78	110			
Cadmium	Cd	830	930	1030	1120	1240
Calcium	Ca	1630	1850	2020	2290	
Chlorine	Cl	–17	+9	30	55	97
Chromium	Cr	2630	2850	3010	3180	
Cobalt	Co	3040	3270			
Copper	Cu	2760	3010	3500	3460	3740
Fluorine	F	–180.7	–169.1	–159.6		
Gallium	Ca	2320	2560	2730		
Germanium	Ge	2970	3200	3430		
Gold	Au	3120	3490	3630	3890	
Indium	In	2230	2440	2600		
Iodine	I	216	265			
Iridium	Ir	4310	4650			
Iron	Fe	2900	3150	3360	3570	
Lanthanum	La	3620	3960	4270		
Lead	Pb	1880	2140	2320	2620	
Lithium	Li	1420	1518			
Magnesium	Mg	1190	1330	1430	1560	
Manganese	Mn	2360	2580	2850		
Mercury	Hg	398	465	517	581	657
Molybdenum	Mo	5050	5340	5680	5980	
Neodymium	Nd	3300	3680	3990		
Nickel	Ni	2880	3120	3300	3310	
Palladium	Pd	3270	3560	3840		
Phosphorus	P	319				
Platinum	Pt	4000	4310	4570	4860	
Polonium	Po	1060	1200	1340		
Potassium	K	850	950	1110	1240	1420
Rhodium	Rh	3930	4230	4440		
Selenium	Se	750	850	920	1010	1120
Silver	Ag	2360	2600	2850	3050	3300
Sodium	Na	980	1120	1230	1370	
Strontium	Sr	1480	1670	1850	2030	

(*Continued*)

TABLE 1.170 (*Continued*) Vapor Pressure of the Elements at High Pressures

		Pressure (atm)				
Element	Symbol	2	5	10	20	40
Sulfur	S	493	574	640	720	
Tellurium	Te	1030	1160	1250		
Thallium	Tl	1560	1750	1900	2050	2260
Tin	Sn	2950	3270	3540	3890	
Titanium	Ti	3400	3650	3800		
Tungsten	W	6260	6670	7250	7670	
Uranium	U	4040	4420			
Vanadium	V	3540	3800			
Zinc	Zn	970	1090	1180	1290	

Source: From R. Loebel, In: R. C. Weast (Ed.), *Handbook of Chemistry and Physics,* 55th Edn., CRC Press, Cleveland, 1974.

Note: To convert atm to MN/m^2 multiply by 0.1013.
This table lists the temperature in degrees Celsius (Centigrade) at which an element has a vapor pressure indicated by the headings of the columns.

TABLE 1.171 Values of the Error Function

z	erf (z)
0.00	0.0000
0.01	0.0113
0.02	0.0226
0.03	0.0338
0.04	0.0451
0.05	0.0564
0.10	0.1125
0.15	0.1680
0.20	0.2227
0.25	0.2763
0.30	0.3286
0.35	0.3794
0.40	0.4284
0.45	0.4755
0.50	0.5205
0.55	0.5633
0.60	0.6039
0.65	0.6420
0.70	0.6778
0.75	0.7112
0.80	0.7421

(*Continued*)

TABLE 1.171 (*Continued*) Values of the Error Function

z	Erf (z)
0.85	0.7707
0.90	0.7969
0.95	0.8209
1.00	0.8427
1.10	0.8802
1.20	0.9103
1.30	0.9340
1.40	0.9523
1.50	0.9661
1.60	0.9763
1.70	0.9838
1.80	0.9891
1.90	0.9928
2.00	0.9953

Source: Data from M. Abramowitz and I. A. Stegun (Eds.), *Handbook of Mathematical Functions*, National Bureau of Standards, Applied Mathematics Series 55, Washington, DC, 1972.

TABLE 1.172 Diffusion in Metallic Systems

Metal	Tracer	Crystalline Form	Purity (%)	Temperature Range (°C)	Activation Energy, Q (kcal/mol)	Frequency Factor, D_o (cm²/s)
Aluminum	Ag^{110}	S	99.999	371–655	27.83	0.118
	Al^{27}	S		450–650	34.0	1.71
	Au^{198}	S	99.999	423–609	27.0	0.077
	Cd^{115}	S	99.999	441–631	29.7	1.04
	Ce^{141}	P	99.995	450–630	26.60	1.9×10^{-6}
	Co^{60}	S	99.999	369–655	27.79	0.131
	Cr^{51}	S	99.999	422–654	41.74	464
	Cu^{64}	S	99.999	433–652	32.27	0.647
	Fe^{59}	S	99.99	550–636	46.0	135
	Ga^{72}	S	99.999	406–652	29.24	0.49
	Ge^{71}	S	99.999	401–653	28.98	0.481
	In^{114}	P	99.99	400–600	27.6	0.123
	La^{140}	P	99.995	500–630	27.0	1.4×10^{-6}
	Mn^{54}	P	99.99	450–650	28.8	0.22
	Mo^{99}	P	99.995	400–630	13.1	1.04×10^{-9}
	Nb^{95}	P	99.95	350–480	19.65	1.66×10^{-7}
	Nd^{147}	P	99.995	450–630	25.0	4.8×10^{-7}
	Ni^{63}	P	99.99	360–630	15.7	2.9×10^{-8}
	Pd^{103}	P	99.995	400–630	20.2	1.92×10^{-7}

(*Continued*)

TABLE 1.172 (*Continued*) Diffusion in Metallic Systems

Metal	Tracer	Crystalline Form	Purity (%)	Temperature Range (°C)	Activation Energy, Q (kcal/mol)	Frequency Factor, D_o (cm²/s)
	Pr^{142}	P	99.995	520–630	23.87	3.58×10^{-7}
	Sb^{124}	P		448–620	29.1	0.09
	Sm^{153}	P	99.995	450–630	22.88	3.45×10^{-7}
	Sn^{113}	P		400–600	28.5	0.245
	V^{48}	P	99.995	400–630	19.6	6.05×10^{-8}
	Zn^{65}	S	99.999	357–653	28.86	0.259
Beryllium	Ag^{110}	S⊥c	99.75	650–900	43.2	1.76
	Ag^{110}	S||c	99.75	650–900	39.3	0.43
	Be^{7}	S⊥c	99.75	565–1065	37.6	0.52
	Be^{7}	S||c	99.75	565–1065	39.4	0.62
	Fe^{59}	S	99.75	700–1076	51.6	0.67
	Ni^{63}	P		800–1250	58.0	0.2
Cadmium	Ag^{110}	S	99.99	180–300	25.4	2.21
	Cd^{115}	S	99.95	110–283	19.3	0.14
	Zn^{65}	S	99.99	180–300	19.0	0.0016
Calcium	C^{14}		99.95	550–800	29.8	3.2×10^{-5}
	Ca^{45}		99.95	500–800	38.5	8.3
	Fe^{59}		99.95	500–800	23.3	2.7×10^{-3}
	Ni^{63}		99.95	550–800	28.9	1.0×10^{-6}
	U^{235}		99.95	500–700	34.8	1.1×10^{-5}
Carbon	Ag^{110}	⊥c		750–1050	64.3	9280
	C^{14}			2000–2200	163	5
	Ni^{63}	⊥c		540–920	47.2	102
	Ni^{63}	||c		750–1060	53.3	2.2
	Th^{228}	⊥c		1400–2200	145.4	1.33×10^{-5}
	Th^{228}	||c		1800–2200	114.7	2.48
	U^{232}	⊥c		140–2200	115.0	6760
	U^{232}	||c		1400–1820	129.5	385
Chromium	C^{14}	P		120–1500	26.5	9.0×10^{-3}
	Cr^{51}	P	99.98	1030–1545	73.7	0.2
	Fe^{59}	P	99.8	980–1420	79.3	0.47
	Mo^{99}	P		1100–1420	58.0	2.7×10^{-3}
Cobalt	C^{14}	P	99.82	600–1400	34.0	0.21
	Co^{60}	P	99.9	1100–1405	67.7	0.83
	Fe^{59}	P	99.9	1104–1303	62.7	0.21
	Ni^{63}	P		1192–1297	60.2	0.10
	S^{35}	P	99.99	1150–1250	5.4	1.3
Copper	Ag^{110}	S, P		580–980	46.5	0.61
	As^{76}	P		810–1075	42.13	0.20
	Au^{193}	S, P		400–1050	42.6	0.03
	Cd^{115}	S	99.98	725–950	45.7	0.935
	Ce^{141}	P	99.999	766–947	27.6	2.17×10^{-3}

(*Continued*)

TABLE 1.172 (*Continued*) Diffusion in Metallic Systems

Metal	Tracer	Crystalline Form	Purity (%)	Temperature Range (°C)	Activation Energy, Q (kcal/mol)	Frequency Factor, D_o (cm²/s)
	Cr^{51}	S, P		800–1070	53.5	1.02
	Co^{60}	S	99.998	701–1077	54.1	1.93
	Cu^{67}	S	99.999	698–1061	50.5	0.78
	Eu^{152}	P	99.999	750–970	26.85	1.17×10^{-7}
	Fe^{59}	S. P		460–1070	52.0	1.36
	Ga^{72}		–		45.90	0.55
	Ge^{68}	S	99.998	653–1015	44.76	0.397
	Hg^{203}	P			44.0	0.35
	Lu^{177}	P	99.999	857–1010	26.15	4.3×10^{-9}
	Mn^{54}	S	99.99	754–950	91.4	10^{7}
	Nb^{95}	P	99.999	807–906	60.06	2.04
	Ni^{63}	P		620–1080	53.8	1.1
	Pd^{102}	S	99.999	807–1056	54.37	1.71
	Pm^{147}	P	99.999	720–955	27.5	3.62×10^{-8}
	Pt^{195}	P		843–997	37.5	4.8×10^{-4}
	S^{35}	S	99.999	800–1000	49.2	23
	Sb^{124}	S	99.999	600–1000	42.0	0.34
	Sn^{113}	P		680–910	45.0	0.11
	Tb^{160}	P	99.999	770–980	27.45	8.96×10^{-9}
	Tl^{204}	S	99.999	785–996	43.3	0.71
	Tm^{170}	P	99.999	705–950	24.15	7.28×10^{-9}
	Zn^{65}	P	99.999	890–1000	47.50	0.73
Germanium	Cd^{115}	S		750–950	102.0	1.75×10^{9}
	Fe^{59}	S		775–930	24.8	0.13
	Ge^{71}	S		766–928	68.5	7.8
	In^{114}	S		600–920	39.9	2.9×10^{-4}
	Sb^{124}	S		720–900	50.2	0.22
	Te^{125}	S		770–900	56.0	2.0
	Tl^{204}	S		800–930	78.4	1700
Gold	Ag^{110}	S	99.99	699–1007	40.2	0.072
	Au^{198}	S	99.97	850–1050	42.26	0.107
	Co^{60}	P	99.93	702–948	41.6	0.068
	Fe^{59}	P	99.93	701–948	41.6	0.082
	Hg^{203}	S	99.994	600–1027	37.38	0.116
	Ni^{63}	P	99.96	880–940	46.0	0.30
	Pt^{195}	P, S	99.98	800–1060	60.9	7.6
β–Hafnium	Hf^{181}	P	97.9	1795–1995	38.7	1.2×10^{-3}
Indium	Ag^{110}	S⊥c	99.99	25–140	12.8	0.52
	Ag^{110}	S||c	99.99	25–140	11.5	0.11
	Au^{198}	S	99.99	25–140	6.7	9×10^{-3}
	In^{114}	S⊥c	99.99	44–144	18.7	3.7
	In^{114}	S||c	99.99	44–144	18.7	2.7

(*Continued*)

TABLE 1.172 (*Continued*) Diffusion in Metallic Systems

Metal	Tracer	Crystalline Form	Purity (%)	Temperature Range (°C)	Activation Energy, Q (kcal/mol)	Frequency Factor, D_o (cm²/s)
	Tl^{204}	S	99.99	49–157	15.5	0.049
α-Iron	Ag^{110}	P		748–888	69.0	1950
	Au^{198}	P	99.999	800–900	62.4	31
	C^{14}	P	99.98	616–844	29.3	2.2
	Co^{60}	P	99.995	638–768	62.2	7.19
	Cr^{51}	P	99.95	775–875	57.5	2.53
	Cu^{64}	P	99.9	800–1050	57.0	0.57
	Fe^{55}	P	99.92	809–889	60.3	5.4
	K^{42}	P	99.92	500–800	42.3	0.036
	Mn^{54}	P	99.97	800–900	52.5	0.35
	Mo^{99}	P		750–875	73.0	7800
	Ni^{63}	P	99.97	680–800	56.0	1.3
	P^{32}	P		860–900	55.0	2.9
	Sb^{124}	P		800–900	66.6	1100
	V^{48}	P		755–875	55.4	1.43
	W^{185}	P		755–875	55.1	0.29
γ-Iron	Be^{7}	P	99.9	1100–1350	57.6	0.1
	C^{14}	P	99.34	800–1400	34.0	0.15
	Co^{60}	P	99.98	1138–1340	72.9	1.25
	Cr^{51}	P	99.99	950–1400	69.7	10.8
	Fe^{59}	P	99.98	1171–1361	67.86	0.49
	Hf^{181}	P	99.99	1110–1360	97.3	3600
	Mn^{54}	P	99.97	920–1280	62.5	0.16
	Ni^{63}	P	99.97	930–2050	67.0	0.77
	P^{32}	P	99.99	950–1200	43.7	0.01
	S^{35}	P		900–1250	53.0	1.7
	V^{48}	P	99.99	1120–1380	69.3	0.28
	W^{185}	P	99.5	1050–1250	90.0	1000
δ-Iron	Co^{60}	P	99.995	1428–1521	61.4	6.38
	Fe^{59}	P	99.95	1428–1492	57.5	2.01
	P^{32}	P	99.99	1370–1460	55.0	2.9
Lanthanum	Au^{198}	P	99.97	600–800	45.1	1.5
	La^{140}	P	99.97	690–850	18.1	2.2×10^{-2}
Lead	Ag^{110}	P	99.9	200–310	14.4	0.064
	Au^{198}	S	99.999	190–320	10.0	8.7×10^{-3}
	Cd^{115}	S	99.999	150–320	21.23	0.409
	Cu^{64}	S		150–320	14.44	0.046
	Pb^{204}	S	99.999	150–320	25.52	0.887
	Tl^{205}	P	99.999	207–322	24.33	0.511
Lithium	Ag^{110}	P	92.5	65–161	12.83	0.37
	Au^{195}	P	92.5	47–153	10.49	0.21
	Bi	P	99.95	141–177	47.3	5.3×10^{13}

(*Continued*)

TABLE 1.172 (*Continued*) Diffusion in Metallic Systems

Metal	Tracer	Crystalline Form	Purity (%)	Temperature Range (°C)	Activation Energy, Q (kcal/mol)	Frequency Factor, D_o (cm²/s)
	Cd^{115}	P	92.5	80–174	16.05	2.35
	Cu^{64}	P	99.98	51–120	9.22	0.47
	Ga^{72}	P	99.98	58–173	12.9	0.21
	Hg^{203}	P	99.98	58–173	14.18	1.04
	In^{114}	P	92.5	80–175	15.87	0.39
	Li^{6}	P	99.98	35–178	12.60	0.14
	Na^{22}	P	92.5	52–176	12.61	0.41
	Pb^{204}	P	99.95	129–169	25.2	160
	Sb^{124}	P	99.95	141–176	41.5	1.6×10^{10}
	Sn^{113}	P	99.95	108–174	15.0	0.62
	Zn^{65}	P	92.5	60–175	12.98	0.57
Magnesium	Ag^{110}	P	99.9	476–621	28.50	0.34
	Fe^{59}	P	99.95	400–600	21.2	4×10^{-6}
	In^{114}	P	99.9	472–610	28.4	5.2×10^{-2}
	Mg^{28}	S⊥c		467–635	32.5	1.5
	Mg^{28}	S‖c		467–635	32.2	1.0
	Ni^{63}	P	99.95	400–600	22.9	1.2×10^{-5}
	U^{235}	P	99.95	500–620	27.4	1.6×10^{-5}
	Zn^{65}	P	99.9	467–620	28.6	0.41
Molybdenum	C^{14}	P	99.98	1200–1600	41.0	2.04×10^{-2}
	Co^{60}	P	99.98	1850–2350	106.7	18
	Cr^{51}	P		1000–1500	54.0	2.5×10^{-4}
	Cs^{134}	S	99.99	1000–1470	28.0	8.7×10^{-11}
	K^{42}	S		800–1100	25.04	5.5×10^{-9}
	Mo^{99}	P		1850–2350	96.9	0.5
	Na^{24}	S		800–1100	21.25	2.95×10^{-9}
	Nb^{95}	P	99.98	1850–2350	108.1	14
	P^{32}	P	99.97	2000–2200	80.5	0.19
	Re^{186}	P		1700–2100	94.7	0.097
	S^{35}	S	99.97	2220–2470	101.0	320
	Ta^{182}	P		1700–2150	83.0	3.5×10^{-4}
	U^{235}	P	99.98	1500–2000	76.4	7.6×10^{-3}
	W^{185}	P	99.98	1700–2260	110	1.7
Nickel	Au^{198}	S, P	99.999	700–1075	55.0	0.02
	Be^{7}	P	99.9	1020–1400	46.2	0.019
	C^{14}	P	99.86	600–1400	34.0	0.012
	Co^{60}	P	99.97	1149–1390	65.9	1.39
	Cr^{51}	P	99.95	1100–1270	65.1	1.1
	Cu^{64}	P	99.95	1050–1360	61.7	0.57
	Fe^{59}	P		1020–1263	58.6	0.074
	Mo^{99}	P		900–1200	51.0	1.6×10^{-3}
	Ni^{63}	P	99.95	1042–1404	68.0	1.9

(*Continued*)

TABLE 1.172 (*Continued*) Diffusion in Metallic Systems

Metal	Tracer	Crystalline Form	Purity (%)	Temperature Range (°C)	Activation Energy, Q (kcal/mol)	Frequency Factor, D_o (cm²/s)
	Pu^{238}	P		1025–1125	51.0	0.5
	Sb^{124}	P	99.97	1020–1220	27.0	1.8×10^{-5}
	Sn^{113}	P	99.8	700–1350	58.0	0.83
	V^{48}	P	99.99	800–1300	66.5	0.87
	W^{185}	P	99.95	1100–1300	71.5	2.0
Niobium	C^{14}	P		800–1250	32.0	1.09×10^{-5}
	Co^{60}	P	99.85	1500–2100	70.5	0.74
	Cr^{51}	S		943–1435	83.5	0.30
	Fe^{51}	P	99.85	1400–2100	77.7	1.5
	K^{42}	S		900–1100	22.10	2.38×10^{-7}
	Nb^{95}	P, S	99.99	878–2395	96.0	1.1
	P^{32}	P	99.0	1300–1800	51.5	5.1×10^{-2}
	S^{35}	S	99.9	1100–1500	73.1	2600
	Sn^{113}	P	99.85	1850–2400	78.9	0.14
	Ta^{182}	P, S	99.997	878–2395	99.3	1.0
	Ti^{44}	S		994–1492	86.9	0.099
	U^{235}	P	99.55	1500–2000	76.8	8.9×10^{-3}
	V^{48}	S	99.99	1000–1400	85.0	2.21
	W^{185}	P	99.8	1800–2200	91.7	5×10^{-4}
Palladium	Pd^{103}	S	99.999	1060–1500	63.6	0.205
Phosphorus	P^{32}	P		0–44	9.4	1.07×10^{-3}
Platinum	Co^{60}	P	99.99	900–1050	74.2	19.6
	Cu^{64}	P		1098–1375	59.5	0.074
	Pt^{195}	P	99.99	1325–1600	68.2	0.33
Potassium	Au^{198}	P	99.95	5.6–52.5	3.23	1.29×10^{-3}
	K^{42}	S	99.7	52–61	9.36	0.16
	Na^{22}	P	99.7	0–62	7.45	0.058
	Rb^{86}	P	99.95	0.1–59.9	8.78	0.090
γ–Plutonium	Pu^{238}	P		190–310	16.7	2.1×10^{-5}
δ–Plutonium	Pu^{238}	P		350–440	23.8	4.5×10^{-3}
ε-Plutonium	Pu^{238}	P		500–612	18.5	2.0×10^{-2}
α-Praseodymium	Ag^{110}	P	99.93	610–730	25.4	0.14
	Au^{195}	P	99.93	650–780	19.7	4.3×10^{-2}
	Co^{60}	P	99.93	660–780	16.4	4.7×10^{-2}
	Zn^{65}	P	99.96	766–603	24.8	0.18
β-Praseodymium	Ag^{110}	P	99.93	800–900	21.5	3.2×10^{-2}
	Au^{195}	P	99.93	800–910	20.1	3.3×10^{-2}
	Ho^{166}	P	99.96	800–930	26.3	9.5
	In^{114}	P	99.96	800–930	28.9	9.6
	La^{140}	P	99.96	800–930	25.7	1.8
	Pr^{142}	P	99.93	800–900	29.4	8.7

(*Continued*)

TABLE 1.172 (*Continued*) Diffusion in Metallic Systems

Metal	Tracer	Crystalline Form	Purity (%)	Temperature Range (°C)	Activation Energy, Q (kcal/mol)	Frequency Factor, D_o (cm²/s)
	Zn^{65}	P	99.96	822–921	27.0	0.63
Selenium	Fe^{59}	P		40–100	8.88	–
	Hg^{203}	P	99.996	25–100	1.2	–
	S^{35}	S⊥c		60–90	29.9	1700
	S^{35}	S∥c		60–90	15.6	1100
	Se^{75}	P		35–140	11.7	1.4×10^{-4}
Silicon	Au^{198}	S		700–1300	47.0	2.75×10^{-3}
	C^{14}	P		1070–1400	67.2	0.33
	Cu^{64}	P		800–1100	23.0	4×10^{-2}
	Fe^{59}	S		1000–1200	20.0	6.2×10^{-3}
	Ni^{63}	P		450–800	97.5	1000
	P^{32}	S		1100–1250	41.5	–
	Sb^{124}	S		1190–1398	91.7	12.9
	Si^{31}	S	99.99999	1225–1400	110.0	1800
Silver	Au^{198}	P	99.99	718–942	48.28	0.85
	Ag^{110}	S	99.999	640–955	45.2	0.67
	Cd^{115}	S	99.99	592–937	41.69	0.44
	Co^{60}	S	99.999	700–940	48.75	1.9
	Cu^{64}	P	99.99	717–945	46.1	1.23
	Fe^{59}	S	99.99	720–930	49.04	2.42
	Ge^{77}	P		640–870	36.5	0.084
	Hg^{203}	P	99.99	653–948	38.1	0.079
	In^{114}	S	99.99	592–937	40.80	0.41
	Ni^{63}	S	99.99	749–950	54.8	21.9
	Pb^{210}	P		700–865	38.1	0.22
	Pd^{102}	S	99.999	736–939	56.75	9.56
	Ru^{103}	S	99.99	793–945	65.8	180
	S^{35}	S	99.999	600–900	40.0	1.65
	Sb^{124}	P	99.999	780–950	39.07	0.234
	Sn^{113}	S	99.99	592–937	39.30	0.255
	Te^{125}	P		770–940	38.90	0.47
	Tl^{204}	P		640–870	37.9	0.15
	Zn^{65}	S	99.99	640–925	41.7	0.54
Sodium	Au^{198}	P	99.99	1.0–77	2.21	3.34×10^{-4}
	K^{42}	P	99.99	0–91	8.43	0.08
	Na^{22}	P	99.99	0–98	10.09	0.145
	Rb^{86}	P	99.99	0–85	8.49	0.15
Tantalum	C^{14}	P		1450–2200	40.3	1.2×10^{-2}
	Fe^{59}	P		930–1240	71.4	0.505
	Mo^{99}	P		1750–2220	81.0	1.8×10^{-3}
	Nb^{95}	P, S	99.996	921–2484	98.7	0.23
	S^{35}	P	99.0	1970–2110	70.0	100

(*Continued*)

TABLE 1.172 (*Continued*) Diffusion in Metallic Systems

Metal	Tracer	Crystalline Form	Purity (%)	Temperature Range (°C)	Activation Energy, Q (kcal/mol)	Frequency Factor, D_o (cm²/s)
	Ta^{182}	P, S	99.996	1250–2200	98.7	1.24
Tellurium	Hg^{203}	P		270–440	18.7	3.14×10^{-5}
	Se^{75}	P		320–440	28.6	2.6×10^{-2}
	Tl^{204}	P		360–430	41.0	320
	Te^{127}	S⊥c	99.9999	300–400	46.7	3.91×10^{4}
	Te^{127}	S||c	99.9999	300–400	35.5	130
α-Thallium	Ag^{110}	P⊥c	99.999	80–250	11.8	3.8×10^{-2}
	Ag^{110}	P||c	99.999	80–250	11.2	2.7×10^{-2}
	Au^{198}	P⊥c	99.999	110–260	2.8	2.0×10^{-5}
	Au^{198}	P||c	99.999	110–260	5.2	5.3×10^{-4}
	Tl^{204}	S⊥c	99.9	135–230	22.6	0.4
	Tl^{204}	S||c	99.9	135–230	22.9	0.4
β-Thallium	Ag^{110}	P	99.999	230–310	11.9	4.2×10^{-2}
	Au^{198}	P	99.999	230–310	6.0	5.2×10^{-4}
	Tl^{204}	S	99.9	230–280	20.7	0.7
α-Thorium	Pa^{231}	P	99.85	770–910	74.7	126
	Th^{228}	P	99.85	720–880	716	395
	U^{233}	P	99.85	700–880	79.3	2210
Tin	Ag^{110}	S⊥c		135–225	18.4	0.18
	Ag^{110}	S||c		135–225	12.3	7.1×10^{-3}
	Au^{198}	S⊥c		135–225	17.7	0.16
	Au^{198}	S||c		135–225	11.0	5.8×10^{-3}
	Co^{60}	S, P		140–217	22.0	5.5
	In^{114}	S⊥c	99.998	181–221	25.8	34.1
	In^{114}	S||c	99.998	181–221	25.6	12.2
	Sn^{113}	S⊥c	99.999	160–226	25.1	10.7
	Sn^{113}	S||c	99.999	160–226	25.6	7.7
	Tl^{204}	P	99.999	137–216	14.7	1.2×10^{-3}
α-Titanium	Ti^{44}	P	99.99	700–850	35.9	8.6×10^{-6}
β-Titanium	Ag^{110}	P	99.95	940–1570	43.2	3×10^{-3}
	Be^{7}	P	99.96	915–1300	40.2	0.8
	C^{14}	P	99.62	1100–1600	20.0	3.02×10^{-3}
	Cr^{51}	P	99.7	950–1600	35.1	5×10^{-3}
	Co^{60}	P	99.7	900–1600	30.6	1.2×10^{-2}
	Fe^{59}	P	99.7	900–1600	31.6	7.8×10^{-3}
	Mo^{99}	P	99.7	900–1600	43.0	8.0×10^{-3}
	Mn^{54}	P	99.7	900–1600	33.7	6.1×10^{-3}
	Nb^{95}	P	99.7	1000–1600	39.3	5.0×10^{-3}
	Ni^{63}	P	99.7	925–1600	29.6	9.2×10^{-3}
	P^{32}	P	99.7	950–1600	24.1	3.62×10^{-3}
	Sc^{46}	P	99.95	940–1590	32.4	4.0×10^{-3}

(*Continued*)

TABLE 1.172 (*Continued*) Diffusion in Metallic Systems

Metal	Tracer	Crystalline Form	Purity (%)	Temperature Range (°C)	Activation Energy, Q (kcal/mol)	Frequency Factor, D_o (cm²/s)
	Sn^{113}	P	99.7	950–1600	31.6	3.8×10^{-4}
	Ti^{44}	P	99.95	900–1540	31.2	3.58×10^{-4}
	U^{235}	P	99.9	900–400	29.3	5.1×10^{-4}
	V^{48}	P	99.95	900–1545	32.2	3.1×10^{-4}
	W^{185}	P	99.94	900–1250	43.9	3.6×10^{-3}
	Zr^{95}	P	98.94	920–1500	35.4	4.7×10^{-3}
Tungsten	C^{14}	P	99.51	1200–1600	53.5	8.91×10^{-3}
	Fe^{59}	P		940–1240	66.0	1.4×10^{-2}
	Mo^{99}	P		1700–2100	101.0	0.3
	Nb^{95}	P	99.99	1305–2367	137.6	3.01
	Re^{186}	S		2100–2400	141.0	19.5
	Ta^{182}	P	99.99	1305–2375	139.9	3.05
	W^{185}	P	99.99	1800–2403	140.3	1.88
α–Uranium	U^{234}	P		580–650	40.0	2×10^{-3}
β–Uranium	Co^{60}	P	99.999	692–763	27.45	1.5×10^{-2}
	U^{235}	P		690–750	44.2	2.8×10^{-3}
γ-Uranium	Au^{195}	P	99.99	785–1007	30.4	4.86×10^{-3}
	Co^{60}	P	99.99	783–989	12.57	3.51×10^{-4}
	Cr^{51}	P	99.99	797–1037	24.46	5.37×10^{-3}
	Cu^{64}	P	99.99	787–1039	24.06	1.96×10^{-3}
	Fe^{55}	P	99.99	787–990	12.0	2.69×10^{-4}
	Mn^{54}	P	99.99	787–939	13.88	1.81×10^{-4}
	Nb^{95}	P	99.99	791–1102	39.65	4.87×10^{-2}
	Ni^{63}	P	99.99	787–1039	15.66	5.36×10^{-4}
	U^{233}	P	99.99	800–1070	28.5	2.33×10^{-3}
	Zr^{95}	P		800–1000	16.5	3.9×10^{-4}
Vanadium	C^{14}	P	99.7	845–1130	27.3	4.9×10^{-3}
	Cr^{51}	P	99.8	960–1200	64.6	9.54×10^{-3}
	Fe^{59}	P		960–1350	71.0	0.373
	P^{32}	P	99.8	1200–1450	49.8	2.45×10^{-2}
	S^{35}	P	99.8	1320–1520	34.0	3.1×10^{-2}
	V^{48}	S, P	99.99	880–1360	73.65	0.36
	V^{48}	S, P	99.99	1360–1830	94.14	214.0
Yttrium	Y^{90}	S⊥c		900–1300	67.1	5.2
	Y^{90}	S‖c		900–1300	60.3	0.82
Zinc	Ag^{110}	S⊥c	99.999	271–413	27.6	0.45
	Ag^{110}	S‖c	99.999	271–413	26.0	0.32
	Au^{198}	S⊥c	99.999	315–415	29.72	0.29
	Au^{198}	S‖c	99.999	315–415	29.73	0.97
	Cd^{115}	S⊥c	99.999	225–416	20.12	0.117
	Cd^{115}	S‖c	99.999	225–416	20.54	0.114

(*Continued*)

TABLE 1.172 (*Continued*) Diffusion in Metallic Systems

Metal	Tracer	Crystalline Form	Purity (%)	Temperature Range (°C)	Activation Energy, Q (kcal/mol)	Frequency Factor, D_o (cm²/s)
	Cu^{64}	S⊥c	99.999	338–415	~20	~2
	Cu^{64}	S‖c	99.999	338–415	29.53	2.22
	Ga^{72}	S⊥c		240–403	18.15	0.018
	Ga^{72}	S‖c		240–403	18.4	0.016
	Hg^{203}	S⊥c		260–413	20.18	0.073
	Hg^{203}	S‖c		260–413	19.70	0.056
	In^{114}	S⊥c		271–413	19.60	0.14
	In^{114}	S‖c		271–413	19.10	0.062
	Sn^{113}	S⊥c		298–400	18.4	0.13
	Sn^{113}	S‖c		298–400	19.4	0.15
	Zn^{65}	S⊥c	99.999	240–418	23.0	0.18
	Zn^{65}	S‖c	99.999	240–418	21.9	0.13
α-Zirconium	Cr^{51}	P	99.9	700–850	18.0	1.19×10^{-8}
	Fe^{55}	P		750–840	48.0	2.5×10^{-2}
	Mo^{99}	P		600–850	24.76	6.22×10^{-8}
	Nb^{95}	P	99.99	740–857	31.5	6.6×10^{-6}
	Sn^{113}	P		300–700	22.0	1.0×10^{-8}
	Ta^{182}	P	99.6	700–800	70.0	100
	V^{48}	P	99.99	600–850	22.9	1.12×10^{-8}
	Zr^{95}	P	99.95	750–850	45.5	5.6×10^{-4}
β-Zirconium	Be^{7}	P	99.7	915–1300	31.1	8.33×10^{-2}
	C^{14}	P	96.6	1100–1600	34.2	3.57×10^{-2}
	Ce^{141}	P		880–1600	41.4	3.16
	Co^{60}	P	99.99	920–1600	21.82	3.26×10^{-3}
	Cr^{51}	P	99.9	700–850	18.0	1.19×10^{-8}
	Fe^{55}	P		750–840	48.0	2.5×10^{-2}
	Mo^{99}	P		900–1635	35.2	1.99×10^{-6}
	Nb^{95}	P		1230–1635	36.6	7.8×10^{-4}
	P^{32}	P	99.94	950–1200	33.3	0.33
	Sn^{113}	P		300–700	22.0	1×10^{-8}
	Ta^{182}	P	99.6	900–1200	27.0	5.5×10^{-5}
	U^{235}	P		900–1065	30.5	5.7×10^{-4}
	V^{48}	P	99.99	870–1200	45.8	7.59×10^{-3}
	V^{48}	P	99.99	1200–1400	57.7	0.32
	W^{185}	P	99.7	900–1250	55.8	0.41
	Zr^{95}	P		1100–1500	30.1	2.4×10^{-4}

Source: Data from J. Askill, In: R. C. Weast (Ed.), *Handbook of Chemistry and Physics,* 55th Edn., CRC Press, Cleveland, 1974, F61.

[a] The diffusion coefficient D_T at a temperature T (K) is given by the following:

$$D_T = D_o e^{-Q/RT}$$

For activation energy in KJ/mol, multiply values in Kcal/mol by 4.184.

For frequency factor in m²/s, multiply values in cm²/s by 10^{-4}.

Abbreviations: P = polycrystalline; S = single crystal and ⊥c = perpendicular to c direction; ‖c = parallel to c direction.

TABLE 1.173 Diffusion of Metals into Metals

Diffusing Metal	Matrix Metal	Temperature (°C)	Diffusion Coefficient (cm²/h)
Ag	Al	466	$6.84–8.1 \times 10^{-7}$
		500	$7.2–3.96 \times 10^{-8}$
		573	1.26×10^{-5}
	Pb	220	5.40×10^{-5}
		250	1.08×10^{-4}
		285	3.29×10^{-4}
	Sn	500	1.73×10^{-1}
Al	Cu	500	6.12×10^{-9}
		850	7.92×10^{-6}
As	Si		$0.32\ e^{-82,000/RT}$
Au	Ag	456	1.76×10^{-9}
		491	$0.92–2.38 \times 10^{-13}$
		585	3.6×10^{-8}
		601	3.96×10^{-8}
		624	$2.5–5 \times 10^{-11}$
		717	$1.04–2.25 \times 10^{-9}$
		729	1.76×10^{-9}
		767	1.15×10^{-6}
		847	2.30×10^{-6}
		858	3.63×10^{-8}
		861	3.92×10^{-8}
		874	3.92×10^{-8}
		916	5.40×10^{-6}
		1040	1.17×10^{-6}
		1120	2.29×10^{-5}
		1189	5.42×10^{-6}
	Au	800	1.17×10^{-8}
		900	9×10^{-8}
		1020	5.4×10^{-7}
	Bi	500	1.88×10^{-1}
	Cu	970	5.04×10^{-6}
	Hg	11	3×10^{-2}
	Pb	100	8.28×10^{-8}
		150	1.80×10^{-4}
		200	3.10×10^{-4}
		240	1.58×10^{-3}
		300	5.40×10^{-3}
		500	1.33×10^{-1}
			$0.001\ e^{-25,000/RT}$
	Sn	500	1.94×10^{-1}

(*Continued*)

TABLE 1.173 (*Continued*) Diffusion of Metals into Metals

Diffusing Metal	Matrix Metal	Temperature (°C)	Diffusion Coefficient (cm^2/h)
B	Si		$10.5\ e^{-85,000/RT}$
Ba	Hg	7.8	2.17×10^{-2}
Bi	Si		$1030\ e^{-107,000/RT}$
	Pb	220	1.73×10^{-7}
		250	1.33×10^{-6}
		285	1.58×10^{-6}
C	W	1700	1.87×10^{-3}
	Fe	930	$7.51–9.18 \times 10^{-9}$
Ca	Hg	10.2	2.25×10^{-2}
Cd	Ag	650	9.36×10^{-7}
		800	4.68×10^{-6}
		900	2.23×10^{-5}
	Hg	8.7	6.05×10^{-2}
		15	6.51×10^{-2}
		20	5.47×10^{-2}
		99.1	1.23×10^{-1}
	Pb	200	4.59×10^{-7}
		252	3.10×10^{-6}
Cd, 1 atom%	Pb	167	1.66×10^{-7}
Ce	W	1727	3.42×10^{-6}
Cs	Hg	7.3	1.88×10^{-2}
	W	27	4.32×10^{-3}
		227	5.40×10^{-4}
		427	2.88×10^{-2}
		540	1.44×10^{-1}
Cu	Al	440	1.8×10^{-7}
		457	2.88×10^{-7}
		540	5.04×10^{-6}
		565	$4.68–5.00 \times 10^{-4}$
	Ag	650	1.04×10^{-6}
		760	1.30×10^{-6}
		895	3.38×10^{-6}
	Au	301	5.40×10^{-10}
		443	8.64×10^{-9}
		560	3.38×10^{-7}
		604	5.10×10^{-7}
		616	7.92×10^{-7}
		740	3.35×10^{-6}

(*Continued*)

TABLE 1.173 (*Continued*) Diffusion of Metals into Metals

Diffusing Metal	Matrix Metal	Temperature (°C)	Diffusion Coefficient (cm^2/h)
	Cu	650	1.15×10^{-5}
		750	2.34×10^{-8}
		830	1.44×10^{-7}
		850	9.36×10^{-7}
		950	2.30×10^{-6}
		1030	1.01×10^{-5}
	Ge	700–900	$1.01 \pm 0.1 \times 10^{-1}$
	Pt	1041	7.83×10^{-8}
		1213	5.04×10^{-7}
		1401	6.12×10^{-6}
Fe	Au	753	1.94×10^{-6}
		1003	2.70×10^{-5}
			$0.0062\ e^{-20,000/RT}$
Ga	Si		$3.6\ e^{-81,000/RT}$
Ge	Al	630	3.31×10^{-1}
	Au	529	1.84×10^{-1}
		563	2.80×10^{-1}
	Ge	766–928	$7.8\ e^{-68,509/RT}$
		1060–1200 K	$87\ e^{-73,000/RT}$
Hg	Cd	156	9.36×10^{-7}
		176	2.55×10^{-6}
		202	9×10^{-6}
	Pb	177	8.34×10^{-8}
		197	2.09×10^{-5}
In	Ag	650	1.04×10^{-6}
		800	6.84×10^{-6}
		895	4.68×10^{-5}
			$16.5\ e^{-90,000/RT}$
K	Hg	10.5	2.21×10^{-2}
	W	207	2.05×10^{-2}
		317	3.6×10^{-1}
		507	$1.1 \times 10^{+1}$
Li	Hg	8.2	2.75×10^{-2}

(*Continued*)

TABLE 1.173 (*Continued*) Diffusion of Metals into Metals

Diffusing Metal	Matrix Metal	Temperature (°C)	Diffusion Coefficient (cm²/h)
Mg	Al	365	3.96×10^{-8}
		395	$1.98–2.41 \times 10^{-7}$
		420	$2.38–2.74 \times 10^{-7}$
		440	1.19×10^{-7}
		447	9.36×10^{-7}
		450	6.84×10^{-6}
		500	$3.96–7.56 \times 10^{-6}$
		577	1.58×10^{-5}
	Pb	220	4.32×10^{-7}
Mn	Cu	400	7.2×10^{-10}
		850	4.68×10^{-7}
Mo	W	1533	9.36×10^{-10}
		1770	4.32×10^{-9}
		2010	7.92×10^{-8}
		2260	2.81×10^{-7}
Na	W	20	2.88×10^{-2}
		227	1.80
		417	9.72
		527	1.19×10^{-1}
Ni	Au	800	2.77×10^{-6}
		1003	2.48×10^{-5}
	Cu	550	2.56×10^{-9}
		950	7.56×10^{-7}
		1320	1.26×10^{-6}
	Pt	1043	1.81×10^{-8}
		1241	1.73×10^{-6}
		1401	5.40×10^{-6}
Ni, 1 atom %	Pb	285	8.34×10^{-7}
Ni, 3 atom %	Pb	252	1.25×10^{-7}
Pb	Cd	252	2.88×10^{-8}
	Pb	250	5.42×10^{-8}
		285	2.92×10^{-7}
	Sn	500	1.33×10^{-1}
Pb, 2 atom %	Hg	9.4	6.46×10^{-9}
		15.6	5.71×10^{-2}
		99.2	8×10^{-2}
Pd	Ag	444	4.68×10^{-9}
		571	1.33×10^{-7}
		642	4.32×10^{-7}
		917	4.32×10^{-6}

(*Continued*)

TABLE 1.173 (*Continued*) Diffusion of Metals into Metals

Diffusing Metal	Matrix Metal	Temperature (°C)	Diffusion Coefficient (cm²/h)
	Au	727	2.09×10^{-8}
		970	1.15×10^{-6}
	Cu	490	3.24×10^{-9}
		950	$9.0–10.44 \times 10^{-7}$
P	Au	470	4.59×10^{-11}
	Al	20	1.08×10^{-9}
		500	1.80×10^{-7}
	Bi	150	1.80×10^{-7}
		200	1.80×10^{-6}
	Pb	150	4.59×10^{-11}
		200	4.59×10^{-9}
		310	5.41×10^{-7}
Pt	Au	740	1.69×10^{-8}
		986	$6.12–10.08 \times 10^{-7}$
	Cu	490	2.01×10^{-9}
		960	$3.96–8.28 \times 10^{-7}$
	Pb	490	7.04×10^{-2}
Ra	Au	470	1.42×10^{-8}
	Pt	470	3.42×10^{-8}
Ra($\beta + \gamma$)	Ag	470	1.57×10^{-8}
Rb	Hg	7.3	1.92×10^{-9}
Rh	Pb	500	1.27×10^{-1}
Sb	Ag	650	1.37×10^{-6}
		760	5.40×10^{-6}
		895	1.55×10^{-5}
			$5.6\ e^{-91,000/RT}$
Si	Al	465	1.22×10^{-6}
		510	7.2×10^{-6}
		600	3.35×10^{-5}
		667	1.44×10^{-1}
		697	3.13×10^{-1}
	Fe + C[a]	1400–1600	$3.24–5.4 \times 10^{-2}$
Sn	Ag	650	2.23×10^{-6}
		895	2.63×10^{-6}
	Cu	400	1.69×10^{-9}
		650	2.48×10^{-7}
		850	1.40×10^{-5}

(*Continued*)

TABLE 1.173 (*Continued*) Diffusion of Metals into Metals

Diffusing Metal	Matrix Metal	Temperature (°C)	Diffusion Coefficient (cm^2/h)
	Hg	10.7	6.38×10^{-2}
	Pb	245	1.12×10^{-7}
		250	1.83×10^{-7}
		285	5.76×10^{-7}
Sr	Hg	9.4	1.96×10^{-2}
Th	Mo	1615	1.30×10^{-6}
		2000	3.60×10^{-3}
	Tl	285	8.76×10^{-7}
	W	1782	3.96×10^{-7}
		2027	4.03×10^{-6}
		2127	1.29×10^{-5}
		2227	2.45×10^{-5}
Th(β)	Pb	165	2.54×10^{-12}
		260	2.54×10^{-8}
		324	5.84×10^{-6}
Tl	Hg	11.5	3.63×10^{-2}
	Pb	220	1.01×10^{-7}
		250	7.92×10^{-7}
		270	3.96×10^{-7}
		285	1.12×10^{-6}
		315	2.09×10^{-6}
			$16.5\ e^{-85,000/RT}$
U	W	1727	4.68×10^{-8}
Y	W	1727	6.55×10^{-5}
Zn	Ag	750	1.66×10^{-5}
		850	4.37×10^{-5}
	Al	415	9×10^{-7}
		473	1.91×10^{-6}
		500	$7.2–13.68 \times 10^{-6}$
		555	1.8×10^{-5}
	Hg	11.5	9.09×10^{-2}
		15	8.72×10^{-2}
		99.2	1.20×10^{-1}
	Pb	285	5.84
Zr	W	1727	1.17×10^{-5}

Source: Data from R. Loebel, In: R. C. Weast (Ed.), *Handbook of Chemistry and Physics,* 51st Edn., Chemical Rubber Company, Cleveland, 1970, F-55.

[a] Saturated FeC alloy.

For diffusion coefficients in m^2/s, multiply values in cm^2/h by 2.778×10^{-8}.

TABLE 1.174 Standard Electromotive Force Potentials

Reaction	Reduction Potential E° (V)
$F_2 + 2H^+ + 2e^- = 2\ HF$	3.053
$F_2 + 2e^- = 2F^-$	2.866
$H_2N_2O_2 + 2H^+ + 2e^- = N_2 + 2H_2O$	2.65
$O(g) + 2H^+ + 2e^- = H_2O$	2.421
$FeO_4^{2-} + 8H^+ + 3e^- = Fe^{3+} + 4H_2O$	2.20
$F_2O + 2H^+ + 4e^- = H_2O + 2F^-$	2.153
$S_2O_8^{2-} + 2H^+ + 2e^- = 2HSO_4^-$	2.123
$O_3 + 2H^+ + 4e^- = O_2 + H_2O$	2.076
$OH + e^- = OH^-$	2.02
$S_2O_8^{2-} + 2e^- = 2SO_4^{2-}$	2.010
$Ag^{2+} + e^- = Ag^+$	1.980
$Co^{3+} + e^- = Co^{2+}(2\ mol/L\ H_2SO_4)$	1.83
$H_2O_2 + 2H^+ + 2e^- = 2H_2O$	1.776
$N_2O + 2H^+ + 2e^- = N_2 + H_2O$	1.766
$CeOH^{3+} + H^+ + e^- = Ce^{3+} + H_2O$	1.715
$Au^+ + e^- = Au$	1.692
$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- = PbSO_4 + 2H_2O$	1.6913
$MnO_4^- + 4H^+ + 3e^- = MnO_2 + 2H_2O$	1.679
$NiO_2 + 4H^+ + 2e^- = Ni^{2+} + 2H_2O$	1.678
$HClO_2 + 2H^+ + 2e^- = HClO + H_2O$	1.645
$HClO_2 + 3H^+ + 3e^- = 1/2\ Cl_2 + 2H_2O$	1.628
$HClO + H^+ + e^- = 1/2\ Cl_2 + H_2O$	1.611
$Ce^{4+} + e^- = Ce^{3+}$	1.61
$H_5IO_6 + H^+ + 2e^- = IO_3^- + 3H_2O$	1.601
$HBrO + H^+ + e^- = 1/2\ Br_2(l) + H_2O$	1.596
$Bi_2O_4 + 4H^+ + 2e^- = 2\ BiO^+ + 2H_2O$	1.593
$2NO + 2H^+ + 2e^- = N_2O + H_2O$	1.591
$HBrO + H^+ + e^- = 1/2\ Br_2(aq) + H_2O$	1.574
$HClO_2 + 3H^+ + 4e^- = Cl^- + H_2O$	1.570
$Mn^{3+} + e^- = Mn^{2+}$	1.5415
$MnO_4^- + 8H^+ + 5e^- = Mn^{2+} + 4H_2O$	1.507
$Au^{3+} + 3e^- = Au$	1.498
$HO_2 + H^+ + e^- = H_2O_2$	1.495
$HClO + H^+ + 2e^- = Cl^- + H_2O$	1.482
$BrO_3^- + 6H^+ + 5e^- = 1/2\ Br_2 + 3H_2O$	1.482
$ClO_3^- + 6H^+ + 5e^- = 1/2\ Cl_2 + 3H_2O$	1.47
$PbO_2 + 4H^+ + 2e^- = Pb^{2+} + 2H_2O$	1.455
$ClO_3^- + 6H^+ + 6e^- = Cl^- + H_2O$	1.451
$Au(OH)_3 + 3H^+ + 3e^- = Au^- + 3H_2O$	1.45
$2HIO + 2H^+ + 2e^- = I_2 + 2H_2O$	1.439

(*Continued*)

TABLE 1.174 (*Continued*) Standard Electromotive Force Potentials

Reaction	Reduction Potential E° (V)
$BrO_3^- + 6H^+ + 6e^- = Br^- + 3H_2O$	1.423
$2NH_3OH^+ + H^+ + 2e^- = N_2H_5 + +2H_2O$	1.42
$Au^{3+} + 2e^- = Au^+$	1.401
$ClO_4^- + 8H^+ + 7e^- = 1/2\ Cl_2 + 4H_2O$	1.39
$ClO_4^- + 8H^+ + 8e^- = Cl^- + 4H_2O$	1.389
$Cl_2(g) + 2e^- = 2Cl^-$	1.35827
$HCrO_4^- + 7H^+ + 3e^- = Cr^{3+} + 4H_2O$	1.350
$HBrO + H^+ + 2e^- = Br^- + H_2O$	1.331
$PuO_2(OH)_2 + H^+ + 3e^- = Pu(OH)_4$	1.325
$2HNO_2 + 4H^+ + 4e^- = NO_2 + 3H_2O$	1.297
$[PdCl_6]^{2-} + 2e^- = [PdCl_4]^{2-} + 2Cl^-$	1.288
$ClO_2 + H^+ + e^- = HClO_2$	1.277
$N_2H_5^+ + 3H^+ + 2e^- = 2NH_4^+$	1.275
$Tl^{3+} + 2e^- = Tl^+$	1.252
$O_3 + H_2O + 2e^- = O_2 + 2OH^-$	1.24
$Cr_2O_7^{2-} + 14H^+ + 3e^- = 2Cr^{3+} + 7H_2O$	1.232
$O_2 + 4H^+ + 4e^- = 2H_2O$	1.229
$MnO_2 + 4H^+ + 2e^- = Mn^{2+} + 2H_2O$	1.224
$ClO_3^- + 3H^+ + 2e^- = HClO_2 + H_2O$	1.214
$2IO_3^- + 12H^+ + 10e^- = I_2 + 6H_2O$	1.195
$ClO_4^- + 2H^+ + 2e^- = ClO_3^- + H_2O$	1.189
$Ir^{3+} + 3e^- = Ir$	1.156
$ClO_3^- + 2H^+ + e^- = ClO_2 + H_2O$	1.152
$SeO_4^{2-} + 4H^+ + 2e^- = H_2SeO_3 + H_2O$	1.151
$[Fe(pheneathroline)_3]^{3+} + e^- = [Fe(phen)_3]^{2+}$	1.147
$RuO_2 + 4H^+ + 2e^- = Ru^{2+} + 2H_2O$	1.120
$Pt^{2-} + 2e^- = Pt$	1.118
$Pu^{5+} + e^- = Pu^{4+}$	1.099
$Br_2(aq) + 2e^- = 2Br^-$	1.0873
$IO_3^- + 6H^+ + 6e^- = I^- + 3H_2O$	1.085
$Br_2(l) + 2e^- = 2Br^-$	1.066
$N_2O_4 + 2H^+ + 2e^- = 2HNO_2$	1.065
$PuO_2(OH)_2 + H^+ + e^- = PuO_2OH + H_2O$	1.062
$[Fe(phen)_3]^{3+} + e^- = [Fe(phen)_3]^{2+}(1\ mol/L\ H_2SO_4)$	1.06
$N_2O_4 + 4H^+ + 4e^- = 2NO + 2H_2O$	1.035
$H_6TeO_6 + 2H^+ + 2e^- = TeO_2 + 4H_2O$	1.02
$Pu^{4+} + e^- = Pu^{3+}$	1.006
$AuCl_4^- + 3e^- = Au + 4Cl^-$	1.002
$V(OH)_4^+ + 2H^+ + e^- = VO^{2+} + 3H_2O$	1.00

(*Continued*)

TABLE 1.174 (*Continued*) Standard Electromotive Force Potentials

Reaction	Reduction Potential E° (V)
$RuO_4 + e^- = RuO_4^-$	1.00
$VO_2 + +2H^+ + e^- = VO^{2+} + H_2O$	0.991
$HIO + H^+ + 2e^- = I^- + H_2O$	0.987
$HNO_2 + H^+ + e^- = NO + H_2O$	0.983
$AuBr_2^- + e^- = Au + 2Br^-$	0.959
$NO_3^- + 4H^+ + 3e^- = NO + 2H_2O$	0.957
$ClO_2(aq) + e^- = ClO_2^-$	0.954
$Pd^{2+} + 2e^- = Pd$	0.951
$NO_3^- + 3H^+ + 2e^- = HNO + H_2O$	0.934
$2Hg^{2+} + 2e^- = Hg_2^{2+}$	0.920
$HO_2^- + H_2O + 2e^- = 3OH^-$	0.878
$N_2O_4 + 2e^- = 2NO_2^-$	0.867
$[IrCl_6]^{2-} + e^- = [IrCl_6]^{3-}$	0.8665
$2HNO_2 + 4H^+ + 4e^- = H_2N_2O_2 + H_2O$	0.86
SiO_2(quartz) $+ 4H^+ + 4e^- = Si + 2H_2O$	0.857
$AuBr_4^- + 3e^- = Au + 4Br$	0.854
$Hg^{2+} + 2e^- = Hg$	0.851
$OsO_4 + 8H^+ + 8e^- = Os + 4H_2O$	0.85
$ClO^- + H_2O + 2e^- = Cl^- + 2OH^-$	0.841
$2NO_3^- + 4H^+ + 2e^- = N_2O_4 + 2H_2O$	0.803
$Ag^+ + e^- = Ag$	0.7996
$Hg_2^{2+} + 2e^- = Hg$	0.7973
$TcO_4^- + 4H^+ + 3e^- = TcO_2 + 2H_2O$	0.782
$AgF + e^- = Ag + F^-$	0.779
$Fe^{3+} + e^- = Fe^{2+}$	0.771
$[IrCl_6]^{3-} + 3e = Ir + 6Cl^-$	0.77
$(CNS)_2 + 2e^- = 2CNS^-$	0.77
$ReO_4^- + 2H^+ + e^- = ReO_3 + H_2O$	0.768
$BrO^- + H_2O + 2e^- = Br^- + 2OH^-$	0.761
$2NO + H_2O + 2e^- = N_2O + 2OH^-$	0.76
$ClO_2^- + 2H_2O + 4e^- = Cl^- + 4OH^-$	0.76
$Rh^{3+} + 3e^- = Rh$	0.758
$[PtCl_4]^{2-} + 2e^- = Pt + 4Cl^-$	0.755
$Ag_2O_3 + H_2O + 2e^- = 2AgO + 2OH^-$	0.739
$H_3IO_6 + 2e^- = IO_3^- + 3OH^-$	0.7
p-benzoquinone $+ 2H^+ + 2e^- =$ hydroquinone	0.6992
$O_2 + 2H^+ + 2e^- = H_2O_2$	0.695
$[PtCl_6]^{2-} + 2e^- = [PtCl_4]^{2-} + 2Cl^-$	0.68
Sb_2O_5(senarmontite) $+ 4H^+ + 4e^- = Sb_2O_3 + 2H_2O$	0.671

(*Continued*)

TABLE 1.174 (*Continued*) Standard Electromotive Force Potentials

Reaction	Reduction Potential E° (V)
$ClO_2^- + H_2O + 2e^- = ClO^- + 2OH^-$	0.66
$Ag_2SO_4 + 2e^- = 2Ag + SO_4^{2-}$	0.654
Sb_2O_5(valentinite) $+ 4H^+ + 4e^- = Sb_2O_3 + 2H_2O$	0.649
$Ag(ac) + e^- = Ag + (ac)^-$	0.643
$Hg_2HPO_4 + 2e^- = 2Hg + HPO_4^{2-}$	0.6359
$ClO_3^- + 3H_2O + 6e^- = Cl^- + 6OH^-$	0.62
$Hg_2SO_4 + 2e^- = 2Hg + SO_4^{2-}$	0.6125
$UO_2^+ + 4H^+ + e^- = U^{4+} + 2H_2O$	0.612
$BrO_3^- + 3H_2O + 6e^- = Br^- + 6OH^-$	0.61
$2AgO + H_2O + 2e^- = Ag_2O + 2OH^-$	0.607
$MnO_4^{2-} + 2H_2O + 2e^- = MnO_2 + 4OH^-$	0.60
$Rh^+ + e^- = Rh$	0.600
$Rh^{2+} + 2e^- = Rh$	0.600
$MnO_4^- + 2H_2O + 3e^- = MnO_2 + 4OH^-$	0.595
$TeO_2 + 4H^+ + 4e^- = Te + 2H_2O$	0.593
$[PdCl_4]^{2-} + 2e^- = Pd + 4Cl^-$	0.591
$RuO_4^- + e^- = RuO_4^{2-}$	0.59
$Sb_2O_5 + 6H^+ + 4e^- = 2SbO^+ + 3H_2O$	0.581
$Te^{4+} + 4e^- = Te$	0.568
$AgNO_2 + e^- = Ag + NO_2^-$	0.564
$S_2O_6^{2-} + 4H^+ + 2e^- = 2H_2SO_3$	0.564
$H_3AsO_4 + 2H^+ + 2e^- = HAsO_2 + 2H_2O$	0.560
$MnO_4^- + e^- = MnO_4^{2-}$	0.558
$AgBrO_3 + e^- = Ag + BrO_3^-$	0.546
$I_3^- + 2e^- = 3I^-$	0.536
$I_2 + 2e^- = 2I^-$	0.5355
$Cu^+ + e^- = Cu$	0.521
$Hg_2(ac)_2 + 2e^- = 2Hg + 2(ac)^-$	0.51163
$ReO_4^- + 4H^+ + 3e^- = ReO_2 + 2H_2O$	0.510
$NiO_2 + 2H_2O + 2e^- = Ni(OH)_2 + 2OH^-$	0.490
$IO^- + H_2O + 2e^- = I^- + 2OH^-$	0.485
$TeO_4^- + 8H^+ + 7e^- = Te + 4H_2O$	0.472
$Ag_2CO_3 + 2e^- = 2Ag + CO_3^{2-}$	0.47
$Ag_2WO_4 + 2e^- = 2Ag + WO_4^{2-}$	0.4660
$Ag_2C_2O_4 + 2e^- = 2Ag + C_2O_4^{2-}$	0.4647
$Ag_2MoO_4 + 2e^- = 2Ag + MoO_4^{2-}$	0.4573
$Ru^{2+} + 2e^- = Ru$	0.455
$H_2SO_3 + 4H^+ + 4e^- = S + 3H_2O$	0.449

(*Continued*)

TABLE 1.174 (*Continued*) Standard Electromotive Force Potentials

Reaction	Reduction Potential E° (V)
$Ag_2CrO_4 + 2e^- = 2Ag + CrO_4^{2-}$	0.4470
$[RhCl_6]^{3-} + 3e^- = Rh + 6Cl^-$	0.431
$AgOCN + e^- = Ag + OCN^-$	0.41
$O_2 + H_2O + 4e^- = 4OH^-$	0.401
$Tc^{2+} + 2e^- = Tc$	0.400
$(ferricinium)^+ + e^- = ferrocene$	0.400
$(CN)_2 + 2H^+ + 2e^- = 2HCN$	0.373
$ReO_4^- + 8H^+ + 7e^- = Re + 4H_2O$	0.368
$Ag_2SeO_3 + 2e^- = 2Ag + SeO_3^{2-}$	0.3629
$ClO_4^- + H_2O + 2e^- = ClO_3^- + 2OH^-$	0.36
$[Fe(CN)_6]^{3-} + e^- = [Fe(CN)_6]^{4-}$	0.358
$AgIO_3 + e^- = Ag + IO_3^-$	0.354
$Cu^{2+} + 2e^- = Cu$	0.3419
$VO^{2+} + 2H^+ + e^- = V^{3+} + H_2O$	0.337
Calomel electrode, 0.1 mol/L KCl	0.3337
$2HCNO + 2H^+ + 2e^- = (CN)_2 + 2H_2O$	0.330
$ClO_3^- + H_2O + 2e^- = ClO_2^- + 2OH^-$	0.33
$UO_2^{2+} + 4H^+ + 2e^- = U^{4+} + 2H_2O$	0.327
$BiO^+ + 2H^+ + 3e^- = Bi + H_2O$	0.320
$Re^{3+} + 3e^- = Re$	0.300
Calomel electrode, 1 mol/L KCl (NCE)	0.2801
Calomel electrode, molal KCl	0.2800
$Hg_2Cl_2 + 2e^- = 2Hg^+ + 2Cl^-$	0.26808
$IO_3^- + 3H_2O + 6e^- = I^- + 6OH^-$	0.26
$ReO_2 + 4H^+ + 4e^- = Re + 2H_2O$	0.2513
$Ru^{3+} + e^- = Ru^{2+}$	0.2487
$HAsO_2 + 3H^+ + 3e^- = As + 2H_2O$	0.248
$PbO_2 + H_2O + 2e^- = PbO + 2OH^-$	0.247
Calomel electrode, saturated KCl	0.2412
$Ge^{2+} + 2e^- = Ge$	0.24
Calomel electrode, saturated NaCl (SSCE)	0.2360
$As_2O_3 + 6H^+ + 6e^- = 2As + 3H_2O$	0.234
$AgCl + e^- = Ag + Cl^-$	0.22233
$SbO^+ + 2H^+ + 3e^- = Sb + H_2O$	0.212
$SO_4^{2-} + 4H^+ + 2e^- = H_2SO_3 + H_2O$	0.172
$Co(OH)_3 + e^- = Co(OH)_2 + OH^-$	0.17
$Bi(Cl)_4^- + 3e^- = Bi + 4Cl^-$	0.16
$BiOCl + 2H^+ + 3e^- = Bi + Cl^- + H_2O$	0.1583
$Cu^{2+} + e^- = Cu^+$	0.153

(*Continued*)

TABLE 1.174 (*Continued*) Standard Electromotive Force Potentials

Reaction	Reduction Potential E° (V)
$Sb_2O_3 + 6H^+ + 6e^- = 2Sb + 3H_2O$	0.152
$Sn^{4+} + 2e^- = Sn^{2+}$	0.151
$2NO_2^- + 3H_2O + 4e^- = N_2O + 6OH^-$	0.15
$Mn(OH)_3 + e^- = Mn(OH)_2 + OH^-$	0.15
$IO_3^- + 2H_2O + 4e^- = IO^- + 4OH^-$	0.15
$Ag_4[Fe(CN)_6] + 4e^- = 4Ag + [Fe(CN)_6]^{4-}$	0.1478
$Np^{4+} + e^- = Np^{3+}$	0.147
$S + 2H^+ + 2e^- = H_2S(aq)$	0.142
$Pt(OH)_2 + 2e^- = Pt + 2OH^-$	0.14
$Hg_2Br_2 + 2e^- = 2Hg + 2Br^-$	0.13923
$Ge^{4+} + 4e^- = Ge$	0.124
$Hg_2O + H_2O + 2e^- = 2Hg + 2OH^-$	0.123
$[Co(NH_3)_6]^{3+} + e^- = [Co(NH_3)_6]^{2+}$	0.108
$2NO + 2e^- = N_2O_2^{2-}$	0.10
$Ir_2O_3 + 3H_2O + 6e^- = 2Ir + 6OH^-$	0.098
$HgO + H_2O + 2e^- = Hg + 2OH^-$	0.0977
$N_2 + 2H_2O + 6H^+ + 6e^- = 2NH_4OH$	0.092
$AgSCN + e^- = Ag + SCN^-$	0.08951
$S_4O_6^{2-} + 2e^- = 2S_2O_3^{2-}$	0.08
$AgBr + e^- = Ag + Br^-$	0.07133
$Pd(OH)_2 + 2e^- = Pd + 2OH^-$	0.07
$UO_2^{2+} + e^- = UO_2^+$	0.062
$SeO_4^{2-} + H_2O + 2e^- = SeO_3^{2-} + 2OH^-$	0.05
$Tl_2O_3 + 3H_2O + 4e^- = 2Tl^{2+} + 6OH^-$	0.02
$NO_3^- + H_2O + 2e^- = NO_2^- + 2OH^-$	0.01
$Ge^{4+} + 2e^- = Ge^{2+}$	0.00
$CuI_2^- + e^- = Cu + 2I^-$	0.00
$2H^+ + 2e^- = H_2$	0.00000
$AgCN + e^- = Ag + CN^-$	−0.017
$2WO_3 + 2H^+ + 2e^- = W_2O_5 + H_2O$	−0.029
$W_2O_5 + 2H^+ + 2e^- = 2WO_2 + H_2O$	−0.031
$D^+ + e^- = 1/2\ D_2$	−0.034
$Ag_2S + 2H^+ + 2e^- = 2Ag + H_2S$	−0.0366
$Fe^{3+} + 3e^- = Fe$	−0.037
$Hg_2I_2 + 2e^- = 2Hg + 2I^-$	−0.0405
$2D^+ + 2e^- = D_2$	−0.044
$Tl(OH)_3 + 2e^- = TlOH + 2OH^-$	−0.05
$TiOH^{3+} + H^+ + e^- = Ti^{3+} + H_2O$	−0.055
$2H_2SO_3 + H^+ + 2e^- = HS_2O_4^- + 2H_2O$	−0.056
$P(white) + 3H^+ + 3e^- = PH_3(g)$	−0.063

(*Continued*)

TABLE 1.174 (*Continued*) Standard Electromotive Force Potentials

Reaction	Reduction Potential E° (V)
$O_2^- + H_2O + 2e^- = HO_2^- + OH^-$	–0.076
$2Cu(OH)_2 + 2e^- = Cu_2O + 2OH^- + H_2O$	–0.080
$WO_3 + 6H^+ + 6e^- = W + 3H_2O$	–0.090
$P(red) + 3H^+ + 3e^- = PH_3(g)$	–0.111
$GeO_2 + 2H^+ + 2e^- = GeO + H_2O$	–0.118
$WO_2 + 4H^+ + 4e^- = W + 2H_2O$	–0.119
$Pb^{2+} + 2e^- = Pb(Hg)$	–0.1205
$Pb^{2+} + 2e^- = Pb$	–0.1262
$CrO_4^{2-} + 4H_2O + 3e^- = Cr(OH)_3 + 5OH^-$	–0.13
$Sn^{2+} + 2e^- = Sn$	–0.1375
$In^+ + e^- = In$	–0.14
$O_2 + 2H_2O + 2e^- = H_2O_2 + 2OH^-$	–0.146
$AgI + e^- = Ag + I^-$	–0.15224
$2NO_2^- + 2H_2O + 4e^- = N_2O_2^{2-} + 4OH^-$	–0.18
$H_2GeO_3 + 4H^+ + 4e^- = Ge + 3H_2O$	–0.182
$CO_2 + 2H^+ + 2e^- = HCOOH$	–0.199
$Mo^{3+} + 3e^- = Mo$	–0.200
$2SO_2^{2-} + 4H^+ + 2e^- = S_2O_6^{2-} + H_2O$	–0.22
$Cu(OH)_2 + 2e^- = Cu + 2OH^-$	–0.222
$CdSO_4 + 2e^- = Cd + SO_4^{2-}$	–0.246
$V(OH)_4^+ + 4H^+ + 5e^- = V + 4H_2O$	–0.254
$V^{3+} + e^- = V^{2+}$	–0.255
$Ni^{2+} + 2e^- = Ni$	–0.257
$PbCl_2 + 2e^- = Pb + 2Cl^-$	–0.2675
$H_3PO_4 + 2H^+ + 2e^- = H_3PO_3 + H_2O$	–0.276
$Co^{2+} + 2e^- = Co$	–0.28
$PbBr_2 + 2e^- = Pb + 2Br^-$	–0.284
$Tl^+ + e^- = Tl(Hg)$	–0.3338
$Tl^+ + e^- = Tl$	–0.336
$In^{3+} + 3e^- = In$	–0.3382
$TlOH + e^- = Tl + OH^-$	–0.34
$PbF_2 + 2e^- = Pb + 2F^-$	–0.3444
$PbSO_4 + 2e^- = Pb(Hg) + SO_4^{2-}$	–0.3505
$Cd^{2+} + 2e^- = Cd(Hg)$	–0.3521
$PbSO_4 + 2e^- = Pb + SO_4^{2-}$	–0.3588
$Cu_2O + H_2O + 2e^- = 2Cu + 2OH^-$	–0.360
$Eu^{3+} + e^- = Eu^{2+}$	–0.36
$PbI_2 + 2e^- = Pb + 2I^-$	–0.365
$SeO_3^{2-} + 3H_2O + 4e^- = Se + 6OH^-$	–0.366

(*Continued*)

TABLE 1.174 (*Continued*) Standard Electromotive Force Potentials

Reaction	Reduction Potential E° (V)
$Ti^{3+} + e^- = Ti^{2+}$	−0.368
$Se + 2H^+ + 2e^- = H_2Se(aq)$	−0.399
$In^{2+} + e^- = In^+$	−0.40
$Cd^{2+} + e^- = Cd$	−0.4030
$Cr^{3+} + e^- = Cr^{2+}$	−0.407
$2S + 2e^- = S_2^{2-}$	−0.42836
$Tl_2SO_4 + 2e^- = Tl + SO_4^{2-}$	−0.4360
$In^{3+} + 2e^- = In^+$	−0.443
$Fe^{2+} + 2e^- = Fe$	−0.447
$H_3PO_3 + 3H^+ + 3e^- = P + 3H_2O$	−0.454
$Bi_2O_3 + 3H_2O + 6e^- = 2Bi + 6OH^-$	−0.46
$NO_2^- + H_2O + e^- = NO + 2OH^-$	−0.46
$PbHPO_4 + 2e^- = Pb + HPO_4^{2-}$	−0.465
$S + 2e^- = S^{2-}$	−0.47627
$S + H_2O + 2e^- = HS^- + OH^-$	−0.478
$In^{3+} + e^- = In^{2+}$	−0.49
$H_3PO_3 + 2H^+ + 2e^- = H_3PO_2 + H_2O$	−0.499
$TiO_2 + 4H^+ + 2e^- = Ti^{2+} + 2H_2O$	−0.502
$H_3PO_2 + H^+ + e^- = P + 2H_2O$	−0.508
$Sb + 3H^+ + 3e^- = SbH_3$	−0.510
$HPbO_2^- + H_2O + 2e^- = Pb + 3OH^-$	−0.537
$TlCl + e^- = Tl + Cl^-$	−0.5568
$Ga^{3+} + 3e^- = Ga$	−0.560
$Fe(OH)_3 + e^- = Fe(OH)_2 + OH^-$	−0.56
$TeO_3^{2-} + 3H_2O + 4e^- = Te + 6OH^-$	−0.57
$2SO_3^- + 3H_2O + 4e^- = S_2O_3^- + 6OH^-$	−0.571
$PbO + H_2O + 2e^- = Pb + 2OH^-$	−0.580
$ReO_2^- + 4H_2O + 7e^- = Re + 8OH^-$	−0.584
$SbO_3^- + H_2O + 2e^- = SbO_2^- + 2OH^-$	−0.59
$U^{4+} + e^- = U^{3+}$	−0.607
$As + 3H^+ + 3e^- = AsH_3$	−0.608
$Nb_2O_5 + 10H^+ + 3e^- = 2Nb + 5H_2O$	−0.644
$TlBr + e^- = Tl + Br^-$	−0.658
$SbO_2^- + 2H_2O + 3e^- = Sb + 4OH^-$	−0.66
$AsO_2^- + 2H_2O + 3e^- = As + 4OH^-$	−0.68
$Ag_2S + 2e^- = 2Ag + S^{2-}$	−0.691
$AsO_4^{3-} + 2H_2O + 2e^- = AsO_2^- + 4OH^-$	−0.71
$Ni(OH)_2 + 2e^- = Ni + 2OH^-$	−0.72

(*Continued*)

TABLE 1.174 (*Continued*) Standard Electromotive Force Potentials

Reaction	Reduction Potential E° (V)
$Co(OH)_2 + 2e^- = Co + 2OH^-$	–0.73
$H_2SeO_3 + 4H^+ + 4e^- = Se + 3H_2O$	–0.74
$Cr^{3+} + 3e^- = Cr$	–0.744
$Ta_2O_5 + 10H^+ + 4e^- = 2Ta + 5H_2O$	–0.75
$TlI + e^- = Tl + I^-$	–0.752
$Zn^{2+} + 2e^- = Zn$	–0.7618
$Zn^{2+} + 2e^- = Zn(Hg)$	–0.7628
$Te + 2H^+ + 2e^- = H_2Te$	–0.793
$ZnSO_4 7H_2O + 2e^- = Zn(Hg) + SO_4^{2-}(Sat'dZnSO_4)$	–0.7993
$Cd(OH)_2 + 2e^- = Cd(Hg) + 2OH^-$	–0.809
$2H_2O + 2e^- = H_2 + 2OH^-$	–0.8277
$2NO_3^- + 2H_2O + 2e^- = N_2O_4 + 4OH^-$	–0.85
$H_3BO_3 + 3H^+ + 3e^- = B + 3H_2O$	–0.8698
$P + 3H_2O + 3e^- = PH_3(g) + 3OH^-$	–0.87
$HSnO_2^- + H_2O + 3e^- = Sn + 3OH^-$	–0.909
$Cr^{2+} + 2e^- = Cr$	–0.913
$Se + 2e^- = Se^{2-}$	–0.924
$SO_4^{2-} + H_2O + 2e^- = SO_3^{2-} + 2OH^-$	–0.93
$Sn(OH)_6^{2-} + 2e^- = HSnO_2^- + 3OH^- + H_2O$	–0.93
$NpO_2 + H_2O + H^+ + e^- = Np(OH)_3$	–0.962
$PO_4^{3-} + 2H_2O + 2e^- = HPO_3^{2-} + 3OH^-$	–1.05
$Nb^{3+} + 3e^- = Nb$	–1.099
$2SO_3^{2-} + 2H_2O + 2e^- = S_2O_4^{2-} + 4OH^-$	–1.12
$Te + 2e^- = Te^{2-}$	–1.143
$V^{2+} + 2e^- = V$	–1.175
$Mn^{2+} + 2e^- = Mn$	–1.185
$CrO_2^- + 2H_2O + 3e^- = Cr + 4OH^-$	–1.2
$ZnO_2^- + 2H_2O + 2e^- = Zn + 4OH^-$	–1.215
$H_2GaO_3^- + H_2O + 3e^- = Ga + 4OH^-$	–1.219
$H_2BO_3^- + 5H_2O + 8e^- = BH_4^- + 8OH^-$	–1.24
$SiF_6^{2-} + 4e^- = Si + 6F^-$	–1.24
$Ce^{3+} + 3e^- = Ce(Hg)$	–1.4373
$UO_2^{2+} + 4H^+ + 6e^- = U + 2H_2O$	–1.444
$Cr(OH)_3 + 3e^- = Cr + 3OH^-$	–1.48
$HfO_2 + 4H^+ + 4e^- = Hf + 2H_2O$	–1.505
$ZrO_2 + 4H^+ + 4e^- = Zr + 2H_2O$	–1.553
$Mn(OH)_2 + 2e^- = Mn + 2OH^-$	–1.56
$Ba^{2+} + 2e^- = Ba(Hg)$	–1.570
$Ti^{2+} + 2e^- = Ti$	–1.63

(*Continued*)

TABLE 1.174 (*Continued*) Standard Electromotive Force Potentials

Reaction	Reduction Potential E° (V)
$HPO_3^{2-} + 2H_2O + 2e^- = H_2PO_2^- + 3OH^-$	–1.65
$Al^{3+} + 3e^- = Al$	–1.662
$SiO_3^- + H_2O + 4e^- = Si + 6OH^-$	–1.697
$HPO_3^{2-} + 2H_2O + 3e^- = P + 5OH^-$	–1.71
$HfO^{2+} + 2H^+ + 4e^- = Hf + H_2O$	–1.724
$ThO_2 + 4H^+ + 4e^- = Th + 2H_2O$	–1.789
$H_2BO_3^- + H_2O + 3e^- = B + 4OH^-$	–1.79
$Sr^{2+} + 2e^- = Sr(Hg)$	–1.793
$U^{3+} + 3e^- = U$	–1.798
$H_2PO_2^- + e^- = P + 2OH^-$	–1.82
$Be^{2+} + 2e^- = Be$	–1.847
$Np^{3+} + 3e^- = Np$	–1.856
$Th^{4+} + 4e^- = Th$	–1.899
$Pu^{3+} + 3e^- = Pu$	–2.031
$AlF_6^{3-} + 3e^- = Al + 6F^-$	–2.069
$Sc^{3+} + 3e^- = Sc$	–2.077
$H_2 + 2e^- = 2H^-$	–2.23
$H_2AlO_3^- + H_2O + 3e^- = Al + 4OH^-$	–2.33
$ZrO(OH)_2 + H_2O + 4e^- = Zr + 4OH^-$	–2.36
$Mg^{2+} + 2e^- = Mg$	–2.372
$Y^{3+} + 3e^- = Y$	–2.372
$Eu^{3+} + 3e^- = Eu$	–2.407
$Nd^{3+} + 3e^- = Nd$	–2.431
$Th(OH)_4 + 4e^- = Th + 4OH^-$	–2.48
$Ce^{3+} + 3e^- = Ce$	–2.483
$HfO(OH)_2 + H_2O + 4e^- = Hf + 4OH^-$	–2.50
$La^{3+} + 3e^- = La$	–2.522
$Be_2O_3^{2-} + 3H_2O + 4e^- = 2Be + 6OH^-$	–2.63
$Mg(OH)_2 + 2e^- = Mg + 2OH^-$	–2.690
$Mg^+ + e^- = Mg$	–2.70
$Na^+ + e^- = Na$	–2.71
$Ca^{2+} + 2e^- = Ca$	–2.868
$Sr(OH)_2 + 2e^- = Sr + 2OH^-$	–2.88
$Sr^{2+} + 2e^- = Sr$	–2.89
$La(OH)_3 + 3e^- = La + 3OH^-$	–2.90
$Ba^{2+} + 2e^- = Ba$	–2.912
$Cs^+ + e^- = Cs$	–2.92
$K^+ + e^- = K$	–2.931
$Rb^+ + e^- = Rb$	–2.98
$Ba(OH)_3 + 2e^- = Ba + 2OH^-$	–2.99

(*Continued*)

TABLE 1.174 (*Continued*) Standard Electromotive Force Potentials

Reaction	Reduction Potential E° (V)
$Ca(OH)_3 + 2e^- = Ca + 2OH^-$	−3.02
$Li^+ + e^- = Li$	−3.0401
$3N_2 + 2H^+ + 2e^- = 2NH_3$	−3.09
$Eu^{2+} + 2e^- = Eu$	−3.395
$Ca^+ + e^- = Ca$	−3.80
$Sr^+ + e^- = Sr$	−4.10

Source: Data compiled by J. S. Park from P. Vanysek (Ed.), *Handbook of Chemistry and Physics*, 69th Edn., CRC Press, Boca Raton, FL, 1988.

TABLE 1.175 Galvanic Series of Metals

Metal	Potential, volts (V)
	Anodic or corroded end
Lithium	−3.04
Rubidium	−2.93
Potassium	−2.92
Barium	−2.90
Strontium	−2.89
Calcium	−2.8
Sodium	−2.71
Magnesium	−2.37
Beryllium	−1.7
Aluminum	−1.7
Manganese	−1.04
Zinc	−0.76
Chromium	−0.6
Cadmium	−0.4
Titanium	−0.33
Cobalt	−0.28
Nickel	−0.23
Tin	−0.14
Lead	−0.126
Hydrogen	0.00
Copper	0.52
Silver	0.80
Mercury	0.85
Palladium	1.0
Platinum	1.2
Gold	1.5
	Cathodic or noble metal end

Source: Data compiled by J. S. Park from R. E. Bolz and G. L. Tuve (Eds.), *CRC Handbook of Tables for Applied Engineering Science,* Second Edn., CRC Press, Boca Raton, FL, 1973.

TABLE 1.176 Galvanic Series of Metals in Sea Water

	Metal
Active end (–)	Magnesium
	Magnesium alloys
	Zinc
	Galvanized steel
	Aluminum 1100
	Aluminum 6053
	Alcad
	Cadmium
	Aluminum 2024 (4.5 Cu, 1.5 Mg, 0.6 Mn)
	Mild steel
	Wrought iron
	Cast iron
	13% Chromium stainless steel
	Type 410 (active) 18–8 stainless steel
	Type 304 (active) 18–12–3 stainless steel
	Type 316 (Active)
	Lead–tin solders
	Lead
	Tin
	Muntz metal
	Manganese bronze
	Naval brass
	Nickel (active)
	76 Ni–16 Cr–7 Fe alloy (active)
	60 Ni–30 Mo–6 Fe–1 Mn
	Yellow brass
	Admiralty brass
	Aluminum brass
	Red brass
	Copper
	Silicon bronze
	70:30 Cupro nickel
	G-Bronze
	M-Bronze
	Silver solder
	Nickel (passive)
	76 Ni–16 Cr–7 Fe alloy (passive)
	67 Ni–33 Cu alloy (Monel)
	13% Chromium stainless steel
	Type 410 (passive)

(*Continued*)

TABLE 1.176 (*Continued*) Galvanic Series of Metals in Sea Water

	Metal
	Titanium
	18–8 Stainless steel
	Type 304 (passive)
	18–12–3 stainless steel
	Type 316 (passive)
	Silver
	Graphite
	Gold
Noble or passive end (+)	Platinum

Source: Data compiled by J. S. Park from Standard Guide for Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance, G 82, *Annual Book of ASTM Standards*, American Society for Testing and Materials, 1989.

TABLE 1.177 Corrosion Rate of Metals in Acidic Solutions

	Corrosive Environment		
Metal	Sulfuric, 5% (Nonoxidizing)	Acetic, 5% (Nonoxidizing)	Nitric, 5% (Oxidizing)
Aluminum	8–100	0.5–5	15–80
Copper alloys	2–50[a]	2–15[a]	150–1500
Gold	<0.1	<0.1	<0.1
Iron	15–400[a]	10–400	1000–10000
Lead	0–2	10–150[a]	100–6000
Molybdenum	0–0.2	<0.1	High
Nickel alloys	2–35[a]	2–10[a]	0.1–1500
Platinum	<0.1	<0.1	<0.1
Silicon iron	0–5	0–0.2	0–20
Silver	0–1	<0.1	High
Stainless steel	0–100[b]	0–0.5	0–2
Tantalum	<0.1	<0.1	<0.1
Tin	2–500[a]	2–500[a]	100–400
Titanium	10–100	<0.1	0.1–1
Zinc	High	600–800	High
Zirconium	<0.5	<0.1	<0.1

Source: Data compiled by J. S. Park from R.E. Bolz and G.L. Tuve, *CRC Handbook of Tables for Applied Engineering Science*, 2nd Edn., CRC Press, Inc., Boca Raton, FL, 1973.

Note: Corrosion rate ranges are expressed in mils penetration per year (1 mil = 0.001 in = 25.4 μm).

The corrosion-rate ranges for the solutions are based on temperature up to 100°C.

[a] Aeration leads to the higher rates in the range.

[b] Aeration leads to passivity, scarcity of dissolved air to activity.

TABLE 1.178 Corrosion Rate of Metals in Neutral and Alkaline Solutions

	Corrosive Environment		
Metal	Sodium Hydroxide, 5%	Fresh Water	Sea Water
Aluminum	13,000	0.1	1–50
Copper alloys	2–5	0–1	0.2–15[a]
Gold	<0.1	<0.1	<0.1
Iron	0–0.2	0.1–10[a]	0.1–10[a]
Lead	5–500[a]	0.1–2	0.2–15
Molybdenum	<0.1	<0.1	<0.1
Nickel alloys	0–0.2	0–0.2	0–1
Platinum	<0.1	<0.1	<0.1
Silicon iron	0–10	0–0.2	0–3
Silver	<0.1	<0.1	<0.1
Stainless steel	0–0.2	0–0.2	0–200[b]
Tantalum	<1	<0.1	<0.1
Tin	5–20	0–0.5	0.1
Titanium	<0.2	<0.1	<0.1
Zinc	15–200	0.5–10	0.5–10[a]
Zirconium	<0.1	<0.1	<0.1

Source: Data compiled by J. S. Park from R. E. Bolz and G. L. Tuve, *CRC Handbook of Tables for Applied Engineering Science,* 2nd Edn., CRC Press, Inc., Boca Raton, FL, 1973.

Note: Corrosion rate ranges are expressed in mils penetration per year (1 mil = 0.001 in = 25.4 μm).

The corrosion-rate ranges for the solutions are based on temperature up to 100°C.

[a] Aeration leads to the higher rates in the range.

[b] Aeration leads to passivity, scarcity of dissolved air to activity.

TABLE 1.179 Corrosion Rate of Metals in Air

Metal	Normal Outdoor Air (Urban Exposure)
Aluminum	0–0.5
Copper alloys	0–0.2
Gold	<0.1
Iron	1–8
Lead	0–0.2
Molybdenum	<0.1
Nickel alloys	0–0.2
Platinum	<0.1
Silicon iron	0–0.2
Silver	<0.1
Stainless steel	0–0.2
Tantalum	<0.1
Tin	0–0.2
Titanium	<0.1
Zinc	0–0.5
Zirconium	<0.1

Source: Data compiled by J. S. Park from R. E. Bolz and G. L. Tuve, *CRC Handbook of Tables for Applied Engineering Science,* 2nd Edn., CRC Press, Inc., Boca Raton, FL, 1973.

Note: Corrosion rate ranges are expressed in mils penetration per year (1 mil = 0.001 in = 25.4 μm).

TABLE 1.180 Corrosion Rates of 1020 Steel at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	<0.05	<0.002
Acetic acid (aerated)	>0.05	>0.05
Acetic acid (air free)	>0.05	>0.05
Acetic anhydride	–	>0.05
Acetoacetic acid	>0.05	>0.05
Acetone	<0.05	<0.002
Acetylene	–	<0.002
Acrolein	<0.02	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.02	<0.002
Alcohol (methyl)	<0.02	<0.002
Alcohol (allyl)	–	<0.002
Alcohol (amyl)	–	<0.02
Alcohol (benzyl)	–	<0.002
Alcohol (butyl)	–	<0.002
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.002
Allylamine	<0.02 (30%)	<0.02

(*Continued*)

TABLE 1.180 (*Continued*) Corrosion Rates of 1020 Steel at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Allyl chloride	–	<0.002
Allyl sulfide	–	<0.02
Aluminum acetate	>0.05	–
Aluminum chloride	>0.05	<0.002
Aluminum fluoride	<0.02	–
Aluminum fluorosilicate	–	>0.05
Aluminum formate	<0.05	>0.05
Aluminum hydroxide	<0.02	–
Aluminum nitrate	>0.05	–
Aluminum potassium sulfate	>0.05	–
Aluminum sulfate	>0.05	–
Ammonia	<0.002	<0.002
Ammonium acetate	–	<0.002
Ammonium bicarbonate	<0.02	<0.002
Ammonium bromide	>0.05	>0.05
Ammonium carbonate	<0.02	<0.002
Ammonium chloride	<0.05	<0.02
Ammonium citrate	>0.05	<0.002
Ammonium nitrate	<0.002	<0.02
Ammonium sulfate	<0.02	–
Ammonium sulfite	>0.05	–
Ammonium thiocyanate	<0.02	–
Amyl acetate	<0.002	<0.02
Amyl chloride	>0.05	<0.02
Aniline	–	<0.002
Aniline hydrochloride	>0.05	>0.05
Anthracine	–	<0.02
Antimony trichloride	>0.05	<0.05
Barium carbonate	<0.02	<0.02
Barium chloride	<0.02	<0.002
Barium hydroxide	–	<0.02
Barium nitrate	<0.02	<0.02
Barium oxide	–	<0.002
Barium peroxide	<0.05	<0.002
Benzaldehyde	>0.05	<0.002
Benzene	–	<0.02
Benzoic acid	>0.05	>0.05
Boric acid	<0.05	–
Bromic acid	>0.05	>0.05
Bromine (dry)	–	<0.05
Bromine (wet)	–	>0.05
Butyric acid	<0.05	>0.05
Cadmium chloride	>0.05	<0.002

(*Continued*)

TABLE 1.180 (*Continued*) Corrosion Rates of 1020 Steel at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Cadmium sulfate	<0.02	<0.02
Calcium acetate	<0.02	<0.05
Calcium bicarbonate	<0.02	<0.02
Calcium bromide	–	<0.05
Calcium chlorate	<0.002	<0.02
Calcium chloride	<0.002	<0.002
Calcium hydroxide	<0.02	<0.02
Calcium hypochlorite	<0.05	<0.02
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	–	<0.002
Carbon acid (air free)	<0.02	<0.02
Chloroacetic acid	>0.05	>0.05
Chlorine gas	>0.05	<0.02
Chlorine liquid	–	<0.02
Chloroform (dry)	–	<0.002
Chromic acid	>0.05	<0.002
Chromic hydroxide	–	<0.02
Chromic sulfates	>0.05	>0.05
Citric acid	>0.05	<0.002
Copper nitrate	>0.05	–
Copper sulfate	>0.05	–
Diethylene glycol	<0.002 (60%)	<0.002
Ethyl chloride	>0.05 (90%)	<0.002
Ethylene glycol	<0.02	<0.002
Ethylene oxide	–	<0.002
Fatty acids	–	>0.05
Ferric chloride	>0.05	<0.02
Ferric nitrate	>0.05	–
Ferrous chloride	>0.05	–
Ferrous sulfate	>0.05	–
Fluorine	–	<0.002
Formaldehyde	<0.05 (40%)	<0.002
Formic acid	>0.05	>0.05
Furfural	<0.02 (30%)	<0.02
Hydrazine	>0.05	>0.05
Hydrobromic acid	>0.05	<0.02
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	>0.05	–
Hydrocyanic acid	–	<0.002
Hydrofluoric acid (aerated)	>0.05	<0.02
Hydrofluoric acid (air free)	>0.05	<0.05
Hydrogen chloride	>0.05 (90%)	<0.002

(*Continued*)

TABLE 1.180 (*Continued*) Corrosion Rates of 1020 Steel at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Hydrogen fluoride	–	<0.002
Hydrogen iodide	<0.05 (1%)	<0.02
Hydrogen peroxide	>0.05 (20%)	–
Hydrogen sulfide	<0.02	<0.02
Lactic acid	>0.05	>0.05
Lead acetate	>0.05 (20%)	<0.002
Lead chromate	–	<0.02
Lead nitrate	>0.05	<0.02
Lead sulfate	–	<0.02
Lithium chloride	<0.02 (30%)	<0.002
Lithium hydroxide	<0.02	<0.002
Magnesium chloride	<0.02	<0.002
Magnesium hydroxide	<0.02	<0.002
Magnesium sulfate	<0.02	<0.02
Maleic acid	>0.05	<0.002
Malic acid	>0.05	–
Manganous chloride	>0.05 (40%)	–
Mercuric chloride	>0.05	–
Mercurous nitrate	–	<0.02
Methallyl-amine	<0.02	<0.02
Methanol	<0.02	<0.002
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylamine	<0.02	<0.02
Methylene chloride	–	<0.02
Monochloroacetic acid	>0.05	<0.002
Monorthanolamine	<0.02	<0.02
Monoethalamine	<0.02	<0.02
Monoethylamine	<0.02	<0.02
Monosodium phosphate	>0.05	–
Nickel chloride	>0.05	–
Nickel nitrate	<0.02	–
Nickel sulfate	>0.05	–
Nitric acid	>0.05	>0.05
Nitric acid (red fuming)	–	<0.05
Nitric + hydrochloric acid	–	>0.05
Nitric + hydrofluoric acid	–	>0.05
Nitric + sulfuric acid	–	>0.05
Nitrobenzene	–	<0.002
Nitrocellulose	–	<0.02
Nitroglycerine	–	<0.05
Nitrotoluene	–	<0.02
Nitrous acid	–	>0.05
Oleic acid	–	<0 .02

(*Continued*)

TABLE 1.180 (*Continued*) Corrosion Rates of 1020 Steel at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Oxalic acid	>0.05	>0.05
Phenol	–	<0.002
Phosphoric acid (aerated)	>0.05	>0.05
Phosphoric acid (air free)	>0.05	>0.05
Picric acid	>0.05	>0.05
Potassium bicarbonate	<0.02	<0.002
Potassium bromide	<0.05	>0.05
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	<0.002
Potassium chromate	<0.02	–
Potassium cyanide	<0.02	<0.002
Potassium dichromate	<0.02	–
Potassium ferricyanide	<0.02	<0.02
Potassium ferrocyanide	>0.05	–
Potassium hydroxide	<0.02	<0.002
Potassium hypochlorite	>0.05	<0.002
Potassium iodide	<0.02	<0.02
Potassium nitrate	<0.02	<0.002
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	<0.002
Potassium silicate	<0.02	<0.02
Propionic acid	>0.05	<0.02
Pyridine	<0.02	<0.02
Quinine sulfate	>0.05	>0.05
Salicylic acid	–	>0.05
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	>0.05	>0.05
Silver chloride	>0.05	>0.05
Silver nitrate	>0.05	–
Sodium acetate	<0.02	<0.002
Sodium bicarbonate	<0.02	<0.05
Sodium bisulfate	>0.05	<0.002
Sodium bromide	<0.02	<0.02
Sodium carbonate	<0.002	<0.02
Sodium chloride	<0.02	<0.002
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.002	<0.02
Sodium hypochlorite	>0.05	>0.05
Sodium metasilicate	<0.02	<0.002
Sodium nitrate	<0.02	<0.02
Sodium nitrite	<0.02	<0.002
Sodium phosphate	<0.02	<0.02

(*Continued*)

TABLE 1.180 (*Continued*) Corrosion Rates of 1020 Steel at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.02	<0.02
Sodium sulfide	<0.05	<0.02
Sodium sulfite	<0.02	–
Stannic chloride	>0.05	<0.002
Stannous chloride	>0.05	<0.02
Strontium nitrate	>0.05	>0.05
Succinic acid	<0.02	<0.02
Sulfur dioxide	>0.05	<0.002
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	>0.05	<0.02
Sulfuric acid (air free)	>0.05	<0.02
Sulfuric acid (fuming)	–	<0.02
Sulfurous acid	<0.05	>0.05
Tannic acid	>0.05	<0.002
Tartaric acid	>0.05	<0.05
Tetraphosphoric acid	>0.05	>0.05
Trichloroacetic acid	>0.05	>0.05
Trichloroethylene	–	<0.002
Urea	<0.05	–
Zinc chloride	>0.05	<0.002
Zinc sulfate	>0.05	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.181 Corrosion Rates of Grey Cast Iron at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	<0.05	<0.002
Acetic acid (aerated)	>0.05	0.05
Acetic acid (air free)	>0.05	>0.05
Acetic anhydride	–	>0.05
Acetoacetic acid	>0.05	>0.05
Acetone	–	<0.002
Acetylene	–	<0.002
Acrolein	–	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.02	<0.02
Alcohol (methyl)	<0.02	<0.002
Alcohol (allyl)	–	<0.02
Alcohol (amyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (isopropyl)	–	<0.02
Allylamine	–	<0.02
Allyl chloride	–	<0.02
Allyl sulfide	–	<0.02
Aluminum acetate	>0.05	–
Aluminum chloride	>0.05	>0.05
Aluminum fluoride	<0.02	–
Aluminum fluorosilicate	–	>0.05
Aluminum hydroxide	<0.02	–
Aluminum nitrate	>0.05	–
Aluminum potassium sulfate	>0.05	–
Aluminum sulfate	>0.05	–
Ammonia	<0.002	<0.002
Ammonium acetate	–	<0.02
Ammonium bicarbonate	<0.02	<0.02
Ammonium bromide	>0.05	>0.05
Ammonium carbonate	<0.02	<0.02
Ammonium chloride	>0.05	–
Ammonium citrate	>0.05	–
Ammonium nitrate	<0.02	<0.05
Ammonium sulfate	<0.05	<0.02
Ammonium sulfite	>0.05	–
Ammonium thiocyanate	<0.02	–
Amyl acetate	–	<0.02
Amyl chloride	–	<0.02
Aniline	–	<0.002
Aniline hydrochloride	>0.05	>0.05

(*Continued*)

TABLE 1.181 (*Continued*) Corrosion Rates of Grey Cast Iron at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Anthracine	–	<0.02
Antimony trichloride	>0.05	–
Barium carbonate	<0.02	<0.02
Barium chloride	>0.05	<0.02
Barium hydroxide	–	<0.02
Benzaldehyde	>0.05	>0.05
Benzene	–	<0.02
Benzoic acid	>0.05	>0.05
Boric acid	>0.05	–
Bromic acid	>0.05	>0.05
Bromine (dry)	–	>0.05
Bromine (wet)	–	>0.05
Butyric acid	>0.05	–
Cadmium chloride	>0.05	–
Cadmium sulfate	<0.02	<0.02
Calcium acetate	<0.05	<0.05
Calcium bicarbonate	–	<0.02
Calcium bromide	–	<0.05
Calcium chlorate	<0.02	<0.02
Calcium chloride	<0.02	<0.002
Calcium hydroxide	<0.02	<0.02
Calcium hypochlorite	<0.05	<0.02
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	–	<0.05
Carbon acid (air free)	–	<0.05
Chloroacetic acid	>0.05	>0.05
Chlorine gas	>0.05	<0.02
Chloroform (dry)	–	<0.002
Chromic acid	<0.05	<0.02
Citric acid	>0.05	–
Copper nitrate	>0.05	–
Copper sulfate	>0.05	–
Ethylene glycol	–	<0.02
Ethylene oxide	–	<0.02
Fatty acids	–	>0.05
Ferric chloride	>0.05	–
Ferric nitrate	>0.05	–
Ferrous chloride	>0.05	–
Ferrous sulfate	>0.05	–
Fluorine	–	>0.05

(*Continued*)

TABLE 1.181 (*Continued*) Corrosion Rates of Grey Cast Iron at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Formaldehyde	<0.05 (40%)	<0.02
Formic acid	>0.05	>0.05
Furfural	–	<0.02
Hydrazine	>0.05	–
Hydrobromic acid	>0.05	<0.02
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	>0.05	–
Hydrocyanic acid	–	<0.02
Hydrofluoric acid (aerated)	>0.05	>0.05
Hydrofluoric acid (air free)	>0.05	>0.05
Hydrogen chloride	>0.05 (90%)	<0.02
Hydrogen iodide	>0.05	<0.02
Hydrogen peroxide	>0.05 (20%)	–
Hydrogen sulfide	<0.02	<0.02
Lactic acid	>0.05	>0.05
Lead acetate	>0.05	–
Lead chromate	–	<0.02
Lead nitrate	>0.05	<0.02
Lead sulfate	–	<0.02
Lithium chloride	<0.02 (30%)	<0.002
Lithium hydroxide	<0.02	–
Magnesium chloride	<0.02	<0.02
Magnesium hydroxide	<0.02	–
Magnesium sulfate	>0.05	<0.02
Maleic acid	>0.05	–
Malic acid	>0.05	–
Manganous chloride	>0.05 (40%)	–
Mercuric chloride	>0.05	–
Methallylamine	–	<0.02
Methanol	<0.02	<0.002
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylamine	<0.02	<0.02
Methylene chloride	–	<0.02
Monochloroacetic acid	>0.05	>0.05
Monorthanolamine	–	<0.02
Monoethylamine	<0.02	<0.02
Monosodium phosphate	>0.05	–
Nickel chloride	>0.05	–
Nickel nitrate	<0.02	–
Nickel sulfate	>0.05	–

(*Continued*)

TABLE 1.181 (*Continued*) Corrosion Rates of Grey Cast Iron at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Nitric acid	>0.05	>0.05
Nitric acid (red fuming)	–	>0.05
Nitric + hydrochloric acid	–	>0.05
Nitric + hydrofluoric acid	–	>0.05
Nitric + sulfuric acid	–	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.02
Nitroglycerine	–	<0.05
Nitrotoluene	–	<0.02
Oleic acid	–	<0.02
Oxalic acid	>0.05	>0.05
Phenol	–	<0.02
Phosphoric acid (aerated)	>0.05	>0.05
Phosphoric acid (air free)	>0.05	>0.05
Picric acid	>0.05	>0.05
Potassium bicarbonate	<0.02	–
Potassium bromide	<0.05	>0.05
Potassium carbonate	<0.02	<0.02
Potassium chromate	<0.02	–
Potassium cyanide	>0.05	<0.02
Potassium dichromate	<0.02	–
Potassium ferricyanide	<0.02	<0.02
Potassium ferrocyanide	>0.05	–
Potassium hydroxide	<0.02	<0.02
Potassium hypochlorite	>0.05	–
Potassium nitrate	<0.02	<0.02
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	<0.02
Potassium silicate	<0.02	<0.02
Propionic acid	>0.05	–
Pyridine	<0.02	<0.02
Quinine sulfate	>0.05	>0.05
Salicylic acid	–	>0.05
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	>0.05	>0.05
Silver chloride	>0.05	>0.05
Silver nitrate	>0.05	–
Sodium acetate	–	<0.002
Sodium bicarbonate	<0.02	<0.05
Sodium bisulfate	>0.05	–

(*Continued*)

TABLE 1.181 (*Continued*) Corrosion Rates of Grey Cast Iron at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Sodium bromide	–	<0.05
Sodium carbonate	<0.002	<0.02
Sodium chloride	<0.02	<0.02
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.02	–
Sodium hypochlorite	>0.05	–
Sodium metasilicate	<0.02	<0.02
Sodium nitrate	<0.02	<0.02
Sodium nitrite	<0.02	–
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.02	<0.02
Sodium sulfide	<0.05	<0.02
Sodium sulfite	>0.05	–
Stannic chloride	>0.05	–
Stannous chloride	>0.05	<0.02
Strontium nitrate	>0.05	>0.05
Succinic acid	<0.02	<0.02
Sulfur dioxide	–	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	>0.05	<0.02
Sulfuric acid (air free)	>0.05	<0.02
Sulfuric acid (fuming)	–	<0.02
Sulfurous acid	–	>0.05
Tannic acid	–	<0.02
Tartaric acid	>0.05	>0.05
Tetraphosphoric acid	>0.05	>0.05
Trichloroacetic acid	>0.05	>0.05
Trichloroethylene	–	<0.02
Zinc chloride	>0.05	<0.02
Zinc sulfate	>0.05	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.182 Corrosion Rates of Ni-Resist Cast Iron at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	–	<0.002
Acetic acid (aerated)	<0.02	>0.05
Acetic acid (air free)	<0.02	>0.05
Acetic anhydride	–	<0.02
Acetone	–	<0.002
Acetylene	–	<0.002
Acrolein	–	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.02	<0.02
Alcohol (methyl)	<0.02	<0.002
Alcohol (allyl)	–	<0.02
Alcohol (amyl)	–	<0.02
Alcohol (isopropyl)	–	<0.02
Allylamine	–	<0.02
Allyl sulfide	–	<0.02
Aluminum acetate	–	<0.02
Aluminum chloride	>0.05	>0.05
Aluminum hydroxide	<0.02	–
Aluminum potassium sulfate	>0.05	–
Aluminum sulfate	<0.02	–
Ammonia	<0.002	<0.002
Ammonium acetate	<0.002	<0.002
Ammonium bicarbonate	<0.02	<0.02
Ammonium carbonate	<0.02	<0.02
Ammonium chloride	<0.02	–
Ammonium citrate	>0.05	–
Ammonium nitrate	<0.02	–
Ammonium sulfate	>0.05	<0.02
Ammonium sulfite	>0.05	–
Ammonium thiocyanate	<0.02	–
Amyl acetate	–	<0.002
Aniline	<0.02	<0.02
Aniline hydrochloride	>0.05	>0.05
Anthracine	–	<0.02
Antimony trichloride	>0.05	–
Barium carbonate	<0.02	<0.02
Barium chloride	<0.02	–
Benzaldehyde	<0.02	<0.002
Benzene	–	<0.02
Benzoic acid	–	<0.02
Boric acid	<0.002	<0.02

(*Continued*)

TABLE 1.182 (*Continued*) Corrosion Rates of Ni-Resist Cast Iron at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Bromine (dry)	–	<0.02
Bromine (wet)	–	>0.05
Butyric acid	>0.05	>0.05
Cadmium chloride	>0.05	–
Calcium chlorate	<0.05	<0.02
Calcium chloride	<0.02	–
Calcium hydroxide	<0.02	–
Calcium hypochlorite	<0.02	–
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	–	<0.02
Carbon acid (air free)	–	<0.002
Chloroacetic acid	>0.05	>0.05
Chlorine gas	>0.05	<0.02
Chromic acid	<0.05	<0.02
Chromic hydroxide	–	<0.02
Citric acid	>0.05	>0.05
Copper nitrate	>0.05	–
Copper sulfate	>0.05	–
Ethylene glycol	–	<0.02
Fatty acids	–	<0.02
Ferric chloride	>0.05	–
Ferrous chloride	>0.05	–
Formaldehyde	<0.05 (40%)	–
Formic acid	>0.05	>0.05
Furfural	<0.02 (30%)	<0.02
Hydrobromic acid	–	>0.05
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	<0.05	–
Hydrocyanic acid	–	<0.02
Hydrofluoric acid (aerated)	<0.002	<0.02
Hydrofluoric acid (air free)	<0.002	<0.02
Hydrogen chloride	–	<0.002
Hydrogen fluoride	–	<0.02
Hydrogen iodide	–	<0.02
Hydrogen sulfide	<0.02	<0.02
Lactic acid	>0.05	>0.05
Lead chromate	–	<0.02
Lead sulfate	–	<0.02
Lithium chloride	<0.002 (30%)	–
Lithium hydroxide	<0.02	–

(*Continued*)

TABLE 1.182 (*Continued*) Corrosion Rates of Ni-Resist Cast Iron at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Magnesium chloride	<0.02	<0.02
Magnesium hydroxide	<0.02	<0.02
Magnesium sulfate	<0.02	<0.02
Maleic acid	>0.05	–
Manganous chloride	<0.05 (40%)	–
Mercuric chloride	>0.05	–
Methallylamine	<0.02	<0.02
Methanol	<0.02	<0.002
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylamine	<0.02	<0.02
Methylene chloride	–	<0.02
Monochloroacetic acid	–	<0.05
Monorthanolamine	–	<0.02
Monoethalamine	<0.02	<0.02
Monoethylamine	<0.02	<0.02
Monosodium phosphate	>0.05	–
Nickel chloride	>0.05	–
Nickel nitrate	<0.02	–
Nitric acid	>0.05	>0.05
Nitric acid (red fuming)	–	>0.05
Nitric + hydrochloric acid	–	>0.05
Nitric + hydrofluoric acid	–	>0.05
Nitric + sulfuric acid	–	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.02
Nitroglycerine	–	<0.02
Nitrotoluene	–	<0.02
Oleic acid	–	<0.002
Oxalic acid	>0.05	<0.02
Phenol	–	<0.02
Phosphoric acid (aerated)	>0.05	>0.05
Phosphoric acid (air free)	>0.05	>0.05
Picric acid	–	>0.05
Potassium bicarbonate	<0.02	–
Potassium bromide	<0.02	<0.02
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	–
Potassium chromate	<0.02	–
Potassium cyanide	<0.02	–
Potassium dichromate	<0.02	<0.02

(*Continued*)

TABLE 1.182 (*Continued*) Corrosion Rates of Ni-Resist Cast Iron at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Potassium ferricyanide	<0.02	<0.02
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	<0.02	–
Potassium hypochlorite	>0.05	–
Potassium iodide	<0.02	–
Potassium nitrate	<0.02	–
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	–
Potassium silicate	<0.02	<0.02
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Salicylic acid	–	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	>0.05	>0.05
Sodium acetate	<0.02	–
Sodium bicarbonate	<0.02	<0.02
Sodium bisulfate	<0.002	<0.002
Sodium bromide	<0.02	<0.02
Sodium carbonate	<0.002	<0.02
Sodium chloride	<0.02	<0.02
Sodium chromate	<0.002	<0.02
Sodium hydroxide	<0.002	<0.02
Sodium hypochlorite	<0.05	–
Sodium metasilicate	<0.002	<0.02
Sodium nitrate	<0.02	<0.02
Sodium nitrite	<0.02	–
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.02	<0.02
Sodium sulfite	<0.02	–
Stannic chloride	>0.05	–
Stannous chloride	>0.05	<0.02
Strontium nitrate	<0.02	–
Succinic acid	<0.02	<0.02
Sulfur dioxide	–	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	<0.02	<0.02
Sulfuric acid (air aree)	<0.02	<0.02
Sulfuric acid (fuming)	–	<0.05
Sulfurous acid	<0.05	>0.05

(*Continued*)

TABLE 1.182 (*Continued*) Corrosion Rates of Ni-Resist Cast Iron at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Tartaric acid	<0.02	–
Tetraphosphoric acid	>0.05	<0.05
Trichloroacetic acid	>0.05	>0.05
Trichloroethylene	–	<0.02
Zinc chloride	<0.02	<0.02
Zinc sulfate	<0.02	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.183 Corrosion Rates of 12% Cr Steel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	–	<0.002
Acetic acid (aerated)	<0.02	>0.05
Acetic acid (air free)	<0.02	>0.05
Acetic anhydride	–	<0.05
Acetone	<0.02	<0.002
Acetylene	–	<0.002
Acrolein	<0.02	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.02	<0.02
Alcohol (methyl)	<0.02	<0.02
Alcohol (allyl)	–	<0.02
Alcohol (amyl)	–	<0.02
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.02
Allylamine	–	<0.02
Allyl chloride	–	<0.02
Allyl sulfide	–	<0.02
Aluminum acetate	<0.02	<0.02
Aluminum chloride	>0.05	<0.002
Aluminum fluoride	>0.05	>0.05
Aluminum fluorosilicate	–	<0.02

(*Continued*)

TABLE 1.183 (*Continued*) Corrosion Rates of 12% Cr Steel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Aluminum formate	<0.02	<0.02
Aluminum hydroxide	<0.02	–
Aluminum nitrate	<0.02	<0.02
Aluminum potassium sulfate	>0.05	<0.05
Aluminum sulfate	>0.05	>0.05
Ammonia	<0.002	<0.002
Ammonium acetate	<0.002	<0.002
Ammonium bicarbonate	<0.02	–
Ammonium bromide	<0.05	>0.05
Ammonium carbonate	<0.02	<0.02
Ammonium chloride	<0.05	>0.05
Ammonium nitrate	<0.02	<0.02
Ammonium sulfate	>0.05	–
Ammonium sulfite	>0.05	–
Amyl acetate	–	<0.002
Amyl chloride	–	<0.05
Aniline	<0.02	<0.02
Aniline hydrochloride	>0.05	>0.05
Anthracine	–	<0.02
Antimony trichloride	>0.05	>0.05
Barium carbonate	<0.02	<0.02
Barium chloride	<0.05	–
Barium hydroxide	–	<0.02
Barium oxide	–	<0.02
Barium peroxide	>0.05	–
Benzaldehyde	–	<0.02
Benzene	<0.02	<0.02
Benzoic acid	<0.02	<0.02
Boric acid	<0.02	<0.02
Bromic acid	>0.05	>0.05
Bromine (dry)	–	>0.05
Bromine (wet)	–	>0.05
Butyric acid	<0.05	–
Cadmium chloride	>0.05	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02
Calcium bromide	<0.02	<0.02
Calcium chlorate	<0.02	–
Calcium chloride	<0.02	–

(*Continued*)

TABLE 1.183 (*Continued*) Corrosion Rates of 12% Cr Steel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Calcium hydroxide	<0.02	<0.02
Calcium hypochlorite	>0.05	>0.05
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	>0.05	<0.02
Carbon acid (air free)	–	<0.002
Chloroacetic acid	>0.05	>0.05
Chlorine gas	>0.05	<0.05
Chloroform (dry)	–	<0.002
Chromic acid	>0.05	<0.02
Chromic hydroxide	–	<0.02
Chromic sulfates	>0.05	>0.05
Citric acid	<0.05	–
Copper nitrate	<0.02	–
Copper sulfate	<0.02	–
Ethyl chloride	>0.05 (90%)	<0.002
Ethylene glycol	–	<0.02
Ethylene oxide	–	<0.02
Fatty acids	–	<0.02
Ferric chloride	>0.05	–
Ferric nitrate	<0.02	–
Ferrous chloride	>0.05	–
Ferrous sulfate	<0.02	–
Fluorine	–	>0.05
Formaldehyde	<0.02	<0.02
Formic acid	<0.05	<0.02
Furfural	<0.02 (80%)	–
Hydrobromic acid	>0.05	–
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air aree)	>0.05	–
Hydrocyanic acid	–	>0.05
Hydrofluoric acid (air free)	>0.05	>0.05
Hydrogen chloride	>0.05 (90%)	>0.05
Hydrogen fluoride	–	<0.02
Hydrogen iodide	<0.05	>0.05
Hydrogen peroxide	<0.02 (20%)	<0.02
Hydrogen sulfide	<0.02	<0.02
Lactic acid	>0.05	–

(*Continued*)

TABLE 1.183 (*Continued*) Corrosion Rates of 12% Cr Steel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Lead acetate	<0.02	<0.02
Lead chromate	–	<0.02
Lead nitrate	<0.02	–
Lead sulfate	–	<0.02
Lithium hydroxide	<0.02	–
Magnesium chloride	<0.05	–
Magnesium hydroxide	<0.02	<0.02
Magnesium sulfate	>0.05	<0.05
Maleic acid	–	<0.05
Malic acid	<0.02	–
Mercuric chloride	>0.05	>0.05
Mercurous nitrate	<0.02	<0.02
Methallylamine	<0.02	<0.02
Methanol	<0.02	<0.002
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylamine	<0.02	<0.02
Methylene chloride	–	<0.02
Monochloroacetic acid	>0.05	>0.05
Monorthanolamine	<0.02	–
Monoethalamine	<0.02	<0.02
Monoethylamine	<0.02	<0.02
Monosodium phosphate	>0.05	–
Nickel chloride	>0.05	–
Nickel nitrate	<0.02	–
Nitric acid	<0.02	>0.05
Nitric acid (red fuming)	–	<0.002
Nitric + hydrochloric acid	–	>0.05
Nitric + hydrofluoric acid	–	>0.05
Nitric + sulfuric acid	–	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.02
Nitroglycerine	–	<0.02
Nitrotoluene	–	<0.02
Nitrous acid	<0.05	–
Oleic acid	<0.02	<0.02
Oxalic acid	>0.05	>0.05
Phenol	–	<0.02
Phosphoric acid (aerated)	<0.02	–

(*Continued*)

TABLE 1.183 (*Continued*) Corrosion Rates of 12% Cr Steel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Phosphoric acid (air free)	>0.05	>0.05
Picric acid	<0.02	<0.02
Potassium bicarbonate	<0.02	–
Potassium bromide	<0.02	<0.002
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	<0.02
Potassium chromate	<0.02	<0.02
Potassium cyanide	<0.02	<0.02
Potassium dichromate	<0.02	<0.02
Potassium ferricyanide	<0.02	–
Potassium ferrocyanide	>0.05	–
Potassium hydroxide	<0.02	<0.002
Potassium hypochlorite	>0.05	–
Potassium iodide	>0.05	–
Potassium nitrate	<0.02	<0.02
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.002	<0.02
Potassium silicate	<0.02	<0.02
Pyridine	<0.02	<0.02
Salicylic acid	–	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	>0.05	>0.05
Silver chloride	>0.05	>0.05
Silver nitrate	<0.02	–
Sodium acetate	<0.02	<0.02
Sodium bicarbonate	<0.02	–
Sodium bisulfate	<0.002	>0.05
Sodium bromide	<0.05	–
Sodium carbonate	<0.02	<0.02
Sodium chloride	<0.02	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.002	–
Sodium hypochlorite	>0.05	>0.05
Sodium metasilicate	<0.002	<0.002
Sodium nitrate	<0.02	<0.02
Sodium nitrite	<0.02	<0.002
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.05	>0.05

(*Continued*)

TABLE 1.183 (*Continued*) Corrosion Rates of 12% Cr Steel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Sodium sulfide	>0.05	<0.02
Sodium sulfite	<0.02	–
Stannic chloride	>0.05	–
Stannous chloride	>0.05	–
Strontium nitrate	<0.02	–
Succinic acid	<0.02	<0.02
Sulfur dioxide	>0.05	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	<0.05	>0.05
Sulfuric acid (air free)	>0.05	<0.05
Sulfuric acid (fuming)	–	<0.002
Sulfurous acid	>0.05	>0.05
Tannic acid	<0.02	<0.02
Tartaric acid	<0.02	–
Tetraphosphoric acid	>0.05	>0.05
Trichloroacetic acid	>0.05	>0.05
Trichloroethylene	–	<0.02
Urea	<0.02	–
Zinc chloride	–	>0.05
Zinc sulfate	<0.05	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.184 Corrosion Rates of 17% Cr Steel at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	–	<0.002
Acetic acid (aerated)	<0.002	<0.002
Acetic acid (air free)	<0.02	<0.05
Acetic anhydride	–	<0.05
Acetoacetic acid	<0.02	<0.02
Acetone	<0.02	<0.002
Acetylene	–	<0.002
Acrolein	<0.02	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.02	<0.02
Alcohol (methyl)	<0.02	<0.02
Alcohol (allyl)	–	<0.02
Alcohol (amyl)	–	<0.02
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.02
Allylamine	–	<0.02
Allyl chloride	–	<0.02
Allyl sulfide	–	<0.02
Aluminum chlorate	<0.002	–
Aluminum chloride	>0.05	<0.002
Aluminum fluoride	>0.05	>0.05
Aluminum fluorosilicate	–	<0.02
Aluminum formate	<0.02	<0.02
Aluminum hydroxide	<0.02	<0.02
Aluminum nitrate	<0.02	<0.02
Aluminum potassium sulfate	<0.05	>0.05
Aluminum sulfate	–	>0.05
Ammonia	<0.002	<0.002
Ammonium acetate	<0.002	<0.002
Ammonium bicarbonate	<0.02	–
Ammonium bromide	<0.05	–
Ammonium carbonate	<0.02	<0.02
Ammonium chloride	<0.05	>0.05
Ammonium citrate	<0.02	–
Ammonium nitrate	<0.002	<0.02
Ammonium sulfate	<0.05	–
Ammonium sulfite	>0.05	–
Ammonium thiocyanate	<0.02	–
Amyl acetate	–	<0.02
Amyl chloride	–	<0.05
Aniline	<0.02	<0.02

(*Continued*)

TABLE 1.184 (*Continued*) Corrosion Rates of 17% Cr Steel at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Aniline hydrochloride	>0.05	>0.05
Anthracine	–	<0.02
Antimony trichloride	>0.05	>0.05
Barium carbonate	<0.02	<0.02
Barium chloride	<0.02	<0.02
Barium hydroxide	–	<0.02
Barium nitrate	<0.02	–
Barium oxide	–	<0.02
Benzaldehyde	–	<0.02
Benzene	<0.02	<0.02
Benzoic acid	<0.02	<0.02
Boric acid	<0.02	<0.02
Bromic acid	>0.05	>0.05
Bromine (dry)	–	>0.05
Bromine (wet)	–	>0.05
Butyric acid	<0.05	<0.05
Cadmium chloride	>0.05	–
Cadmium sulfate	<0.002	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02
Calcium bromide	<0.02	<0.02
Calcium chlorate	<0.02	–
Calcium chloride	<0.05	<0.02
Calcium hydroxide	<0.02	<0.02
Calcium hypochlorite	>0.05	>0.05
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	<0.002	<0.002
Carbon acid (air free)	–	<0.002
Chloroacetic acid	>0.05	>0.05
Chlorine gas	>0.05	<0.05
Chloroform (dry)	–	<0.02
Chromic acid	<0.02	–
Chromic hydroxide	–	<0.02
Chromic sulfates	>0.05	>0.05
Citric acid	<0.02	–
Copper nitrate	<0.02	–
Copper sulfate	<0.02	–
Diethylene glycol	–	<0.002
Ethyl chloride	>0.05 (90%)	<0.002
Ethylene glycol	–	<0.02
Ethylene oxide	–	<0.02

(*Continued*)

TABLE 1.184 (*Continued*) Corrosion Rates of 17% Cr Steel at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Fatty acids	–	<0.02
Ferric chloride	>0.05	–
Ferric nitrate	<0.02	–
Ferrous chloride	>0.05	–
Ferrous sulfate	<0.02	–
Fluorine	–	<0.002
Formaldehyde	<0.002	<0.002
Formic acid	<0.05	<0.05
Furfural	<0.002 (30%)	–
Hydrobromic acid	>0.05	–
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	>0.05	–
Hydrocyanic acid	–	<0.05
Hydrofluoric acid (air free)	>0.05	>0.05
Hydrogen chloride	>0.05 (90%)	>0.05
Hydrogen fluoride	–	<0.02
Hydrogen iodide	–	>0.05
Hydrogen peroxide	<0.02 (20%)	<0.02
Hydrogen sulfide	<0.02	<0.05
Lactic acid	>0.05	–
Lead acetate	<0.02	<0.02
Lead chromate	–	<0.02
Lead nitrate	<0.02	–
Lead sulfate	–	<0.02
Lithium hydroxide	<0.02	–
Magnesium chloride	<0.05	–
Magnesium hydroxide	<0.02	<0.02
Magnesium sulfate	<0.002	<0.02
Maleic acid	<0.02	<0.02
Malic acid	<0.02	–
Mercuric chloride	>0.05	>0.05
Mercurous nitrate	<0.02	–
Methallylamine	<0.02	<0.02
Methanol	<0.02	<0.002
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylamine	<0.02	<0.02
Methylene chloride	–	<0.02
Monochloroacetic acid	>0.05	>0.05
Monorthanolamine	<0.002	–
Monoethalamine	<0.02	<0.02
Monoethylamine	<0.02	<0.02
Monosodium phosphate	>0.05	–

(*Continued*)

TABLE 1.184 (*Continued*) Corrosion Rates of 17% Cr Steel at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Nickel chloride	>0.05	–
Nickel nitrate	<0.02	–
Nitric acid	<0.02	<0.05
Nitric acid (red fuming)	–	<0.002
Nitric + hydrochloric acid	–	>0.05
Nitric + hydrofluoric acid	–	>0.05
Nitric + sulfuric acid	–	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.02
Nitroglycerine	–	<0.02
Nitrotoluene	–	<0.02
Nitrous acid	<0.02	–
Oleic acid	<0.02	<0.02
Oxalic acid	>0.05	>0.05
Phenol	–	<0.02
Phosphoric acid (aerated)	<0.02	–
Phosphoric acid (air free)	>0.05	>0.05
Picric acid	<0.02	<0.02
Potassium bicarbonate	<0.02	<0.02
Potassium bromide	<0.02	<0.02
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	<0.02
Potassium chromate	<0.02	<0.02
Potassium cyanide	<0.02	<0.02
Potassium dichromate	<0.02	<0.02
Potassium ferricyanide	<0.02	<0.02
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	<0.02	<0.002
Potassium hypochlorite	>0.05	–
Potassium iodide	>0.05	–
Potassium nitrate	<0.02	<0.02
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	<0.02
Potassium silicate	<0.02	<0.02
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Salicylic acid	–	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	>0.05	>0.05
Silver chloride	>0.05	>0.05
Silver nitrate	<0.02	–

(*Continued*)

TABLE 1.184 (*Continued*) Corrosion Rates of 17% Cr Steel at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Sodium acetate	<0.02	<0.02
Sodium bicarbonate	<0.02	<0.02
Sodium bisulfate	<0.002	–
Sodium bromide	<0.05	–
Sodium carbonate	<0.02	<0.02
Sodium chloride	<0.02	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.002	–
Sodium hypochlorite	>0.05	>0.05
Sodium metasilicate	<0.002	<0.002
Sodium nitrate	<0.02	<0.002
Sodium nitrite	<0.02	–
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.05	>0.05
Sodium sulfide	>0.05	>0.05
Sodium sulfite	<0.02	–
Stannic chloride	>0.05	–
Stannous chloride	>0.05	<0.05
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	<0.02
Sulfur dioxide	>0.05	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	<0.05	>0.05
Sulfuric acid (air free)	>0.05	<0.05
Sulfuric acid (fuming)	–	<0.002
Sulfurous acid	>0.05	>0.05
Tannic acid	<0.02	<0.02
Tartaric acid	<0.02	–
Tetraphosphoric acid	>0.05	>0.05
Trichloroacetic acid	>0.05	>0.05
Trichloroethylene	–	<0.02
Urea	<0.02	–
Zinc chloride	–	>0.05
Zinc sulfate	<0.05	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.185 Corrosion Rates of 14% Si Iron at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	<0.002	<0.002
Acetic acid (aerated)	<0.002	<0.002
Acetic acid (air free)	<0.002	<0.002
Acetic anhydride	<0.002	<0.002
Acetoacetic acid	<0.02	<0.02
Acetone	<0.002	<0.002
Acetylene	–	<0.002
Acrolein	<0.02	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.002	<0.002
Alcohol (methyl)	<0.002	<0.002
Alcohol (allyl)	<0.02	<0.02
Alcohol (amyl)	–	<0.02
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.02
Allylamine	<0.002 (30%)	<0.02
Allyl chloride	–	<0.002
Allyl sulfide	–	<0.02
Aluminum acetate	<0.02	<0.002
Aluminum chlorate	<0.02	<0.002
Aluminum chloride	<0.002	<0.02
Aluminum fluoride	>0.05	>0.05
Aluminum fluorosilicate	–	<0.02
Aluminum formate	<0.02	<0.02
Aluminum hydroxide	<0.02	–
Aluminum potassium sulfate	–	<0.002
Aluminum sulfate	<0.002	<0.02
Ammonia	<0.02	<0.02
Ammonium acetate	<0.002	<0.02
Ammonium bicarbonate	<0.002	<0.002
Ammonium bromide	<0.002	–
Ammonium carbonate	<0.002	<0.02
Ammonium chloride	<0.002	<0.02
Ammonium formate	<0.02	<0.02
Ammonium nitrate	<0.002	–
Ammonium sulfate	<0.002	<0.002
Ammonium sulfite	<0.02	–
Ammonium thiocyanate	<0.02	–
Amyl acetate	<0.002	<0.002
Amyl chloride	<0.02	<0.02

(*Continued*)

TABLE 1.185 (*Continued*) Corrosion Rates of 14% Si Iron at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Aniline	<0.002	<0.002
Aniline hydrochloride	<0.02	<0.02
Anthracine	–	<0.02
Antimony trichloride	<0.002	–
Barium carbonate	<0.02	<0.02
Barium chloride	<0.02	–
Barium hydroxide	–	<0.02
Barium nitrate	<0.02	<0.02
Barium oxide	–	<0.02
Barium peroxide	<0.02	–
Benzaldehyde	<0.02	<0.02
Benzene	<0.002	<0.002
Benzoic acid	<0.02	<0.02
Boric acid	<0.02	<0.02
Bromine (dry)	–	>0.05
Bromine (wet)	–	>0.05
Butyric acid	<0.002	<0.002
Cadmium chloride	<0.02	–
Cadmium sulfate	<0.002	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02
Calcium bromide	–	<0.02
Calcium chlorate	<0.02	–
Calcium chloride	<0.002	<0.02
Calcium hydroxide	<0.02	–
Calcium hypochlorite	<0.02	<0.05
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	<0.002	<0.002
Carbon acid (air free)	<0.02	<0.002
Chloroacetic acid	>0.05	>0.05
Chlorine gas	–	<0.02
Chromic acid	<0.002	<0.02
Chromic hydroxide	–	<0.02
Chromic sulfates	<0.002	<0.02
Citric acid	<0.002	<0.002
Copper nitrate	<0.002	–
Copper sulfate	<0.002	–
Diethylene glycol	–	<0.002
Ethyl chloride	–	<0.002
Ethylene glycol	<0.02	<0.02
Ethylene oxide	–	<0.02

(*Continued*)

TABLE 1.185 (*Continued*) Corrosion Rates of 14% Si Iron at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Fatty acids	–	<0.002
Ferric chloride	>0.05	–
Ferric nitrate	<0.02	–
Ferrous chloride	>0.05	–
Ferrous sulfate	<0.02	–
Fluorine	–	>0.05
Formaldehyde	<0.002	<0.002
Formic acid	<0.002	<0.002
Furfural	<0.02 (20%)	<0.02
Hydrobromic acid	>0.05	>0.05
Hydrochloric acid (aerated)	<0.02	–
Hydrochloric acid (air free)	<0.02	–
Hydrocyanic acid	–	<0.02
Hydrofluoric acid (aerated)	>0.05	>0.05
Hydrofluoric acid (air free)	>0.05	>0.05
Hydrogen chloride	<0.02 (90%)	<0.02
Hydrogen iodide	>0.05	<0.02
Hydrogen peroxide	<0.02 (20%)	<0.02
Hydrogen sulfide	–	<0.02
Lactic acid	<0.002	<0.02
Lead acetate	<0.02	<0.05
Lead chromate	–	<0.02
Lead nitrate	<0.002	<0.002
Lead sulfate	–	<0.02
Lithium chloride	<0.02 (30%)	<0.02
Lithium hydroxide	>0.05	–
Magnesium chloride	<0.002	>0.05
Magnesium hydroxide	<0.02	–
Magnesium sulfate	<0.002	<0.002
Maleic acid	<0.02	<0.02
Mercuric chloride	<0.02	<0.02
Mercurous nitrate	<0.02	<0.002
Methallylamine	<0.02	<0.002
Methanol	<0.002	<0.002
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylamine	<0.02	<0.02
Methylene chloride	–	<0.02
Monochloroacetic acid	<0.02	<0.02
Monoethalamine	<0.02	<0.02
Monoethylamine	<0.02	<0.02

(*Continued*)

TABLE 1.185 (*Continued*) Corrosion Rates of 14% Si Iron at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Monosodium phosphate	<0.02	–
Nickel chloride	<0.02	–
Nickel nitrate	<0.002	–
Nickel sulfate	<0.002	–
Nitric acid	<0.002	<0.002
Nitric acid (red fuming)	–	<0.002
Nitric + hydrochloric acid	–	<0.05
Nitric + hydrofluoric acid	–	>0.05
Nitric + sulfuric acid	<0.02	<0.02
Nitrobenzene	–	<0.002
Nitrocellulose	–	<0.02
Nitroglycerine	–	<0.05
Nitrotoluene	–	<0.02
Nitrous acid	<0.002	<0.002
Oleic acid	<0.002	<0.002
Oxalic acid	<0.02	<0.02
Phenol	–	<0.002
Phosphoric acid (aerated)	<0.002	<0.002
Phosphoric acid (air free)	<0.02	<0.02
Picric acid	<0.02	<0.02
Potassium bicarbonate	<0.02	–
Potassium bromide	<0.02	<0.02
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	<0.02
Potassium chromate	<0.02	–
Potassium cyanide	<0.02	<0.02
Potassium dichromate	<0.002	–
Potassium ferricyanide	<0.02	–
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	>0.05	>0.05
Potassium hypochlorite	<0.002	<0.002
Potassium iodide	<0.02	<0.02
Potassium nitrate	<0.002	<0.002
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	–
Potassium silicate	<0.02	<0.02
Propionic acid	<0.02	<0.02
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Salicylic acid	–	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	<0.002

(*Continued*)

TABLE 1.185 (*Continued*) Corrosion Rates of 14% Si Iron at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Silver bromide	–	<0.02
Silver chloride	–	<0.02
Silver nitrate	<0.002	–
Sodium acetate	<0.002	<0.02
Sodium bicarbonate	<0.002	–
Sodium bisulfate	<0.002	<0.002
Sodium bromide	<0.05	–
Sodium carbonate	<0.02	<0.02
Sodium chloride	<0.02	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	>0.05	–
Sodium metasilicate	<0.02	<0.02
Sodium nitrate	<0.002	<0.002
Sodium nitrite	<0.02	–
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.002	<0.002
Sodium sulfide	<0.02	<0.02
Sodium sulfite	<0.002	–
Stannic chloride	>0.05	–
Stannous chloride	<0.002	–
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	–
Sulfur dioxide	–	>0.05
Sulfur trioxide	–	>0.05
Sulfuric acid (aerated)	<0.002	<0.02
Sulfuric acid (fuming)	–	<0.02
Sulfurous acid	<0.02	<0.02
Tannic acid	<0.002	<0.002
Tartaric acid	<0.02	<0.02
Tetraphosphoric acid	–	<0.05
Trichloroacetic acid	<0.002	<0.002
Trichloroethylene	–	<0.002
Urea	<0.02	–
Zinc sulfate	<0.002	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in/year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.186 Corrosion Rates of Stainless Steel 301 at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	–	<0.002
Acetic acid (aerated)	<0.002	<0.002
Acetic acid (air free)	<0.02	<0.002
Acetic anhydride	–	<0.02
Acetoacetic acid	<0.02	<0.02
Acetone	<0.02	<0.002
Acetylene	–	<0.002
Acrolein	<0.02	<0.002
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.02	<0.02
Alcohol (methyl)	<0.02	<0.02
Alcohol (allyl)	–	<0.02
Alcohol (amyl)	–	<0.02
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.02
Allylamine	<0.002 (30%)	<0.02
Allyl chloride	–	<0.02
Allyl sulfide	–	<0.02
Aluminum acetate	<0.02	<0.02
Aluminum chlorate	<0.002	–
Aluminum chloride	>0.05	<0.002
Aluminum fluoride	>0.05	>0.05
Aluminum fluorosilicate	–	<0.02
Aluminum formate	<0.02	<0.02
Aluminum hydroxide	<0.02	<0.02
Aluminum nitrate	<0.02	<0.02
Aluminum potassium sulfate	<0.02	<0.02
Aluminum sulfate	<0.02	<0.02
Ammonia	<0.002	<0.002
Ammonium acetate	<0.002	<0.002
Ammonium bicarbonate	<0.02	<0.05
Ammonium bromide	<0.05	<0.05
Ammonium carbonate	<0.02	<0.02
Ammonium chloride	<0.02	>0.05
Ammonium citrate	<0.02	–
Ammonium formate	<0.02	<0.02
Ammonium nitrate	<0.002	<0.002
Ammonium sulfate	<0.05	–
Ammonium sulfite	<0.05	<0.05

(*Continued*)

TABLE 1.186 (*Continued*) Corrosion Rates of Stainless Steel 301 at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Ammonium thiocyanate	<0.02	–
Amyl acetate	<0.002	<0.002
Amyl chloride	>0.05	<0.002
Aniline	<0.02	<0.02
Aniline hydrochloride	>0.05	>0.05
Anthracine	–	<0.02
Antimony trichloride	>0.05	>0.05
Barium carbonate	<0.02	<0.02
Barium chloride	<0.02	<0.05
Barium hydroxide	–	<0.02
Barium nitrate	<0.02	<0.02
Barium oxide	–	<0.02
Barium peroxide	<0.02	–
Benzaldehyde	<0.02	<0.02
Benzene	<0.02	<0.02
Benzoic acid	<0.02	<0.02
Boric acid	<0.002	<0.02
Bromic acid	>0.05	–
Bromine (dry)	–	>0.05
Bromine (wet)	–	>0.05
Butyric acid	<0.02	<0.02
Cadmium chloride	<0.02	–
Cadmium sulfate	<0.002	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02
Calcium bromide	<0.02	<0.02
Calcium chlorate	<0.02	–
Calcium chloride	<0.02	<0.02
Calcium hydroxide	<0.02	–
Calcium hypochlorite	<0.05	–
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	>0.05	<0.02
Carbon acid (air free)	<0.02	<0.02
Chloroacetic acid	>0.05	–
Chlorine gas	–	<0.002
Chloroform (dry)	–	<0.002
Chromic acid	<0.02	–
Chromic hydroxide	–	<0.02
Chromic sulfates	<0.02	<0.05
Citric acid	<0.02	<0.02

(*Continued*)

TABLE 1.186 (*Continued*) Corrosion Rates of Stainless Steel 301 at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Copper nitrate	<0.02	–
Copper sulfate	<0.02	–
Diethylene glycol	–	<0.002
Ethyl chloride	>0.05 (90%)	<0.002
Ethylene glycol	–	<0.02
Ethylene oxide	–	<0.02
Fatty acids	–	<0.02
Ferric chloride	>0.05	–
Ferric nitrate	<0.02	–
Ferrous chloride	>0.05	–
Ferrous sulfate	<0.02	–
Fluorine	–	<0.002
Formaldehyde	<0.002 (20%)	<0.002
Formic acid	<0.02	<0.02
Furfural	<0.002 (30%)	<0.02
Hydrazine	<0.002	–
Hydrobromic acid	>0.05	>0.05
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	>0.05	–
Hydrocyanic acid	–	<0.02
Hydrofluoric acid (aerated)	<0.002	<0.02
Hydrofluoric acid (air free)	>0.05	>0.05
Hydrogen chloride	>0.05 (90%)	<0.002
Hydrogen fluoride	–	<0.002
Hydrogen iodide	<0.02 (1%)	<0.02
Hydrogen peroxide	<0.02 (20%)	<0.02
Hydrogen sulfide	>0.05	<0.05
Lactic acid	<0.02	<0.02
Lead acetate	<0.02	<0.02
Lead chromate	–	<0.02
Lead nitrate	<0.02	<0.02
Lead sulfate	–	<0.02
Lithium chloride	<0.002 (30%)	<0.002
Lithium hydroxide	<0.02	–
Magnesium chloride	<0.05	–
Magnesium hydroxide	<0.02	<0.02
Magnesium sulfate	<0.002	<0.02
Maleic acid	<0.02	<0.02
Malic acid	<0.002	<0.002
Manganous chloride	<0.02 (40%)	–
Mercuric chloride	>0.05	>0.05

(*Continued*)

TABLE 1.186 (*Continued*) Corrosion Rates of Stainless Steel 301 at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Mercurous nitrate	<0.02	<0.02
Methallylamine	<0.02	<0.02
Methanol	<0.02	<0.002
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylamine	<0.02	<0.02
Methylene chloride	<0.02	<0.02
Monochloroacetic acid	<0.05	<0.02
Monorthanolamine	<0.002	<0.02
Monoethalamine	<0.02	<0.02
Monoethylamine	<0.02	<0.02
Monosodium phosphate	<0.02	–
Nickel chloride	>0.05	–
Nickel nitrate	<0.02	–
Nickel sulfate	<0.002	–
Nitric acid	<0.002	<0.002
Nitric acid (red fuming)	–	<0.002
Nitric + hydrochloric acid	–	>0.05
Nitric + hydrofluoric acid	–	>0.05
Nitric + sulfuric acid	–	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.02
Nitroglycerine	–	<0.02
Nitrotoluene	–	<0.02
Nitrous acid	<0.02	<0.02
Oleic acid	<0.02	<0.02
Oxalic acid	<0.02	>0.05
Phenol	–	<0.02
Phosphoric acid (aerated)	<0.02	>0.05
Phosphoric acid (air free)	<0.02	–
Picric acid	<0.02	<0.02
Potassium bicarbonate	<0.02	<0.02
Potassium bromide	<0.02	<0.05
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	<0.02
Potassium chromate	<0.02	<0.02
Potassium cyanide	<0.02	<0.02
Potassium dichromate	<0.002	<0.02
Potassium ferricyanide	<0.02	<0.02
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	<0.02	<0.002

(*Continued*)

TABLE 1.186 (*Continued*) Corrosion Rates of Stainless Steel 301 at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Potassium hypochlorite	>0.05	–
Potassium iodide	<0.02	<0.02
Potassium nitrate	<0.02	<0.02
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	<0.02
Potassium silicate	<0.02	<0.02
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Salicylic acid	–	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	>0.05	<0.05
Silver chloride	>0.05	>0.05
Silver nitrate	<0.02	–
Sodium acetate	<0.02	<0.02
Sodium bicarbonate	<0.02	–
Sodium bisulfate	<0.002	>0.05
Sodium bromide	<0.05	–
Sodium carbonate	<0.02	<0.02
Sodium chloride	<0.02	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.002	–
Sodium hypochlorite	>0.05	>0.05
Sodium metasilicate	<0.002	<0.002
Sodium nitrate	<0.002	<0.02
Sodium nitrite	<0.02	<0.02
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.02	<0.002
Sodium sulfide	<0.02	>0.05
Sodium sulfite	<0.002	–
Stannic chloride	>0.05	–
Stannous chloride	>0.05	<0.05
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	<0.02
Sulfur dioxide	>0.05	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	>0.05	<0.02
Sulfuric acid (air free)	>0.05	<0.05
Sulfuric acid (fuming)	–	<0.02
Sulfurous acid	<0.02	>0.05

(*Continued*)

TABLE 1.186 (*Continued*) Corrosion Rates of Stainless Steel 301 at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Tannic acid	<0.02	<0.02
Tartaric acid	<0.002	–
Tetraphosphoric acid	–	<0.02
Trichloroacetic acid	>0.05	>0.05
Trichloroethylene	–	<0.02
Urea	<0.02	–
Zinc sulfate	<0.002	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./ year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.187 Corrosion Rates of Stainless Steel 316 at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	–	<0.002
Acetic acid (aerated)	<0.002	<0.002
Acetic acid (air free)	<0.002	<0.02
Acetic anhydride	–	<0.02
Acetoaceticacid	<0.02	<0.02
Acetone	<0.02	<0.002
Acetylene	–	<0.002
Acrolein	<0.02	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.002	<0.002
Alcohol (methyl)	<0.002	<0.002
Alcohol (allyl)	–	<0.02
Alcohol (amyl)	–	<0.02
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.02
Allylamine	<0.002 (30%)	<0.02
Allyl chloride	–	<0.002
Allyl sulfide	–	<0.02
Aluminum acetate	<0.02	<0.02
Aluminum chloride	<0.05	–

(*Continued*)

TABLE 1.187 (*Continued*) Corrosion Rates of Stainless Steel 316 at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Aluminum fluoride	–	<0.05
Aluminum fluorosilicate	–	<0.02
Aluminum formate	<0.02	<0.02
Aluminum hydroxide	<0.02	<0.02
Aluminum nitrate	<0.02	<0.02
Aluminum potassium sulfate	<0.02	–
Aluminum sulfate	<0.02	<0.02
Ammonia	<0.002	<0.002
Ammonium acetate	<0.002	<0.002
Ammonium bicarbonate	<0.02	<0.02
Ammonium bromide	<0.02	–
Ammonium carbonate	<0.02	<0.02
Ammonium chloride	<0.02	–
Ammonium citrate	<0.02	–
Ammonium formate	<0.02	<0.02
Ammonium nitrate	<0.002	<0.002
Ammonium sulfate	<0.02	–
Ammonium sulfite	<0.02	<0.02
Ammonium thiocyanate	<0.02	–
Amyl acetate	<0.002	<0.002
Amyl chloride	–	<0.002
Aniline	<0.02	<0.02
Aniline hydrochloride	>0.05	>0.05
Anthracine	–	<0.02
Antimony trichloride	>0.05	–
Barium carbonate	<0.02	<0.02
Barium chloride	<0.02	<0.02
Barium hydroxide	–	<0.02
Barium nitrate	<0.02	<0.02
Barium oxide	–	<0.02
Barium peroxide	<0.02	–
Benzaldehyde	–	<0.02
Benzene	<0.02	<0.02
Benzoic acid	<0.02	<0.02
Boric acid	<0.002	<0.02
Bromic acid	>0.05	–
Bromine (dry)	–	>0.05
Bromine (wet)	–	>0.05
Butyric acid	<0.02	<0.02
Cadmium chloride	<0.02	–
Cadmium sulfate	<0.002	–

(*Continued*)

TABLE 1.187 (*Continued*) Corrosion Rates of Stainless Steel 316 at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02
Calcium bromide	<0.02	<0.02
Calcium chlorate	<0.02	–
Calcium chloride	<0.02	<0.002
Calcium hydroxide	<0.02	–
Calcium hypochlorite	<0.05	–
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	<0.02	<0.02
Carbon acid (air free)	<0.02	<0.02
Chloroacetic acid	>0.05	–
Chlorine gas	–	<0.02
Chloroform (dry)	–	<0.002
Chromic acid	<0.02	–
Chromic hydroxide	–	<0.02
Chromic sulfates	<0.02	–
Citric acid	<0.02	<0.02
Copper nitrate	<0.002	–
Copper sulfate	<0.02	–
Diethylene glycol	–	<0.002
Ethyl chloride	–	<0.002
Ethylene glycol	–	<0.02
Ethylene oxide	–	<0.02
Fatty acids	–	<0.002
Ferric chloride	>0.05	–
Ferric nitrate	<0.02	–
Ferrous chloride	>0.05	–
Ferrous sulfate	<0.02	–
Fluorine	–	<0.002
Formaldehyde	<0.02	<0.002
Formic acid	<0.002	<0.002
Furfural	<0.002	<0.02
Hydrazine	<0.002	–
Hydrobromic acid	>0.05	–
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	>0.05	–
Hydrocyanic acid	–	<0.02
Hydrofluoric acid (aerated)	<0.002	<0.02
Hydrofluoric acid (air free)	>0.05	<0.02
Hydrogen chloride	–	<0.002

(*Continued*)

TABLE 1.187 (*Continued*) Corrosion Rates of Stainless Steel 316 at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Hydrogen fluoride	–	<0.002
Hydrogen iodide	–	<0.02
Hydrogen peroxide	<0.02 (20%)	<0.02
Hydrogen sulfide	<0.002	<0.02
Lactic acid	<0.02	<0.02
Lead acetate	<0.02	<0.02
Lead chromate	–	<0.02
Lead nitrate	<0.02	<0.02
Lead sulfate	–	<0.02
Lithium chloride	<0.002 (30%)	<0.002
Lithium hydroxide	<0.02	–
Magnesium chloride	<0.02	–
Magnesium hydroxide	<0.02	<0.02
Magnesium sulfate	<0.002	<0.02
Maleic acid	<0.02	<0.02
Malic acid	<0.002	<0.002
Manganous chloride	<0.02 (40%)	–
Mercuric chloride	>0.05	–
Mercurous nitrate	<0.02	<0.02
Methallylamine	<0.02	<0.02
Methanol	<0.02	<0.002
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylamine	<0.02	<0.02
Methylene chloride	<0.02	<0.02
Monochloroacetic acid	<0.05	<0.02
Monorthanolamine	<0.02	<0.02
Monoethalamine	<0.02	<0.02
Monoethylamine	<0.02	<0.02
Monosodium phosphate	<0.02	–
Nickel chloride	>0.05	–
Nickel nitrate	<0.02	–
Nickel sulfate	<0.02	–
Nitric acid	<0.002	<0.002
Nitric acid (red fuming)	–	<0.002
Nitric + hydrochloric acid	–	>0.05
Nitric + hydrofluoric acid	–	>0.05
Nitric + sulfuric acid	–	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.02
Nitroglycerine	–	<0.02

(*Continued*)

TABLE 1.187 (*Continued*) Corrosion Rates of Stainless Steel 316 at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Nitrotoluene	–	<0.02
Nitrous acid	<0.02	<0.02
Oleic acid	<0.02	<0.02
Oxalic acid	<0.02	>0.05
Phenol	–	<0.02
Phosphoric acid (aerated)	<0.002	<0.02
Phosphoric acid (air free)	<0.02	–
Picric acid	<0.02	<0.02
Potassium bicarbonate	<0.02	<0.02
Potassium bromide	<0.02	–
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	<0.02
Potassium chromate	<0.02	<0.02
Potassium cyanide	<0.02	<0.02
Potassium dichromate	<0.002	<0.02
Potassium ferricyanide	<0.02	<0.02
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	<0.02	–
Potassium hypochlorite	<0.05	<0.02
Potassium iodide	<0.02	<0.02
Potassium nitrate	<0.02	–
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	–
Potassium silicate	<0.02	<0.02
Propionic acid	–	<0.02
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Salicylic acid	–	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silver bromide	>0.05	–
Silver chloride	>0.05	–
Silver nitrate	<0.002	<0.02
Sodium acetate	<0.02	<0.02
Sodium bicarbonate	<0.02	–
Sodium bisulfate	<0.002	–
Sodium bromide	<0.05	–
Sodium carbonate	<0.02	<0.02
Sodium chloride	<0.02	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.002	–
Sodium hypochlorite	>0.05	>0.05

(*Continued*)

TABLE 1.187 (*Continued*) Corrosion Rates of Stainless Steel 316 at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Sodium metasilicate	<0.002	<0.002
Sodium nitrate	<0.002	<0.02
Sodium nitrite	<0.02	–
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.002	<0.002
Sodium sulfide	>0.05	–
Sodium sulfite	<0.002	–
Stannic chloride	>0.05	–
Stannous chloride	<0.02	–
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	<0.02
Sulfur dioxide	<0.002	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	<0.002	<0.02
Sulfuric acid (air free)	<0.05	<0.02
Sulfuric acid (fuming)	–	<0.02
Sulfurous acid	<0.02	<0.002
Tannic acid	<0.02	<0.02
Tartaric acid	<0.02	–
Tetraphosphoric acid	–	<0.02
Trichloroacetic acid	>0.05	>0.05
Trichloroethylene	–	<0.02
Urea	<0.02	–
Zinc sulfate	<0.02	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.188 Corrosion Rates of Aluminum at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	<0.02	<0.002
Acetic acid (aerated)	<0.02	<0.002
Acetic acid (air free)	<0.002	<0.002
Acetic anhydride	–	<0.002
Acetoacetic acid	<0.02	<0.02
Acetone	<0.02	<0.002
Acetylene	–	<0.002
Acrolein	<0.02	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.02	<0.02
Alcohol (methyl)	–	<0.02
Alcohol (allyl)	–	<0.02
Alcohol (amyl)	–	<0.002
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	<0.002	<0.002
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.02
Allyl chloride	–	>0.05
Allyl sulfide	–	<0.02
Aluminum acetate	<0.002	<0.002
Aluminum chloride	>0.05	<0.02
Aluminum fluoride	<0.002	–
Aluminum formate	<0.02	<0.02
Aluminum hydroxide	<0.02	–
Aluminum nitrate	<0.02	<0.02
Aluminum potassium sulfate	<0.02	<0.02
Aluminum sulfate	<0.002	>0.05
Ammonia	<0.002	<0.002
Ammonium acetate	<0.002	<0.002
Ammonium bicarbonate	<0.02	<0.02
Ammonium bromide	>0.05	–
Ammonium carbonate	<0.02	<0.02
Ammonium chloride	>0.05	<0.02
Ammonium citrate	<0.02	<0.02
Ammonium formate	<0.02	–
Ammonium nitrate	<0.02	<0.02
Ammonium sulfate	>0.05	<0.02
Amyl acetate	–	<0.002
Amyl chloride	–	<0.02
Aniline	–	<0.02
Aniline hydrochloride	>0.05	>0.05
Anthracine	–	<0.02
Antimony trichloride	>0.05	<0.02

(*Continued*)

TABLE 1.188 (*Continued*) Corrosion Rates of Aluminum at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Barium carbonate	–	>0.05
Barium chloride	<0.02	>0.05
Barium hydroxide	>0.05	>0.05
Barium nitrate	<0.02	–
Barium peroxide	>0.05	–
Benzaldehyde	<0.02	<0.002
Benzene	<0.02	<0.02
Benzoic acid	<0.02	<0.02
Boric acid	<0.05	<0.02
Bromic acid	>0.05	–
Bromine (dry)	–	<0.02
Bromine (wet)	–	>0.05
Butyric acid	<0.02	<0.002
Cadmium chloride	>0.05	–
Cadmium sulfate	<0.02	–
Calcium acetate	–	<0.05
Calcium bicarbonate	–	<0.02
Calcium bromide	<0.05	<0.05
Calcium chlorate	<0.02	–
Calcium chloride	<0.002	>0.05
Calcium hydroxide	>0.05	>0.05
Calcium hypochlorite	>0.05	–
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	–	<0.02
Carbon acid (air free)	<0.02	<0.002
Chloroacetic acid	>0.05	>0.05
Chlorine gas	–	<0.02
Chloroform (dry)	–	<0.02
Chromic acid	>0.05	>0.05
Chromic hydroxide	–	<0.02
Chromic sulfates	–	<0.05
Citric acid	<0.02	<0.02
Copper nitrate	>0.05	–
Copper sulfate	>0.05	>0.05
Diethylene glycol	–	<0.02
Ethyl chloride	–	<0.002
Ethylene glycol	<0.002	<0.002
Ethylene oxide	–	<0.002
Fatty acids	–	<0.002
Ferric chloride	>0.05	>0.05
Ferric nitrate	>0.05	–

(*Continued*)

TABLE 1.188 (*Continued*) Corrosion Rates of Aluminum at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Ferrous chloride	>0.05	–
Ferrous sulfate	<0.002	–
Fluorine	–	>0.05
Formaldehyde	<0.02	<0.002
Formic acid	<0.02	<0.02
Furfural	–	<0.02
Hydrazine	–	<0.002
Hydrobromic acid	>0.05	>0.05
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	>0.05	–
Hydrocyanic acid	<0.02	<0.002
Hydrofluoric acid (aerated)	>0.05	–
Hydrofluoric acid (air free)	>0.05	–
Hydrogen chloride	–	>0.05
Hydrogen fluoride	–	<0.02
Hydrogen iodide	–	>0.05
Hydrogen peroxide	<0.002	<0.002
Hydrogen sulfide	–	<0.002
Lactic acid	<0.02	<0.02
Lead acetate	–	>0.05
Lead chromate	>0.05	–
Lead nitrate	>0.05	–
Lead sulfate	>0.05	–
Lithium chloride	<0.05	–
Lithium hydroxide	>0.05	>0.05
Magnesium chloride	>0.05	–
Magnesium hydroxide	>0.05	>0.05
Magnesium sulfate	<0.02	<0.02
Maleic acid	<0.02	–
Malic acid	<0.02	<0.002
Mercuric chloride	>0.05	–
Mercurous nitrate	>0.05	>0.05
Mercury	–	>0.05
Methallylamine	–	<0.02
Methanol	–	<0.02
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.002
Methylamine	<0.02	<0.02
Methylene chloride	>0.05	<0.002
Monochloroacetic acid	>0.05	>0.05
Monorthanolamine	–	<0.02
Monoethalamine	<0.02	<0.02
Monoethylamine	<0.02	<0.02

(*Continued*)

TABLE 1.188 (*Continued*) Corrosion Rates of Aluminum at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Monosodium phosphate	>0.05	–
Nickel chloride	>0.05	>0.05
Nickel nitrate	>0.05	–
Nickel sulfate	>0.05	>0.05
Nitric acid	>0.05	<0.02
Nitric acid (red fuming)	–	<0.002
Nitric + hydrochloric acid	–	>0.05
Nitric + sulfuric acid	>0.05	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.002
Nitroglycerine	–	<0.002
Nitrotoluene	–	<0.02
Nitrous acid	<0.05	–
Oleic acid	–	<0.002
Oxalic acid	<0.02	<0.02
Phenol	–	<0.002
Phosphoric acid (aerated)	>0.05	<0.02
Phosphoric acid (air free)	>0.05	>0.05
Picric acid	>0.05	<0.02
Potassium bicarbonate	>0.05	<0.02
Potassium bromide	<0.02	–
Potassium carbonate	>0.05	>0.05
Potassium chlorate	<0.02	<0.02
Potassium chromate	<0.02	<0.02
Potassium cyanide	>0.05	–
Potassium dichromate	<0.002	<0.02
Potassium ferricyanide	<0.02	–
Potassium ferrocyanide	<0.002	<0.02
Potassium hydroxide	>0.05	–
Potassium hypochlorite	>0.05	–
Potassium iodide	<0.02	–
Potassium nitrate	<0.002	<0.02
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	<0.02
Potassium silicate	>0.05	<0.02
Propionic acid	<0.02	<0.02
Pyridine	<0.02	<0.02
Salicylic acid	>0.05	<0.02
Silicon tetrachloride (dry)	–	<0.02
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	>0.05	–
Silver chloride	>0.05	–

(*Continued*)

TABLE 1.188 (*Continued*) Corrosion Rates of Aluminum at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Silver nitrate	>0.05	–
Sodium acetate	<0.02	<0.002
Sodium bicarbonate	>0.05	<0.02
Sodium bisulfate	>0.05	–
Sodium bromide	<0.05	–
Sodium carbonate	>0.05	–
Sodium chloride	<0.05	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	>0.05	–
Sodium hypochlorite	>0.05	>0.05
Sodium metasilicate	>0.05	<0.02
Sodium nitrate	<0.002	<0.02
Sodium nitrite	<0.02	–
Sodium phosphate	>0.05	–
Sodium silicate	>0.05	<0.002
Sodium sulfate	<0.002	–
Sodium sulfide	>0.05	>0.05
Sodium sulfite	<0.02	–
Stannic chloride	>0.05	–
Stannous chloride	>0.05	–
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	<0.02
Sulfur dioxide	>0.05	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	>0.05	>0.05
Sulfuric acid (air free)	>0.05	>0.05
Sulfuric acid (fuming)	–	<0.02
Sulfurous acid	<0.02	<0.02
Tannic acid	<0.02	>0.05
Tartaric acid	<0.02	–
Tetraphosphoric acid	>0.05	>0.05
Trichloroacetic acid	>0.05	>0.05
Trichloroethylene	–	<0.002
Urea	<0.02	<0.02
Zinc chloride	>0.05	–
Zinc sulfate	<0.05	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.189 Corrosion Resistance of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Corrosion Resistance[b]
C10100 Oxygen-free electronic	99.99 Cu	F, R, W, T, P, S	G-E
C10200 Oxygen-free copper	99.95 Cu	F, R, W, T, P, S	G-E
C10300 Oxygen-free extra-low phosphorus	99.95 Cu, 0.003 P	F, R, T, P, S	G-E
C10400, C10500, C10700 Oxygen-free, silver-bearing	99.95 Cu[c]	F, R, W, S	G-E
C10800 Oxygen-free, low phosphorus	99.95 Cu, 0.009 P	F, R, T, P	G-E
CS11000 Electrolytic tough pitch copper	99.90 Cu, 0.04 O	F, R, W, T, P, S	G-E
C11100 Electrolytic tough pitch, anneal resistant	99.90 Cu, 0.04 O, 0.01 Cd	W	G-E
C11300, C11400, C11500, C11600 Silver-bearing tough pitch copper	99.90 Cu, 0.04 O, Ag[d]	F, R, W, T, S	G-E
C12000, C12100	99.9 Cu[e]	F, T, P	G-E
C12200 Phosphorus deoxidized copper, high residual phosphorus	99.90 Cu, 0.02 P	F, R, T, P	G-E
C12500, C12700, C12800, C12900, C13000 Fire-refined tough pitch with silver	99.88 Cu[f]	F, R, W, S	G-E
C14200 Phosphorus deoxidized, arsenical	99.68 Cu, 0.3 As, 0.02 P	F, R, T	G-E
C19200	98.97 Cu, 1.0 Fe, 0.03 P	F, T	G-E
C14300	99.9 Cu, 0.1 Cd	F	G-E
C14310	99.8 Cu, 0.2 Cd	F	G-E
C14500 Phosphorus deoxidized, tellurium bearing	99.5 Cu, 0.50 Te, 0.008 P	F, R, W, T	G-E
C14700 Sulfur bearing	99.6 Cu, 0.40 S	R, W	G-E
C15000 Zirconium copper	99.8 Cu, 0.15 Zr	R, W	G-E
C15500	99.75 Cu, 0.06 P, 0.11 Mg, Ag[g]	F	G-E
C16200 Cadmium copper	99.0 Cu, 1.0 Cd	F, R, W	G-E
C16500	98.6 Cu, 0.8 Cd, 0.6 Sn	F, R, W	G-E
C17000 Beryllium copper	99.5 Cu, 1.7 Be, 0.20 Co	F, R	G-E
C17200 Beryllium copper	99.5 Cu, 1.9 Be, 0.20 Co	F, R, W, T, P, S	G-E
C17300 Beryllium copper	99.5 Cu, 1.9 Be, 0.40 Pb	R	G-E
C17500 Copper–cobalt–beryllium alloy	99.5 Cu, 2.5 Co, 0.6 Be	F, R	G-E
C18200, C18400, C18500 Chromium copper	99.5 Cu[h]	F, W, R, S, T	G-E
C18700 Leaded copper	99.0 Cu, 1.0 Pb	R	G-E
C18900	98.75 Cu, 0.75 Sn, 0.3 Si, 0.20 Mn	R, W	G-E
C19000 Copper–nickel–phosphorus alloy	98.7 Cu, 1.1 Ni, 0.25 P	F, R, W	G-E
C19100 Copper–nickel–phosphorus–tellurium alloy	98.15 Cu, 1.1 Ni, 0.50 Te, 0.25 P	R, F	G-E
C19400	97.5 Cu, 2.4 Fe, 0.13 Zn, 0.03 P	F	G-E
C19500	97.0 Cu, 1.5 Fe, 0.6 Sn, 0.10 P, 0.80 Co	F	G-E
C21000 Gilding, 95%	95.0 Cu, 5.0 Zn	F, W	G-E
C22000 Commercial bronze, 90%	90.0 Cu, 10.0 Zn	F, R, W, T	G-E
C22600 Jewelry bronze, 87.5%	87.5 Cu, 12.5 Zn	F, W	G-E
C23000 Red brass, 85%	85.0 Cu, 15.0 Zn	F, W, T, P	G-E
C24000 Low brass, 80%	80.0 Cu, 20.0 Zn	F, W	F-E
C26000 Cartridge brass, 70%	70.0 Cu, 30.0 Zn	F, R, W, T	F-E
C26800, C27000 Yellow brass	65.0 Cu, 35.0 Zn	F, R, W	F-E

(*Continued*)

TABLE 1.189 (*Continued*) Corrosion Resistance of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Corrosion Resistance[b]
C28000 Muntz metal	60.0 Cu, 40.0 Zn	F, R, T	F-E
C31400 Leaded commercial bronze	89.0 Cu, 1.75 Pb, 9.25 Zn	F, R	G-E
C31600 Leaded commercial bronze, nickel-bearing	89.0 Cu, 1.9 Pb, 1.0 Ni, 8.1 Zn	F, R	G-E
C33000 Low-leaded brass tube	66.0 Cu, 0.5 Pb, 33.5 Zn	T	F-E
C33200 High-leaded brass tube	66.0 Cu, 1.6 Pb, 32.4 Zn	T	F-E
C33500 Low-leaded brass	65.0 Cu, 0.5 Pb, 34.5 Zn	F	F-E
C34000 Medium-leaded brass	65.0 Cu, 1.0 Pb, 34.0 Zn	F, R, W, S	F-E
C34200 High-leaded brass	64.5 Cu, 2.0 Pb, 33.5 Zn	F, R	F-E
C34900	62.2 Cu, 0.35 Pb, 37.45 Zn	R, W	F-E
C35000 Medium-leaded brass	62.5 Cu, 1.1 Pb, 36.4 Zn	F, R	F-E
C35300 High-leaded brass	62.0 Cu, 1.8 Pb, 36.2 Zn	F, R	F-E
C35600 Extra-high-leaded brass	63.0 Cu, 2.5 Pb, 34.5 Zn	F	F-E
C36000 Free-cutting brass	61.5 Cu, 3.0 Pb, 35.5 Zn	F, R, S	F-E
C36500 to C36800 Leaded Muntz metal	60.0 Cu[i], 0.6 Pb, 39.4 Zn	F	F-E
C37000 Free-cutting Muntz metal	60.0 Cu, 1.0 Pb, 39.0 Zn	T	F-E
C37700 Forging brass	59.0 Cu, 2.0 Pb, 39.0 Zn	R, S	F-E
C38500 Architectural bronze	57.0 Cu, 3.0 Pb, 40.0 Zn	R, S	F-E
C40500	95 Cu, 1 Sn, 4 Zn	F	G-E
C40800	95 Cu, 2 Sn, 3 Zn	F	G-E
C41100	91 Cu, 0.5 Sn, 8.5 Zn	F, W	G-E
C41300	90.0 Cu, 1.0 Sn, 9.0 Zn	F, R, W	G-E
C41500	91 Cu, 1.8 Sn, 7.2 Zn	F	G-E
C42200	87.5 Cu, 1.1 Sn, 11.4 Zn	F	G-E
C42500	88.5 Cu, 2.0 Sn, 9.5 Zn	F	G-E
C43000	87.0 Cu, 2.2 Sn, 10.8 Zn	F	G-E
C43400	85.0 Cu, 0.7 Sn, 14.3 Zn	F	G-E
C43500	81.0 Cu, 0.9 Sn, 18.1 Zn	F, T	G-E
C44300, C44400, C44500 Inhibited admiralty	71.0 Cu, 28.0 Zn, 1.0 Sn	F, W, T	G-E
C46400 to C46700 Naval brass	60.0 Cu, 39.25 Zn, 0.75 Sn	F, R, T, S	F-E
C48200 Naval brass, medium-leaded	60.5 Cu, 0.7 Pb, 0.8 Sn, 38.0 Zn	F, R, S	F-E
C48500 Leaded naval brass	60.0 Cu, 1.75 Pb, 37.5 Zn, 0.75 Sn	F, R, S	F-E
C50500 Phosphor bronze, 1.25% E	98.75 Cu, 1.25 Sn, trace P	F, W	G-E
C51000 Phosphor bronze, 5% A	95.0 Cu, 5.0 Sn, trace P	F, R, W, T	G-E
C51100	95.6 Cu, 4.2 Sn, 0.2 P	F	G-E
C52100 Phosphor bronze, 8% C	92.0 Cu, 8.0 Sn, trace P	F, R, W	G-E
C52400 Phosphor bronze, 10% D	90.0 Cu, 10.0 Sn, trace P	F, R, W	G-E
C54400 Free-cutting phosphor bronze	88.0 Cu, 4.0 Pb, 4.0 Zn, 4.0 Sn	F, R	G-E
C60800 Aluminum bronze, 5%	95.0 Cu, 5.0 Al	T	G-E
C61000	92.0 Cu, 8.0 Al	R, W	G-E
C61300	92.65 Cu, 0.35 Sn, 7.0 Al	F, R, T, P, S	G-E
C61400 Aluminum bronze, D	91.0 Cu, 7.0 Al, 2.0 Fe	F, R, W, T, P, S	G-E
C61500	90.0 Cu, 8.0 Al, 2.0 Ni	F	G-E

(*Continued*)

TABLE 1.189 (*Continued*) Corrosion Resistance of Wrought Coppers and Copper Alloys

UNS Number and Name	Nominal Composition (%)	Commercial Forms[a]	Corrosion Resistance[b]
C61800	89.0 Cu, 1.0 Fe, 10.0 Al	R	G-E
C61900	86.5 Cu, 4.0 Fe, 9.5 Al	F	G-E
C62300	87.0 Cu, 10.0 Al, 3.0 Fe	F, R	G-E
C62400	86.0 Cu, 3.0 Fe, 11.0 Al	F, R	G-E
C62500	82.7 Cu, 4.3 Fe, 13.0 Al	F, R	G-E
C63000	82.0 Cu, 3.0 Fe, 10.0 Al, 5.0 Ni	F, R	G-E
C63200	82.0 Cu, 4.0 Fe, 9.0 Al, 5.0 Ni	F, R	G-E
C63600	95.5 Cu, 3.5 Al, 1.0 Si	R, W	G-E
C63800	99.5 Cu, 2.8 Al, 1.8 Si, 0.40 Co	F	G-E
C64200	91.2 Cu, 7.0 Al	F, R	G-E
C65100 Low-silicon bronze, B	98.5 Cu, 1.5 Si	R, W, T	G-E
C65500 High-silicon bronze, A	97.0 Cu, 3.0 Si	F, R, W, T	G-E
C66700 Manganese brass	70.0 Cu, 28.8 Zn, 1.2 Mn	F, W	G-E
C67400	58.5 Cu, 36.5 Zn, 1.2 Al, 2.8 Mn, 1.0 Sn	F, R	F-E
C67500 Manganese bronze, A	58.5 Cu, 1.4 Fe, 39.0 Zn, 1.0 Sn, 0.1 Mn	R, S	F-E
C68700 Aluminum brass, arsenical	77.5 Cu, 20.5 Zn, 2.0 Al, 0.1 As	T	G-E
C68800	73.5 Cu, 22.7 Zn, 3.4 Al, 0.40 Co	F	G-E
C69000	73.3 Cu, 3.4 Al, 0.6 Ni, 22.7 Zn	F	G-E
C69400 Silicon red brass	81.5 Cu, 14.5 Zn, 4.0 Si	R	G-E
C70400	92.4 Cu, 1.5 Fe, 5.5 Ni, 0.6 Mn	F, T	G-E
C70600 Copper nickel, 10%	88.7 Cu, 1.3 Fe, 10.0 Ni	F, T	E
C71000 Copper nickel, 20%	79.00 Cu, 21.0 Ni	F, W, T	E
C71500 Copper nickel, 30%	70.0 Cu, 30.0 Ni	F, R, T	E
C71700	67.8 Cu, 0.7 Fe, 31.0 Ni, 0.5 Be	F, R, W	G-E
C72500	88.20 Cu, 9.5 Ni, 2.3 Sn	F, R, W, T	E
C73500	72.0 Cu, 18.0 Ni, 10.0 Zn	F, R, W, T	E
C74500 Nickel silver, 65–10	65.0 Cu, 25.0 Zn, 10.0 Ni	F, W	E
C75200 Nickel silver, 65–18	65.0 Cu, 17.0 Zn, 18.0 Ni	F, R, W	E
C75400 Nickel silver, 65–15	65.0 Cu, 20.0 Zn, 15.0 Ni	F	E
C75700 Nickel silver, 65–12	65.0 Cu, 23.0 Zn, 12.0 Ni	F, W	E
C76200	59.0 Cu, 29.0 Zn, 12.0 Ni	F, T	G-E
C77000 Nickel silver, 55–18	55.0 Cu, 27.0 Zn, 18.0 Ni	F, R, W	E
C72200	82.0 Cu, 16.0 Ni, 0.5 Cr, 0.8 Fe, 0.5 Mn	F, T	G-E
C78200 Leaded nickel silver, 65–8–2	65.0 Cu, 2.0 Pb, 25.0 Zn, 8.0 Ni	F	E

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Ed., ASM International, Materials Park, OH, 1993, pp. 442-454.

[a] F, flat products; R, rod; W, wire; T, tube; P, pipe; S, shapes.

[b] E, excellent; G, good; F, fair.

[c] C10400, 8 oz/ton Ag; C10500, 10 oz/ton; C10700, 25 oz/ton.

[d] C11300, 8 oz/ton Ag; C11400, 10 oz/ton; C11500, 16 oz/ton; C11600, 25 oz/ton.

[e] C12000, 0.008 P; C12100, 0.008 P and 4 oz/ton Ag.

[f] C12700, 8 oz/ton Ag; C12800, 10 oz/ton; C12900, 16 oz/ton; C13000, 25 oz/ton.

[g] 8.30 oz/ton Ag.

[h] C18200, 0.9 Cr; C18400, 0.8 Cr; C18500, 0.7 Cr.

[i] Rod, 61.0 Cu min.

TABLE 1.190 Corrosion Rates of 70–30 Brass at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	<0.02	<0.002
Acetic acid (aerated)	>0.05	>0.05
Acetic acid (air free)	>0.05	>0.05
Acetic anhydride	–	>0.05
Acetone	<0.002	<0.002
Acetylene	–	<0.002
Acrolein	<0.02	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.002	<0.002
Alcohol (methyl)	<0.02	<0.02
Alcohol (allyl)	–	<0.02
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (isopropyl)	–	<0.02
Allylamine	–	>0.05
Allyl chloride	–	<0.02
Allyl sulfide	–	>0.05
Aluminum acetate	–	<0.02
Aluminum chloride	>0.05	>0.05
Aluminum fluoride	>0.05	–
Aluminum fluorosilicate	–	<0.02
Aluminum hydroxide	<0.02	–
Aluminum potassium sulfate	>0.05	>0.05
Aluminum sulfate	<0.02	<0.05
Ammonia	>0.05	<0.002
Ammonium acetate	–	>0.05
Ammonium bicarbonate	>0.05	–
Ammonium bromide	>0.05	–
Ammonium carbonate	>0.05	–
Ammonium chloride	>0.05	>0.05
Ammonium citrate	>0.05	–
Ammonium nitrate	>0.05	>0.05
Ammonium sulfate	>0.05	<0.02
Ammonium sulfite	>0.05	>0.05
Ammonium thiocyanate	>0.05	–
Amyl acetate	<0.02	<0.02
Amyl chloride	–	<0.02
Aniline	–	>0.05
Aniline hydrochloride	>0.05	–
Anthracine	–	<0.02
Antimony trichloride	>0.05	–

(*Continued*)

TABLE 1.190 (*Continued*) Corrosion Rates of 70–30 Brass at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Barium carbonate	<0.02	<0.02
Barium chloride	>0.05	<0.02
Barium hydroxide	>0.05	–
Barium nitrate	>0.05	–
Barium peroxide	>0.05	–
Benzaldehyde	>0.05	<0.02
Benzene	<0.02	<0.02
Benzoic acid	<0.02	<0.02
Boric acid	<0.02	<0.02
Bromic acid	>0.05	>0.05
Bromine (dry)	–	<0.02
Bromine (wet)	–	>0.05
Butyric acid	<0.05	–
Cadmium chloride	>0.05	–
Cadmium sulfate	<0.02	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02
Calcium bromide	<0.02	<0.02
Calcium chlorate	>0.05	<0.02
Calcium chloride	<0.02	<0.02
Calcium hydroxide	<0.02	–
Calcium hypochlorite	<0.02	–
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	–	<0.05
Carbon acid (air free)	–	>0.05
Chloroacetic acid	>0.05	>0.05
Chlorine gas	–	>0.05
Chloroform (dry)	–	<0.02
Chromic acid	>0.05	>0.05
Chromic hydroxide	–	<0.02
Chromic sulfates	<0.02	–
Citric acid	>0.05	<0.02
Copper nitrate	>0.05	>0.05
Copper sulfate	>0.05	>0.05
Diethylene glycol	–	<0.002
Ethyl chloride	–	<0.002
Ethylene glycol	–	<0.02
Ethylene oxide	–	>0.05
Fatty acids	–	<0.05
Ferric chloride	>0.05	<0.02
Ferric nitrate	>0.05	–

(*Continued*)

TABLE 1.190 (*Continued*) Corrosion Rates of 70–30 Brass at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Ferrous chloride	>0.05	–
Ferrous sulfate	>0.05	<0.05
Fluorine	–	<0.02
Formaldehyde	<0.002	<0.02
Formic acid	<0.05	<0.02
Furfural	<0.02	<0.02
Hydrazine	>0.05	–
Hydrobromic acid	>0.05	>0.05
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	>0.05	–
Hydrocyanic acid	>0.05	<0.02
Hydrofluoric acid (aerated)	>0.05	–
Hydrofluoric acid (air free)	>0.05	<0.02
Hydrogen chloride	–	<0.02
Hydrogen fluoride	–	<0.02
Hydrogen iodide	–	>0.05
Hydrogen peroxide	>0.05	>0.05
Hydrogen sulfide	<0.02	<0.02
Lactic acid	<0.05	<0.05
Lead acetate		<0.05
Lead chromate	–	<0.02
Lead sulfate	–	<0.02
Lithium chloride	<0.02 (30%)	–
Lithium hydroxide	>0.05	–
Magnesium chloride	<0.02	–
Magnesium hydroxide	<0.02	<0.02
Magnesium sulfate	<0.02	<0.02
Maleic acid	<0.02	–
Mercuric chloride	>0.05	>0.05
Mercurous nitrate	>0.05	>0.05
Mercury	–	>0.05
Methallylamine	–	>0.05
Methanol	<0.02	<0.02
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylamine	–	>0.05
Methylene chloride	–	<0.002
Monochloroacetic acid	>0.05	>0.05
Monorthanolamine	–	>0.05
Monoethalamine	–	>0.05
Monoethylamine	–	>0.05
Monosodium phosphate	<0.02	–

(*Continued*)

TABLE 1.190 (*Continued*) Corrosion Rates of 70–30 Brass at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Nickel chloride	>0.05	–
Nickel nitrate	<0.05	–
Nickel sulfate	<0.05	<0.02
Nitric acid	>0.05	>0.05
Nitric acid (red fuming)	–	>0.05
Nitric + hydrochloric acid	–	>0.05
Nitric + sulfuric acid	>0.05	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.02
Nitroglycerine	–	<0.02
Nitrotoluene	–	<0.02
Nitrous acid	–	>0.05
Oleic acid	>0.05	<0.02
Oxalic acid	<0.02	<0.05
Phenol	–	<0.002
Phosphoric acid (aerated)	>0.05	>0.05
Phosphoric acid (air free)	<0.02	>0.05
Picric acid	>0.05	>0.05
Potassium bicarbonate	<0.02	<0.02
Potassium bromide	<0.02	<0.02
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	<0.05
Potassium chromate	<0.02	<0.02
Potassium cyanide	>0.05	>0.05
Potassium dichromate	<0.02	–
Potassium ferricyanide	<0.02	–
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	<0.02	–
Potassium hypochlorite	>0.05	–
Potassium nitrate	<0.02	<0.02
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	–
Potassium silicate	<0.02	<0.02
Propionic acid	<0.02	–
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	>0.05	–
Silver chloride	>0.05	–
Silver nitrate	>0.05	–
Sodium acetate	<0.02	–

(*Continued*)

TABLE 1.190 (*Continued*) Corrosion Rates of 70–30 Brass at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Sodium bicarbonate	<0.02	–
Sodium bisulfate	>0.05	<0.05
Sodium bromide	<0.05	–
Sodium carbonate	>0.05	–
Sodium chloride	<0.05	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	>0.05	–
Sodium hypochlorite	>0.05	>0.05
Sodium metasilicate	<0.02	<0.02
Sodium nitrate	<0.05	<0.05
Sodium nitrite	<0.02	–
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.02	>0.05
Sodium sulfide	<0.05	>0.05
Sodium sulfite	>0.05	>0.05
Stannic chloride	>0.05	–
Stannous chloride	>0.05	–
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	<0.02
Sulfur dioxide	>0.05	<0.05
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	>0.05	>0.05
Sulfuric acid (air free)	<0.05	–
Sulfuric acid (fuming)	–	>0.05
Sulfurous acid	<0.02	>0.05
Tannic acid	–	<0.05
Tartaric acid	<0.05	–
Tetraphosphoric acid	>0.05	<0.05
Trichloroacetic acid	>0.05	>0.05
Trichloroethylene	–	<0.02
Urea	<0.02	–
Zinc chloride	>0.05	–
Zinc sulfate	<0.05	<0.02

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.191 Corrosion Rates of Copper, Sn-Braze, Al-Braze at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	<0.002	<0.002
Acetic acid (aerated)	>0.05	<0.02
Acetic acid (air free)	<0.002	<0.002
Acetic anhydride	–	<0.02
Acetone	<0.002	<0.002
Acetylene	–	<0.002
Acrolein	<0.02	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.002	<0.002
Alcohol (methyl)	<0.02	<0.02
Alcohol (allyl)	–	<0.02
Alcohol (amyl)	–	<0.002
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.02
Allylamine	–	>0.05
Allyl chloride	–	<0.02
Allyl sulfide	–	>0.05
Aluminum acetate	<0.02	<0.02
Aluminum chloride	<0.02	<0.02
Aluminum fluoride	<0.02	–
Aluminum fluorosilicate	–	<0.02
Aluminum formate	–	<0.02
Aluminum hydroxide	<0.02	–
Aluminum potassium sulfate	<0.02	<0.02
Aluminum sulfate	<0.02	<0.002
Ammonia	>0.05	<0.002
Ammonium acetate	–	>0.05
Ammonium bicarbonate	>0.05	–
Ammonium bromide	>0.05	–
Ammonium carbonate	>0.05	–
Ammonium chloride	>0.05	>0.05
Ammonium citrate	>0.05	–
Ammonium nitrate	>0.05	>0.05
Ammonium sulfate	<0.05	<0.02
Ammonium sulfite	>0.05	>0.05
Ammonium thiocyanate	>0.05	–
Amyl acetate	<0.02	<0.02
Amyl chloride	<0.02	<0.002
Aniline	–	>0.05

(*Continued*)

TABLE 1.191 (*Continued*) Corrosion Rates of Copper, Sn-Braze, Al-Braze at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Aniline hydrochloride	>0.05	–
Anthracine	–	<0.02
Antimony trichloride	>0.05	<0.05
Barium carbonate	<0.02	<0.02
Barium chloride	<0.02	<0.02
Barium hydroxide	>0.05	–
Barium nitrate	>0.05	–
Barium peroxide	>0.05	–
Benzaldehyde	>0.05	<0.02
Benzene	<0.002	<0.02
Benzoic acid	<0.02	<0.02
Boric acid	<0.02	<0.02
Bromic acid	>0.05	>0.05
Bromine (dry)	–	<0.02
Bromine (wet)	–	>0.05
Butyric acid	<0.05	<0.02
Cadmium chloride	<0.02	–
Cadmium sulfate	<0.02	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02
Calcium bromide	<0.02	<0.02
Calcium chlorate	<0.02	–
Calcium chloride	<0.002	<0.02
Calcium hydroxide	<0.02	–
Calcium hypochlorite	<0.02	–
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	–	<0.002
Carbon acid (air free)	<0.02	<0.02
Chloroacetic acid	>0.05	>0.05
Chlorine gas	–	<0.02
Chloroform (dry)	–	<0.002
Chromic acid	>0.05	–
Chromic hydroxide	–	<0.02
Chromic sulfates	<0.02	<0.05
Citric acid	<0.05	<0.02
Copper nitrate	>0.05	>0.05
Copper sulfate	>0.05	>0.05
Diethylene glycol	–	<0.002
Ethyl chloride	<0.02	<0.002

(*Continued*)

TABLE 1.191 (*Continued*) Corrosion Rates of Copper, Sn-Braze, Al-Braze at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Ethylene glycol	<0.02	<0.02
Ethylene oxide	–	>0.05
Fatty acids	–	<0.05
Ferric chloride	>0.05	<0.02
Ferric nitrate	>0.05	–
Ferrous chloride	<0.02	<0.02
Ferrous sulfate	<0.02	<0.02
Fluorine	–	<0.002
Formaldehyde	<0.002	<0.002
Formic acid	<0.02	<0.02
Furfural	<0.02	<0.02
Hydrazine	>0.05	–
Hydrobromic acid	>0.05	<0.02
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	>0.05	–
Hydrocyanic acid	>0.05	<0.02
Hydrofluoric acid (aerated)	<0.02	<0.02
Hydrofluoric acid (air free)	<0.02	<0.02
Hydrogen chloride	–	<0.02
Hydrogen fluoride	–	<0.02
Hydrogen iodide	–	<0.02
Hydrogen peroxide	>0.05	>0.05
Hydrogen sulfide	<0.02	<0.02
Lactic acid	<0.002	<0.02
Lead acetate	<0.05	–
Lead chromate	–	<0.02
Lead sulfate	–	<0.02
Lithium chloride	<0.02 (30%)	–
Lithium hydroxide	>0.05	–
Magnesium chloride	<0.02	<0.02
Magnesium hydroxide	<0.02	<0.02
Magnesium sulfate	<0.002	<0.02
Maleic acid	<0.02	<0.02
Mercuric chloride	>0.05	>0.05
Mercurous nitrate	>0.05	>0.05
Mercury	–	>0.05
Methallylamine	–	>0.05
Methanol	<0.02	<0.02
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02

(*Continued*)

TABLE 1.191 (*Continued*) Corrosion Rates of Copper, Sn-Braze, Al-Braze at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Methylamine	–	>0.05
Methylene chloride	<0.02	<0.002
Monochloroacetic acid	>0.05	>0.05
Monorthanolamine	–	>0.05
Monoethalamine	–	>0.05
Monoethylamine	–	>0.05
Monosodium phosphate	<0.02	–
Nickel chloride	>0.05	–
Nickel nitrate	<0.05	–
Nickel sulfate	<0.02	<0.02
Nitric acid	>0.05	>0.05
Nitric acid (red fuming)	–	>0.05
Nitric + hydrochloric acid	–	>0.05
Nitric + hydrofluoric acid	–	>0.05
Nitric + sulfuric acid	>0.05	>0.05
Nitrobenzene	–	<0.02
Nitroglycerine	–	<0.02
Nitrotoluene	–	<0.02
Nitrous acid	–	>0.05
Oleic acid	–	<0.002
Oxalic acid	<0.02	<0.05
Phenol	–	<0.002
Phosphoric acid (aerated)	>0.05	>0.05
Phosphoric acid (air free)	<0.02	–
Picric acid	>0.05	>0.05
Potassium bicarbonate	<0.02	<0.02
Potassium bromide	<0.02	<0.02
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	<0.05
Potassium chromate	<0.02	–
Potassium cyanide	>0.05	>0.05
Potassium dichromate	<0.02	–
Potassium ferricyanide	<0.02	<0.02
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	<0.02	–
Potassium hypochlorite	<0.02	–
Potassium iodide	<0.02	<0.02
Potassium nitrate	<0.02	<0.002
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	<0.02

(*Continued*)

TABLE 1.191 (*Continued*) Corrosion Rates of Copper, Sn-Braze, Al-Braze at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Potassium silicate	<0.02	<0.02
Propionic acid	<0.02	<0.02
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Salicylic acid	–	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	>0.05	–
Silver chloride	>0.05	<0.02
Silver nitrate	>0.05	–
Sodium acetate	<0.02	<0.02
Sodium bicarbonate	<0.02	<0.02
Sodium bisulfate	–	<0.02
Sodium bromide	<0.02	<0.05
Sodium carbonate	<0.02	–
Sodium chloride	<0.02	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.002	–
Sodium hypochlorite	>0.05	–
Sodium metasilicate	<0.02	<0.02
Sodium nitrate	<0.02	<0.05
Sodium nitrite	<0.02	–
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.02	<0.02
Sodium sulfide	>0.05	>0.05
Sodium sulfite	<0.02	<0.05
Stannic chloride	>0.05	–
Stannous chloride	>0.05	–
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	<0.02
Sulfur dioxide	<0.02	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	>0.05	>0.05
Sulfuric acid (air free)	<0.02	–
Sulfuric acid (fuming)	–	>0.05
Sulfurous acid	<0.02	<0.05
Tannic acid	<0.02	<0.02
Tartaric acid	<0.02	<0.02
Tetraphosphoric acid	–	<0.05

(*Continued*)

TABLE 1.191 (*Continued*) Corrosion Rates of Copper, Sn-Braze, Al-Braze at 70°F (=21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Trichloroacetic acid	>0.05	>0.05
Trichloroethylene	–	<0.002
Urea	<0.02	–
Zinc chloride	<0.02	–
Zinc sulfate	<0.02	<0.02

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.192 Corrosion Rates of Silicon Bronze at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	<0.02	<0.002
Acetic acid (aerated)	>0.05	>0.05
Acetic acid (air free)	>0.05	<0.02
Acetic anhydride	–	<0.02
Acetone	<0.002	<0.002
Acetylene	–	<0.002
Acrolein	<0.02	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.002	<0.002
Alcohol (methyl)	<0.02	<0.02
Alcohol (allyl)	–	<0.02
Alcohol (amyl)	–	<0.02
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (isopropyl)	–	<0.02
Allylamine	–	>0.05
Allyl chloride	–	<0.02
Allyl sulfide	–	>0.05
Aluminum acetate	<0.02	<0.02
Aluminum chloride	<0.02	<0.02
Aluminum fluoride	<0.02	–
Aluminum fluorosilicate	–	<0.02
Aluminum formate	<0.02	<0.02
Aluminum hydroxide	<0.02	<0.02

(*Continued*)

TABLE 1.192 (*Continued*) Corrosion Rates of Silicon Bronze at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Aluminum potassium sulfate	<0.02	<0.02
Aluminum sulfate	<0.02	<0.02
Ammonia	>0.05	<0.002
Ammonium acetate	–	>0.05
Ammonium bicarbonate	>0.05	–
Ammonium bromide	>0.05	–
Ammonium carbonate	>0.05	<0.02
Ammonium chloride	>0.05	>0.05
Ammonium citrate	>0.05	–
Ammonium nitrate	>0.05	>0.05
Ammonium sulfate	<0.02	<0.02
Ammonium sulfite	>0.05	>0.05
Ammonium thiocyanate	>0.05	–
Amyl acetate	<0.02	<0.02
Amyl chloride	–	<0.002
Aniline hydrochloride	>0.05	–
Anthracine	–	<0.02
Antimony trichloride	>0.05	–
Barium carbonate	<0.02	<0.02
Barium chloride	<0.02	<0.02
Barium hydroxide	>0.05	–
Barium nitrate	>0.05	–
Barium peroxide	>0.05	–
Benzaldehyde	>0.05	<0.02
Benzene	<0.02	<0.02
Benzoic acid	<0.02	<0.02
Boric acid	<0.02	<0.02
Bromic acid	>0.05	>0.05
Bromine (dry)	–	<0.02
Bromine (wet)	–	>0.05
Butyric acid	<0.02	<0.02
Cadmium chloride	<0.02	–
Cadmium sulfate	<0.02	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02
Calcium bromide	<0.02	<0.02
Calcium chlorate	<0.02	–
Calcium chloride	<0.02	<0.02
Calcium hydroxide	<0.02	–
Calcium hypochlorite	<0.02	–

(*Continued*)

TABLE 1.192 (*Continued*) Corrosion Rates of Silicon Bronze at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	–	<0.002
Carbon acid (air free)	<0.02	<0.02
Chloroacetic acid	–	<0.05
Chlorine gas	–	<0.02
Chloroform (dry)	–	<0.02
Chromic acid	>0.05	–
Chromic hydroxide	–	<0.02
Chromic sulfates	<0.02	–
Citric acid	<0.05	<0.02
Copper nitrate	>0.05	<0.05
Copper sulfate	<0.02	>0.05
Diethylene glycol	–	<0.002
Ethyl chloride	–	<0.002
Ethylene glycol	–	<0.02
Ethylene oxide	–	>0.05
Fatty acids	–	<0.05
Ferric chloride	>0.05	<0.02
Ferric nitrate	>0.05	–
Ferrous chloride	<0 .05	<0.02
Ferrous sulfate	<0.02	<0.02
Fluorine	–	>0.05
Formaldehyde	<0.002	<0.02
Formic acid	<0.02	<0.02
Furfural	<0.02	<0.02
Hydrazine	>0.05	–
Hydrobromic acid	<0.02	<0.02
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	<0.02	–
Hydrocyanic acid	>0.05	<0.02
Hydrofluoric acid (aerated)	>0.05	–
Hydrofluoric acid (air free)	<0.02	<0.02
Hydrogen chloride	–	<0.02
Hydrogen fluoride	–	<0.02
Hydrogen iodide	–	<0.02
Hydrogen peroxide	>0.05	>0.05
Hydrogen sulfide	<0.02	<0.02
Lactic acid	<0.05	<0.02
Lead acetate	–	<0.02
Lead chromate	–	<0.02

(*Continued*)

TABLE 1.192 (*Continued*) Corrosion Rates of Silicon Bronze at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Lead sulfate	–	<0.02
Lithium chloride	<0.02 (30%)	–
Lithium hydroxide	>0.05	–
Magnesium chloride	<0.02	<0.02
Magnesium hydroxide	<0.02	<0.02
Magnesium sulfate	<0.002	<0.02
Maleic acid	<0.02	–
Mercuric chloride	>0.05	>0.05
Mercurous nitrate	>0.05	–
Mercury	–	>0.05
Methallylamine	–	>0.05
Methanol	<0.02	<0.02
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylamine	–	>0.05
Methylene chloride	<0.02	<0.02
Monochloroacetic acid	>0.05	>0.05
Monorthanolamine	–	>0.05
Monoethalamine	–	>0.05
Monoethylamine	–	>0.05
Monosodium phosphate	<0.02	–
Nickel chloride	>0.05	<0.02
Nickel nitrate	<0.05	–
Nickel sulfate	<0.02	<0.02
Nitric acid	>0.05	>0.05
Nitric acid (red fuming)	–	>0.05
Nitric + hydrochloric acid	–	>0.05
Nitric + sulfuric acid	>0.05	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.02
Nitroglycerine	–	<0.02
Nitrotoluene	–	<0.02
Nitrous acid	–	>0.05
Oleic acid	–	<0.02
Oxalic acid	<0.02	<0.02
Phenol	–	<0.002
Phosphoric acid (aerated)	>0.05	>0.05
Phosphoric acid (air free)	<0.02	–
Picric acid	>0.05	>0.05
Potassium bicarbonate	<0.02	<0.02
Potassium bromide	<0.02	<0.02

(*Continued*)

TABLE 1.192 (*Continued*) Corrosion Rates of Silicon Bronze at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	<0.05
Potassium chromate	<0.02	<0.02
Potassium cyanide	>0.05	>0.05
Potassium dichromate	<0.02	–
Potassium ferricyanide	<0.02	–
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	<0.02	>0.05
Potassium hypochlorite	>0.05	–
Potassium iodide	<0.02	<0.02
Potassium nitrate	<0.02	<0.02
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	<0.02
Potassium silicate	<0.02	<0.02
Propionic acid	<0.02	–
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Salicylic acid	–	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	>0.05	–
Silver chloride	>0.05	–
Silver nitrate	>0.05	–
Sodium acetate	<0.02	–
Sodium bicarbonate	<0.02	–
Sodium bisulfate	<0.02	<0.02
Sodium bromide	<0.02	–
Sodium carbonate	<0.02	<0.02
Sodium chloride	<0.02	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.02	–
Sodium hypochlorite	<0.02	>0.05
Sodium metasilicate	<0.02	<0.02
Sodium nitrate	<0.02	<0.02
Sodium nitrite	<0.02	–
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.02	<0.02
Sodium sulfide	>0.05	>0.05
Sodium sulfite	<0.02	<0.02
Stannic chloride	>0.05	>0.05

(*Continued*)

TABLE 1.192 (*Continued*) Corrosion Rates of Silicon Bronze at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Stannous chloride	<0.02	<0.02
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	<0.02
Sulfur dioxide	–	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	>0.05	>0.05
Sulfuric acid (air free)	<0.02	–
Sulfuric acid (fuming)	–	>0.05
Sulfurous acid	<0.02	<0.02
Tannic acid	<0.02	<0.02
Tartaric acid	<0.05	<0.02
Tetraphosphoric acid	>0.05	<0.05
Trichloroacetic acid	–	<0.05
Trichloroethylene	–	<0.02
Urea	<0.02	–
Zinc chloride	<0.02	>0.05
Zinc sulfate	<0.02	<0.02

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other% corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.193 Corrosion Rates of Hastelloy at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	–	<0.002
Acetic acid (aerated)	<0.002	<0.002
Acetic acid (air free)	<0.002	<0.002
Acetic anhydride	<0.002	<0.002
Acetoacetic acid	<0.02	<0.02
Acetone	<0.002	<0.002
Acetylene	–	<0.002
Acrolein	–	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.002	<0.002
Alcohol (methyl)	<0.002	<0.002
Alcohol (allyl)	–	<0.02

(*Continued*)

TABLE 1.193 (*Continued*) Corrosion Rates of Hastelloy at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Alcohol (benzyl)	<0.02	<0.02
Alcohol (isopropyl)	–	<0.02
Allyl chloride	–	<0.02
Aluminum acetate	<0.02	<0.02
Aluminum chlorate	<0.02	<0.02
Aluminum chloride	<0.002	<0.002
Aluminum fluoride	<0.02	–
Aluminum fluorosilicate	–	<0.02
Aluminum formate	<0.02	<0.02
Aluminum hydroxide	<0.02	–
Aluminum nitrate	<0.02	–
Aluminum potassium sulfate	<0.02	–
Aluminum sulfate	<0.002	<0.02
Ammonia	<0.002	<0.002
Ammonium acetate	<0.002	<0.002
Ammonium bromide	<0.02	–
Ammonium carbonate	>0.05	–
Ammonium chloride	<0.002	<0.02
Ammonium citrate	<0.02	–
Ammonium formate	<0.002	–
Ammonium nitrate	<0.02	–
Ammonium sulfate	<0.02	<0.02
Amyl acetate	<0.002	<0.002
Amyl chloride	–	<0.02
Aniline	–	<0.02
Aniline hydrochloride	<0.02	<0.05
Anthracine	–	<0.02
Antimony trichloride	>0.05	<0.002
Barium carbonate	–	<0.02
Barium chloride	<0.02	<0.02
Barium hydroxide	<0.02	<0.02
Barium nitrate	<0.02	<0.02
Barium oxide	–	<0.02
Benzaldehyde	–	<0.02
Benzene	<0.02	<0.02
Benzoic acid	<0.002	–
Boric acid	<0.002	<0.002
Bromine (dry)	–	<0.002
Bromine (wet)	–	<0.002
Butyric acid	<0.002	<0.002

(*Continued*)

TABLE 1.193 (*Continued*) Corrosion Rates of Hastelloy at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Cadmium chloride	<0.02	–
Cadmium sulfate	<0.002	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02
Calcium bromide	<0.02	<0.02
Calcium chlorate	<0.02	<0.02
Calcium chloride	<0.002	<0.002
Calcium hydroxide	<0.002	–
Calcium hypochlorite	<0.02	<0.02
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	<0.002	<0.002
Carbon acid (air free)	<0.002	<0.002
Chloroacetic acid	<0.02	<0.002
Chlorine gas	–	<0.02
Chloroform (dry)	–	<0.02
Chromic acid	<0.02	<0.02
Chromic hydroxide	–	<0.02
Chromic sulfates	<0.02	<0.02
Citric acid	<0.002	<0.002
Copper nitrate	<0.02	<0.02
Copper sulfate	<0.002	<0.002
Diethylene glycol	–	<0.02
Ethyl chloride	–	<0.02
Ethylene oxide	–	<0.002
Fatty acids	–	<0.002
Ferric chloride	<0.002	<0.02
Ferric nitrate	<0.002	–
Ferrous chloride	<0.02	<0.02
Ferrous sulfate	<0.02	<0.02
Fluorine	–	<0.02
Formaldehyde	<0.02	<0.02
Formic acid	<0.002	<0.002
Furfural	<0.02	<0.02
Hydrazine	–	<0.002
Hydrobromic acid	<0.02	–
Hydrochloric acid (aerated)	<0.02	–
Hydrochloric acid (air free)	<0.02	–
Hydrocyanic acid	–	<0.02
Hydrofluoric acid (aerated)	<0.02	<0.02

(*Continued*)

TABLE 1.193 (*Continued*) Corrosion Rates of Hastelloy at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Hydrofluoric acid (air free)	<0.02	<0.05
Hydrogen chloride	–	<0.002
Hydrogen fluoride	–	<0.02
Hydrogen iodide	–	<0.02
Hydrogen peroxide	<0.002	<0.002
Hydrogen sulfide	–	<0.002
Lactic acid	<0.02	<0.02
Lead acetate	<0.02	>0.05
Lead chromate	–	<0.02
Lead nitrate	–	<0.02
Lead sulfate	–	<0.02
Lithium chloride	<0.002 (30%)	–
Lithium hydroxide	<0.02	<0.02
Magnesium chloride	<0.002	<0.002
Magnesium hydroxide	<0.02	–
Magnesium sulfate	<0.002	<0.002
Maleic acid	<0.002	<0.02
Manganous chloride	<0.02	–
Mercuric chloride	<0.02	–
Mercurous nitrate	<0.02	<0.02
Mercury	–	<0.02
Methallylamine	–	<0.02
Methanol	<0.002	<0.02
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.002
Methylene chloride	<0.02	–
Monochloroacetic acid	–	<0.002
Monosodium phosphate	<0.02	–
Nickel chloride	<0.002	<0.002
Nickel nitrate	<0.02	<0.02
Nickel sulfate	<0.02	<0.02
Nitric acid	<0.002	–
Nitric acid (red fuming)	–	<0.02
Nitric + hydrochloric acid	–	>0.05
Nitric + hydrofluoric acid	–	<0.05
Nitrobenzene	–	<0.02
Oleic acid	–	<0.02
Oxalic acid	<0.02	<0.02
Phenol	–	<0.002
Phosphoric acid (aerated)	<0.002	<0.002

(*Continued*)

TABLE 1.193 (*Continued*) Corrosion Rates of Hastelloy at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Phosphoric acid (air free)	<0.002	<0.002
Picric acid	<0.02	<0.02
Potassium bicarbonate	<0.02	–
Potassium bromide	<0.002	<0.02
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	–
Potassium chromate	<0.002	–
Potassium cyanide	<0.02	–
Potassium dichromate	<0.02	–
Potassium ferricyanide	<0.02	–
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	<0.02	–
Potassium hypochlorite	<0.02	<0.02
Potassium iodide	<0.02	<0.02
Potassium nitrate	<0.02	–
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.002	<0.002
Potassium silicate	<0.02	<0.02
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Salicylic acid	–	<0.02
Silicon tetrachloride (dry)	–	<0.02
Silicon tetrachloride (wet)	–	<0.02
Silver bromide	<0.002	–
Silver chloride	<0.02	–
Silver nitrate	<0.002	–
Sodium acetate	<0.02	–
Sodium bicarbonate	<0.02	–
Sodium bisulfate	<0.02	<0.02
Sodium bromide	<0.02	–
Sodium carbonate	<0.02	<0.02
Sodium chloride	<0.02	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.002	<0.002
Sodium hypochlorite	<0.002	<0.05
Sodium metasilicate	<0.002	<0.002
Sodium nitrate	<0.02	–
Sodium nitrite	<0.02	–
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02

(*Continued*)

TABLE 1.193 (*Continued*) Corrosion Rates of Hastelloy at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Sodium sulfate	<0.02	<0.002
Sodium sulfide	<0.02	–
Sodium sulfite	<0.02	–
Stannic chloride	<0.02	<0.02
Stannous chloride	<0.02	<0.02
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	–
Sulfur dioxide	<0.002	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	<0.002	<0.02
Sulfuric acid (air free)	<0.002	<0.02
Sulfuric acid (fuming)	–	<0.002
Sulfurous acid	<0.02	<0.02
Tannic acid	<0.02	–
Tartaric acid	<0.02	<0.02
Tetraphosphoric acid	–	<0.02
Trichloroacetic acid	<0.02	<0.02
Trichloroethylene	–	<0.002
Urea	<0.02	–
Zinc chloride	<0.02	<0.02
Zinc sulfate	<0.02	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other% corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.194 Corrosion Rates of Inconel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	–	<0.002
Acetic acid (aerated)	<0.02	<0.02
Acetic acid (air free)	<0.02	<0.02
Acetic anhydride	–	<0.02
Acetone	<0.002	<0.002
Acetylene	–	<0.002
Acrolein	–	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.002	<0.002

(*Continued*)

TABLE 1.194 (*Continued*) Corrosion Rates of Inconel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Alcohol (methyl)	<0.002	<0.002
Alcohol (allyl)	–	<0.02
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.02
Allyl chloride	–	<0.02
Aluminum acetate	<0.02	–
Aluminum chlorate	<0.02	<0.02
Aluminum chloride	>0.05	–
Aluminum fluorosilicate	–	<0.02
Aluminum formate	<0.02	<0.02
Aluminum nitrate	<0.02	–
Aluminum sulfate	<0.02	–
Ammonia	<0.002	<0.002
Ammonium acetate	<0.002	<0.002
Ammonium carbonate	>0.05	<0.02
Ammonium chloride	<0.02	<0.02
Ammonium citrate	<0.02	<0.02
Ammonium formate	<0.02	<0.02
Ammonium sulfate	<0.02	–
Ammonium sulfite	>0.05	–
Amyl acetate	–	<0.02
Aniline hydrochloride	>0.05	–
Anthracine	–	<0.02
Barium chloride	<0.02	<0.02
Barium hydroxide	<0.02	<0.02
Barium nitrate	<0.02	<0.02
Barium oxide	–	<0.02
Benzaldehyde	–	<0.02
Benzene	<0.002	<0.02
Benzoic acid	<0.02	–
Boric acid	<0.02	<0.02
Bromic acid	>0.05	>0.05
Bromine (dry)	–	<0.002
Bromine (wet)	–	>0.05
Butyric acid	<0.05	<0.05
Cadmium sulfate	<0.002	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02

(*Continued*)

TABLE 1.194 (*Continued*) Corrosion Rates of Inconel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Calcium bromide	<0.02	<0.02
Calcium chlorate	<0.02	–
Calcium chloride	<0.002	<0.02
Calcium hydroxide	<0.02	<0.02
Calcium hypochlorite	>0.05	–
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	<0.002	<0.002
Carbon acid (air free)	<0.02	<0.002
Chloroacetic acid	–	<0.05
Chlorine gas	–	<0.02
Chloroform (dry)	–	<0.002
Chromic acid	<0.02	–
Chromic hydroxide	–	<.02
Citric acid	<0.02	<0.02
Copper nitrate	>0.05	–
Copper sulfate	<0.02	–
Diethylene glycol	–	<0.02
Ethyl chloride	–	<0.002
Ethylene glycol	–	<0.02
Ethylene oxide	–	<0.02
Fatty acids	–	<0.02
Ferric chloride	<0.05	>0.05
Ferric nitrate	>0.05	–
Ferrous chloride	>0.05	–
Ferrous sulfate	<0.02	–
Fluorine	–	<0.002
Formaldehyde	<0.002	<0.02
Formic acid	<0.02	<0.02
Furfural	<0.02	<0.02
Hydrazine	–	<0.002
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	>0.05	–
Hydrocyanic acid	–	<0.02
Hydrofluoric acid (aerated)	<0.02	<0.02
Hydrofluoric acid (air free)	<0.02	<0.02
Hydrogen chloride	–	<0.002
Hydrogen fluoride	–	<0.02
Hydrogen peroxide	<0.02	<0.02
Hydrogen sulfide	<0.02	<0.02

(*Continued*)

TABLE 1.194 (*Continued*) Corrosion Rates of Inconel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Lactic acid	<0.02	–
Lead acetate	<0.02	–
Lead chromate	–	<0.02
Lead nitrate	–	<0.02
Lead sulfate	–	<0.02
Lithium chloride	<0.002 (30%)	–
Lithium hydroxide	<0.02	<0.02
Magnesium chloride	<0 .002	<0.02
Magnesium sulfate	<0.02	<0.02
Maleic acid	<0.02	–
Malic acid	<0.002	<0.02
Mercuric chloride	>0.05	–
Mercury	–	<0.02
Methallylamine	–	<0.02
Methanol	<0.002	<0.002
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylene chloride	–	<0.02
Monochloroacetic acid	<0.02	<0.02
Monorthanolamine	–	<0.02
Monosodium phosphate	<0.02	–
Nickel chloride	–	<0.02
Nickel nitrate	>0.05	<0.02
Nickel sulfate	<0.02	<0.02
Nitric acid	<0.02	–
Nitric acid (red fuming)	–	<0.02
Nitric + hydrochloric acid	–	>0.05
Nitric + sulfuric acid	>0.05	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.02
Nitroglycerine	–	<0.02
Nitrotoluene	–	<0.02
Oleic acid	–	<0.002
Oxalic acid	<0.02	<0.02
Phenol	–	<0.002
Phosphoric acid (aerated)	<0.02	>0.05
Phosphoric acid (air free)	<0.02	–
Picric acid	–	<0.02
Potassium bicarbonate	<0.02	–
Potassium bromide	<0.02	<0.02

(*Continued*)

TABLE 1.194 (*Continued*) Corrosion Rates of Inconel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.05	–
Potassium chromate	<0.002	–
Potassium cyanide	<0.02	<0.02
Potassium dichromate	<0.02	–
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	<0.02	–
Potassium hypochlorite	<0.05	–
Potassium iodide	<0.02	<0.02
Potassium nitrate	<0.02	–
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	–
Potassium silicate	<0.02	<0.02
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Salicylic acid	–	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silver nitrate	<0.02	–
Sodium acetate	<0.02	<0.02
Sodium bicarbonate	<0.02	–
Sodium bisulfate	<0.02	<0 .02
Sodium bromide	<0.02	–
Sodium carbonate	<0.02	<0.02
Sodium chloride	<0.002	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.002	<0.002
Sodium hypochlorite	>0.05	–
Sodium metasilicate	<0.002	<0.002
Sodium nitrate	<0.002	–
Sodium nitrite	<0.02	<0.02
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.02	<0.02
Sodium sulfide	<0.02	–
Sodium sulfite	<0.02	<0.02
Stannic chloride	>0.05	–
Stannous chloride	>0.05	<0.02
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	<0.02
Sulfur dioxide	<0.02	<0.02

(*Continued*)

TABLE 1.194 (*Continued*) Corrosion Rates of Inconel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	>0.05	>0.05
Sulfuric acid (air free)	<0.05	–
Sulfuric acid (fuming)	–	<0.02
Sulfurous acid	<0.05	<0.02
Tannic acid	–	<0.02
Tartaric acid	<0.02	–
Tetraphosphoric acid	–	<0.02
Trichloroethylene	–	<0.02
Urea	<0.02	–
Zinc chloride	–	<0.02
Zinc sulfate	<0.002	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.195 Corrosion Rates of Nickel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	<0.002	<0.002
Acetic acid (aerated)	<0.05	>0.05
Acetic acid (air free)	<0.02	<0.02
Acetic anhydride	–	<0.02
Acetoacetic acid	<0.02	<0.02
Acetone	<0.002	<0.002
Acetylene	–	<0.002
Acrolein	–	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.002	<0.002
Alcohol (methyl)	<0.002	<0.002
Alcohol (allyl)	–	<0.02
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.02
Allyl chloride	–	<0.02
Aluminum acetate	<0.02	–

(*Continued*)

TABLE 1.195 (*Continued*) Corrosion Rates of Nickel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Aluminum chlorate	<0.02	<0.02
Aluminum chloride	<0.05	<0.02
Aluminum fluoride	<0.02	–
Aluminum fluorosilicate	–	<0.02
Aluminum formate	<0.02	<0.02
Aluminum hydroxide	<0.02	–
Aluminum nitrate	<0.02	–
Aluminum potassium sulfate	<0.02	–
Aluminum sulfate	<0.02	<0.02
Ammonia	>0.05	<0.002
Ammonium acetate	<0.002	<0.002
Ammonium bromide	<0.02	–
Ammonium carbonate	>0.05	<0.02
Ammonium chloride	<0.02	<0.02
Ammonium citrate	<0.02	–
Ammonium formate	<0.02	–
Ammonium nitrate	<0.02	<0.02
Ammonium sulfate	<0.02	<0.02
Ammonium sulfite	>0.05	–
Ammonium thiocyanate	<0.02	<0.02
Amyl acetate	–	<0.02
Amyl chloride	<0.02	<0.02
Aniline	<0.02	<0.02
Aniline hydrochloride	<0.05	–
Anthracine	–	<0.02
Antimony trichloride	>0.05	<0.02
Barium carbonate	<0.02	<0.02
Barium chloride	<0.02	<0.02
Barium hydroxide	<0.002	<0.02
Barium nitrate	<0.02	–
Barium peroxide	<0.02	–
Benzaldehyde	–	<0.02
Benzene	<0.002	<0.02
Benzoic acid	<0.02	<0.02
Boric acid	<0.02	<0.02
Bromic acid	>0.05	>0.05
Bromine (dry)	–	<0.002
Bromine (wet)	–	>0.05
Butyric acid	<0.05	<0.05

(*Continued*)

TABLE 1.195 (*Continued*) Corrosion Rates of Nickel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Cadmium chloride	<0.02	–
Cadmium sulfate	<0.002	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02
Calcium bromide	<0.02	<0.02
Calcium chlorate	<0.02	–
Calcium chloride	<0.002	<0.02
Calcium hydroxide	<0.02	<0.02
Calcium hypochlorite	>0.05	–
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	<0.02	<0.002
Carbon acid (air free)	<0.02	<0.02
Chloroacetic acid	–	<0.02
Chlorine gas	–	<0.002
Chloroform (dry)	–	<0.002
Chromic acid	>0.05	–
Chromic hydroxide	–	<0.02
Citric acid	<0.02	<0.02
Copper nitrate	>0.05	–
Copper sulfate	<0.02	–
Diethylene glycol	–	<0.02
Ethyl chloride	–	<0.002
Ethylene glycol	–	<0.02
Ethylene oxide	–	<0.02
Fatty acids	–	<0.02
Ferric chloride	>0.05	–
Ferric nitrate	>0.05	–
Ferrous chloride	<0.05	–
Ferrous sulfate	>0.05	<0.02
Fluorine	–	<0.002
Formaldehyde	<0.002	<0.002
Formic acid	<0.02	<0.02
Furfural	<0.02	<0.02
Hydrazine	–	<0.002
Hydrobromic acid	>0.05	<0.02
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	>0.05	–
Hydrocyanic acid	–	<0.02
Hydrofluoric acid (aerated)	<0.02	<0.02

(*Continued*)

TABLE 1.195 (*Continued*) Corrosion Rates of Nickel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Hydrofluoric acid (air free)	<0.02	<0.02
Hydrogen chloride	–	<0.002
Hydrogen fluoride	–	<0.002
Hydrogen iodide	–	<0.02
Hydrogen peroxide	<0.02	<0.02
Hydrogen sulfide	–	<0.02
Lactic acid	<0.02	–
Lead acetate	<0.02	–
Lead chromate	–	<0.02
Lead nitrate	<0.02	<0.02
Lead sulfate	<0.02	<0.02
Lithium chloride	<0.002 (30%)	–
Lithium hydroxide	<0.02	<0.02
Magnesium chloride	<0.002	<0.02
Magnesium hydroxide	–	<0.02
Magnesium sulfate	<0.02	<0.02
Maleic acid	<0.02	–
Malic acid	<0.02	<0.02
Mercuric chloride	<0.05	–
Mercury	–	<0.02
Methallylamine	–	<0.02
Methanol	<0.002	<0.002
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylene chloride	–	<0.02
Monochloroacetic acid	<0.02	<0.02
Monorthanolamine	–	<0.02
Monosodium phosphate	<0.02	–
Nickel nitrate	>0.05	<0.02
Nickel sulfate	<0.02	–
Nitric acid	>0.05	>0.05
Nitric acid (red fuming)	–	>0.05
Nitric + hydrochloric acid	–	>0.05
Nitric + sulfuric acid	>0.05	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.02
Nitrotoluene	–	<0.02
Nitrous acid	>0.05	>0.05
Oleic acid	–	<0.002

(*Continued*)

TABLE 1.195 (*Continued*) Corrosion Rates of Nickel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Oxalic acid	<0.02	<0.05
Phenol	–	<0.002
Phosphoric acid (aerated)	<0.05	>0.05
Phosphoric acid (air free)	<0.02	–
Picric acid	>0.05	<0.02
Potassium bicarbonate	<0.02	–
Potassium bromide	<0.02	<0.02
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.02	–
Potassium chromate	<0.002	–
Potassium cyanide	<0.02	<0.02
Potassium dichromate	<0.02	–
Potassium ferricyanide	<0.02	–
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	<0.002	–
Potassium hypochlorite	<0.05	–
Potassium iodide	<0.02	<0.02
Potassium nitrate	<0.02	<0.02
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.02	–
Potassium silicate	<0.02	<0.02
Propionic acid	<0.02	–
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Salicylic acid	<0.02	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	–	<0.02
Silver nitrate	>0.05	–
Sodium acetate	<0.02	<0.02
Sodium bicarbonate	<0.02	–
Sodium bisulfate	<0.02	<0.02
Sodium bromide	<0.02	–
Sodium carbonate	<0.02	<0.02
Sodium chloride	<0.002	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.002	<0.002
Sodium hypochlorite	>0.05	–
Sodium metasilicate	<0.002	<0.002
Sodium nitrate	<0.02	<0.02

(*Continued*)

TABLE 1.195 (*Continued*) Corrosion Rates of Nickel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Sodium nitrite	<0.02	<0.02
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.02	<0.02
Sodium sulfide	<0.02	–
Sodium sulfite	<0.02	–
Stannic chloride	>0.05	–
Stannous chloride	<0.05	<0.02
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	<0.02
Sulfur dioxide	>0.05	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	<0.05	>0.05
Sulfuric acid (air free)	<0.02	>0.05
Sulfuric acid (fuming)	–	>0.05
Sulfurous acid	<0.05	>0.05
Tannic acid	–	<0.02
Tartaric acid	<0.02	–
Tetraphosphoric acid	–	>0.05
Trichloroacetic acid	–	<0.02
Trichloroethylene	–	<0.002
Urea	<0.02	–
Zinc chloride	<0.02	<0.02
Zinc sulfate	<0.02	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.196 Corrosion Rates of Monel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	<0.002	<0.002
Acetic Acid (aerated)	<0.02	<0.02
Acetic acid (air free)	<0.02	<0.02
Acetic anhydride	–	<0.02
Acetoacetic acid	<0.02	<0.02
Acetone	<0.002	<0.002
Acetylene	–	<0.002
Acrolein	–	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.002	<0.002
Alcohol (methyl)	<0.002	<0.002
Alcohol (allyl)	–	<0.02
Alcohol (benzyl)	–	<0.02
Alcohol (butyl)	–	<0.002
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.02
Allyl chloride	–	<0.02
Aluminum acetate	<0.02	–
Aluminum chlorate	<0.02	<0.02
Aluminum chloride	<0.02	–
Aluminum fluoride	<0.002	–
Aluminum fluorosilicate	–	<0.02
Aluminum formate	<0.02	<0.02
Aluminum hydroxide	<0.02	–
Aluminum nitrate	<0.02	–
Aluminum potassium sulfate	<0.02	–
Aluminum sulfate	<0.02	<0.02
Ammonia	>0.05	<0.002
Ammonium acetate	<0.002	<0.002
Ammonium bromide	<0.02	–
Ammonium carbonate	<0.02	<0.02
Ammonium chloride	<0.02	<0.02
Ammonium citrate	<0.02	–
Ammonium formate	<0.02	–
Ammonium nitrate	>0.05	<0.02
Ammonium sulfate	<0.02	<0.02
Ammonium sulfite	>0.05	–
Ammonium thiocyanate	<0.02	<0.02
Amyl acetate	<0.02	<0.02
Amyl chloride	<0.02	<0.02
Aniline	<0.02	<0.02
Aniline hydrochloride	>0.05	–
Anthracine	–	<0.02

(*Continued*)

TABLE 1.196 (*Continued*) Corrosion Rates of Monel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Antimony trichloride	>0.05	–
Barium carbonate	<0.02	<0.02
Barium chloride	<0.02	<0.02
Barium hydroxide	<0.02	<0.02
Barium oxide	–	<0.02
Barium peroxide	<0.02	–
Benzaldehyde	–	<0.02
Benzene	<0.002	<0.02
Benzoic acid	<0.02	<0.02
Boric acid	<0.02	<0.02
Bromic acid	>0.05	>0.05
Bromine (dry)	–	<0.002
Bromine (wet)	–	>0.05
Butyric acid	<0.05	<0.02
Cadmium chloride	<0.02	–
Cadmium sulfate	<0.002	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.02
Calcium bromide	<0.02	<0.02
Calcium chlorate	<0.02	–
Calcium chloride	<0.002	<0.02
Calcium hydroxide	<0.02	<0.02
Calcium hypochlorite	>0.05	–
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	<0.02	<0.002
Carbon acid (air free)	<0.02	<0.05
Chloroacetic acid	<0.02	<0.05
Chlorine gas	–	<0.02
Chlorine liquid	–	<0.02
Chloroform (dry)	–	<0.002
Chromic acid	>0.05	–
Chromic hydroxide	–	<0.02
Chromic sulfates	–	<0.05
Citric acid	<0.02	<0.02
Copper nitrate	>0.05	–
Copper sulfate	<0.02	–
Diethylene glycol	–	<0.02
Ethyl chloride	<0.02	<0.02
Ethylene glycol	–	<0.02
Ethylene oxide	–	<0.02
Fatty acids	–	<0.02

(*Continued*)

TABLE 1.196 (*Continued*) Corrosion Rates of Monel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Ferric chloride	>0.05	>0.05
Ferric nitrate	>0.05	–
Ferrous chloride	>0.05	–
Ferrous sulfate	–	<0.02
Fluorine	–	<0.002
Formaldehyde	<0.002	<0.002
Formic acid	<0.02	–
Furfural	<0.02	<0.02
Hydrazine	–	>0.05
Hydrobromic acid	>0.05	–
Hydrochloric acid (aerated)	>0.05	–
Hydrochloric acid (air free)	>0.05	–
Hydrocyanic acid	>0.05	<0.02
Hydrofluoric acid (aerated)	<0.02	<0.02
Hydrofluoric acid (air free)	<0.02	<0.02
Hydrogen chloride	–	<0.002
Hydrogen fluoride	–	<0.02
Hydrogen iodide	<0.02	–
Hydrogen peroxide	<0.02	<0.002
Hydrogen sulfide	–	<0.02
Lactic acid	>0.05	–
Lead acetate	<0.02	<0.02
Lead chromate	–	<0.02
Lead nitrate	–	<0.02
Lead sulfate	–	<0.02
Lithium chloride	<0.002 (30%)	<0.002
Lithium hydroxide	<0.02	<0.02
Magnesium chloride	<0.002	<0.02
Magnesium hydroxide	<0.02	<0.02
Magnesium sulfate	<0.02	<0.02
Maleic acid	<0.05	–
Malic acid	<0.02	–
Mercuric chloride	>0.05	–
Mercurous nitrate	<0.02	–
Mercury	–	<0.02
Methallylamine	–	<0.05
Methanol	<0.002	<0.002
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.02
Methylene chloride	–	<0.002
Monochloroacetic acid	–	<0.05
Monorthanolamine	–	<0.02
Monosodium phosphate	<0.02	–

(*Continued*)

TABLE 1.196 (*Continued*) Corrosion Rates of Monel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Nickel chloride	<0.02	<0.02
Nickel nitrate	>0.05	<0.02
Nickel sulfate	–	<0.02
Nitric acid	>0.05	>0.05
Nitric acid (red fuming)	–	>0.05
Nitric + hydrochloric acid	–	>0.05
Nitric + sulfuric acid	>0.05	>0.05
Nitrobenzene	–	<0.02
Nitrocellulose	–	<0.002
Nitroglycerine	–	<0.02
Nitrotoluene	–	<0.02
Nitrous acid	–	>0.05
Oleic acid	–	<0.002
Oxalic acid	<0.02	<0.02
Phenol	<0.002	<0.002
Phosphoric acid (aerated)	<0.05	–
Phosphoric acid (air aree)	<0.02	–
Picric acid	<0.05	>0.05
Potassium bicarbonate	<0.02	–
Potassium bromide	<0.02	<0.02
Potassium carbonate	<0.02	<0.02
Potassium chlorate	<0.05	–
Potassium chromate	<0.02	–
Potassium cyanide	<0.02	<0.02
Potassium dichromate	<0.02	–
Potassium ferricyanide	<0.02	–
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	<0.002	–
Potassium hypochlorite	<0.05	–
Potassium iodide	<0.02	<0.02
Potassium nitrate	<0.02	<0.02
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.05	–
Potassium silicate	<0.02	<0.02
Propionic acid	<0.02	<0.02
Pyridine	<0.02	<0.02
Quinine sulfate	<0.02	<0.02
Salicylic acid	<0.02	<0.02
Silicon tetrachloride (dry)	–	<0.002
Silicon tetrachloride (wet)	–	>0.05
Silver bromide	–	<0.02
Silver nitrate	>0.05	–

(*Continued*)

TABLE 1.196 (*Continued*) Corrosion Rates of Monel at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Sodium acetate	<0.05	<0.02
Sodium bicarbonate	<0.02	–
Sodium bisulfate	<0.02	<0.02
Sodium bromide	<0.02	–
Sodium carbonate	<0.02	<0.02
Sodium chloride	<0.002	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.002	<0.002
Sodium hypochlorite	>0.05	<0.02
Sodium metasilicate	<0.002	<0.002
Sodium nitrate	<0.02	<0.02
Sodium nitrite	<0.02	<0.002
Sodium phosphate	<0.02	<0.02
Sodium silicate	<0.02	<0.02
Sodium sulfate	<0.02	<0.02
Sodium sulfide	<0.02	–
Sodium sulfite	<0.02	<0.02
Stannic chloride	>0.05	–
Stannous chloride	>0.05	<0.02
Strontium nitrate	<0.02	<0.02
Succinic acid	<0.02	<0.02
Sulfur dioxide	>0.05	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	<0.05	>0.05
Sulfuric acid (air free)	<0.002	>0.05
Sulfuric acid (fuming)	–	>0.05
Sulfurous acid	>0.05	>0.05
Tannic acid	<0.02	<0.02
Tartaric acid	<0.02	–
Tetraphosphoric acid	–	<0.05
Trichloroacetic acid	–	>0.05
Trichloroethylene	–	<0.002
Urea	<0.02	–
Zinc chloride	<0.02	<0.02
Zinc sulfate	<0.02	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other% corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.197 Corrosion Rates of Lead at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	<0.02	<0.002
Acetic acid (aerated)	>0.05	<0.05
Acetic acid (air free)	>0.05	<0.02
Acetic anhydride	–	<0.002
Acetoacetic acid	–	<0.02
Acetone	<0.002	<0.02
Acetylene	–	<0.002
Acrolein	<0.02	–
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.002	<0.002
Alcohol (methyl)	<0.02	<0.02
Alcohol (allyl)	–	<0.02
Alcohol (benzyl)	–	<0.02
Alcohol (cetyl)	–	<0.02
Alcohol (isopropyl)	–	<0.002
Allyl chloride	–	<0.05
Allyl sulfide	–	>0.05
Aluminum acetate	<0.002	<0.002
Aluminum chlorate	<0.02	<0.02
Aluminum chloride	>0.05	–
Aluminum fluoride	<0.02	–
Aluminum fluorosilicate	–	<0.02
Aluminum formate	–	<0.02
Aluminum hydroxide	<0.02	–
Aluminum nitrate	<0.02	–
Aluminum potassium sulfate	<0.002	<0.02
Aluminum sulfate	<0.02	–
Ammonia	<0.02	<0.02
Ammonium bicarbonate	<0.02	–
Ammonium bromide	>0.05	–
Ammonium carbonate	<0.02	–
Ammonium chloride	>0.05	<0.02
Ammonium nitrate	>0.05	–
Ammonium sulfate	<0.02	<0.02
Amyl acetate	–	<0.02
Amyl chloride	–	>0.05
Aniline	–	>0.05
Aniline hydrochloride	>0.05	–
Anthracine	–	<0.02
Antimony trichloride	<0.02	<0.002
Barium carbonate	–	>0.05

(*Continued*)

TABLE 1.197 (*Continued*) Corrosion Rates of Lead at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Barium chloride	<0.02	–
Barium hydroxide	>0.05	>0.05
Barium nitrate	<0.02	–
Barium peroxide	>0.05	–
Benzaldehyde	>0.05	>0.05
Benzene	<0.02	<0.02
Benzoic acid	>0.05	>0.05
Boric acid	<0.02	<0.02
Bromic acid	<0.02	<0.02
Bromine (dry)	–	<0.002
Bromine (wet)	–	>0.05
Butyric acid	>0.05	>0.05
Cadmium sulfate	<0.002	–
Calcium acetate	<0.02	<0.02
Calcium bicarbonate	–	<0.05
Calcium bromide	<0.02	<0.02
Calcium chlorate	<0.02	–
Calcium chloride	>0.05	–
Calcium hydroxide	>0.05	–
Calcium hypochlorite	<0.05	<0.002
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	–	<0.002
Carbon acid (air free)	–	>0.05
Chloroacetic acid	>0.05	>0.05
Chlorine gas	–	<0.02
Chlorine liquid	–	<0.02
Chloroform (dry)	–	<0.02
Chromic acid	<0.02	–
Chromic hydroxide	–	<0.02
Chromic sulfates	<0.02	<0.02
Citric acid	<0.02	>0.05
Copper sulfate	<0.02	<0.02
Diethylene glycol	–	<0.02
Ethyl chloride	–	<0.02
Ethylene glycol	–	<0.05
Ethylene oxide	–	<0.02
Fatty acids	–	>0.05
Ferric chloride	>0.05	–
Ferric nitrate	<0.002	<0.002
Ferrous chloride	>0.05	–

(*Continued*)

TABLE 1.197 (*Continued*) Corrosion Rates of Lead at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Ferrous sulfate	<0.02	–
Fluorine	–	<0.02
Formaldehyde	<0.02	<0.02
Formic acid	>0.05	>0.05
Furfural	–	<0.02
Hydrazine	>0.05	>0.05
Hydrobromic acid	>0.05	–
Hydrochloric acid (aerated)	<0.02	–
Hydrochloric acid (air free)	<0.02	–
Hydrocyanic acid	>0.05	<0.02
Hydrofluoric acid (aerated)	>0.05	–
Hydrofluoric acid (air free)	<0.002	>0.05
Hydrogen chloride	–	<0.02
Hydrogen fluoride	–	>0.05
Hydrogen peroxide	>0.05	<0.002
Hydrogen sulfide	–	<0.02
Lactic acid	>0.05	>0.05
Lead chromate	–	<0.02
Lead nitrate	–	<0.02
Lead sulfate	–	<0.02
Lithium chloride	<0.02	<0.02
Lithium hydroxide	>0.05	–
Magnesium chloride	>0.05	>0.05
Magnesium hydroxide	>0.05	–
Magnesium sulfate	<0.02	–
Mercuric chloride	<0.05	–
Mercurous nitrate	–	>0.05
Mercury	–	>0.05
Methanol	<0.02	<0.02
Methyl ethyl ketone	<0.02	<0.002
Methyl isobutyl ketone	<0.02	<0.002
Methylene chloride	–	<0.02
Monochloroacetic acid	>0.05	>0.05
Monosodium phosphate	<0 .02	–
Nickel chloride	–	<0.02
Nickel nitrate	–	<0.02
Nickel sulfate	<0.02	<0.02
Nitric acid	>0.05	>0.05
Nitric + hydrochloric acid	–	>0.05
Nitric + sulfuric acid	>0.05	>0.05
Nitrobenzene	–	<0.02

(*Continued*)

TABLE 1.197 (*Continued*) Corrosion Rates of Lead at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Nitrocellulose	–	<0.002
Nitroglycerine	–	<0.05
Nitrotoluene	–	<0.02
Nitrous acid	–	>0.05
Oleic acid	–	>0.05
Oxalic acid	>0.05	>0 .05
Phenol	–	<0.02
Phosphoric acid (aerated)	<0.02	<0.02
Phosphoric acid (air free)	<0.002	<0.02
Picric acid	>0.05	<0.02
Potassium bicarbonate	>0.05	–
Potassium bromide	<0.02	<0.02
Potassium carbonate	>0.05	>0.05
Potassium chlorate	<0.02	–
Potassium chromate	<0.02	–
Potassium cyanide	>0.05	–
Potassium dichromate	<0.02	–
Potassium ferricyanide	<0.02	–
Potassium ferrocyanide	<0.02	–
Potassium hydroxide	>0.05	>0.05
Potassium hypochlorite	<0.02	–
Potassium iodide	>0.05	–
Potassium nitrate	<0.02	–
Potassium nitrite	<0.02	<0.02
Potassium permanganate	<0.05	>0.05
Propionic acid	>0.05	–
Pyridine	<0.02	<0.02
Salicylic acid	–	<0.02
Silicon tetrachloride (dry)	–	<0.02
Silver nitrate	>0.05	–
Sodium acetate	–	<0.02
Sodium bicarbonate	<0.02	–
Sodium bisulfate	<0.02	–
Sodium carbonate	<0.02	–
Sodium chloride	<0.02	–
Sodium chromate	<0.02	<0.02
Sodium hydroxide	<0.02	–
Sodium hypochlorite	>0.05	>0.05
Sodium nitrate	>0.05	–
Sodium nitrite	<0.02	–
Sodium phosphate	<0.02	<0.02

(*Continued*)

TABLE 1.197 (*Continued*) Corrosion Rates of Lead at 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Sodium silicate	>0.05	–
Sodium sulfate	<0.02	<0.02
Sodium sulfide	<0.002	<0.002
Sodium sulfite	<0.02	<0.02
Stannic chloride	>0.05	–
Stannous chloride	>0.05	–
Succinic acid	<0.02	<0.02
Sulfur dioxide	–	<0.02
Sulfur trioxide	–	<0.02
Sulfuric acid (aerated)	<0.002	>0.05
Sulfuric acid (air free)	<0.002	>0.05
Sulfuric acid (fuming)	–	>0.05
Sulfurous acid	<0.02	<0.02
Tannic acid	>0.05	>0.05
Tartaric acid	<0.02	>0.05
Tetraphosphoric acid	>0.05	>0.05
Trichloroacetic acid	>0.05	>0.05
Trichloroethylene	–	>0.05
Zinc chloride	<0.02	<0.02
Zinc sulfate	<0.02	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.198 Corrosion Rates of Titanium At 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Acetaldehyde	–	<0.002
Acetic acid (aerated)	<0.002	<0.002
Acetic acid (air free)	<0.002	<0.002
Acetic anhydride	–	<0.002
Acetone	<0.002	<0.002
Acetylene	–	<0.002
Acrolein	–	<0.02
Acrylonitrile	–	<0.002
Alcohol (ethyl)	<0.002	<0.002
Alcohol (allyl)	–	<0.002
Alcohol (amyl)	–	<0.002
Alcohol (benzyl)	–	<0.002
Alcohol (butyl)	–	<0.002
Alcohol (cetyl)	–	<0.002
Aluminum acetate	–	<0.002
Aluminum chlorate	<0.002	–
Aluminum chloride	>0.05	–
Aluminum formate	–	<0.002
Aluminum hydroxide	<0.002	<0.002
Aluminum nitrate	<0.002	<0.002
Aluminum potassium sulfate	–	<0.002
Aluminum sulfate	<0.002	–
Ammonia	<0.002	<0.002
Ammonium chloride	<0.002	–
Ammonium citrate	<0.002	<0.002
Ammonium formate	<0.002	<0.002
Ammonium nitrate	<0.05	–
Ammonium sulfate	<0.002	–
Amyl acetate	–	<0.002
Aniline hydrochloride	<0.002	–
Anthracine	–	<0.002
Barium chloride	<0.002	–
Benzene	<0.002	<0.002
Benzoic acid	<0.002	<0.002
Boric acid	<0.002	–
Bromine (dry)	–	>0.05
Bromine (wet)	–	>0.05
Butyric acid	<0.002	<0.002
Calcium acetate	<0.002	<0.002
Calcium bicarbonate	–	<0.002
Calcium bromide	–	<0.05
Calcium chlorate	–	<0.002

(*Continued*)

TABLE 1.198 (*Continued*) Corrosion Rates of Titanium At 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Calcium chloride	<0.002	–
Calcium hypochlorite	<0.002	–
Carbon dioxide	–	<0.002
Carbon monoxide	–	<0.002
Carbon tetrachloride	–	<0.002
Chloroacetic acid	–	<0.002
Chlorine gas	–	>0.05
Chromic acid	<0.002	–
Citric acid	<0.002	–
Diethylene glycol	–	<0.002
Ethyl chloride	–	<0.002
Ethylene oxide	–	<0.002
Fatty acids	–	<0.002
Ferric chloride	<0.002	–
Ferric nitrate	<0.002	–
Ferrous chloride	<0.002	–
Ferrous sulfate	<0.002	–
Formaldehyde	<0.002	<0.002
Formic acid	<0.02	<0.02
Furfural	–	<0.002
Hydrochloric acid (aerated)	<0.02	–
Hydrochloric acid (air free)	<0.02	–
Hydrofluoric acid (aerated)	>0.05	–
Hydrofluoric acid (air free)	>0.05	>0.05
Hydrogen fluoride	–	<0.002
Hydrogen peroxide	<0.002	>0.05
Hydrogen sulfide	–	<0.002
Lactic acid	<0.002	<0.002
Lead acetate	<0.002	–
Magnesium chloride	<0.002	<0.002
Malic acid	–	<0.002
Manganous chloride	<0.002	–
Mercuric chloride	<0.002	–
Methyl ethyl ketone	<0.002	<0.002
Methyl isobutyl ketone	<0.002	<0.002
Monochloroacetic acid	–	<0.002
Nickel chloride	<0.02	–
Nitric acid	<0.002	–
Nitric acid (red fuming)	–	<0.002
Nitric + hydrochloric acid	–	<0.02
Nitric + hydrofluoric acid	–	>0.05
Oleic acid	–	<0.002

(*Continued*)

TABLE 1.198 (*Continued*) Corrosion Rates of Titanium At 70°F (= 21°C)[a]

Corrosive Medium	Corrosion Rate[b] in 10% Corrosive Medium (ipy)	Corrosion Rate[c] in 100% Corrosive Medium (ipy)
Oxalic acid	<0.02	–
Phosphoric acid (aerated)	<0.02	>0.05
Phosphoric acid (air free)	–	>0.05
Potassium bromide	<0.002	–
Potassium carbonate	<0.002	–
Potassium chlorate	<0.002	–
Potassium cyanide	–	>0.05
Potassium dichromate	<0.002	–
Potassium hydroxide	<0.002	–
Potassium hypochlorite	<0.002	–
Potassium iodide	<0.002	<0.002
Potassium nitrate	<0.002	–
Potassium nitrite	<0.002	<0.002
Propionic acid	–	>0.05
Quinine sulfate	–	<0.002
Silver bromide	–	<0.002
Silver chloride	<0.002	–
Sodium chloride	<0.002	–
Sodium hydroxide	<0.002	–
Sodium hypochlorite	<0.002	<0.002
Sodium nitrite	<0.002	–
Sodium sulfide	<0.002	–
Stannic chloride	<0.002	–
Succinic acid	<0.002	<0.002
Sulfuric acid (aerated)	<0.02	>0.05
Sulfuric acid (air free)	–	>0.05
Sulfurous acid	<0.002	<0.002
Tannic acid	<0.002	<0.002
Tartaric acid	<0.002	<0.002
Trichloroacetic acid	<0.002	>0.05
Trichloroethylene	–	<0.002
Zinc chloride	<0.002	–

Source: Data compiled by J. S. Park from Earl R. Parker, *Materials Data Book for Engineers and Scientists*, McGraw-Hill Book Company, New York, 1967.

[a] <0.002 means that corrosion rate is likely to be less than 0.002 in./year (excellent).
<0.02 means that corrosion rate is likely to be less than about 0.02 in./year (good).
<0.05 means that corrosion rate is likely to be less than about 0.05 in./year (fair).
>0.05 means that corrosion rate is likely to be more than 0.05 in./year (poor).

[b] 10% corrosive medium in 90% water. (Other % corrosive medium in parentheses.)

[c] Water-free, dry or maximum concentration of corrosive medium. (Note that 1 ipy = 25.4 mm/year.)

TABLE 1.199 Corrosion Rates of ACI Heat-Resistant Castings Alloys in Air

	Oxidation Rate in Air (mils/year)		
Alloy	(870°C)	(980°C)	(1090°C)
HC	10	50	50
HD	10–	50–	50–
HE	5–	25–	35–
HF	5–	50+	100
HH	5–	25–	50
HI	5–	10+	35–
HK	10–	10–	35–
HL	10+	25–	35
HN	5	10+	50–
HP	25–	25	50
HT	5–	10+	50
HU	5–	10–	35–
HW	5–	10–	35
HX	5–	10–	35–

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 392.
Note: Based on 100-h tests.
To convert mils/year to μm/year multiply by 25.4.

TABLE 1.200 Corrosion Rates for ACI Heat-Resistant Castings Alloys in Flue Gas

	Corrosion Rate (mils/year)			
	Flue Gas Sulfur Content 0.12 g/m³		Flue Gas Sulfur Content 2.3 g/m³	
Alloy	Oxidizing	Reducing	Oxidizing	Reducing
HC	25–	25+	25	25–
HD	25–	25–	25–	25–
HE	25–	25–	25–	25–
HF	50+	100+	50+	250–
HH	25–	25	25	25–
HI	25–	25–	25–	25–
HK	25–	25–	25–	25–
HL	25–	25–	25–	25–
HN	25–	25–	25	25
HP	25–	25–	25–	25–
HT	25	25–	25	100
HU	25–	25–	25–	25
HW	25	25–	50–	250
HX	25–	25–	25–	25–

Source: Data from Michael Bauccio (Ed.), *ASM Metals Reference Book,* Third Edn., ASM International, Materials Park, OH, 1993, p. 392.
Note: To convert mils/year to μm/year multiply by 25.4.
Based on 100-h tests.

2

Ceramics

Physical Properties

TABLE 2.1 Periodic Table of Elements in Ceramic Materials

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA																	VIIA
	IIA											IIIA	IVA	VA	VIA	VIIA	
3 Li	4 Be											5 B	6 C	7 N	8 O		
11 Na	12 Mg	IIIB	IVB	VB	VIB	VIIB	-----	VIII	-----	IB	IIB	13 Al	14 Si	15 P	16 S		
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge				
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb			
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi			
87 Fr	88 Ra																

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lw

TABLE 2.2 Bond Length Values between Elements

Elements	Compound	Bond Length (Å)		
B–B	B_2H_6	1.770	±	0.013
B–Br	BBF	1.88		
	BBr_3	1.87	±	0.02
B–Cl	BCl	1.715		
	BCl_3	1.72	±	0.01
B–F	BF	1.262		
	BF_3	1.29	±	0.01
B–H	Hydrides	1.21	±	0.02
B–H bridge	Hydrides	1.39	±	0.02
B–N	$(BClNH)_3$	1.42	±	0.01
B–O	BO	1.2049		
	$B(OH)_3$	1.362	±	0.005 (avg.)
N–Cl	NO_2Cl	1.79	±	0.02
N–F	NF_3	1.36	±	0.02
N–H	$[NH_4]^+$	1.034	±	0.003
	NH	1.038		
	ND	1.041		
	HNCS	1.013	±	0.005
N–N	N_3H	1.02	±	0.01
	N_2O	1.126	±	0.002
	$[N_2]^+$	1.116		
N–O	NO_2Cl	1.24	±	0.01
	NO_2	1.188	±	0.005
N=O	N_2O	1.186	±	0.002
	$[NO]^+$	1.0619		
N–Si	SiN	1.572		
O–H	$[OH]^+$	1.0289		
	OD	0.9699		
	H_2O_2	0.960	±	0.005
O–O	H_2O_2	1.48	±	0.01
	$[O_2]^+$	1.227		
	$[O_2]^-$	1.26	±	0.2
	$[O_2]^{--}$	1.49	±	0.02
P–D	PD	1.429		
P–H	$[PH_4]^+$	1.42	±	0.02
P–N	PN	1.4910		
P–S	$PSBr_3$ (Cl_3, F_3)	1.86	±	0.02
S–Br	$SOBr_2$	2.27	±	0.02
S–F	SOF_2	1.585	±	0.005
S–D	SD	1.3473		
	SD_2	1.345		
S–O	SO_2	1.4321		
	$SOCl_2$	1.45	±	0.02
S–S	S_2Cl_2	2.04	±	0.01
Si–Br	$SiBr_4$	2.17	±	1.01
Si–Cl	$SiCl_4$	2.03	±	1.01 (avg.) 1.02

(*Continued*)

TABLE 2.2 (*Continued*) Bond Length Values between Elements

Elements	Compound	Bond Length (Å)		
Si–F	SiF_4	1.561	±	0.003 (avg.)
Si–H	SiH_4	1.480	±	0.005
Si–O	$[SiO]^+$	1.504		
Si–Si	Si_2Cl_2	2.30	±	0.02

Source: Data from O. Kennard, In: R. C. Weast (Ed.), *Handbook of Chemistry and Physics*, 69th Edn., CRC Press, Boca Raton, FL, 1988, F-167.
Note: To convert Å to nm, multiply by 10^{-1}.

TABLE 2.3 Structure of Ceramics

Ceramic	Structure
	Borides
Chromium diboride (CrB_2)	Hexagonal, AlB_2 structure(C-32 type) Isomorphous with other transition metal diborides $a = 2.969$ Å; $c = 3.066$ Å; $c/a = 1.03$
Hafnium diboride (HfB_2)	Hexagonal, AlB_2 structure (C-32 type) Isomorphous with TiB_2 and ZrB_2 $a = 3.141 \pm 0.002$ Å; $c = 3.470 \pm 0.002$ Å; $c/a = 1.105$
Tantalum diboride (TaB_2)	Hexagonal, AlB_2 structure (C-32 type) Isomorphous with other transition metal diborides $a = 3.078–3.088$ Å; $c = 3.241–3.265$ Å; $c/a = 1.06–1.074$ Low boron composition (64 atom% boron) $a = 3.097–3.099$ Å; $c = 3.244–3.277$ Å High boron composition (72 atom% boron) $a = 3.057–3.060$ Å; $c = 3.291–3.290$ Å
Titanium diboride (TiB_2)	Hexagonal, AlB_2 structure (C-32 type) Isomorphous with ZrB_2 $a = 3.028–3.030$ Å; $c = 3.227–3.228$ Å; $c/a = 1.064$
Zirconium diboride (ZrB_2)	Hexagonal, AlB_2 structure (C-32 type) Isomorphous with TiB_2 $a = 3.1694–3.170$ Å; $c = 3.528–3.5365$ Å; $c/a = 1.114$
	Carbides
Boron carbide (B_4C)	Rhombic, C_3 chains and B_{12} icosahedral in an NaCl structure, extended along a body diagonal
Hafnium monocarbide (HfC)	FCC(B_1), NaCl type Isomorphous with HfB and HfN $a = 4.46–4.643$ Å
Silicon carbide (SiC)	Low-temperature form (β) Cubic High-temperature form (α) Hexagonal β-SiC F43m space group $a = 4.349–4.358$ Å α-SiC C6MC space group $a = 3.073$Å; $c = 15.07$ Å; $c/a = 4.899$
Tantalum monocarbide (TaC)	FCC, NaCl type (B_1) $a = 4.42–4.456$ Å
Titanium monocarbide (TiC)	FCC, NaCl type (B_1) Isomorphous with TiO and TiN $a = 4.315–4.3316$ Å

(*Continued*)

TABLE 2.3 (*Continued*) Structure of Ceramics

Ceramic	Structure
Trichromium dicarbide (Cr_3C_2)	Orthorhombic D^5_{10} type $a = 2.82$ Å, $b = 5.53$ Å, $c = 11.47$ Å
Tungsten monocarbide (WC)	Hexagonal $a = 2.2897–2.90$ Å
Zirconium monocarbide (ZrC)	FCC(B_1), NaCl type Isomorphous with ZrB and ZrN $a = 4.669–4.694$ Å
	Nitrides
Aluminum nitride (AlN)	Hexagonal, Wurtzite structure $a = 3.10–3.114$ Å; $c = 4.96–4.981$ Å
Boron nitride (BN)	Hexagonal (common type) Graphite-type structure $a = 2.5038 \pm 0.0001$ Å; $c = 6.60 \pm 0.01$ Å B–N distance 1.45 Å Cubic Zinc blende structure $a = 3.615$ Å B–N distance 1.57 Å
Titanium mononitride (TiN)	Cubic $a = 4.23$ Å Homogeneity range: $TiN_{0.42}$–$TiN_{1.16}$ yields $a = 4.213–4.24$ Å
Trisilicon tetranitride (Si_3N_4)	α hexagonal $a = 7.748–7.758$ Å; $c = 5.617–5.623$ Å β hexagonal $a = 7.608$ Å; $c = 2.911$ Å
Zirconium mononitride (ZrN)	Cubic, NaCl type, B1 $a = 4.567–4.63$ Å
	Oxides
Aluminum oxide (Al_2O_3)	Hexagonal $a = 4.785$ Å; $c = 12.991$ Å; $c/a = 2.72$
Beryllium oxide (BeO)	Hexagonal $a = 2.690–2.698$ Å; $c = 4.370–4.380$ Å
Calcium oxide (CaO)	Cubic, NaCl type $a = 4.8105$ Å
Cerium dioxide (CeO_2)	Cubic
Dichromium trioxide (Cr_2O_3)	Trigonal Rhombic
Hafnium dioxide (HfO_2)	Monoclinic to 1700°C Tetragonal above 1700°C $a = 5.1170$ Å; $b = 5.1754$ Å; $c = 5.2915$ Å $\beta = 99.216°$
Magnesium oxide (MgO)	Cubic, Fm3m space group $a = 4.313$ Å
Nickel monoxide (NiO)	Face centered cubic, NaCl type
Silicon dioxide (SiO_2)	Hexagonal
Thorium dioxide (ThO_2)	Cubic, fluorite type $a = 5.59525–5.5997$ Å

(*Continued*)

TABLE 2.3 (*Continued*) Structure of Ceramics

Ceramic	Structure
Titanium oxide (TiO_2)	Tetragonal (rutile) $a = 4.594$ Å; $c = 2.958$ Å at 26°C Tetragonal (anatase) Rhombic (brookite)
Uranium dioxide (UO_2)	Cubic, fluorite type $a = 5.471$ Å
Zirconium oxide (ZrO_2)	To 1050°C Monoclinic $a = 5.1505$ Å; $b = 5.2031$ Å; $c = 5.3154$ Å $\beta = 99.194°$ at room temp. 1050–2100°C Tetragonal Above 2100°C cubic (stabilized) $a = 5.132 \pm 0.006$ Å (8.13 mol% Y_2O_3) $a = 5.145 \pm 0.006$ Å (11.09 mol% Y_2O_3) $a = 5.146 \pm 0.006$ Å (12.08 mol% Y_2O_3) $a = 5.153 \pm 0.006$ Å (15.52 mol% Y_2O_3) $a = 5.162 \pm 0.006$ Å (17.88 mol% Y_2O_3)
Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)	Orthorhombic
Mullite ($3Al_2O_3\ 2SiO_2$)	Orthorhombic $a = 7.54 \pm 0.03$ Å; $b = 7.693 \pm 0.03$ Å; $c = 2.890 \pm 0.01$ Å
Sillimanite ($Al_2O_3\ SiO_2$)	Orthorhombic
Spinel (Al_2O_3 MgO)	Cubic $a = 8.0844$ Å
	Silicides
Molybdenum disilicide ($MoSi_2$)	Tetragonal, $D_{4h}17$ space group Isomorphous with WSi_2 $a = 3.197$–3.20 Å; $c = 7.85$–7.871 Å
Tungsten disilicide (WSi_2)	Tetragonal, $D_{4h}17$ space group Isomorphous with $MoSi_2$ $a = 3.212 \pm 0.005$ Å; $c = 7.880 \pm 0.005$ Å

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T. B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

Note: To convert Å to nm, multiply by 10^{-1}.
FCC, face centered cubic.

TABLE 2.4 Density of Selected Ceramics

Class	Ceramic	Density (Mg/m³)
Borides	Chromium diboride (CrB_2)	5.6
	Hafnium diboride (HfB_2)	11.2
	Tantalum diboride (TaB_2)	12.60
	Titanium diboride (TiB_2)	4.5–4.62
	Zirconium diboride (ZrB_2)	6.09–6.102
Carbides	Boron carbide (B_4C)	2.51
	Hafnium monocarbide (HfC)	12.52–12.70
	Silicon carbide (SiC)	
	Hexagonal	3.217
	Cubic	3.210
	Tantalum monocarbide (TaC)	14.48–14.65
	Titanium monocarbide (TiC)	4.92–4.938
	Trichromium dicarbide (Cr_3C_2)	6.70
	Tungsten monocarbide (WC)	15.8
	Zirconium monocarbide (ZrC)	6.44–6.73
Nitrides	Aluminum nitride (AlN)	3.26–3.30
	Boron nitride (BN)	
	Cubic	3.49
	Hexagonal	2.27
	Titanium mononitride (TiN)	5.43
	Trisilicon tetranitride (Si_3N_4)	
	α	3.184
	β	3.187
	Zirconium mononitride (TiN)	7.349
Oxides	Aluminum oxide (Al_2O_3)	3.97–3.986
	Beryllium oxide (BeO)	3.01–3.03
	Calcium oxide (CaO)	3.32
	Cerium dioxide (CeO_2)	7.28
	Dichromium trioxide (Cr_2O_3)	5.21
	Hafnium dioxide (HfO_2)	9.68
	Magnesium oxide (MgO)	3.581
	Nickel monoxide (NiO)	6.8–7.45
	Thorium dioxide (ThO_2)	9.821
	Titanium oxide (TiO_2)	
	Anatase	3.84
	Brookite	4.17
	Rutile	4.25
	Uranium dioxide (UO_2)	10.949–10.97
	Zirconium oxide (ZrO_2)	
	Monoclinic	5.56
	CaO stabilized	5.5
	MgO stabilized	5.43
	Plasma sprayed	5.6–5.7
	Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)	1.61–2.51
	Mullite ($3Al_2O_3\ 2SiO_2$)	2.6–3.26
	Theoretical	3.16–3.22
	Sillimanite ($Al_2O_3\ SiO_2$)	3.23–3.24
	Spinel (Al_2O_3 MgO)	3.580
	Zircon ($SiO_2\ ZrO_2$)	4.6

(*Continued*)

TABLE 2.4 (*Continued*) Density of Selected Ceramics

Class	Ceramic	Density (Mg/m^3)
Silicides	Molybdenum disilicide ($MoSi_2$)	6.24–6.29
	Tungsten disilicide (WSi_2)	9.25–9.3

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T. B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

TABLE 2.5 Heat Capacity of Ceramics

Class	Ceramic	Heat Capacity, C_p (cal/mol/K)
Borides	Chromium diboride (CrB_2)	$9.61 + 10.72 \times 10^{-3}$ T cal/mol for 494–1010 K
	Hafnium diboride (HfB_2)	$9.61 + 10.72 \times 10^{-3}$ T cal/mol for 494–1010 K
	Tantalum diboride (TaB_2)	0.04 cal/g°C
	Titanium diboride (TiB_2)	$10.93 + 7.08 \times 10^{-3}$ T cal/mol for 420–1180 K
	Zirconium diboride (ZrB_2)	15.81 T $+ 4.20 \times 10^{-3}$ T-3.52×10^5 T^{-2} for 429–1171 K
Carbides	Hafnium monocarbide (HfC)	0.05 at room temp.
		15 ± 0.15 at 925°C
		16 ± 0.16 at 1525°C
	Silicon carbide (SiC)	0.26 at 540°C
		0.27 at 700°C
		0.30 at 1000°C
		0.32 at 1200°C
		0.33 at 1350°C
		0.35 at 1550°C
	Titanium monocarbide (TiC)	0.150–0.170 cal/g at 150°C
		0.170–0.187 cal/g at 300°C
		0.183–0.196 cal/g at 450°C
		0.192–0.201 cal/g at 600°C
		0.20–0.207 cal/g at 750°C
		0.209 cal/g at 900°C
		0.210 cal/g at 1000°C
		0.211 cal/g at 1100°C
Nitrides	Aluminum nitride (AlN)	0.1961 cal/g/°C; 0–100°C
		0.2277 cal/g/°C; 0–420°C
		0.2399 cal/g/°C; 0–598°C
	Trisilicon tetranitride (Si_3N_4)	0.17 cal/g/°C
Oxide	Cerium dioxide (CeO_2)	14.24 T $+ 5.62 \times 10^{-3}$ T for 491–1140 K
Silicides	Molybdenum disilicide ($MoSi_2$)	10–14 cal/g/°C; 425–1000°C
	Tungsten disilicide (WSi_2)	8 cal/g/°C; 425–1450°C

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T. B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

TABLE 2.6 Thermal Conductivity of Ceramics

Class	Ceramic	Thermal Conductivity (cal/cm s K)
Borides	Chromium diboride (CrB_2)	0.049–0.076 at room temp.
	Hafnium diboride (HfB_2)	0.015 at room temp.
	Tantalum diboride (TaB_2)	0.026 at room temp.
		0.033 at 200°C
	Titanium diboride (TiB_2)	0.058–0.062 at room temp.
		0.063 at 200°C
	Zirconium diboride (ZrB_2)	0.055–0.058 at room temp.
		0.055–0.060 at 200°C
Carbides	Boron carbide (B_4C)	0.065–0.069 at room temp.
		0.198 at 425°C
	Hafnium monocarbide (HfC)	0.053 at room temp.
		0.15 + 1.20 × 10 T W/cm K from 1000 to 2000 K
	Silicon carbide (SiC)	
	With 1 wt% Be addition	0.621
	With 1 wt% B addition	0.406
	With 1 wt% Al addition	0.143
	With 2 wt% BN addition	0.263
	With 1.6 wt% BeO addition	0.645 at room temp.
	With 3.2 wt% BeO addition	0.645 at room temp.
		0.098–0.10 at 20°C
	Cubic, CVD	0.289 at 127°C
		0.049–0.080 at 600°C
		0.061 at 800°C
		0.051 at 1000°C
		0.0059 at 1250°C
		0.0827 at 1327°C
		0.0032 at 1530°C
	Tantalum monocarbide (TaC)	0.053 at room temp.
	Titanium monocarbide (TiC)	0.041–0.074 at room temp.
		0.0135 at 1000°C
	Trichromium dicarbide (Cr_3C_2)	0.454
	Tungsten monocarbide (WC)	0.201 at 20°C
	6% Co, 1–3 µm grain size	0.239
	12% Co, 1–3 µm grain size	0.251
	24% Co, 1–3 µm grain size	0.239
	6% Co, 2–4 µm grain size	0.251
	6% Co, 3–6 µm grain size	0.256
	Zirconium monocarbide (ZrC)	0.049 at room temp.
		0.098 at 50°C
		0.069 at 150°C
		0.065 at 188°C
		0.061 at 288°C
		0.080 at 600°C
		0.083 at 800°C
		0.086 at 1000°C
		0.089 at 1200°C

(*Continued*)

TABLE 2.6 (*Continued*) Thermal Conductivity of Ceramics

Class	Ceramic	Thermal Conductivity (cal/cm s K)
		0.092 at 1400°C
		0.096 at 1600°C
		0.099 at 1800°C
		0.103 at 2000°C
		0.105 at 2200°C
Nitrides	Aluminum nitride (AlN)	0.072 at 25°C
		0.060 at 200°C
		0.053 at 400°C
		0.048 at 600°C
		0.042 at 800°C
	Boron nitride (BN)	
	Parallel to c axis	0.0687 at 300°C
		0.0646 at 700°C
		0.0637 at 1000°C
	Parallel to a axis	0.0362 at 300°C
		0.0318 at 700°C
		0.0295 at 1000°C
	Titanium mononitride (TiN)	0.069 at 25°C
		0.057 at 127°C
		0.040 at 200°C
		0.027 at 650°C
		0.020 at 1000°C
		0.162 at 1500°C
		0.136 at 2300°C
	Trisilicon tetranitride (Si_3N_4)	
	Pressureless sintered	0.072 at room temp.
		0.022–0.072 at 127°C
		0.041 at 200–750°C
		0.036–0.042 at 500°C
		0.038 at 1000°C
		0.033–0.034 at 1200°C
	Zirconium mononitride (ZrN)	0.040 at 200°C
		0.025 at 425°C
		0.018 at 650°C
		0.016 at 875°C
		0.015 at 1100°C
Oxides	Aluminum oxide (Al_2O_3)	0.06 at room temp.
		0.04–0.069 at 100°C
		0.03–0.064 at 200°C
		0.037 at 315°C
		0.02–0.031 at 400°C
		0.035 at 500°C
		0.021–0.022 at 600°C
		0.015–0.017 at 800°C
		0.014–0.016 at 1000°C

(*Continued*)

TABLE 2.6 (*Continued*) Thermal Conductivity of Ceramics

Class	Ceramic	Thermal Conductivity (cal/cm s K)
		0.013–0.015 at 1200°C
		0.013 at 1400°C
		0.014 at 1600°C
		0.017 at 1800°C
	Aluminum oxide (Al_2O_3) (single crystal)	0.103 at 20°C
		0.047 at 300°C
		0.029 at 800°C
	Beryllium oxide (BeO)	0.038–0.47 at 20°C
		0.032–0.34 at 100°C
		0.14–0.16 at 400°C
		0.089–0.1137 at 600°C
		0.060–0.093 at 800°C
		0.043 at 1100°C
		0.041–0.054 at 1200°C
		0.038 at 1300°C
		0.036 at 1400°C
		0.034 at 1500°C
		0.033–0.039 at 1600°C
		0.033 at 1700°C
		0.036 at 1800°C
		0.036 at 1900°C
		0.036 at 2000°C
	Calcium oxide (CaO)	0.037 at 100°C
		0.027 at 200°C
		0.022 at 400°C
		0.020 at 600°C
		0.019 at 800°C
		0.0186–0.019 at 1000°C
	Cerium dioxide (CeO_2)	0.0229 at 400 K
		0.00287 at 1400 K
	Dichromium trioxide (Cr_2O_3)	0.0239–0.0788
	Hafnium dioxide (HfO_2)	0.0273 at 25–425°C
	Magnesium oxide (MgO)	0.097 at room temp.
		0.078–0.082 at 100°C
		0.064–0.065 at 200°C
		0.038–0.045 at 400°C
		0.0198–0.026 at 800°C
		0.016–0.020 at 1000°C
		0.0139–0.0148 at 1200°C
		0.012–0.014 at 1400°C
		0.0108–0.016 at 1600°C
		0.0096–0.0191 at 1800°C
	Nickel monoxide (NiO)	
	0% porosity	0.029 at 100°C
	0% porosity	0.024 at 200°C
	0% porosity	0.017 at 400°C

(*Continued*)

TABLE 2.6 (*Continued*) Thermal Conductivity of Ceramics

Class	Ceramic	Thermal Conductivity (cal/cm s K)
	0% porosity	0.012 at 800°C
	0% porosity	0.011 at 1000°C
	Silicon dioxide (SiO_2)	0.0025 at 200°C
		0.003 at 400°C
		0.004 at 800°C
		0.005 at 1200°C
		0.006 at 1600°Cl
	Thorium dioxide (ThO_2)	
	0% porosity	0.024 at room temp.
	0% porosity	0.020 at 100°C
	0% porosity	0.019 at 200°C
	0% porosity	0.014 at 400°C
	0% porosity	0.010 at 600°C
	0% porosity	0.008 at 800°C
	0% porosity	0.007–0.0074 at 1000°C
	0% porosity	0.006–0.0076 at 1200°C
	0% porosity	0.006 at 1400°C
	Titanium dioxide (TiO_2)	
	0% porosity	0.016 at 100°C
	0% porosity	0.012 at 200°C
	0% porosity	0.009 at 400°C
	0% porosity	0.008 at 600°C
	0% porosity	0.008 at 800°C
	0% porosity	0.008 at 1000°C
	0% porosity	0.008 at 1200°C
	Uranium dioxide (UO_2)	
	0% porosity	0.025 at 100°C
	0% porosity	0.020 at 200°C
	0% porosity	0.015 at 400°C
	0% porosity	0.010 at 600°C
	0% porosity	0.009 at 800°C
	0% porosity	0.008 at 1000°C
		0.018 at 100°C
		0.012 at 400°C
		0.008 at 600°C
		0.008 at 700°C
		0.006 at 1000°C
		0.006 at 1200°C
	Zirconium dioxide (ZrO_2)	
	Stabilized, 0% porosity	0.005 at 100°C
	Stabilized, 0% porosity	0.005 at 200°C
	Stabilized, 0% porosity	0.005 at 400°C

(*Continued*)

TABLE 2.6 (*Continued*) Thermal Conductivity of Ceramics

Class	Ceramic	Thermal Conductivity (cal/cm s K)
	Stabilized, 0% porosity	0.0055 at 800°C
	Stabilized, 0% porosity	0.006 at 1200°C
	Stabilized, 0% porosity	0.0065 at 1400°C
	Stabilized	0.004 at 100°C
	Stabilized	0.0044 at 500°C
	Stabilized	0.0048–0.0055 at 1000°C
	Stabilized	0.0049–0.0050 at 1200°C
	MgO stabilized	0.0076 at room temp.
	MgO stabilized	0.0057 at 800°C
	Y_2O_3 stabilized	0.0055 at room temp.
	Y_2O_3 stabilized	0.0053 at 800°C
	Plasma sprayed	0.0019–0.0031 at room temp.
	Plasma sprayed	0.0019–0.0022 at 800°C
	Plasma sprayed and coated with Cr_2O_3	0.0033 at room temp.
	Plasma sprayed and coated with Cr_2O_3	0.0033 at 800°C
	5–10% CaO stabilized	0.0045 at 400°C
	5–10% CaO stabilized	0.0049 at 800°C
	5–10% CaO stabilized	0.0057 at 1200°C
	Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)	
	$\rho = 2.3\ g/cm^3$	0.0077 at 20°C
	$\rho = 2.3\ g/cm^3$	0.0062 at 300°C
	$\rho = 2.3\ g/cm^3$	0.0055 at 500°C
	$\rho = 2.3\ g/cm^3$	0.0055 at 800°C
	$\rho = 2.1\ g/cm^3$	0.0043 at 20°C
	$\rho = 2.1\ g/cm^3$	0.0041 at 300°C
	$\rho = 2.1\ g/cm^3$	0.0040 at 500°C
	$\rho = 2.1\ g/cm^3$	0.0038 at 800°C
	Mullite ($3Al_2O_3\ 2SiO_2$)	
	0% porosity	0.0145 at 100°C
	0% porosity	0.013 at 200°C
	0% porosity	0.011 at 400°C
	0% porosity	0.010 at 600°C
	0% porosity	0.0095 at 800°C
	0% porosity	0.009 at 1000°C
	0% porosity	0.009 at 1200°C
	0% porosity	0.009 at 1400°C
	Sillimanite ($Al_2O_3\ SiO_2$)	
	0% porosity	0.0042 at 100°C
	0% porosity	0.004 at 400°C
	0% porosity	0.0035 at 800°C
	0% porosity	0.0035 at 1200°C
	0% porosity	0.003 at 1500°C

(*Continued*)

TABLE 2.6 (*Continued*) Thermal Conductivity of Ceramics

Class	Ceramic	Thermal Conductivity (cal/cm s K)
	Spinel (Al_2O_3 MgO)	
	0% porosity	0.035 at 100°C
	0% porosity	0.031 at 200°C
	0% porosity	0.024 at 400°C
	0% porosity	0.019 at 600°C
	0% porosity	0.015 at 800°C
	0% porosity	0.013–0.0138 at 1000°C
	0% porosity	0.013 at 1200°C
	Zircon (SiO_2 ZrO_2)	
	0% porosity	0.0145 at 100°C
	0% porosity	0.0135 at 200°C
	0% porosity	0.012 at 400°C
	0% porosity	0.010 at 800°C
	0% porosity	0.0095 at 1200°C
	0% porosity	0.0095 at 1400°C
Silicide	Molybdenum disilicide ($MoSi_2$)	0.129 at 150°C
		0.074 at 425°C
		0.053 at 540°C
		0.057 at 650°C
		0.046 at 875°C
		0.041 at 1100°C

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T. B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

TABLE 2.7 Thermal Conductivity of Special Concretes[a]

Description; Type of Aggregate	Thermal Conductivity Btu/(h ft °F)
Frost resisting; 1% $CaCl_2$; normal aggregates	1.0
Frost-resisting porous; 6% air entrainment	0.85
Lightweight; with expanded shale or clay	0.25
Lightweight; with foamed slag	0.20
Cinder concrete; fine and coarse	0.25
Pulverized fuel ash	0.25
Lightweight refractory concrete with aluminous cement	0.20
Lightweight; insulating, with perlite	0.15
Lightweight; insulating, with expanded vermiculite	0.10

Source: Data from R. E. Bolz and C. L. Tuve (Eds.), *Handbook of Tables for Applied Engineering Science,* 2nd Edn., CRC Press, Cleveland, 1973, p. 645.

Note: To convert Btu/(h ft F) to W/m K, multiply by 1.7307.

[a] A great many varieties of aggregates have been used for concrete, dependent largely on the materials available. In general, high-density concretes have high strength and high thermal conductivity, although such variables as water/cement ratio, percentage of fines, and curing conditions may result in wide differences in properties with the same materials.

TABLE 2.8 Thermal Expansion of Ceramics

Class	Ceramic	Thermal Expansion (°C^{-1})
Borides	Chromium diboride (CrB_2)	4.6–11.1 × 10^{-6} for 20–1000°C
	Hafnium diboride (HfB_2)	5.5–5.54 × 10^{-6} for room temp. to 1000°C
	Tantalum diboride (TaB_2)	5.1 × 10^{-6} at room temp.
	Titanium diboride (TiB_2)	4.6–8.1 × 10^{-6}
	Zirconium diboride (ZrB_2)	5.69 × 10^{-6} for 25–500°C
		5.5–6.57 × 10^{-6} °C for 25–1000°C
		6.98 × 10^{-6} for 20–1500°C
Carbides	Boron carbide (B_4C)	4.5 × 10^{-6} for room temp. to 800°C
		4.78 × 10^{-6} for 25–500°C
		5.54 × 10^{-6} for 25–1000°C
		6.02 × 10^{-6} for 25–1500°C
		6.53 × 10^{-6} for 25–2000°C
		7.08 × 10^{-6} for 25–2500°C
	Hafnium monocarbide (HfC)	6.27–6.59 × 10^{-6} for 25–650°C
		6.25 × 10^{-6} for 25–1000°C
	Silicon carbide (SiC)	4.63 × 10^{-6} for 25–500°C
		5.12 × 10^{-6} for 25–1000°C
		5.48 × 10^{-6} for 25–1500°C
		5.77 × 10^{-6} for 25–2000°C
		5.94 × 10^{-6} for 25–2500°C
		4.70 × 10^{-6} for 20–1500°C
		4.70 × 10^{-6} for 0–1700°C
	Tantalum monocarbide (TaC)	6.29–6.32 × 10^{-6} for 25–500°C
		6.67 × 10^{-6} for 25–1000°C
		7.12 × 10^{-6} for 25–1500°C
		7.64 × 10^{-6} for 25–2000°C
		8.40 × 10^{-6} for 25–2500°C
		6.50 × 10^{-6} for 0–1000°C
		6.64 × 10^{-6} for 0–1200°C
	Titanium monocarbide (TiC)	6.52–7.15 × 10^{-6} for 25–500°C
		7.18–7.45 × 10^{-6} for 25–750°C
		7.40–8.82 × 10^{-6} for 25–1000°C
		9.32 × 10^{-6} for 25–1250°C
		8.15–9.45 × 10^{-6} for 25–1500°C
		8.81 × 10^{-6} for 25–2000°C
		7.90 × 10^{-6} for 0–2500°C
		7.08 × 10^{-6} for 0–750°C
		7.85–7.86 × 10^{-6} for 0–1000°C
		8.02 × 10^{-6} for 0–1275°C
		8.29 × 10^{-6} for 0–1400°C
		8.26 × 10^{-6} for 0–1525°C
		8.40 × 10^{-6} for 0–1775°C
	Trichromium dicarbide (Cr_3C_2)	8.00 × 10^{-6} for 25–500°C
		9.95 × 10^{-6} for 25–500°C
		8.8 × 10^{-6} for 25–120°C
		10.9 × 10^{-6} for 150–980°C
	Tungsten monocarbide (WC)	4.42 × 10^{-6} for 25–500°C
		4.84–4.92 × 10^{-6} for 25–1000°C
		5.35–5.8 × 10^{-6} for 25–1500°C
		5.82–7.4 × 10^{-6} for 25–2000°C
	Zirconium monocarbide (ZrC)	6.10 × 10^{-6} for 25–500°C
		6.65 × 10^{-6} for 25–800°C

(*Continued*)

TABLE 2.8 (*Continued*) Thermal Expansion of Ceramics

Class	Ceramic	Thermal Expansion (°C^{-1})
		6.56×10^{-6} for 25–1000°C 7.06×10^{-6} for 25–1500°C 7.65×10^{-6} for 25–650°C $6.10–6.73 \times 10^{-6}$ for 25–650°C 6.32×10^{-6} for 0–750°C $6.46–6.66 \times 10^{-6}$ for 0–1000°C 6.68×10^{-6} for 0–1275°C 6.83×10^{-6} for 0–1525°C 6.98×10^{-6} for 0–1775°C 9.0×10^{-6} for 1000–2000°C
Nitrides	Aluminum nitride (AlN)	4.03×10^{-6} for 25–200°C 4.84×10^{-6} for 25–500°C 4.83×10^{-6} for 25–600°C $5.54–5.64 \times 10^{-6}$ for 25–1000°C 6.09×10^{-6} for 25–1350°C
	Boron nitride (BN)	12.2×10^{-6} for 25–500°C 13.3×10^{-6} for 25–1000°C
	Parallel to c axis	10.15×10^{-6} for 25–350°C 8.06×10^{-6} for 25–700°C 7.15×10^{-6} for 25–1000°C
	Parallel to a axis	0.59×10^{-6} for 25–350°C 0.89×10^{-6} for 25–700°C 0.77×10^{-6} for 25–1000°C
	Titanium mononitride (TiN)	9.35×10^{-6}
	Trisilicon tetranitride (Si_3N_4)	2.11×10^{-6} for 25–500°C 2.87×10^{-6} for 25–1000°C 3.66×10^{-6} for 25–1500°C
	Hot pressed	$3–3.9 \times 10^{-6}$ for 20–1000°C
	Sintered	3.5×10^{-6} for 20–1000°C
	Reaction sintered	2.9×10^{-6} for 20–1000°C
	Pressureless sintered	3.7×10^{-6} for 40–1000°C
	Zirconium mononitride (ZrN)	6.13×10^{-6} for 20–450°C 7.03×10^{-6} for 20–680°C
Oxides	Aluminum oxide (Al_2O_3) (single crystal) Parallel to c axis	1.95×10^{-6} for 0 to −273°C 3.01×10^{-6} for 0 to −173°C 4.39×10^{-6} for 0 to −73°C 5.31×10^{-6} for 0–27°C 6.26×10^{-6} for 0–127°C 6.86×10^{-6} for 0–227°C 7.31×10^{-6} for 0–327°C 7.68×10^{-6} for 0–427°C 7.96×10^{-6} for 0–527°C 8.19×10^{-6} for 0–627°C 8.38×10^{-6} for 0–727°C 8.52×10^{-6} for 0–827°C 8.65×10^{-6} for 0–927°C 8.75×10^{-6} for 0–1027°C 8.84×10^{-6} for 0–1127°C 8.92×10^{-6} for 0–1227°C 8.98×10^{-6} for 0–1327°C 9.02×10^{-6} for 0–1427°C

(*Continued*)

TABLE 2.8 (*Continued*) Thermal Expansion of Ceramics

Class	Ceramic	Thermal Expansion (°C^{-1})
		9.08×10^{-6} for 0–1527°C
		9.13×10^{-6} for 0–1627°C
		9.18×10^{-6} for 0–1727°C
	Aluminum oxide (Al_2O_3) (single crystal)	1.65×10^{-6} for 0 to –273°C
	Perpendicular to c axis	2.55×10^{-6} for 0 to –173°C
		3.75×10^{-6} for 0 to –73°C
		4.78×10^{-6} for 0–27°C
		5.51×10^{-6} for 0–127°C
		6.10×10^{-6} for 0–227°C
		6.52×10^{-6} for 0–327°C
		6.88×10^{-6} for 0–427°C
		7.15×10^{-6} for 0–527°C
		7.35×10^{-6} for 0–627°C
		7.53×10^{-6} for 0–727°C
		7.67×10^{-6} for 0–827°C
		7.80×10^{-6} for 0–927°C
		7.88×10^{-6} for 0–1027°C
		7.96×10^{-6} for 0–1127°C
		8.05×10^{-6} for 0–1227°C
		8.12×10^{-6} for 0–1327°C
		8.16×10^{-6} for 0–1427°C
		8.20×10^{-6} for 0–1527°C
		8.26×10^{-6} for 0–1627°C
		8.30×10^{-6} for 0–1727°C
	Aluminum oxide (Al_2O_3)	1.89×10^{-6} for 0 to –273°C
	Polycrystalline	2.91×10^{-6} for 0 to –173°C
		4.10×10^{-6} for 0 to –73°C
		5.60×10^{-6} for 0–27°C
		6.03×10^{-6} for 0–127°C
		6.55×10^{-6} for 0–227°C
		6.93×10^{-6} for 0–327°C
		7.24×10^{-6} for 0–427°C
		7.50×10^{-6} for 0–527°C
		7.69×10^{-6} for 0–627°C
		7.83×10^{-6} for 0 to 727°C
		7.97×10^{-6} for 0–827°C
		8.08×10^{-6} for 0–927°C
		8.18×10^{-6} for 0–1027°C
		8.25×10^{-6} for 0–1127°C
		8.32×10^{-6} for 0–1227°C
		8.39×10^{-6} for 0–1327°C
		8.45×10^{-6} for 0–1427°C
		8.49×10^{-6} for 0–1527°C
		8.53×10^{-6} for 0–1627°C
		8.58×10^{-6} for 0–1727°C
	Beryllium oxide (BeO) (single crystal)	
	Parallel to c axis	6.3×10^{-6} for 28–252°C
		6.7×10^{-6} for 28–474°C
		7.8×10^{-6} for 28–749°C
		8.2×10^{-6} for 28–872°C
		8.9×10^{-6} for 28–1132°C

(*Continued*)

TABLE 2.8 (*Continued*) Thermal Expansion of Ceramics

Class	Ceramic	Thermal Expansion (°C^{-1})
	Beryllium oxide (BeO) (single crystal)	
	Perpendicular to c axis	7.1×10^{-6} for 28–252°C
		7.8×10^{-6} for 28–474°C
		8.5×10^{-6} for 28–749°C
		9.2×10^{-6} for 28–872°C
		9.9×10^{-6} for 28–1132°C
	Beryllium oxide (BeO) (single crystal)	
	Average for $(2a + c)/3$	6.83×10^{-6} for 28–252°C
		7.43×10^{-6} for 28–474°C
		8.27×10^{-6} for 28–749°C
		8.87×10^{-6} for 28–872°C
		9.57×10^{-6} for 28–1132°C
	Beryllium oxide (BeO) (polycrystalline)	2.4×10^{-6} for 25–200°C
		$6.3–6.4 \times 10^{-6}$ for 25–300°C
		7.59×10^{-6} for 25–500°C
		$8.4–8.5 \times 10^{-6}$ for 25–800°C
		9.03×10^{-6} for 25–1000°C
		9.18×10^{-6} for 25–1250°C
		10.3×10^{-6} for 25–1500°C
		11.1×10^{-6} for 25–2000°C
		9.40×10^{-6} for 500–1200°C
	Cerium dioxide (CeO_2)	8.22×10^{-6} for 25–500°C
		8.92×10^{-6} for 25–1000°C
		8.5 + 0.54T for 0–1000°C
	Dichromium trioxide (Cr_2O_3)	8.43×10^{-6} for 25–500°C
		8.62×10^{-6} for 25–1000°C
		8.82×10^{-6} for 25–1500°C
		9.55×10^{-6} for 20–1400°C
	Hafnium dioxide (HfO_2) (monoclinic single crystal)	
	Parallel to a axis	6.8×10^{-6} for 28–262°C
		6.2×10^{-6} for 28–494°C
		6.7×10^{-6} for 28–697°C
		7.5×10^{-6} for 28–903°C
		7.9×10^{-6} for 28–1098°C
	Parallel to b axis	0 for 28–262°C
		0.9×10^{-6} for 28–494°C
		1.3×10^{-6} for 28–697°C
		1.4×10^{-6} for 28–903°C
		2.1×10^{-6} for 28–1098°C
	Parallel to c axis	11×10^{-6} for 28–262°C
		11.4×10^{-6} for 28–494°C
		10.8×10^{-6} for 28–697°C
		11.9×10^{-6} for 28–903°C
		12.1×10^{-6} for 28–1098°C
	Hafnium dioxide (HfO_2)	
	Monoclinic polycrystalline	5.47×10^{-6} for 25–500°C
		5.85×10^{-6} for 25–1000°C
		5.8×10^{-6} for 25–1300°C
		6.30×10^{-6} for 25–1500°C
		6.45×10^{-6} for 20–1700°C

(*Continued*)

TABLE 2.8 (*Continued*) Thermal Expansion of Ceramics

Class	Ceramic	Thermal Expansion (°C^{-1})
	Hafnium dioxide (HfO_2)	
	Tetragonal polycrystalline	1.31×10^{-6} for 25–1700°C
		3.03×10^{-6} for 25–2000°C
	Magnesium oxide (MgO)	12.83×10^{-6} for 25–500°C
		13.63×10^{-6} for 25–1000°C
		15.11×10^{-6} for 25–1500°C
		15.89×10^{-6} for 25–1800°C
		14.0×10^{-6} for 20–1400°C
		$14.2–14.9 \times 10^{-6}$ for 20–1700°C
		13.3×10^{-6} for 20–1700°C
		13.90×10^{-6} for 0–1000°C
		14.46×10^{-6} for 0–1200°C
		15.06×10^{-6} for 0–1400°C
	Silicon dioxide (SiO_2)	19.35×10^{-6} for 25–500°C
	α quartz	22.2×10^{-6} for 25–575°C
	β quartz	27.8×10^{-6} for 25–575°C
		14.58×10^{-6} for 25–1000°C
	α tridymite	18.5×10^{-6} for 25–117°C
	β_1 tridymite	25.0×10^{-6} for 25–117°C
		27.5×10^{-6} for 25–163°C
	β_2 tridymite	31.9×10^{-6} for 25–163°C
		19.35×10^{-6} for 25–500°C
		10.45×10^{-6} for 25–1000°C
	Vitreous	0.527×10^{-6} for 25–500°C
		0.564×10^{-6} for 25–1000°C
		0.5×10^{-6} for 20–1250°C
	Thorium dioxide (ThO_2)	3.67×10^{-6} for 0 to −273°C
		5.32×10^{-6} for 0 to −173°C
		6.47×10^{-6} for 0 to −73°C
		8.10×10^{-6} for 0–27°C
		8.06×10^{-6} for 0–127°C
		8.31×10^{-6} for 0–227°C
		8.53×10^{-6} for 0–327°C
		8.71×10^{-6} for 0–427°C
		8.87×10^{-6} for 0–527°C
		9.00×10^{-6} for 0–627°C
		9.14×10^{-6} for 0–727°C
		9.24×10^{-6} for 0–827°C
		9.34×10^{-6} for 0–927°C
		9.42×10^{-6} for 0–1027°C
		9.53×10^{-6} for 0–1127°C
		9.60×10^{-6} for 0–1227°C
		9.68×10^{-6} for 0–1327°C
		9.76×10^{-6} for 0–1427°C
		9.83×10^{-6} for 0–1527°C
		9.91×10^{-6} for 0–1627°C
		9.97×10^{-6} for0–1727°C
		8.63×10^{-6} for 25–500°C
		9.44×10^{-6} for 25–1000°C
		10.17×10^{-6} for 25–1500°C
		10.43×10^{-6} for 25–1700°C

(*Continued*)

TABLE 2.8 (*Continued*) Thermal Expansion of Ceramics

Class	Ceramic	Thermal Expansion (°C^{-1})
		9.55×10^{-6} for 20–800°C 9.55×10^{-6} for 20–1400°C 7.8×10^{-6} for 27–223°C 8.7×10^{-6} for 27–498°C 8.9×10^{-6} for 27–755°C 9.2×10^{-6} for 27 to 994°C 9.1×10^{-6} for 27–1087°C 8.96×10^{-6} for 0–1000°C 9.35×10^{-6} for 0–1200°C 9.84×10^{-6} for 0–1400°C
	α_l (linear expansion coefficient)	$0.6216 \times 10^{-5} + 3.541 \times 10^{-9}$ T-0.1124T^{-2} from 298 to 1073 K
	α_v (volume expansion coefficient)	$1.85 \times 10^{-5} + 10.96 \times 10^{-9}$ T-0.3375 T^{-2} from 298 to 1073 K
	Titanium dioxide (TiO_2) (polycrystalline)	8.22×10^{-6} for 25–500°C 8.83×10^{-6} for 25–1000°C 9.50×10^{-6} for 25–1500°C 7.8×10^{-6} for 20–600°C 8.98×10^{-6} for 0–1000°C
	Titanium dioxide (TiO_2) (single crystal) Parallel to c axis	 9.8×10^{-6} for 26–240°C 10.5×10^{-6} for 26–455°C 10.6×10^{-6} for 26–670°C 10.5×10^{-6} for 26–940°C 10.8×10^{-6} for 26–1110°C
	Titanium dioxide (TiO_2) (single crystal) Parallel to a axis	7.9×10^{-6} for 26–240°C 8.2×10^{-6} for 26–455°C 8.1×10^{-6} for 26–670°C 8.2×10^{-6} for 26–940°C 8.3×10^{-6} for 26–1110°C
	Titanium dioxide (TiO_2) (single crystal) Average for $(2a + c)/3$	 8.53×10^{-6} for 26–240°C 8.97×10^{-6} for 26–455°C 8.93×10^{-6} for 26–670°C 8.97×10^{-6} for 26–940°C 9.13×10^{-6} for 26–1110°C
	Uranium dioxide (UO_2)	9.47×10^{-6} for 25–500°C 11.19×10^{-6} for 25–1000°C 12.19×10^{-6} for 25–1200°C 11.15×10^{-6} for 25–1750°C 9.18×10^{-6} for 27–400°C
	Heating	9.07×10^{-6} for 27–400°C 11.1×10^{-6} for 400–800°C 13.0×10^{-6} for 800–1200°C
	Cooling	9.28×10^{-6} for 27–400°C 10.8×10^{-6} for 400–800°C 12.6×10^{-6} for 800–1250°C 12.9×10^{-6} for 800–1200°C

(*Continued*)

TABLE 2.8 (*Continued*) Thermal Expansion of Ceramics

Class	Ceramic	Thermal Expansion (°C^{-1})
	Zirconium dioxide (ZrO_2) (monoclinic)	6.53×10^{-6} for 25–500°C
		7.59×10^{-6} for 25–1000°C
		7.72×10^{-6} for 25–1050°C
		8.0×10^{-6} for 25–1080°C
	Zirconium dioxide (ZrO_2) (tetragonal)	-21.7×10^{-6} for 25–1050°C
		-11.11×10^{-6} for 25–1500°C
		-9.53×10^{-6} for 25–1600°C
		4.0×10^{-6} for 0–500°C
		10.5×10^{-6} for 0–1000°C
		10.52×10^{-6} for 0–1000°C (MgO)
		10.6×10^{-6} for 0–1200°C (CaO)
		5.0×10^{-6} for 0–1400°C
		11.0×10^{-6} for 0–1500°C
		$5.5–5.58 \times 10^{-6}$ for 20–1200°C
		7.2×10^{-6} for −10 to 1000°C
		8.64×10^{-6} for −20 to 600°C
	Zirconium dioxide (ZrO_2) (tetragonal, single crystal)	
	Parallel to a axis	8.4×10^{-6} for 27–264°C
		7.5×10^{-6} for 27–504°C
		6.8×10^{-6} for 27–759°C
		7.8×10^{-6} for 27–964°C
		8.7×10^{-6} for 27–1110°C
	Zirconium dioxide (ZrO_2) (tetragonal, single crystal)	
	Parallel to b axis	3×10^{-6} for 27–264°C
		2×10^{-6} for 27–504°C
		1.1×10^{-6} for 27–759°C
		1.5×10^{-6} for 27–964°C
		1.9×10^{-6} for 27–1110°C
	Zirconium dioxide (ZrO_2) (tetragonal, single crystal)	
	Parallel to c axis	14×10^{-6} for 27–264°C
		13×10^{-6} for 27–504°C
		11.9×10^{-6} for 27–759°C
		12.8×10^{-6} for 27–964°C
		13.6×10^{-6} for 27–1110°C
	Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)	
	ρ = 2.51 g/cm³	2.7×10^{-6} for 25–1100°C
	ρ = 2.3 g/cm³	2.3×10^{-6} for 25–400°C
	ρ = 2.3 g/cm³	3.3×10^{-6} for 25–700°C
	ρ = 2.3 g/cm³	3.7×10^{-6} for 25–900°C
	ρ = 2.1 g/cm³	2.2×10^{-6} for 25–400°C
	ρ = 2.1 g/cm³	2.8×10^{-6} for 25–700°C
	ρ = 2.1 g/cm³	2.8×10^{-6} for 25–900°C
	ρ = 1.8 g/cm³	0.6×10^{-6} for 25–400°C
	ρ = 1.8 g/cm³	1.5×10^{-6} for 25–700°C
	ρ = 1.8 g/cm³	1.7×10^{-6} for 25–900°C
	Glass	$3.7–3.8 \times 10^{-6}$ for 25–900°C
	Mullite ($3Al_2O_3\ 2SiO_2$)	4.5×10^{-6} for 20–1325°C
		4.63×10^{-6} for 25–500°C
		5.0×10^{-6} for 25–800°C
		5.13×10^{-6} for 25–1000°C
		5.62×10^{-6} for 20–1500°C

(*Continued*)

TABLE 2.8 (*Continued*) Thermal Expansion of Ceramics

Class	Ceramic	Thermal Expansion (°C^{-1})
	Sillimanite (Al_2O_3 SiO_2)	6.58×10^{-6} at 20°C
	Spinel (Al_2O_3 MgO)	7.79×10^{-6} for 25–500°C 8.41×10^{-6} for 25–1000°C 9.17×10^{-6} for 25–1500°C 9.0×10^{-6} for 20–1250°C
	Zircon (SiO_2 ZrO_2)	5.5×10^{-6} for 20–1200°C 3.79×10^{-6} for 25–500°C 4.62×10^{-6} for 25–1000°C 5.63×10^{-6} for 20–1500°C
Silicides	Molybdenum disilicide ($MoSi_2$)	7.79×10^{-6} for 25–500°C 8.51×10^{-6} for 25–1000°C $9.00–9.18 \times 10^{-6}$ for 25–1500°C 8.41×10^{-6} for 0–1000°C 8.56×10^{-6} for 0–1400°C
	Tungsten disilicide (WSi_2)	7.79×10^{-6} for 25–500°C 8.31×10^{-6} for 25–1000°C 8.21×10^{-6} for 0–1000°C 8.81×10^{-6} for 0–1400°C

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T. B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

TABLE 2.9 Thermal Expansion Coefficients of Materials for Integrated Circuits

Material	Coefficient Range ($\times 10^{-6}$ K^{-1})	Temperature Range (°C)
Aluminum oxide ceramic	6.0–7.0	25–300
Brass	17.7–21.2	25–300
Kanthal A	13.9–15.1	20–900
Kovar	5.0	25–300
Pyrex glass	3.2	25–300
Pyroceram (#9608)	420	25–300
Pyroceram cement (vitreous #45)	4	0–300
Pyroceram cement (devitrified)	2.4	25–300
Pyroceram cement (#89, #95)	8–10	–
Silicon carbide	4.8	0–1000
Silicon nitride (α)	2.9	25–1000
Silicon nitride (β)	2.25	25–1000
Solder glass (Kimble CV-101)	809	0–300

Source: From Beadles, R.L., *Interconnections and Encapsulation, Integrated Silicon Device Technology*, Vol. 14, Research Triangle Institute, Research Triangle Park, NC, 1967, as cited in C. T. Lynch (Ed.), *CRC Handbook of Materials Science*, CRC Press, Cleveland, 1974.

TABLE 2.10 Tensile Strength of Ceramics

Type	Ceramic	Tensile Strength (psi)	Temperature (°C)
Borides	Chromium diboride (CrB_2)	10.6×10^4	
	Titanium diboride (TiB_2)	18.4×10^3	
	Zirconium diboride (ZrB_2)	28.7×10^3	
Carbides	Boron carbide (B_4C)	22.5×10^3	980
	Silicon carbide (SiC)	$5–20 \times 10^3$	25
	Hot pressed	29×10^3	20
	Hot pressed	$5.75–21.75 \times 10^3$	1400
	Reaction bonded	11.17×10^3	20
	Tantalum monocarbide (TaC)	$2–42 \times 10^3$	
	Titanium monocarbide (TiC)	17.2×10^3	1000
	Tungsten monocarbide (WC)	50×10^3	
	Zirconium monocarbide (ZrC)	16.0×10^3	Room temp.
		$11.7–14.45 \times 10^3$	980
		$12.95–15.85 \times 10^3$	1250
Nitrides	Boron nitride (BN)	0.35×10^3	1000
		0.35×10^3	1500
		1.15×10^3	1800
		2.25×10^3	2000
		6.80×10^3	2400
	Trisilicon tetranitride (Si_3N_4)		
	Hot pressed	54.4×10^3	20
	Hot pressed	21.8×10^3	1400
	Reaction bonded	24.7×10^3	20
	Reaction bonded	20.3×10^3	1400
Oxides	Aluminum oxide (Al_2O_3)	$37–37.8 \times 10^3$	Room temp.
		33.6×10^3	300
		40×10^3	500
		34.6×10^3	800
		35×10^3	1000
		33.9×10^3	1050
		31.4×10^3	1140
		$18.5–20 \times 10^3$	1200
		6.4×10^3	1300
		4.3×10^3	1400
		1.5×10^3	1460
	Beryllium oxide (BeO)	$13.5–20 \times 10^3$	Room temp.
		11.1×10^3	500
		7.0×10^3	900
		5.0×10^3	1000
		2.0×10^3	1140
		0.6×10^3	1300
	Magnesium oxide (MgO)	14×10^3	Room temp.
		14×10^3	200
		15.2×10^3	400
		16×10^3	800
		11.5×10^3	1000
		10×10^3	1100
		8×10^3	1200
		6×10^3	1300

(*Continued*)

TABLE 2.10 (*Continued*) Tensile Strength of Ceramics

Type	Ceramic	Tensile Strength (psi)	Temperature (°C)
	Thorium dioxide (ThO_2)	14×10^3	Room temp.
	Zirconium dioxide (ZrO_2)	$17.9–20 \times 10^3$	Room temp.
		16.8×10^3	200
		17.5×10^3	400
		20.0×10^3	500
		17.6×10^3	600
		16.0×10^3	800
		$6.75–17.0 \times 10^3$	1000
		$13.0–13.5 \times 10^3$	1100
		12.1×10^3	1200
		10.2×10^3	1300
	MgO stabilized	21×10^6	Room temp.
	Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)		
	$\rho = 2.51$ g/cm^3	7.8×10^3	25
	$\rho = 2.1$ g/cm^3	3.5×10^3	800
	$\rho = 1.8$ g/cm^3	2.5×10^3	1200
	Mullite ($3Al_2O_3\ 2SiO_2$)	16×10^3	25
	Spinel ($Al_2O_3\ MgO$)	19.2×10^3	Room temp.
		13.7×10^3	550
		110.8×10^3	900
		6.1×10^3	1150
		1.1×10^3	1300
	Zircon ($SiO_2\ ZrO_2$)	12.7×10^3	Room temp.
		8.7×10^3	1050
		3.6×10^3	1200
Silicide	Molybdenum disilicide ($MoSi_2$)	40×10^3	980
		42.16×10^3	1090
		42.8×10^3	1200
		41.07×10^3	1300

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T.B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

Note: To convert psi to MPa, divide by 145.

TABLE 2.11 Compressive Strength of Ceramics

Class	Ceramic	Compressive Strength (psi)	Temperature (°C)
Boride	Titanium diboride (TiB_2)	$47–97 \times 10^3$	
Carbides	Boron carbide (B_4C)	41.4×10^4	Room temp.
	Silicon carbide (SiC)	$82–200 \times 10^3$	25
	Titanium monocarbide (TiC)	$10.9–19 \times 10^4$	Room temp.
	Trichromium dicarbide (Cr_3C_2)	60×10^4	
	Zirconium monocarbide (ZrC)	238×10^3	Room temp.
Nitrides	Boron nitride (BN)		
	Parallel to c axis	34.0×10^3	
	Parallel to a axis	45×10^3	
	Titanium mononitride (TiN)	141×10^3	
	Trisilicon tetranitride (Si_3N_4)	$10–100 \times 10^3$	25
		$10–30 \times 10^3$	1000
Oxides	Aluminum oxide (Al_2O_3)	427×10^3	Room temp.
		214×10^3	400
		199×10^3	600
		183×10^3	800
		128×10^3	1000
		85×10^3	1100
		71×10^3	1200
		35.6×10^3	1400
		14×10^3	1500
		7×10^3	1600
	Beryllium oxide (BeO)	$114–310 \times 10^3$	Room temp.
		71×10^3	500
		64×10^3	800
		$35.5–40 \times 10^3$	1000
		28.5×10^3	1145
		24×10^3	1400
		17×10^3	1500
		7×10^3	1600
	Magnesium oxide (MgO)	112×10^3	Room temp.
	Thorium dioxide (ThO_2)	$146–214 \times 10^3$	Room temp.
		156×10^3	400
		85×10^3	600
		71×10^3	800
		51×10^3	1000
		28.5×10^3	1200
		5.7×10^3	1400
		1.5×10^3	1500
	Zirconium dioxide (ZrO_2)	$205–300 \times 10^3$	Room temp.
		228×10^3	500
		171×10^3	1000
		114×10^3	1200
		18.5×10^3	1400
		2.8×10^3	1500
	CaO stabilized	$85–190 \times 10^6$	Room temp.

(*Continued*)

TABLE 2.11 (*Continued*) Compressive Strength of Ceramics

Class	Ceramic	Compressive Strength (psi)	Temperature (°C)
	Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)		
	ρ = 2.51 g/cm^3	50×10^3	25
	ρ = 2.3 g/cm^3	50×10^3	400
	ρ = 2.1 g/cm^3	30×10^3	800
	ρ = 1.8 g/cm^3	18.5×10^3	1200
	Mullite ($3Al_2O_3\ 2SiO_2$)	$80–190 \times 10^3$	25
	Spinel (Al_2O_3 MgO)	270×10^3	Room temp.
		199×10^3	500
		171×10^3	800
		85.5×10^3	1100
		71×10^3	1200
		21.4×10^3	1400
		8.5×10^3	1600

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T. B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

Note: To convert psi to MPa, divide by 145.

TABLE 2.12 Hardness of Ceramics

Class	Ceramic	Hardness
Borides	Chromium diboride (CrB_2)	Micro 100 g: 1800 kg/mm^2 Vickers 50 g: 1800 kg/mm^2 Knoop 100 g: 1700 kg/mm^2
	Hafnium diboride (HfB_2)	
	Polycrystalline	Knoop 160 g: 2400 kg/mm at 24°C
	Single crystal	Knoop 160 g: 3800 kg/mm at 24°C
	Tantalum diboride (TaB_2)	Micro: 1700 kg/mm^2 Knoop 30 g: 2537 kg/mm^2 Knoop 100 g: 2615 ± 120 kg/mm^2 Rockwell A: 89
	Titanium diboride (TiB_2)	Vickers 50 g: 3400 kg/mm^2 Knoop 30 g: 3370 kg/mm^2 Knoop 100 g: 2710–3000 kg/mm^2 Knoop 160 g: 3500 kg/mm^2
	Single crystal	Knoop 100 g: 3250 ± 100 kg/mm^2
	Zirconium diboride (ZrB_2)	Rockwell A: 87–89 Vickers 50 g: 2200 kg/mm^2 Knoop 100 g: 1560 kg/mm^2 Knoop 160g: 2100 kg/mm^2
	Single crystal	Knoop 160 g: 2000 kg/mm^2
Carbides	Boron carbide (B_4C)	Knoop 100 g: 2800 kg/mm^2 Knoop 1000 g: 2230 kg/mm^2 Vickers: 2400 kg/mm^2
	Hafnium monocarbide (HfC)	Knoop: 1790–1870 kg/mm^2 Vickers 50 g: 2533–3202 kg/mm^2

(*Continued*)

TABLE 2.12 (*Continued*) Hardness of Ceramics

Class	Ceramic	Hardness
	Silicon carbide (SiC)	Mohs: 9.2 Vickers 25 g: 3000–3500 kg/mm^2 Knoop 100 g: 2500–2550 kg/mm^2 Knoop 100 g: 2960 kg/mm^2 (black) Knoop 100 g: 2745 kg/mm^2 (green)
	Cubic, CVD	Knoop or Vickers: 2853–4483 kg/mm^2
	Tantalum monocarbide (TaC)	Knoop 50 g: 1800–1952 kg/mm^2 Knoop 100 g: 825 kg/mm^2 Vickers 50 g: 1800 kg/mm^2 Rockwell A: 89 Brinell: 840
	Titanium monocarbide (TiC)	Knoop 100 g: 2470 kg/mm^2 Knoop 1000 g: 1905 kg/mm^2 Vickers 50 g: 2900–3200 kg/mm^2 Vickers 100 g: 2850–3390 kg/mm^2 Micro 20 g: 3200 kg/mm^2
	98.6% density	Rockwell A: 88–89
	99.5% density	Rockwell A: 91–93.5
	100% density	Rockwell A: 91–93.5
	Trichromium dicarbide (Cr_3C_2)	Knoop or Vickers: 1019–1834 kg/mm^2
	Tungsten monocarbide (WC)	Knoop 100 g: 1870–1880 kg/mm^2 Vickers 50 g: 2400 kg/mm^2 Vickers 100 g: 1730 kg/mm^2 Rockwell A: 92
	6% Co, 1–3 μm grain size 12% Co, 1–3 μm grain size 24% Co, 1–3 μm grain size 6% Co, 2–4 μm grain size 6% Co, 3–6 μm grain size	Rockwell A: 81.4 ± 0.4 Rockwell A: 89.4 ± 0.5 Rockwell A: 86.9 ± 0.6 Rockwell A: 88.6 ± 0.5 Rockwell A: 87.3 ± 0.5
	Zirconium monocarbide (ZrC)	Knoop: 2138 kg/mm^2 Vickers 50 g: 2600 kg/mm^2 Vickers 100 g: 2836–3840 kg/mm^2 Micro: 2090 kg/mm^2 Rockwell A: 92.5
Nitrides	Aluminum nitride (AlN)	Mohs: 5–5.5 Knoop 100 g: 1225–1230 kg/mm^2
	Thick film	Rockwell 15 N: 94.5
	Thin film	Rockwell 15 N: 94.0
	Boron nitride (BN)	Mohs: 2 (hexagonal)
	Titanium mononitride (TiN)	Mohs: 8–10 Knoop 30 g: 2160 kg/mm^2 Knoop 100 g: 1770 kg/mm^2
	Trisilicon tetranitride (Si_3N_4)	Mohs: 9+
	α	Knoop or Vickers: 815–1936 kg/mm^2
		Rockwell A: 99
	Zirconium mononitride (ZrN)	Mohs: 8+ Knoop 30 g: 1983 kg/mm^2 Knoop 100 g: 1510 kg/mm^2

(*Continued*)

TABLE 2.12 (*Continued*) Hardness of Ceramics

Class	Ceramic	Hardness
Oxides	Aluminum oxide (Al_2O_3)	
	Single crystal	Mohs: 9 Knoop 100 g: 2000–2050 kg/mm^2 Vickers 20 g: 2600 kg/mm^2 Vickers 50 g: 2720 kg/mm^2 R45N: 78–90
	Beryllium oxide (BeO)	Knoop 100 g: 1300 kg/mm^2 R45N: 64–67
	Calcium oxide (CaO)	Knoop 100 g: 560 kg/mm^2
	Dichromium trioxide (Cr_2O_3)	Knoop or Vickers: 2955 kg/mm^2
	Magnesium oxide (MgO)	Mohs: 5.5
	Silicon dioxide (SiO_2)	
	Parallel to optical axis	Knoop 100 g: 710 kg/mm^2
	Normal to optical axis	Knoop 100 g: 790 kg/mm^2
	Parallel to optical axis	Vickers 500 g: 1260 kg/mm^2
	Normal to optical axis	Vickers 500 g: 1103 kg/mm^2
		Vickers 500 g: 1120 kg/mm^2
	(1010 face) 10 μm diagonal	Vickers 500 g: 1120–1230 kg/mm^2
	(1011 face) 10 μm diagonal	Vickers 500 g: 1040–1130 kg/mm^2
	(polished 1010 face) 10 μm diagonal	Vickers 500 g: 1300 kg/mm^2
	Thorium dioxide (ThO_2)	Mohs: 6.5 Knoop 100 g: 945 kg/mm^2
	Titanium dioxide (TiO_2)	Knoop or Vickers: 713–1121 kg/mm^2
	Uranium dioxide (UO_2)	Mohs: 6–7 Knoop 100 g: 600 kg/mm^2
	Zirconium dioxide (ZrO_2)	Mohs: 6.5 Knoop 100 g: 1200 kg/mm^2
	Partially stabilized	Knoop or Vickers: 1019–1121 kg/mm^2
	Fully stabilized	Knoop or Vickers: 1019–1529 kg/mm^2
	Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)	Vickers: 835.6 kg/mm^2
	Glass	Vickers: 672.5 kg/mm^2
	Mullite ($3Al_2O_3\ 2SiO_2$)	Mohs: 7.5 Vickers: 1120 kg/mm^2 R45N: 71
	Sillimanite ($Al_2O_3\ SiO_2$)	Mohs: 6–7
	Zircon ($SiO_2\ ZrO_2$)	Mohs: 7.5
Silicides	Molybdenum disilicide ($MoSi_2$)	Knoop 100 g: 1257 kg/mm^2 Vickers 100 g: 1290–1550 kg/mm^2 Micro 50 g: 1200 kg/mm^2 Micro 100 g: 1290 kg/mm^2
	Tungsten disilicide (WSi_2)	Knoop 100 g: 1090 kg/mm^2 Vickers 100 g: 1090 kg/mm^2 Vickers 10 g: 1632 kg/mm^2 Micro 50 g: 1260 kg/mm^2

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T. B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

TABLE 2.13 Young's Modulus of Ceramics

Class	Ceramic	Young's Modulus (psi)	Temperature (°C)
Borides	Chromium diboride (CrB_2)	30.6×10^6	
	Tantalum diboride (TaB_2)	37×10^6	
	Titanium diboride (TiB_2)	53.2×10^6	
	6.0 μm grain size, ρ = 4.46 g/cm³	81.6×10^6	
	3.5 μm grain size, ρ = 4.37 g/cm³, 0.8 wt% Ni	75.0×10^6	
	6.0 μm grain size, ρ = 4.56 g/cm³, 0.16 wt% Ni	77.9×10^6	
	12.0 μm grain size, ρ = 4.66 g/cm³, 9.6 wt% Ni	6.29×10^6	
	Zirconium diboride (ZrB_2)	$49.8–63.8 \times 10^6$	
	22.4% density, foam	3.305×10^6	
Carbides	Boron carbide (B_4C)	$42–65.2 \times 10^6$	Room temp.
	Hafnium monocarbide (HfC)		
	ρ = 11.94 g/cm³	61.55×10^6	Room temp.
	Silicon carbide (SiC)		
	Pressureless sintered	43.9×10^6	Room temp.
	Hot pressed	63.8×10^6	Room temp.
	Self-bonded	59.5×10^6	Room temp.
	Cubic, CVD	$60.2–63.9 \times 10^6$	Room temp.
	Silicon carbide (ρ = 3.128 g/cm³)	58.2×10^6	Room temp.
	ρ = 3.120 g/cm³	59.52×10^6	Room temp.
	Hot pressed	$62.4–65.3 \times 10^6$	20
	Sintered	$54.38–60.9 \times 10^6$	20
	Reaction sintered	$50.75–54.38 \times 10^6$	20
		55×10^6	400
		53×10^6	800
		51×10^6	1200
	Hot pressed	55.1×10^6	1400
	Sintered	$43.5–58.0 \times 10^6$	1400
	Reaction sintered	$29–46.4 \times 10^6$	1400
	Tantalum monocarbide (TaC)	$41.3–91.3 \times 10^6$	Room temp.
	Titanium monocarbide (TiC)	63.715×10^6	Room temp.
		$45–55 \times 10^6$	1000
	Trichromium dicarbide (Cr_3C_2)	54.1×10^6	
	Tungsten monocarbide (WC)	$96.91–103.5 \times 10^6$	Room temp.
	Zirconium monocarbide (ZrC)	$28.3–69.6 \times 10^6$	Room temp.
Nitrides	Aluminum nitride (AlN)	50×10^6	25
		46×10^6	1000
		40×10^6	1400
	Boron nitride (BN)		
	Parallel to c axis	4.91×10^6	23
		3.47×10^6	300
		0.51×10^6	700
	Parallel to a axis	12.46×10^6	23
		8.79×10^6	300
		1.54×10^6	700
		1.65×10^6	1000

(*Continued*)

TABLE 2.13 (*Continued*) Young's Modulus of Ceramics

Class	Ceramic	Young's Modulus (psi)	Temperature (°C)
	Titanium mononitride (TiN)	$11.47–36.3 \times 10^6$	
	Trisilicon tetranitride (Si_3N_4)		
	Hot pressed	$36.25–47.13 \times 10^6$	20
	Sintered	$28.28–45.68 \times 10^6$	20
	Reaction sintered	$14.5–31.9 \times 10^6$	20
	Hot pressed	$25.38–36.25 \times 10^6$	1400
	Reaction sintered	$17.4–29.0 \times 10^6$	1400
Oxides	Aluminum oxide (Al_2O_3)	$50–59.3 \times 10^6$	Room temp.
		$50–57.275 \times 10^6$	500
		51.2×10^6	800
		$45.5–50 \times 10^6$	1000
		$39.8–53.65 \times 10^6$	1200
		32×10^6	1250
		32.7×10^6	1400
		25.6×10^6	1500
	Beryllium oxide (BeO)	$42.8–45.5 \times 10^6$	Room temp.
		40×10^6	800
		33×10^6	1000
		20×10^6	1145
	Cerium dioxide (CeO_2)	24.9×10^6	
	Dichromium trioxide (Cr_2O_3)	$>14.9 \times 10^6$	
	Hafnium dioxide (HfO_2)	8.2×10^6	
	Magnesium oxide (MgO)	$30.5–36.3 \times 10^6$	Room temp.
		29.5×10^6	600
		21×10^6	1000
		10×10^6	1200
		4×10^6	1300
	$\rho = 3.506$ g/cm^3	42.74×10^6	Room temp.
	Thorium dioxide (ThO_2)	$17.9–34.87 \times 10^6$	Room temp.
		$18–18.5 \times 10^6$	800
		17.1×10^6	1000
		12.8×10^6	1200
	Titanium dioxide (TiO_2)	41×10^6	
	Uranium dioxide (UO_2)	21×10^6	0–1000
		25×10^6	20
	$\rho = 10.37$ g/cm^3	27.98×10^6	Room temp.
	Zirconium dioxide (ZrO_2)		
	Partially stabilized	29.7×10^6	Room temp.
	Fully stabilized	$14.1–30.0 \times 10^6$	Room temp.
	Plasma sprayed	6.96×10^6	Room temp.
		$24.8–27 \times 10^6$	Room temp.
		36×10^6	20
		2×10^6	500
		18.9×10^6	800
		$18.5–25 \times 10^6$	1000
		3.05×10^6	1100
		$17.1–18.0 \times 10^6$	1200
		14.2×10^6	1400
		12.8×10^6	1500
	Stabilized, $\rho = 5.634$ g/cm^3	19.96×10^6	Room temp.
	Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)	20.16×10^6	
	Glass	13.92×10^6	

(*Continued*)

TABLE 2.13 (*Continued*) Young's Modulus of Ceramics

Class	Ceramic	Young's Modulus (psi)	Temperature (°C)
	Mullite ($3Al_2O_3$ $2SiO_2$)		
	ρ = 2.779 g/cm³	20.75×10^6	Room temp.
	ρ = 2.77 g/cm³	18.42×10^6	25
	ρ = 2.77 g/cm³	18.89×10^6	400
	ρ = 2.77 g/cm³	14.79×10^6	800
	ρ = 2.77 g/cm³	4.00×10^6	1200
	Full density	33.35×10^6	Room temp.
	Spinel (Al_2O_3 MgO)	34.5×10^6	Room temp.
		34.4×10^6	200
		34.5×10^6	400
		34×10^6	600
		32.9×10^6	800
		30.4×10^6	1000
		25.0×10^6	1200
		20.1×10^6	1300
	ρ = 3.510 g/cm³	8.23×10^6	Room temp.
	Zircon (SiO_2 ZrO_2)	24×10^6	Room temp.
Silicide	Molybdenum disilicide ($MoSi_2$)	$39.3–56.36 \times 10^6$	Room temp.

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T. B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

Note: To convert from psi to MPa, divide by 145.

TABLE 2.14 Modulus of Rupture for Ceramics

Class	Ceramic	Modulus of Rupture (psi)	Temperature (°C)
Boride	Titanium diboride (TiB_2)	19×10^3	
	98% dense	5.37×10^3	
	6.0 μm grain size, ρ = 4.46g/cm³	6.2×10^3	
	3.5 μm grain size, ρ = 4.37 g/cm³, 0.8 wt% Ni	5.7×10^3	
	6.0 μm grain size, ρ = 4.56 g/cm³, 0.16 wt% Ni	11.0×10^3	
	12.0 μm grain size, ρ = 4.66 g/cm³, 9.6 wt% Ni	6.29×10^3	
Carbides	Hafnium monocarbide (HfC)		
	ρ = 11.9 g/cm³	34.67×10^3	Room temp.
	ρ = 11.9 g/cm³	12.64×10^3	2000
	ρ = 11.9 g/cm³	4.78×10^3	2200
	Silicon carbide (SiC)	27×10^3	Room temp.
		25×10^3	1300
		11×10^3	1400
		15×10^3	1800
	With 1 wt% Be addition	58×10^3	
	With 1 wt% B addition	42×10^3	
	With 1 wt% Al addition	136×10^3	
	Titanium monocarbide (TiC)		
	ρ = 4.85 g/cm³	32.67×10^3	Room temp.
	ρ = 4.85 g/cm³	13.6×10^3	2000
	Tungsten monocarbide (WC)	$55.65–84 \times 10^3$	Room temp.

(*Continued*)

TABLE 2.14 (*Continued*) Modulus of Rupture for Ceramics

Class	Ceramic	Modulus of Rupture (psi)	Temperature (°C)
	Zirconium monocarbide (ZrC)	$16.6–22.5 \times 10^3$	Room temp.
		8.3×10^3	1250
		5.14×10^3	1750
		2.5×10^3	2000
Nitrides	Aluminum nitride (AlN)		
	Hot pressed	38.5×10^3	25
		27×10^3	1000
		18.1×10^3	1400
	Boron nitride (BN)		
	Parallel to c axis	$7.28–13.2 \times 10^3$	25
		7.03×10^3	300
		1.90×10^3	700
		1.08×10^3	1000
		1.25×10^3	1500
		1.50×10^3	1800
		2.45×10^3	2000
	Boron nitride (BN)	15.88×10^3	25
	Parallel to a axis	15.14×10^3	300
		3.84×10^3	700
		2.18×10^3	1000
	Titanium mononitride (TiN)	34×10^3	
	10 wt% AlO and 10 wt% AlN	13.34×10^3	
	30 wt% AlO and 10 wt% AlN	23.93×10^3	
	30 wt% AlO and 30 wt% AlN	33.25×10^3	
	Trisilicon tetranitride (Si_3N_4)		
	Hot pressed	$65.3–159.5 \times 10^3$	20
	Sintered	$39.9–121.8 \times 10^3$	20
	Reaction sintered	$7.25–43.5 \times 10^3$	20
Oxides	Aluminum oxide (Al_2O_3)		
	Single crystal	131×10^3	
		60×10^3	Room temp.
	80% dense, 3 μm grain size	56×10^3	20
	80% dense, 3 μm grain size	62×10^3	600
	80% dense, 3 μm grain size	58×10^3	900
	80% dense, 3 μm grain size	42×10^3	1100
	80% dense, 20 μm grain size	30×10^3	20
	80% dense, 20 μm grain size	28×10^3	600
	80% dense, 20 μm grain size	31×10^3	900
	80% dense, 20 μm grain size	30×10^3	1100
	Zirconia toughened alumina, 15 vol% ZrO_2	137×10^3	
	Zirconia toughened alumina, 25 vol% ZrO_2	139×10^3	
	Zirconia toughened alumina, 50 vol% ZrO_2	145×10^3	
	Beryllium oxide (BeO)	$24–29 \times 10^3$	Room temp.
	Dichromium trioxide (Cr_2O_3)	$>38 \times 10^3$	
	Hafnium dioxide (HfO_2)	10×10^3	
	Titanium oxide (TiO_2)	$10–14.9 \times 10^3$	Room temp.
	Zirconium oxide (ZrO_2)		
	5–10 CaO stabilized	$20–35 \times 10^3$	Room temp.
	MgO stabilized	30×10^3	Room temp.
	Hot pressed yttria doped zirconia	222×10^3	
	Sintered yttria doped zirconia	148×10^3	

(*Continued*)

TABLE 2.14 (*Continued*) Modulus of Rupture for Ceramics

Class	Ceramic	Modulus of Rupture (psi)	Temperature (°C)
	Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)		
	ρ = 2.51 g/cm³	16×10^3	25
	ρ = 2.3 g/cm³	15×10^3	400
	ρ = 2.1 g/cm³	8×10^3	800
	ρ = 1.8 g/cm³	3.4×10^3	1200
	Mullite ($3Al_2O_3\ 2SiO_2$)	$6–27 \times 10^3$	25
	ρ = 2.77 g/cm³	8.5×10^3	25
	ρ = 2.77 g/cm³	13.5×10^3	400
	ρ = 2.77 g/cm³	16.7×10^3	800
	ρ = 2.77 g/cm³	11.5×10^3	1200
Silicide	Molybdenum disilicide ($MoSi_2$)		
	ρ = 5.57 g/cm³	18.57×10^3	Room temp.
	Sintered	50.7×10^3	Room temp.
	Sintered	67.25×10^3	980
	Sintered	86.00×10^3	1090
	Hot pressed	$36–57 \times 10^3$	Room temp.
	Hot pressed	72.00×10^3	1090
	Hot pressed	55.00×10^3	1200

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T. B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

Note: To convert from psi to MPa, divide by 145.

TABLE 2.15 Poisson's Ratio for Ceramics

Class	Ceramic	Poisson's Ratio
Borides	Titanium diboride (TiB_2)	0.09–0.28
	6.0 μm grain size, ρ = 4.46 g/cm³	0.10
	3.5 μm grain size, ρ = 4.37 g/cm³, 0.8wt% Ni	0.12
	6.0 μm grain size, ρ = 4.56 g/cm³, 0.16 wt% Ni	0.11
	12.0 μm grain size, ρ = 4.66 g/cm³, 9.6 wt% Ni	0.15
	Zirconium diboride (ZrB_2)	0.144
Carbides	Boron carbide (B_4C)	0.207
	Hafnium monocarbide (HfC)	0.166
	Silicon carbide (SiC)	
	ρ = 3.128 g/cm³	0.183–0.192 at room temp.
	Tantalum monocarbide (TaC)	0.1719–0.24
	Titanium monocarbide (TiC)	0.187–189
	Tungsten monocarbide (WC)	0.24
	Zirconium monocarbide (ZrC)	
	ρ = 6.118 g/cm³	0.257
Nitride	Trisilicon tetranitride (Si_3N_4)	0.24
	Pressureless sintered	0.22–0.27
Oxides	Aluminum oxide (Al_2O_3)	0.21–0.27
	Beryllium oxide (BeO)	0.26–0.34
	Cerium dioxide (CeO_2)	0.27–0.31
	Magnesium oxide (MgO)	
	ρ = 3.506 g/cm³	0.163 at room temp.

(*Continued*)

TABLE 2.15 (*Continued*) Poisson's Ratio for Ceramics

Class	Ceramic	Poisson's Ratio
	Thorium dioxide (ThO_2)	
	ρ = 9.722 g/cm^3	0.275
	Titanium dioxide (TiO_2)	0.28
	Uranium dioxide (UO_2)	
	ρ = 10.37 g/cm^3	0.302
	Zirconium dioxide (ZrO_2)	0.324–0.337 at room temp.
	Partially stabilized	0.23
	Fully stabilized	0.23–0.32
	Plasma sprayed	0.25
	Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)	
	ρ = 2.3 g/cm^3	0.21
	ρ = 2.1 g/cm^3	0.17
	Glass	0.26
	Mullite ($3Al_2O_3\ 2SiO_2$)	
	ρ = 2.779 g/cm^3	0.238
	Spinel ($Al_2O_3\ MgO$)	
	ρ = 3.510 g/cm^3	0.294
Silicide	Molybdenum disilicide ($MoSi_2$)	0.158–0.172

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T. B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

TABLE 2.16 Resistivity of Ceramics

Class	Ceramic	Resistivity (Ω cm)	Temperature Range of Validity
Borides	Chromium diboride (CrB_2)	21×10^6	
	Hafnium diboride (HfB_2)	$10–12 \times 10^6$	Room temp.
	Tantalum diboride (TaB_2)	68×10^6	
	Titanium diboride (TiB_2)		
	Polycrystalline		
	85% dense	$26.5–28.4 \times 10^6$	Room temp.
	85% dense	9.0×10^6	Room temp.
	100% dense, extrapolated values	$8.7–14.1 \times 10^6$	Room temp.
		3.7×10^6	Liquid air temp.
	Monocrystalline		
	Crystal length 5 cm, 39° and 59°		
	orientation with respect to growth axis	$6.6 \pm 0.2 \times 10^6$	Room temp.
	Crystal length 1.5 cm, 16.5° and 90° orientation with respect to growth axis	$6.7 \pm 0.2 \times 10^6$	Room temp.
	Zirconium diboride (ZrB_2)	9.2×10^6	20°C
		1.8×10^6	Liquid air temperature
Carbides	Boron carbide (B_4C)	0.3–0.8	

(*Continued*)

TABLE 2.16 (*Continued*) Resistivity of Ceramics

Class	Ceramic	Resistivity (Ω cm)	Temperature Range of Validity
	Hafnium monocarbide (HfC)	41×10^6	4.2 K
		41×10^6	80 K
		45×10^6	160 K
		49×10^6	240 K
		60×10^6	300 K
		$(30 + 0.0628\ T) \times 10^6$	300–2000 K
	Silicon carbide (SiC)	10^2–10^{12}	20°C
	With 1 wt% Be addition	3×10^{13}	
	With 1 wt% B addition	2×10^4	
	With 1 wt% Al addition	0.8	
	With 1.6 wt% BeO addition	$>10^{13}$	
	With 3.2 wt% BeO addition	4×10^{13}	
	With 2.0 wt% BN addition	1×10^{11}	
	Tantalum monocarbide (TaC)		
	80% dense	8×10^6	4.2 K
	80% dense	10×10^6	80 K
	80% dense	15×10^6	160 K
	80% dense	20×10^6	240 K
	80% dense	25×10^6	300 K
	Titanium monocarbide (TiC)	0.3–0.8	
	Zirconium monocarbide (ZrC)	41×10^6	4.2 K
		45×10^6	80 K
		47×10^6	160 K
		53×10^6	240 K
		$61–64 \times 10^6$	300 K
		97×10^6	773 K
		137×10^6	1273 K
Nitrides	Aluminum nitride (AlN)	2×10^{11}–10^{13}	Room temp.
	Boron nitride (BN)	1.7×10^{13}	25°C
		2.3×10^{10}	480°C
		3.1×10^4	1000°C
	20% humidity	1.0×10^{12}	25°C
	50% humidity	7.0×10^{10}	25°C
	90% humidity	5.0×10^9	25°C
	Titanium mononitride (TiN)	$11.07–130 \times 10^6$	Room temp.
		340×10^6	Melting temp.
		8.13×10^6	Liquid air
	Trisilicon tetranitride (Si_3N_4)	$>10^{13}$	
	Zirconium mononitride (TiN)	$11.52–160 \times 10^6$	Room temp.
		320×10^6	Melting temp.
		3.97×10^6	Liquid air
Oxides	Aluminum oxide (Al_2O_3)	$>10 \times 10^{14}$	25°C
		2×10^{13}	100°C
		1×10^{13}	300°C
		6.3×10^{10}	500°C
		5.0×10^8	700°C
		2×10^6	1000°C

(*Continued*)

TABLE 2.16 (*Continued*) Resistivity of Ceramics

Class	Ceramic	Resistivity (Ω cm)	Temperature Range of Validity
	Beryllium oxide (BeO)	$>10^{17}$	25°C
		$>10^{15}$	300°C
		$1–5 \times 10^{15}$	500°C
		$1.5–2 \times 10^{15}$	700°C
		$4–7 \times 10^{15}$	1000°C
	Magnesium oxide (MgO)	1.3×10^{15}	27°C
		$0.2–1 \times 10^{8}$	1000°C
		4×10^{2}	1727°C
	Silicon dioxide (SiO_2)	10^{18}	Room temp.
	Zirconium dioxide (ZrO_2)		
	Stabilized	2300	700°C
	Stabilized	77	1200°C
	Stabilized	9.4	1300°C
	Stabilized	1.6	1700°C
	Stabilized	0.59	2000°C
	Stabilized	0.37	2200°C
	Cordierite ($2MgO\ 2Al_2O_3\ 5SiO_2$)		
	$\rho = 2.3$ g/cm^3	1×10^{14}	25°C
	$\rho = 2.3$ g/cm^3	2.5×10^{11}	100°C
	$\rho = 2.3$g/cm^3	3.3×10^{7}	300°C
	$\rho = 2.3$ g/cm^3	7.7×10^{5}	500°C
	$\rho = 2.3$ g/cm^3	8.0×10^{4}	700°C
	$\rho = 2.3$ g/cm^3	1.9×10^{4}	900°C
	$\rho = 2.1$ g/cm^3	$>1 \times 10^{14}$	25°C
	$\rho = 2.1$ g/cm^3	3.0×10^{13}	100°C
	$\rho = 2.1$ g/cm^3	2.0×10^{10}	300°C
	$\rho = 2.1$ g/cm^3	9.0×10^{7}	500°C
	$\rho = 2.1$ g/cm^3	3.0×10^{6}	700°C
	$\rho = 2.1$ g/cm^3	3.5×10^{5}	900°C
	$\rho = 1.8$ g/cm^3	1.0×10^{14}	25°C
	$\rho = 1.8$ g/cm^3	1.0×10^{13}	100°C
	$\rho = 1.8$ g/cm^3	3.0×10^{9}	300°C
	$\rho = 1.8$ g/cm^3	4.9×10^{7}	500°C
	$\rho = 1.8$ g/cm^3	4.7×10^{6}	700°C
	$\rho = 1.8$ g/cm^3	7.0×10^{5}	900°C
	Mullite ($3Al_2O_3\ 2SiO_2$)	$>10^{14}$	25°C
		10^{10}	300°C
		10^{8}	500°C
Silicides	Molybdenum disilicide ($MoSi_2$)	21.5×10^{6}	22°C
		18.9×10^{6}	−80°C
		$75–80 \times 10^{6}$	1600°C
	Tungsten disilicide (WSi_2)	$33.4–54.9 \times 10^{6}$	

Source: Data compiled by J. S. Park from *No. 1 Materials Index*, Peter T. B. Shaffer, Plenum Press, New York, 1964; *Smithells Metals Reference Book*, 6th Edn., Eric A. Brandes (Ed.), in association with Fulmer Research Institute Ltd., Butterworths, Boston, 1983; *Ceramic Source*, Patricia A. Janeway (Ed.), American Ceramic Society, Westerville, OH, 1986–1991.

TABLE 2.17 Transmission Range of Optical Materials

Material and Crystal Structure	Transmission Region (μm, at 298 K)
Alumina (sapphire, single crystal)	0.15–6.5
Ammonium dihydrogen phosphate (ADP, single crystal)	0.13–1.7
Arsenic trisulfide (glass)	0.6–13
Barium fluoride (single crystal)	0.25–15
Cadmium sulfide (bulk and hexagonal single crystal)	0.5–16
Cadmium telluride (hot pressed polycrystalline)	0.9–16
Calcium carbonate (calcite, single crystal)	0.2–5.5
Calcium fluoride (single crystal)	0.13–12
Cesium bromide (single crystal)	0.3–55
Cesium iodide (single crystal)	0.25–80
Cuprous chloride (single crystal)	0.4–19
Gallium arsenide (intrinsic single crystal)	1.0–15
Germanium (intrinsic single crystal)	1.8–23
Indium arsenide (single crystal)	3.8–7.0
Lead sulfide (single crystal)	3.0–7.0
Lithium fluoride (single crystal)	0.12–9.0
Lithium niobate (single crystal)	0.33–5.2
Magnesium fluoride (film)	0.2–5.0
Magnesium fluoride (single crystal)	0.1–9.7
Magnesium oxide (single crystal)	0.25–8.5
Potassium bromide (single crystal)	0.25–35
Potassium iodide (single crystal)	0.25–45
Selenium (amorphous)	1.0–20
Silica (high purity crystalline)	0.12–4.5
Silica (high purity fused)	0.12–4.5
Silicon (single crystal)	1.2–15
Silver bromide (single crystal)	0.45–35
Silver chloride (single crystal)	0.4–2.8
Sodium fluoride (single crystal)	0.19–15
Strontium titanate (single crystal)	0.39–6.8
Tellurium (polycrystalline film)	3.5–8.0
Tellurium (single crystal)	3.5–8.0
Thallium bromoiodide (KRS-5, mixed crystal)	0.6–40
Thallium chlorobromide (KRS-6, mixed crystal)	0.21–35
Titanium dioxide (rutile, single crystal)	0.43–6.2
Zinc selenide (single crystal, cubic)	~0.5–22
Zinc sulfide (single crystal, cubic)	~0.6–15.6

Source: Data compiled by J. S. Park. Optical properties, in *The CRC Materials Science and Engineering Handbook*, 2nd Edn., J.F. Shackelford, W. Alexander, and J.S. Park (Eds.), CRC Press, Boca Raton, FL, 1994.

Note: External transmittance ≥10% with 2.0 mm thickness.

TABLE 2.18 Dispersion of Optical Materials

Material	Dispersion Equation at 298 K		
Alumina (sapphire, single crystal)	$n^2 - 1 = \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2}$	(λ in μm)	
	where		
	i	λ_i^2	A_i
	1	0.00377588	1.023798
	2	0.0122544	1.058264
	3	321.3616	5.280792
	(λ in μm)		
Arsenic trisulfide (glass)	$n^2 - 1 = \sum_{i=1}^{5} \frac{K_i \lambda^2}{\lambda^2 - \lambda_i^2}$	(λ in μm)	
	where		
	i	λ_i^2	K_i
	1	0.0225	1.8983678
	2	0.0625	1.9222979
	3	0.1225	0.8765134
	4	0.2025	0.1188704
	5	0.705	0.9569903
	(λ in μm)		
Barium fluoride (single crystal)	$n^2 - 1 = \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2}$	(λ in μm)	
	where		
	i	λ_i^2	A_i
	1	0.057789	0.643356
	2	0.10968	0.50676
	3	46.3864	3.8261
	(λ in μm)		
Cadmium sulfide (bulk and hexagonal single crystal)	$n_o^2 = 5.235 + \frac{1.89 \times 10^7}{\lambda^2 - 1.651 \times 10^7}$ for ordinary ray, and		
	$n_e^2 = 5.239 + \frac{2.076 \times 10^7}{\lambda^2 - 1.651 \times 10^7}$ for extraordinary ray.		
	(λ in μm)		
Calcium fluoride (single crystal)	$n^2 - 1 = \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - \lambda_i^2}$	(λ in μm)	
	i	A_i	λ_i^2
	1	0.5675888	0.050263605
	2	0.4710914	0.1003909
	3	3.8484723	34.64904
Cesium bromide (single crystal)	$n^2 = 5.640752 - 3.338 \times 10^{-6}\lambda^2 + \frac{0.0018612}{\lambda^2} + \frac{41110.49}{\lambda^2 - 14390.4} + \frac{0.0290764}{\lambda^2 - 0.024964}$ (λ in μm)		

(*Continued*)

TABLE 2.18 (*Continued*) Dispersion of Optical Materials

Material	Dispersion Equation at 298 K
Cesium iodide (single crystal)	$n^2 - 1 = \sum_{i=1}^{5} \frac{K_i \lambda^2}{\lambda^2 - \lambda_i^2}$ (λ in μm) where i — λ_i^2 — K_i 1 — 0.00052701 — 0.34617251 2 — 0.02149156 — 1.0080886 3 — 0.032761 — 0.28551800 4 — 0.044944 — 0.39743178 5 — 25921 — 3.3605359 (λ in μm)
Germanium (intrinsic single crystal)	$n = A + B\lambda + C\lambda^2 + D\lambda^2 + E\lambda^4$ where $A = 3.99931$ $B = 0.391707$ $C = 0.163492$ $D = -0.0000060$ $E = 0.000000053$ for 2.0 μm ≤ λ ≤ 13.5 μm
Lithium fluoride (single crystal)	$n = A + BL + CL^2 + D\lambda^2 + E\lambda^4$ where $A = 1.38761$ $B = 0.001796$ $C = -0.000041$ $D = -0.0023045$ $E = -0.00000557$ for 0.5 μm ≤ λ ≤ 6.0 μm
Magnesium fluoride (single crystal)	$n_o = 1.36957 + \frac{0.0035821}{\lambda - 0.14925}$ for ordinary wavelengths, and $n_e = 1.38100 + \frac{0.0037415}{\lambda - 0.14947}$ for wavelength within 0.4 μm ≤ λ ≥ 0.7 μm
Magnesium oxide (single crystal)	$n^2 = 2.956362 - 0.1062387\lambda^2 - 2.04968 \times 10^{-5}\lambda^4 - \frac{0.0219577}{\lambda^2 - 0.01428322}$
Potassium bromide (single crystal)	$n^2 = 2.3618102 - 0.00058072\,\lambda^2 + \frac{0.02305269}{\lambda^2 - 0.02425381}$ for 0.4 μm ≤ λ ≤ 0.7
Potassium chloride (single crystal)	$n^2 = 2.174967 + \frac{0.08344206}{\lambda^2 - 0.0119082} + \frac{0.00698382}{\lambda^2 - 0.025555} - 0.000513495\,\lambda^2 - 0.06167587\,\lambda^4$ for ultraviolet wavelengths $n^2 = 3.866619 + \frac{0.08344206}{\lambda^2 - 0.0119082} - \frac{0.00698382}{\lambda^2 - 0.025555} - \frac{5569.715}{\lambda^2 - 3292.472}$ for the visible light

(*Continued*)

TABLE 2.18 (*Continued*) Dispersion of Optical Materials

Material	Dispersion Equation at 298 K
Silica (high purity fused)	$n^2 = 2.978645 + \dfrac{0.008777808}{\lambda^2 - 0.010609} + \dfrac{84.06224}{\lambda^2 - 96.0000}$
Silicon (single crystal)	$n = 3.14696 + 0.138497L + 0.013924L^2 - 0.0000209\lambda^4 + 0.000000148\ \lambda^4$ where $L = (\lambda^2 - 0.028)^{-1}$
Silver bromide (single crystal)	$\dfrac{n^2 - 1}{n^2 + 2} = 0.48484 + \dfrac{0.10279\ \lambda^2}{\lambda^2 - 0.0900} - 0.004796\ \lambda^2$ for $0.54\ \mu m \le \lambda \le 0.65\ \mu m$
Silver chloride (single crystal)	$n = 4.00804 - 0.00085111\ \lambda^2 - 0.00000019762\ \lambda^4 + 0.079086/(\lambda^2 - 0.04584)$
Strontium titanate (single crystal)	$n = A + BL + CL^2 + D\lambda^2 + E\lambda^4$ where $A = 2.28355$ $B = 0.035906$ $C = 0.001666$ $D = -0.0061355$ $E = -0.00001502$ for $1.0\ \mu m \le \lambda \le 5.3\ \mu m$
Thallium bromoiodide (KRS-5, mixed crystal)	$n^2 - 1 = \sum_{i=1}^{5} \dfrac{K_i\lambda^2}{\lambda^2 - \lambda_i^2}$ where i — λ_i^2 — K_i 1 — 0.0225 — 1.8293958 2 — 0.0625 — 1.6675593 3 — 0.1225 — 1.1210424 4 — 0.2025 — 0.4513366 5 — 27089.737 — 12.380234 (λ in μm)
Titanium dioxide (rutile, single crystal)	$n_o^2 = 5.913 + \dfrac{2.441 \times 10^7}{\lambda^2 - 0.803 \times 10^7}$ for ordinary wavelengths, and $n_e^2 = 7.197 + \dfrac{3.322 \times 10^7}{\lambda^2 - 0.843 \times 10^7}$ for extraordinary wavelengths. (λ in Å)
Zinc sulfide (single crystal, cubic)	$n = \dfrac{5.164 + 1.208 \times 10^7}{12 - 0.732 \times 10^7}$ (λ in Å)

Source: Data compiled by J. S. Park from P. Klocek (Ed.), *Handbook of Infrared Optical Materials*, Marcel Dekker, New York, 1991 and related sources.

Chemical Properties

TABLE 2.19 Typical Composition of Glass-Ceramics

	Typical Composition (wt%)							
Glass–Ceramic	SiO_2	Li_2O	Al_2O_3	MgO	ZnO	B_2O_3	TiO_2 (Nucleating Agent)	P_2O_5 (Nucleating Agent)
$Li_2O–Al_2O_3–SiO_2$ system	74	4	16	–	–	–	6	–
$MgO–Al_2O_3–SiO_2$ system	65	–	19	9	–	–	7	–
$Li_2O–MgO–SiO_2$ system	73	11	–	7	–	6	–	3
$Li_2O–ZnO–SiO_2$ system	58	23	–	–	16	–	–	3

Source: Data compiled by J. S. Park from P. C. McMillan, *Glass-Ceramics,* 2nd Edn., Academic Press, London, 1979.

TABLE 2.20 Heat of Formation of Inorganic Oxides

Reaction	Temperature Range of Validity (K)	ΔH_0	2.303*a*	*b*	*c*	*I*
$2Ac(c) + 3/2\ O_2(g) = Ac_2O_3(c)$	298.16–1000	−446,090	−16.12	–	–	+109.89
$2Al(c) + 1/2\ O_2(g) = Al_2O(g)$	298.16–931.7	−31,660	+14.97	–	–	−72.74
$2Al(l) + 1/2\ O_2(g) = Al_2O(g)$	931.7–2000	−38,670	+10.36	–	–	−51.53
$Al(c) + 1/2\ O_2(g) = AlO(g)$	298.16–931.7	+10,740	+5.76	–	–	−37.61
$Al(l) + 1/2\ O_2(g) = AlO(g)$	931.7–2000	+8170	+5.76	–	–	−34.85
$2\ Al(c) + 3/2\ O_2(g) = Al_2O_3$ (corundum)	298.16–931.7	−404,080	−15.68	+2.18	+3.935	+123.64
$2\ Al(l) + 3/2\ O_2(g) = Al_2O_3$ (corundum)	931.7–2000	−407,950	−6.19	−0.78	+3.935	+102.37
$2\ Sb(c) + 3/2\ O_2(g) = Sb_2O_3$ (cubic)	298.16–842	−169,450	+6.12	−6.01	−0.30	+52.21
$2\ Sb(c) + 3/2\ O_2(g) = Sb_2O_3$ (orthorhombic)	298.16–903	−168,060	+6.12	−6.01	−0.30	+50.56
$2\ As(c) + 3/2\ O_2(g) = As_2O_3$ (orthorhombic)	298.16–542	−154,870	+29.54	−21.33	−0.30	−8.83
$2\ As(c) + 3/2\ O_2(g) = As_2O_3$ (monoclinic)	298.16–586	−150,760	+29.54	−21.33	−0.30	−16.95
$2\ As(c) + 5/2\ O_2(g) = As_2O_5(c)$	298.16–883	−217,080	+12.32	−4.65	−0.50	+80.50
$Ba(\alpha) + 1/2\ O_2(g) = BaO(c)$	298.16–648	−134,590	−7.60	+0.87	+0.42	+45.76
$Ba(\beta) + 1/2\ O_2(g) = BaO(c)$	648–977	−134,140	−3.34	−0.56	+0.42	+34.01
$Be(c) + 1/2\ O_2(g) = BeO(c)$	298.16–1556	−144,220	−1.91	−0.46	+1.24	+30.64
$Bi(c) + 1/2\ O_2(g) = BiO(c)$	298.16–544	−50,450	−4.61	–	–	+35.51
$Bi(l) + 1/2\ O_2(g) = BiO(c)$	544–1600	−52,920	−4.61	–	–	+40.05
$2\ Bi(c) + 3/2\ O_2(g) = Bi_2O_3(c)$	298.16–544	−139,000	−11.56	+2.15	−0.30	+96.52
$2\ Bi(l) + 3/2\ O_2(g) = Bi_2O_3(c)$	544–1090	−142,270	+2.30	−3.25	−0.30	+67.55
$2\ B(c) + 3/2\ O_2(g) = B_2O(c)$	298.16–723	−304,690	+11.72	−7.55	+0.355	+34.25
$2\ B(c) + 3/2\ O_2(g) = B_2O_3(gl)$	298.16–723	−298,670	+26.57	−15.90	−0.30	−10.40
$Cd(c) + 1/2\ O_2(g) = CdO(c)$	298.16–594	−62,330	−2.05	+0.71	−0.10	+29.17
$Cd(l) + 1/2\ O_2(g) = CdO(c)$	594–1038	−63,240	+2.07	−0.76	−0.10	+20.14
$Ca(\alpha) + 1/2\ O_2(g) = CaO(c)$	298.16–673	−151,850	−6.56	+1.46	+0.68	+43.93
$Ca(\beta) + 1/2\ O_2(g) = CaO(c)$	673–1124	−151,730	−4.14	+0.41	+0.68	+37.63
$C(graphite) + 1/2\ O_2(g) = CO(g)$	298.16–2000	−25,400	+2.05	+0.27	−1.095	−28.79

(*Continued*)

TABLE 2.20 (*Continued*) Heat of Formation of Inorganic Oxides

Reaction	Temperature Range of Validity (K)	ΔH_0	2.303*a*	*b*	*c*	*I*
C(graphite) + O_2(g) = CO_2(g)	298.16–2000	−93,690	+1.63	−0.7	−0.23	−5.64
2 Ce(c) + 3/2 O_2(g) = Ce_2O_3(c)	298.16–1048	−435,600	−4.60	–	–	+92.84
2 Ce(l) + 3/2 O_2(g) = Ce_2O_3(c)	1048–1900	−440,400	−4.60	–	–	+97.42
Ce(c) + O_2(g) = CeO_2(c)	298.16–1048	−245,490	−6.42	+2.34	−0.20	+67.79
Ce(l) + O_2(g) = CeO_2(c)	1048–2000	−247,930	+0.71	−0.66	−0.20	+51.73
2 Cs(c) + 1/2 O_2(g) = Cs_2O(c)	298.16–301.5	−75,900	–	–	–	+36.60
2 Cs(l) + 1/2 O_2(g) = Cs_2O(c)	301.5–763	−76,900	–	–	–	+39.92
2 Cs(l) + 1/2 O_2(g) = Cs_2O(l)	763–963	−75,370	−9.21	–	–	+64.47
2 Cs(g) + 1/2 O_2(g) = Cs_2O(l)	963–1500	−113,790	−23.03	–	–	+145.60
2 Cs(c) + 3/2 O_2(g) = Cs_2O_3(c)	298.16–301.5	−112,690	−11.51	–	–	+110.10
2 Cs(l) + 3/2 O_2(g) = Cs_2O_3(c)	301.5–775	−113,840	−12.66	–	–	+116.77
2 Cs(l) + 3/2 O_2(g) = Cs_2O_3(l)	775–963	−110,740	−26.48	–	–	+152.70
2 Cs(g) + 3/2 O_2(g) = Cs_2O_3(l)	963–1500	−148,680	−39.14	–	–	+229.87
Cl_2(g) + 1/2 O_2(g) = Cl_2O(g)	298.16–2000	+17,770	−0.71	−0.12	+0.49	+16.81
1/2 Cl_2(g) + 1/2 O_2(g) = ClO(g)	298.16–1000	+33,000	–	–	–	0.24
2 Cl_2(g) + 3/2 O_2(g) = ClO(g)	298.16–500	+37,740	+5.76	–	–	+21.42
2 Cr(c) + 3/2 O_2(g) = Cr_2O_3(β)	298.16–1823	−274,670	−14.07	+2.01	+0.69	+105.65
2 Cr(l) + 3/2 O_2(g) = Cr_2O_3(β)	1823–2000	−278,030	+2.33	−0.35	+1.57	+58.29
Cr(c) + O_2(g) = CrO_2 (c)	298.16–1000	−142,500	–	–	–	+42.00
Cr(c) + 3/2 O_2(g) = CrO_3(c)	298.16–471	−141,590	−13.82	–	–	+103.90
Cr(c) + 3/2 O_2(g) = Cr_2O_3(l)	471–600	−141,580	−32.24	–	–	+153.14
Co(α,β) + 1/2 O_2(g) = CoO(c)	298.16–1400	−56,910	+0.69	–	–	+16.03
Co(γ) + 1/2 O_2(g) = CoO(c)	1400–1763	−58,160	−1.15	–	–	+22.71
2 Cu(c) + 1/2 O_2(g) = Cu_2O(c)	298.16–1357	+10,550	−1.15	−1.10	−0.10	+21.92
2 Cu(l) + 1/2 O_2(g) = Cu_2O(c)	1357–1502	−43,880	+8.47	−2.60	−0.10	−3.72
2 Cu(l) + 1/2 O_2(g) = Cu_2O(l)	1502–2000	−37,710	−12.48	+0.25	−0.10	+54.44
Cu(c) + 1/2 O_2(g) = CuO(c)	298.16–1357	−37,740	−0.64	−1.40	−0.10	+24.87
Cu(l) + 1/2 O_2(g) = CuO(c)	1357–1720	−39,410	+4.17	−2.15	−0.10	+12.05
Cu(l) + 1/2 O_2(g) = CuO(l)	1720–2000	−41,060	−11.35	+0.25	−0.10	+59.09
2 Au(c) + 3/2 O_2(g) = Au_2O_3(c)	298.16–500	−2160	−10.36	–	–	+95.14
Hf(c) + O_2(g) = HfO_2 (monoclinic)	298.16–2000	−268,380	−9.74	−0.28	+1.54	+78.16
H_2(g) + 1/2 O_2(g) = H_2O(l)	298.16–373.16	−70,600	−18.26	+0.64	−0.04	+91.67
H_2(g) + 1/2 O_2(g) = H_2O(g)	298.16–2000	−56,930	+6.75	−0.64	−0.08	−8.74
D_2(g) + 1/2 O_2(g) = D_2O(l)	298.16–374.5	−72,760	−18.10	–	–	+93.59
D_2(g) + 1/2 O_2(g) = D_2O(g)	298.16–2000	−58,970	+5.50	−0.75	+0.085	−3.74
0.947 Fe(α) + 1/2 O_2(g) = $Fe_{0.9470}O$(c)	298.16–1033	−65,320	−11.26	+2.61	+0.44	+48.60
0.947 Fe(α) + 1/2 O_2(g) = $Fe_{0.9470}O$(c)	1033–1179	−62,380	+4.08	−0.75	+0.235	+3.00
0.947 Fe(β) + 1/2 O_2(g) = $Fe_{0.9470}O$(c)	1179–1650	−66,750	−8.04	+0.67	−0.10	+42.28
0.947 Fe(γ) + 1/2 O_2(g) = $Fe_{0.9470}O$(l)	1650–1674	−64,200	−18.72	+1.67	−0.10	+73.45
0.947 Fe(γ) + 1/2 O_2(g) = $Fe_{0.9470}O$(l)	1647–1803	−59,650	−6.84	+0.25	−0.10	+34.81
0.947 Fe(δ) + 1/2 O_2(g) = $Fe_{0.9470}O$(l)	1803–2000	−63,660	−7.48	+0.25	−0.10	+39.12

(*Continued*)

TABLE 2.20 (*Continued*) Heat of Formation of Inorganic Oxides

Reaction	Temperature Range of Validity (K)	ΔH_0	2.303*a*	*b*	*c*	*I*
3 Fe(α) + 2 O_2(g) = Fe_3O_4(magnetite)	298.16–900	−268,310	+5.87	−12.45	+0.245	+73.11
3 Fe(α) + 2 O_2(g) = Fe_3O_4(β)	900–1033	−272,300	−54.27	+11.65	+0.245	+233.52
3 Fe(β) + 2 O_2(g) = Fe_3O_4(β)	1033–1179	−262,990	−5.71	+1.00	−0.40	+89.19
3 Fe(γ) + 2 O_2(g) = Fe_3O_4(β)	1179–1674	−276,990	~4.05	+5.50	−0.40	+213.52
2 Fe(α) + 3/2 O_2(g) = Fe_2O_3(hematite)	298.16–950	−200,000	−13.84	−1.45	+1.905	+108.26
2 Fe(α) + 3/2 O_2(g) = Fe_2O_3(β)	950–1033	−202,960	−42.64	+7.85	+0.13	+188.48
2 Fe(β) + 3/2 O_2(g) = Fe_2O_3(β)	1033–1050	−196,740	−10.27	+0.75	−0.30	+92.26
2 Fe(β) + 3/2 O_2(g) = Fe_2O_3(γ)	1050–1179	−193,200	−0.39	−0.13	−0.30	+59.96
2 Fe(γ) + 3/2 O_2(g) = Fe_2O_3(γ)	1179–1674	−202,540	−25.95	+2.87	−0.30	+142.85
2 Fe(α) + 3/2 O_2(g) = Fe_2O_3(γ)	1674–1800	−192,920	−0.85	−0.13	−0.30	+61.21
I_2(c) + 5/2 O_2(g) = I_2O_5(c)	298.16–386.8	−42,040	+2.30	–	–	+113.71
I_2(l) + 5/2 O_2(g) = I_2O_5(c)	386.8–456	−43,490	+16.12	–	–	+81.70
I_2(g) + 5/2 O_2(g) = I_2O_5(c)	456–500	−58,020	−6.91	–	–	+174.79
Ir(c) + O_2(g) = IrO_2(c)	298.16–1300	−39,480	+8.17	−6.39	−0.20	+20.33
Pb(c) + 1/2 O_2(g) = PbO (red)	298.16–600.5	−52,800	−2.76	−0.80	−0.10	+32.49
Pb(l) + 1/2 O_2(g) = PbO (red)	600.5–762	−53,780	−0.51	−1.75	−0.10	+28.44
Pb(c) + 1/2 O_2(g) = PbO (yellow)	298.16–600.5	−52,040	+0.81	−2.00	−0.10	+ 22.13
Pb(l) + 1/2 O_2(g) = PbO (yellow)	600.5–1159	−53,020	+3.06	−2.95	−0.10	+18.08
3 Pb(c) + 2 O_2(g) = Pb_3O_4(c)	298.16–600.5	−174,920	+8.82	−8.20	−0.40	+72.78
Pb(c) + O_2(g) = PbO_2(c)	298.16–600.5	−66,120	+0.64	−2.45	−0.20	+45.58
2 Li(c) + 1/2 O_2(g) = Li_2O(c)	298.16–452	−142,220	−3.06	+5.77	−0.10	+34.19
Mg(c) + 1/2 O_2(g) = MgO (periclase)	298.16–923	−144,090	−1.06	+0.13	+0.25	+29.16
Mg(l) + 1/2 O_2(g) = MgO (periclase)	923–1393	−145,810	+1.84	−0.62	+0.64	+23.07
Mg(g) + 1/2 O_2(g) = MgO (periclase)	1393–2000	−180,700	−3.75	−0.62	+0.64	+65.69
Mn(α) + 1/2 O_2(g) = MnO(c)	298.16–1000	−92,600	−4.21	+0.97	+0.155	+29.66
Mn(β) + 1/2 O_2(g) = MnO(c)	1000–1374	−91,900	+1.84	−0.39	+0.34	+12.15
Mn(γ) + 1/2 O_2(g) = Mno(c)	1374–1410	−89,810	+7.30	−0.72	+0.34	−6.05
Mn(δ) + 1/2 O_2(g) = MnO(c)	1410–1517	−89,390	+8.68	−0.72	+0.34	−10.70
Mn(l) + 1/2 O_2(g) = MnO(c)	1517–2000	−93,350	+7.99	−0.72	+0.34	−5.90
3 Mn(α) + 2 O_2(g) = Mn_3O_4(α)	298.16–1000	−332,400	−7.41	+0.66	+0.145	+106.62
2 Mn(α) + 3/2 O_2(g) = Mn_2O_3(c)	298.16–1000	−230,610	−5.96	−0.06	+0.945	+80.74
Mn(α) + O_2(g) = MnO_2(c)	298.16–1000	−126,400	−8.61	+0.97	+1.555	+70.14
2 Hg(l) + 1/2 O_2(g) = Hg_2O(c)	298.16–629.88	−22,400	−4.61	–	–	+43.29
Hg(l) + 1/2 O_2(g) = HgO (red)	298.16–629.88	−21,760	+0.85	−2.47	−0.10	+24.81
Mo(c) + O_2(g) = MoO_2(c)	298.16–2000	−132,910	−3.91	–	–	+47.42
Mo(c) + 3/2 O_2(g) = MoO_3(c)	298.16–1068	−182,650	−8.86	−1.55	+1.54	+90.07
Ni(α) + 1/2 O_2(g) = NiO(c)	298.16–633	−57,640	−4.61	+2.16	−0.10	+34.41
Ni(β) + 1/2 O_2(g) = NiO(c)	633–1725	−57,460	−0.14	−0.46	−0.10	+23.27
2 Nb(c) + 2 O_2(g) = Nb_2O_4(c)	298.16–2000	−382,050	−9.67	–	–	+116.23
2 Nb(c) + 5/2 O_2(g) = Nb_2O_5(c)	298.16–1785	−458,640	−16.14	−0.56	+1.94	+157.66

(*Continued*)

TABLE 2.20 (*Continued*) Heat of Formation of Inorganic Oxides

Reaction	Temperature Range of Validity (K)	ΔH_0	2.303*a*	*b*	*c*	*I*
2 Nb(c) + 5/2 O_2(g) = Nb_2O_5(l)	1785–2000	−463,630	−66.04	+2.21	−0.50	+317.84
N_2(g) + 1/2 O_2(g) = N_2O(g)	298.16–2000	18,650	−1.57	−0.27	+0.92	+23.47
3/2 O_2(g) = O_3(g)	298.16–2000	+33,980	+2.03	−0.48	+0.36	+11.45
P (white) + 1/2 O_2(g) = PO(g)	298.16–317.4	−9370	+2.53	–	–	−25.40
P(l) + 1/2 O_2(g) = PO(g)	317.4–553	−9390	+3.45	–	–	−27.63
4 P (white) + 5 O_2(g) = P_4H_{10} (hexagonal)	298.16–317.4	−711,520	+95.67	−51.50	−1.00	−28.24
2 K(c) + 1/2 O_2(g) = K_2O(c)	298.16–336.4	−86,400	–	–	–	+33.90
2 K(l) + 1/2 O_2(g) = K_2O(c)	336.4–1049	−87,380	+1.15	–	–	+33.90
2 K(g) + 1/2 O_2(g) = K_2O(c)	1049–1500	−133,090	−16.12	–	–	+129.64
Ra(c) + 1/2 O_2(g) = RaO(c)	298.16–1000	−130,000	–	–	–	+23.50
Re(c) + 3/2 O_2(g) = ReO_3(c)	298.16–433	−149,090	−16.12	–	–	+110.49
Re(c) + 3/2 O_2(g) = ReO_3(l)	433–1000	−146,750	−31.32	–	–	+145.16
2Re(c) + 7/2 0_2(g) = Re_2O_7(c)	298.16–569	−301,470	−34.64	–	–	+250.57
2 Re(c) + 7/2 0_2(g) = Re_2O_7(l)	569–635.5	−295,810	−73.68	–	–	+348.45
2 Re(c) + 4 O_2(g) = Re_2O_8(l)	420–600	−318,470	−87.50	–	–	+425.32
2 Rb(c) + 1/2 O_2(g) = Rb_2O(c)	298.16–312.2	−78,900	–	–	–	+32.20
2 Rb(l) + 1/2 O_2(g) = Rb_2O(c)	312.2–750	−79,950	–	–	–	+35.56
Se(c) + 1/2 O_2(g) = SeO(g)	298.16–490	+9280	−3.04	+4.40	+0.30	−14.78
Se(l) + 1/2 O_2(g) = SeO(g)	490–1027	+9420	+8.70	–	+0.30	−44.50
1/2 Se_2(g) + 1/2 O_2(g) = SeO(g)	1027–2000	−7400	−0.37	–	+0.19	−0.80
Si(c) + 1/2 O_2(g) = SiO(g)	298.16–1683	−21,090	+3.84	−0.16	−0.295	−33.14
Si(l) + 1/2 O_2(g) = SiO(g)	1683–2000	−30,170	−7.78	−0.12	+0.25	−40.01
Si(c) + O_2(g) = SiO_2(α-quartz)	298.16–848	−210,070	+3.98	−3.32	+0.605	+34.59
Si(c) + O_2(g) = SiO_2(β-quartz)	848–1683	−209,920	−3.36	−0.19	−0.745	+53.44
Si(l) + O_2(g) = SiO_2(l)	1883–2000	−228,590	−15.66	–	–	+103.97
Si(c) + O_2(g) = SiO_2(α-cristobalite)	298.16–523	−207,330	+19.96	−9.75	−0.745	−9.78
Si(c) + O_2(g) = SiO_2(β-cristobalite)	523–1683	−209,820	−3.34	−0.24	−0.745	+53.35
Si(c) + O_2(g) = SiO_2(α-tridymite)	298.16–390	−207,030	+22.29	−11.62	−0.745	−15.64
Si(c) + O_2(g) = SiO_2(β-tridymite)	390–1683	−209,350	−1.59	−0.54	−0.745	+47.86
2 Ag(c) + 1/2 O_2(g) = Ag_2O_2(c)	298.16–1000	7740	−4.14	–	–	+27.84
2 Ag(c) + O_2(g) = Ag_2O_2(c)	298.16–500	−6620	−3.22	–	–	+52.17
2 Na(c) + 1/2 O_2(g) = Na_2O(c)	298.16–371	−99,820	−7.51	+5.47	−0.10	+50.43
2 Na(l) + 1/2 O_2(g) = Na_2O(c)	371–1187	−100,150	+4.97	−2.45	−0.10	+22.19
2 Na(c) + O_2(g) = Na_2O_2(c)	298.16–371	−122,500	−2.30	–	–	+57.51
Sr(c) + 1/2 O_2(g) = SrO(c)	298.16–1043	−142,410	−6.79	+0.305	+0.675	+44.33
S(rhombohedral) + 1/2 O_2(g) = SO(g)	298.16–368.6	+19250	−1.24	+2.95	+0.225	−18.84
S(monoclinic) + 1/2 O_2(g) = SO(g)	368.6–392	+19,200	−1.29	+3.31	+0.225	−18.72
S(lλ,μ) + 1/2 O_2(g) = SO(g)	392–718	+20,320	+10.22	−0.17	+0.225	−50.05
1/2 S_2 (g) + 1/2 O_2(g) = SO(g)	298.16–2000	+3890	+0.07	–	–	−1.50
S(rhombohedral) + O_2(g) = SO_2(g)	298.16–368.6	−70,980	+0.83	+2.35	+0.51	−5.85

(*Continued*)

TABLE 2.20 (*Continued*) Heat of Formation of Inorganic Oxides

Reaction	Temperature Range of Validity (K)	ΔH_0	2.303*a*	*b*	*c*	*I*
S(monoclinic) + O_2(g) = SO_2(g)	368.6–392	−71,020	+0.78	+2.71	+0.51	−5.74
S(lλ,μ) + O_2(g) = SO_2(g)	392–718	−69,900	+12.30	−0.77	+0.51	−37.10
1/2 S_2(g) + O_2(g) = SO_2(g)	298.16–2000	−86,330	+2.42	−0.70	+0.31	+10.71
S(rhombohedral) + 3/2 O_2(g) = SO_3(c – I)	298.16–335.4	−111,370	−6.45	–	–	+88.32
S(rhombohedral) + 3/2 O_2(g) = SO_3(c – II)	298.16–305.7	−108,680	−11.97	–	–	+94.95
S(rhombohedral) + 3/2 O_2(g) = SO_3(l)	298.16–335.4	−107,430	−21.18	–	–	+113.76
S(rhombohedral) + 3/2 O_2(g) = SO_3(g)	298.16–368.6	−95,070	+1.43	+0.66	+1.26	+16.81
S(monoclinic) + 3/2 O_2(g) = SO_3(g)	368.6–392	−95,120	+1.38	+1.02	+1.26	+16.93
S(lλ,μ) + 3/2 O_2(g) = SO_3(g)	392–718	−94,010	+12.89	−2.46	+126	−14.40
1/2 S_2(g) + 3/2 O_2(g) = SO_3(g)	298.16–1500	−110,420	+3.02	−2.39	+106	+33.41
2 Ta(c) + 5/2 O_2(g) = Ta_2O_5(c)	298.16–2000	−492,790	−17.18	−1.25	+2.46	+161.68
Te(c) + 1/2 O_2(g) = TeO(g)	298.16–723	+43,110	+1.91	+0.84	+0.315	−27.22
Te(l) + 1/2 O_2(g) = TeO(g)	723–1360	+39,750	+6.08	+0.09	+0.315	−33.94
2 Tl(α) + O_2(g) = Tl_2O(c)	298.16−505.5	−44,110	−6.91	–	–	+42.30
2 Tl(β) + O_2(g) = Tl_2O(c)	505.5–573	−44,260	−6.91	–	–	+42.60
2 Tl(α) + 3/2 O_2(g) = Tl_2O_3(c)	298.16–505.5	−99,410	−16.12	–	–	+119.09
Th(c) + O_2(g) = ThO_2(c)	298.16–2000	−294,350	−5.25	+0.59	+0.775	+62.81
Sn(c) + 1/2 O_2(g) = SnO(c)	298.16–505	−68,600	−3.57	+1.65	−0.10	+32.59
Sn(l) + 1/2 O_2(g) = SnO(c)	505–1300	−69,670	+3.06	−1.50	−0.10	+18.39
Sn(c) + O_2(g) = SnO_2(c)	298.16–505	−0142	−14.00	+2.45	+2.38	+90.74
Ti(α) + 1/2 O_2(g) = TiO(α)	298.16–1150	−125,010	−4.01	−0.29	+0.83	+36.28
Ti(α) + 1/2 O_2(g) = TiO(α)	1150–1264	−125,040	+1.17	−1.55	+0.83	+21.90
2 Ti(α) + 3/2 O_2(g) = Ti_2O_3(α)	298.16–473	−360,660	+32.08	−23.49	−0.30	−10.66
2 Ti(α) + 3/2 O_2(g) = Ti_2O_3(β)	473–1150	−369,710	−30.95	+2.62	+4.80	+162.79
Ti(α) + O_2(g) = TiO_2 (rutile)	298.16–1150	−228,360	−12.80	+1.62	+1.975	+82.81
Ti(α) + O_2(g) = TiO_2 (rutile)	1150–2000	−228,380	−7.62	+0.36	+1.975	+68.43
W(c) + O_2(g) = WO_2(c)	298.16–1500	−137,180	−1.38	–	–	+45.56
4W(c) + 11/2 O_2(g) = W_4O_{11}(c)	298.16–1700	−745,730	−32.70	–	–	+321.84
W(c) + 3/2 O_2(g) = WO_3(c)	298.16–1743	−201,180	−2.92	−1.81	−0.30	+70.89
W(c) + 3/2 O_2(g) = WO_3(l)	1743–2000	−203,140	−35.74	+1.13	−0.30	+173.27
U(α) + O_2(g) = UO_2(c)	298.16–935	−262,880	−19.92	+3.70	+2.13	+100.54
U(β) + O_2(g) = UO_2(c)	935–1045	−260,660	−4.28	−0.31	+1.78	+55.50
U(γ) + O_2(g) = UO_2(c)	1045–1405	−262,830	−6.54	−0.31	+1.78	+64.41
U(l) + O_2(g) = UO_2(l)	1405–1500	−264,790	−5.92	–	–	+63.50
3 U(α) + 4 O_2(g) = U_3O_8(c)	298.16–935	−863,370	−56.57	+10.68	+5.20	+330.19
3 U(β) + 4 O_2(g) = U_3O_8(c)	935–1045	−856,720	−9.67	−1.35	+4.15	+195.12
3 U(γ) + 4 O_2(g) = U_3O_8(c)	1045–1405	−863,230	−16.44	−1.35	+4.15	+221.79
3 U(l) + 4 O_2(g) = U_3O_8(c)	1405–1500	−869,460	−10.91	−1.35	+4.15	+208.82
U(α) + 3/2 O_2(g) = UO_3 (hexagonal)	298.16–935	−294,090	−18.33	+3.49	+1.535	+114.94
U(β) + 3/2 O_2(g) = UO_3 (hexagonal)	935–1045	−291,870	−2.69	−0.52	+1.185	+69.90

(*Continued*)

TABLE 2.20 (*Continued*) Heat of Formation of Inorganic Oxides

Reaction	Temperature Range of Validity (K)	ΔH_0	2.303*a*	*b*	*c*	*I*
$U(\gamma) + 3/2\ O_2(g) = UO_3$ (hexagonal)	1045–1400	−294,040	−4.95	−0.52	+1.185	+78.80
$V(c) + 1/2\ O_2(g) = VO(c)$	298.16–2000	−101,090	−5.39	−0.36	+0.53	+38.69
$V(c) + 1/2\ O_2(g) = VO(g)$	298.16–2000	+52,090	+1.80	+1.04	+0.35	−28.42
$2\ V(c) + 3/2\ O_2(g) = V_2O_3(c)$	298.16–2000	−299,910	−17.98	+0.37	+2.41	+118.83
$2\ V(c) + 2\ O_2(g) = V_2O_4(\alpha)$	209.16–345	−342,890	−11.03	+3.00	−0.40	+117.38
$2\ V(c) + 2\ O_2(g) = V_2O_4(\beta)$	345–1818	−345,330	−24.36	+1.30	+3.545	+155.55
$6\ V(c) + 13/2\ O_2(g) = V_6O_{13}(c)$	298.16–1000	−1,076,340	−95.33	–	–	+557.61
$2\ V(c) + 5/2\ O_2(g) = V_2O_5(c)$	298.16–943	−381,960	−41.08	+5.20	+6.11	+228.50
$2\ Y(c) + 3/2\ O_2(g) = Y_2O_3(c)$	298.16–1773	−419,600	+2.76	−1.73	−0.30	+66.36
$Zn(c) + 1/2\ O_2(g) = ZnO(c)$	298.16–692.7	−84,670	−6.40	+0.84	+0.99	+43.25
$Zr(\alpha) + O_2(g) = ZrO_2(\alpha)$	298.16–1135	−262,980	−6.10	+0.16	+1.045	+65.00
$Zr(\beta) + O_2(g) = ZrO_2(\alpha)$	1135–1,478	−264,190	−5.09	−0.40	+1.48	+63.58
$Zr(\beta) + O_2(g) = ZrO_2(\beta)$	1478–2000	−262,290	−7.76	+0.50	−0.20	+69.50

Source: Data from C. T. Lynch (Ed.), *CRC Handbook of Materials Science*, Vol. I, CRC Press, Cleveland, 1974.

Note: The ΔH_o values are given in gram calories per mole. The *a*, *b*, and *I* values listed here make it possible for one to calculate the ΔF and ΔS values by use of the following equations:

$$\Delta F_t = \Delta H_o + 2.303aT \log T + b \times 10^{-3}\ T^2 + c \times 10^5\ T^{-1} + IT \quad \text{and}$$
$$\Delta S_t = -a - 2.303a \log T - 2b \times 10^{-3}\ T + c \times 10^5\ T^{-2} - I.$$

TABLE 2.21 Phase Change Thermodynamic Properties of Oxides

Oxide	Phase	Transition Temperature (K)	Heat of Transition (kcal/g · mol)	Entropy of Transition (e.u.)
Ac_2O_3	Solid	(2250)	(20)	(8.9)
	Liquid	–	–	–
Ag_2O	Solid	Dec. 460	–	–
Ag_2O_2	Solid	Dec.	–	–
Al_2O_3	Solid	2300	26	11
	Liquid	Dec.	–	–
Am_2O_3	Solid	(2225)	(17)	(7.6)
	Liquid	(3400)	(85)	(25)
AmO_2	Solid	Dec.	–	–
As_2O_3	Solid, α	503	4.1	8.2
	Solid, β	586	4.4	7.5
	Liquid	730	7.15	9.79
AsO_2	Solid	(1200)	(9.0)	(7.5)
	Liquid	(Dec.)	–	–
As_2O_5	Solid	Dec. >1100	–	–
Au_2O_3	Solid	Dec.	–	–
B_2O_3	Solid	723	5.27	7.29
	Liquid	2520	(55)	(22)
Ba_2O	Solid	(880)	(5.2)	(5.9)
	Liquid	(1040)	(20)	(19)

(*Continued*)

TABLE 2.21 (*Continued*) Phase Change Thermodynamic Properties of Oxides

Oxide	Phase	Transition Temperature (K)	Heat of Transition (kcal/g · mol)	Entropy of Transition (e.u.)
BaO	Solid	2196	13.8	6.28
	Liquid	3000	(62)	(21)
BaO_2	Solid	723	(5.7)	(7.9)
	Liquid	Dec. 1110	–	–
BeO	Solid	Dec.	–	–
BiO	Solid	(1175)	(3.7)	(3.1)
	Liquid	(1920)	(54)	(28)
Bi_2O_3	Solid	1090	6.8	6.2
	Liquid	(Dec.)	–	–
CO	Gas	–	–	–
CO_2	Gas	–	–	–
CaO	Solid	2860	(18)	(6.3)
CdO	Solid	Dec.	–	–
Ce_2O_3	Solid	1960	(20)	(10)
	Liquid	(3500)	(80)	(23)
CeO_2	Solid	3000	(19)	(6.3)
CoO	Solid	2078	(12)	(5.8)
	Liquid	(2900)	(61)	(21)
Co_3O_4	Solid	Dec. 1240	–	–
Cr_2O_3	Solid	2538	(25)	(10)
CrO_2	Solid	Dec. 700	–	–
CrO_3	Solid	460	(6.1)	(13)
	Liquid	(1000)	(25)	(25)
Cs_2O	Solid	763	(4.58)	(6.0)
	Liquid	Dec.	–	–
Cs_2O_2	Solid	867	(5.5)	(6.3)
	Liquid	Dec.	–	–
Cs_2O_3	Solid	775	(7.75)	(10)
	Liquid	Dec.	–	–
Cu_2O	Solid	1503	13.4	8.92
	Liquid	Dec.	–	–
CuO	Solid	1609	(8.9)	(5.5)
	Liquid	Dec.	–	–
FeO	Solid	1641	7.5	4.6
	Liquid	(2700)	(55)	(20)
Fe_3O_4	Solid, α	900	(0)	(0)
	Solid, β	Dec.	–	–
Fe_2O_3	Solid, α	950	0.16	0.17
	Solid, β	1050	0	0
	Solid, γ	Dec.	–	–
Ga_2O	Solid	(925)	(8.5)	(9.2)
	Liquid	(1000)	(20)	(20)
Ga_2O_3	Solid	2013	(22)	(11)
	Liquid	(2900)	(75)	(26)
GeO	Solid	983	(50)	(51)
GeO_2	Solid (α, β)	1389	10.5	7.56
	Liquid	(2625)	(61)	(23)

(*Continued*)

TABLE 2.21 (*Continued*) Phase Change Thermodynamic Properties of Oxides

Oxide	Phase	Transition Temperature (K)	Heat of Transition (kcal/g · mol)	Entropy of Transition (e.u.)
In_2O	Solid	(600)	(4.5)	(7.5)
	Liquid	(800)	(16)	(20)
InO	Solid	(1325)	(4.0)	(3.0)
	Liquid	(2000)	(60)	(30)
In_2O_3	Solid	(2000)	(20)	(10)
	Liquid	(3600)	(85)	(24)
Ir_2O_3	Solid	(1450)	(10)	(6.8)
	Liquid	(2250)	(50)	(22)
IrO_2	Solid	Dec. 1373	–	–
K_2O	Solid	(980)	(6.8)	(6.9)
	Liquid	Dec.	–	–
K_2O_2	Solid	763	(7.0)	(9.2)
	Liquid	(1800)	(45)	(25)
K_2O_3	Solid	703	(6.1)	(8.7)
	Liquid	(975)	(25)	(26)
KO_2	Solid	653	(4.9)	(7.5)
	Liquid	Dec.	–	–
La_2O_3	Solid	2590	(18)	(7)
Li_2O	Solid	2000	(14)	(7)
	Liquid	2600	(56)	(22)
Li_2O_2	Solid	Dec. 470	–	–
MgO	Solid	3075	18.5	5.8
MgO_2	Solid	Dec. 361	–	–
MnO	Solid	2058	13.0	6.32
	Liquid	Dec.	–	–
Mn_3O_4	Solid, α	1445	4.97	3.44
	Solid, β	1863	(33)	(18)
	Liquid	(2900)	(75)	(26)
Mn_2O_3	Solid	Dec. 1620	–	–
MnO_2	Solid	Dec. 1120	–	–
MoO_2	Solid	(2200)	(16)	(7.3)
	Liquid	Dec. 2250	–	–
MoO_3	Solid	1068	12.54	11.74
	Liquid	1530	33	22
N_2O	Gas	–	–	–
Na_2O	Solid	1193	(7.1)	(6.0)
	Liquid	Dec.	–	–
Na_2O_2	Solid	Dec. 919	–	–
NaO_2	Solid	(825)	(6.2)	(7.5)
	Liquid	(1300)	(28)	(22)
NbO	Solid	(2650)	(16)	(6.0)
NbO_2	Solid	(2275)	(16)	(7.0)
	Liquid	(3800)	(85)	(22)
Nb_2O_5	Solid	1733	(28)	(16)
	Liquid	(3200)	(80)	(25)
Nd_2O_3	Solid	2545	(22)	(8.8)

(*Continued*)

TABLE 2.21 (*Continued*) Phase Change Thermodynamic Properties of Oxides

Oxide	Phase	Transition Temperature (K)	Heat of Transition (kcal/g · mol)	Entropy of Transition (e.u.)
NiO	Solid	2230	(12.1)	(5.43)
	Liquid	Dec.	–	–
NpO_2	Solid	(2600)	(15)	(5.7)
Np_2O_5	Solid	Dec. 800–900	–	–
OsO_2	Solid	Dec. 923	–	–
OsO_4	Solid	313.3	3.41	10.9
	Liquid	403	9.45	23.4
P_2O_3	Liquid	448.5	4.5	10
PO_2	Solid	(350)	(2.7)	(7.7)
	Liquid	(Dec.)	–	–
P_2O_5	Solid	631	8.8	13.9
PaO_2	Solid	(2560)	(20)	(7.8)
Pa_2O_5	Solid	(2050)	(26)	(13)
	Liquid	(3350)	(95)	(28)
PbO	Solid, red	762	(0.4)	(0.5)
	Solid, yellow	1159	2.8	2.4
	Liquid	1745	51	29
Pb_2O_4	Solid	Dec.	–	–
PbO_2	Solid	Dec.	–	–
PdO	Solid	Dec. 1150	–	–
PoO_2	Solid	(825)	(5.5)	(6.7)
	Liquid	(Dec.)	–	–
Pr_2O_3	Solid	(2200)	(22)	(10)
	Liquid	(4000)	(90)	(23)
PrO_2	Solid	Dec. 700	–	–
PtO	Solid	Dec. 780	–	–
Pt_3O_4	Solid	(Dec.)	–	–
PtO_2	Solid	723	(4.6)	(6.4)
	Liquid	Dec. 750	–	–
PuO	Solid	(1290)	(7.2)	(5.6)
	Liquid	(2325)	(47)	(20)
Pu_2O_3	Solid	(1880)	(16)	(8.5)
	Liquid	(3250)	(75)	(23)
PuO_2	Solid	(2400)	(15)	(6.2)
	Liquid	(3500)	(90)	(26)
RaO	Solid	(>2500)	–	–
Rb_2O	Solid	(910)	(5.7)	(6.3)
	Liquid	Dec.	–	–
Rb_2O_2	Solid	843	(7.3)	(8.7)
	Liquid	(Dec.)	–	–
Rb_2O_3	Solid	762	(7.6)	(10)
	Liquid	Dec.	–	–
RbO_2	Solid	685	(4.1)	(6.0)
	Liquid	Dec.	–	–
ReO_2	Solid	(1475)	(12)	(8.1)
	Liquid	(3250)	(80)	(25)

(*Continued*)

TABLE 2.21 (*Continued*) Phase Change Thermodynamic Properties of Oxides

Oxide	Phase	Transition Temperature (K)	Heat of Transition (kcal/g · mol)	Entropy of Transition (e.u.)
ReO_3	Solid	433	5.2	12
	Liquid	Dec.	–	–
Re_2O_7	Solid	569	15.8	27.8
	Liquid	635.5	17.7	27.9
ReO_4	Solid	420	(4.2)	(10)
	Liquid	(460)	(9.3)	(20)
Rh_2O	Solid	Dec. 1400	–	–
RhO	Solid	Dec. 1394	–	–
Rh_2O_3	Solid	Dec. 1388	–	–
RuO_2	Solid	Dec. 1400	–	–
RuO_4	Solid	300	(3.2)	(11)
	Liquid	Dec.	–	–
SO_2	Gas	–	–	–
Sb_2O_3	Solid	928	14.74	15.88
	Liquid	1698	8.92	5.25
SbO_2	Solid	Dec.	–	–
Sb_2O_5	Solid	Dec.	–	–
Sc_2O_3	Solid	(2500)	(23)	(9.3)
SeO	Solid	(1375)	(7.6)	(5.5)
	Liquid	(2075)	(45)	(22)
SeO_2	Solid	603	(24.5)	(40.6)
SiO	Solid	(2550)	(12)	(4.7)
SiO_2	Solid, β	856	0.15	0.18
	Solid, α	1883	2.04	1.08
	Liquid	Dec. 2250	–	–
Sm_2O_3	Solid	(2150)	(20)	(9.3)
	Liquid	(3800)	(80)	(21)
SnO	Solid	(1315)	(6.4)	(4.9)
	Liquid	(1800)	(60)	(33)
SnO_2	Solid	1898	(11.39)	(5.95)
	Liquid	(3200)	(75)	(23)
SrO	Solid	2703	16.7	6.2
SrO_2	Solid	Dec. 488	–	–
Ta_2O_5	Solid	2150	(16)	(7.4)
	Liquid	–	–	–
TcO_2	Solid	(2400)	(18)	(7.5)
	Liquid	(4000)	(105)	(26)
TcO_3	Solid	(Dec. <1200)	–	–
Tc_2O_7	Solid	392.7	(11)	(28)
	Liquid	583.8	(14)	(24)
TeO	Solid	(1020)	(7.1)	(7.0)
	Liquid	(1775)	(50)	(28)
TeO_3	Solid	1006	3.2	3.2
	Liquid	Dec.	–	–
TeO_2	Solid	(2150)	(13)	(6.0)
	Liquid	(3250)	(65)	(20)

(*Continued*)

TABLE 2.21 (*Continued*) Phase Change Thermodynamic Properties of Oxides

Oxide	Phase	Transition Temperature (K)	Heat of Transition (kcal/g · mol)	Entropy of Transition (e.u.)
ThO_2	Solid	3225	(18)	(5.6)
TiO	Solid, α	1264	0.82	0.65
	Solid, β	Dec. 2010	–	–
Ti_2O_3	Solid, α	473	0.215	0.455
	Solid, β	2400	(24)	(10)
	Liquid	3300		
Ti_3O_5	Solid, α	450	2.24	4.98
	Solid, β	(2450)	(50)	(20)
	Liquid	(3600)	(85)	(24)
TiO_2	Solid	2128	(16)	(7.5)
	Liquid	Dec. 3200		
Tl_2O	Solid	573	(5.0)	(8.7)
	Liquid	773	(17)	(22)
Tl_2O_3	Solid	990	(12.4)	(13)
	Liquid	(Dec.)	–	–
UO	Solid	(2750)	(14)	(5.1)
UO_2	Solid	3000	–	–
U_3O_8	Solid	Dec.	–	–
UO_3	Solid	Dec. 925	–	–
VO	Solid	(2350)	(15)	(6.4)
	Liquid	(3400)	(70)	(21)
V_2O_3	Solid	2240	(24)	(11)
	Liquid	Dec. 3300	–	–
V_3O_4	Solid	(2100)	(42)	(20)
	Liquid	(Dec.)	–	–
VO_2	Solid, α	345	1.02	2.96
	Solid, β	1818	13.60	7.48
	Liquid	Dec. 3300	–	–
V_2O_5	Solid	943	15.56	16.50
	Liquid	(2325)	(63)	(27)
WO_2	Solid	(1543)	(11.5)	(7.45)
	Liquid	Dec. 2125	–	–
WO_3	Solid	1743	(17)	(9.8)
	Liquid	(2100)	(43)	(20)
Y_2O_3	Solid	(2500)	(25)	(10)
ZnO	Solid	Dec.	–	–
ZrO_2	Solid, α	1478	1.420	0.961
	Solid, β	2950	20.8	7.0

Source: Data from R. C. Weast (Ed.), *Handbook of Chemistry and Physics,* 55th Edn., CRC Press, Cleveland, 1974, D-58.

Note: Values in parentheses are less certain.
Dec. = Decomposes.

TABLE 2.22 Melting Points of Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)
Actinium[227]	Ac	1050 ± 50
Aluminum	Al	658.5
Aluminum bromide	Al_2Br_6	87.4
Aluminum chloride	Al_2Cl_6	192.4
Aluminum iodide	Al_2I_6	190.9
Aluminum oxide	Al_2O_3	2045.0
Antimony	Sb	630
Antimony pentachloride	$SbCl_5$	4.0
Antimony tribromide	$SbBr_3$	96.8
Antimony trichloride	$SbCl_3$	73.3
Antimony trioxide	Sb_4O_6	655.0
Antimony trisulfide	Sb_4S_6	546.0
Argon	Ar	−190.2
Arsenic	As	816.8
Arsenic pentafluoride	AsF_5	80.8
Arsenic tribromide	$AsBr_3$	30.0
Arsenic trichloride	$AsCl_3$	−16.0
Arsenic trifluoride	AsF_3	−6.0
Arsenic trioxide	As_4O_6	312.8
Barium	Ba	725
Barium bromide	$BaBr_2$	846.8
Barium chloride	$BaCl_2$	959.8
Barium fluoride	BaF_2	1286.8
Barium iodide	BaI_2	710.8
Barium nitrate	$Ba(NO_3)_2$	594.8
Barium oxide	BaO	1922.8
Barium phosphate	$Ba_3(PO_4)_2$	1727
Barium sulfate	$BaSO_4$	1350
Beryllium	Be	1278
Beryllium bromide	$BeBr_2$	487.8
Beryllium chloride	$BeCl_2$	404.8
Beryllium oxide	BeO	2550.0
Bismuth	Bi	271
Bismuth trichloride	$BiCl_3$	223.8
Bismuth trifluoride	BiF_3	726.0
Bismuth trioxide	Bi_2O_3	815.8
Boron	B	2300
Boron tribromide	BBr_3	−48.8
Boron trichloride	BCl_3	−107.8
Boron trifluoride	BF_3	−128.0
Boron trioxide	B_2O_3	448.8
Bromine	Br_2	−7.2
Bromine pentafluoride	BrF_5	−61.4
Cadmium	Cd	320.8
Cadmium bromide	$CdBr_2$	567.8
Cadmium chloride	$CdCl_2$	567.8
Cadmium fluoride	CdF_2	1110

(*Continued*)

TABLE 2.22 (*Continued*) Melting Points of Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)
Cadmium iodide	CdI_2	386.8
Cadmium sulfate	$CdSO_4$	1000
Calcium	Ca	851
Calcium bromide	$CaBr_2$	729.8
Calcium carbonate	$CaCO_3$	1282
Calcium chloride	$CaCl_2$	782
Calcium fluoride	CaF_2	1382
Calcium metasilicate	$CaSiO_3$	1512
Calcium nitrate	$Ca(NO_3)_2$	560.8
Calcium oxide	CaO	2707
Calcium sulfate	$CaSO_4$	1297
Carbon dioxide	CO_2	−57.6
Carbon monoxide	CO	−205
Cyanogen	C_2N_2	−27.2
Cyanogen chloride	CNCl	−5.2
Cerium	Ce	775
Cesium	Cs	28.3
Cesium chloride	CsCl	38.5
Cesium nitrate	$CsNO_3$	406.8
Chlorine	Cl_2	−103 ± 5
Chromium	Cr	1890
Chromium (II) chloride	$CrCl_2$	814
Chromium (III) sesquioxide	Cr_2O_3	2279
Chromium trioxide	CrO_3	197
Cobalt	Co	1490
Cobalt (II) chloride	$CoCl_2$	727
Copper	Cu	1083
Copper (II) chloride	$CuCl_2$	430
Copper (I) chloride	CuCl	429
Copper (l) cyanide	$Cu_2(CN)_2$	473
Copper (I) iodide	CuI	587
Copper (II) oxide	CuO	1446
Copper (I) oxide	Cu_2O	1230
Copper (I) sulfide	Cu_2S	1129
Dysprosium	Dy	1407
Erbium	Er	1496
Europium	Eu	826
Europium trichloride	$EuCl_3$	622
Fluorine	F_2	−219.6
Gadolinium	Gd	1312
Gallium	Ga	29
Germanium	Ge	959
Gold	Au	1063
Hafnium	Hf	2214
Holmium	Ho	1461
Hydrogen	H_2	−259.25

(*Continued*)

TABLE 2.22 (*Continued*) Melting Points of Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)
Hydrogen bromide	HBr	−86.96
Hydrogen chloride	HCl	−114.3
Hydrogen fluoride	HF	83.11
Hydrogen iodide	HI	−50.91
Hydrogen nitrate	HNO_3	−47.2
Hydrogen oxide (water)	H_2O	0
Deuterium oxide	D_2O	3.78
Hydrogen peroxide	H_2O_2	−0.7
Hydrogen selenate	H_2SeO_4	57.8
Hydrogen sulfate	H_2SO_4	10.4
Hydrogen sulfide	H_2S	−85.6
Hydrogen sulfide, di-	H_2S_2	−89.7
Hydrogen telluride	H_2Te	−49.0
Indium	In	156.3
Iodine	I_2	112.9
lodine chloride (α)	ICl	17.1
lodine chloride (β)	ICl	13.8
Iron	Fe	1530.0
Iron carbide	Fe_3C	1226.8
Iron (III) chloride	Fe_2Cl_6	303.8
Iron (II) chloride	$FeCl_2$	677
Iron (II) oxide	FeO	1380
Iron oxide	Fe_3O_4	1596
Iron pentacarbonyl	$Fe(CO)_5$	−21.2
Iron (II) sulfide	FeS	1195
Lanthanum	La	920
Lead	Pb	327.3
Lead bromide	$PbBr_2$	487.8
Lead chloride	$PbCl_2$	497.8
Lead fluoride	PbF_2	823
Lead iodide	PbI_2	412
Lead molybdate	$PbMoO_4$	1065
Lead oxide	PbO	890
Lead sulfate	$PbSO_4$	1087
Lead sulfide	PbS	1114
Lithium	Li	178.8
Lithium bromide	LiBr	552
Lithium chloride	LiCl	614
Lithium fluoride	LiF	896
Lithium hydroxide	LiOH	462
Lithium iodide	LiI	440
Lithium metasilicate	Li_2SiO_3	1177
Lithium molybdate	Li_2MoO_4	705
Lithium nitrate	$LiNO_3$	250
Lithium orthosilicate	Li_4SiO_4	1249
Lithium sulfate	Li_2SO_4	857

(*Continued*)

TABLE 2.22 (*Continued*) Melting Points of Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)
Lithium tungstate	Li_2WO_4	742
Lutetium	Lu	1651
Magnesium	Mg	650
Magnesium bromide	$MgBr_2$	711
Magnesium chloride	$MgCl_2$	712
Magnesium fluoride	MgF_2	1221
Magnesium oxide	MgO	2642
Magnesium silicate	$MgSiO_3$	1524
Magnesium sulfate	$MgSO_4$	1327
Manganese	Mn	1220
Manganese dichloride	$MnCl_2$	650
Manganese metasilicate	$MnSiO_3$	1274
Manganese (II) oxide	MnO	1784
Manganese oxide	Mn_3O_4	1590
Mercury	Hg	−39
Mercury bromide	$HgBr_2$	241
Mercury chloride	$HgCl_2$	276.8
Mercury iodide	HgI_2	250
Mercury sulfate	$HgSO_4$	850
Molybdenum	Mo	2622
Molybdenum dichloride	$MoCl_2$	726.8
Molybdenum hexafluoride	MoF_6	17
Molybdenum trioxide	MoO_3	795
Neodymium	Nd	1020
Neon	Ne	−248.6
Nickel	Ni	1452
Nickel chloride	$NiCl_2$	1030
Nickel subsulfide	Ni_3S_2	790
Niobium	Nb	2496
Niobium pentachloride	$NbCl_5$	211
Niobium pentoxide	Nb_2O_5	1511
Nitric oxide	NO	−163.7
Nitrogen	N_2	−210
Nitrogen tetroxide	N_2O_4	−13.2
Nitrous oxide	N_2O	−90.9
Osmium	Os	2700
Osmium tetroxide (white)	OsO_4	41.8
Osmium tetroxide (yellow)	OsO_4	55.8
Oxygen	O_2	−218.8
Palladium	Pd	1555
Phosphoric acid	H_3PO_4	42.3
Phosphoric acid, hypo-	$H_4P_2O_6$	54.8
Phosphorus acid, hypo-	H_3PO_2	17.3
Phosphorus acid, ortho-	H_3PO_3	73.8
Phosphorus oxychloride	$POCl_3$	1.0
Phosphorus pentoxide	P_4O_{10}	569.0

(*Continued*)

TABLE 2.22 (*Continued*) Melting Points of Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)
Phosphorus trioxide	P_4O_6	23.7
Phosphorus, yellow	P_4	44.1
Platinum	Pt	1770
Potassium	K	63.4
Potassium borate, meta-	KBO_2	947
Potassium bromide	KBr	742
Potassium carbonate	K_2CO_3	897
Potassium chloride	KCl	770
Potassium chromate	K_2CrO_4	984
Potassium cyanide	KCN	623
Potassium dichromate	$K_2Cr_2O_7$	398
Potassium fluoride	KF	875
Potassium hydroxide	KOH	360
Potassium iodide	Kl	682
Potassium nitrate	KNO_3	338
Potassium peroxide	K_2O_2	490
Potassium phosphate	K_3PO_4	1340
Potassium pyrophosphate	$K_4P_2O_7$	1092
Potassium sulfate	K_2SO_4	1074
Potassium thiocyanate	KSCN	179
Praseodymium	Pr	931
Rhenium	Re	3167 ± 60
Rhenium heptoxide	Re_2O_7	296
Rhenium hexafluoride	ReF_6	19.0
Rubidium	Rb	38.9
Rubidium bromide	RbBr	677
Rubidium chloride	RbCl	717
Rubidium fluoride	RbF	833
Rubidium iodide	Rbl	638
Rubidium nitrate	$RbNO_3$	305
Samarium	Sm	1072
Scandium	Sc	1538
Selenium	Se	217
Selenium oxychloride	$SeOCl_3$	9.8
Silane, hexafluoro-	Si_2F_6	−28.6
Silicon	Si	1427
Silicon dioxide (cristobalite)	SiO_2	1723
Silicon tetrachloride	$SiCl_4$	−67.7
Silver	Ag	961
Silver bromide	AgBr	430
Silver chloride	AgCl	455
Silver cyanide	AgCN	350
Silver iodide	Agl	557
Silver nitrate	$AgNO_3$	209
Silver sulfate	Ag_2SO_4	657

(*Continued*)

TABLE 2.22 (*Continued*) Melting Points of Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)
Silver sulfide	Ag_2S	841
Sodium	Na	97.8
Sodium borate, meta-	$NaBO_2$	966
Sodium bromide	NaBr	747
Sodium carbonate	Na_2CO_3	854
Sodium chlorate	$NaClO_3$	255
Sodium chloride	NaCl	800
Sodium cyanide	NaCN	562
Sodium fluoride	NaF	992
Sodium hydroxide	NaOH	322
Sodium iodide	Nal	662
Sodium molybdate	Na_2MoO_4	687
Sodium nitrate	$NaNO_3$	310
Sodium peroxide	Na_2O_2	460
Sodium phosphate, meta-	$NaPO_3$	988
Sodium pyrophosphate	$Na_4P_2O_7$	970
Sodium silicate, aluminum-	$NaAlSi_3O_8$	1107
Sodium silicate, di-	$Na_2Si_2O_5$	884
Sodium silicate, meta-	Na_2SiO_3	1087
Sodium sulfate	Na_2SO_4	884
Sodium sulfide	Na_2S	920
Sodium thiocyanate	NaSCN	323
Sodium tungstate	Na_2WO_4	702
Strontium	Sr	757
Strontium bromide	$SrBr_2$	643
Strontium chloride	$SrCl_2$	872
Strontium fluoride	SrF_2	1400
Strontium oxide	SrO	2430
Sulfur (monatomic)	S	119
Sulfur dioxide	SO_2	−73.2
Sulfur trioxide (α)	SO_3	16.8
Sulfur trioxide (β)	SO_3	32.3
Sulfur trioxide (γ)	SO_3	62.1
Tantalum	Ta	2996 ± 50
Tantalum pentachloride	$TaCl_5$	206.8
Tantalum pentoxide	Ta_2O_5	1877
Tellurium	Te	453
Terbium	Tb	1356
Thallium	Tl	302.4
Thallium bromide, mono-	TlBr	460
Thallium carbonate	Tl_2CO_3	273
Thallium chloride, mono-	TICl	427
Thallium iodide, mono-	TlI	440
Thallium nitrate	$TINO_3$	207
Thallium sulfate	Tl_2SO_4	632

(*Continued*)

TABLE 2.22 (*Continued*) Melting Points of Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)
Thallium sulfide	Tl_2S	449
Thorium	Th	1845
Thorium chloride	$ThCl_4$	765
Thorium dioxide	ThO_2	2952
Thulium	Tm	1545
Tin	Sn	231.7
Tin bromide, di-	$SnBr_2$	231.8
Tin bromide, tetra-	$SnBr_4$	29.8
Tin chloride, di-	$SnCl_2$	247
Tin chloride, tetra-	$SnCl_4$	−33.3
Tin iodide, tetra-	SnI_4	143.4
Tin oxide	SnO	1042
Titanium	Ti	1800
Titanium bromide, tetra-	$TiBr_4$	38
Titanium chloride, tetra-	$TiCl_4$	−23.2
Titanium dioxide	TiO_2	1825
Titanium oxide	TiO	991
Tungsten	W	3387
Tungsten dioxide	WO_2	1270
Tungsten hexafluoride	WF_6	−0.5
Tungsten tetrachloride	WCl_4	327
Tungsten trioxide	WO_3	1470
Uranium^{235}	U	~1133
Uranium tetrachloride	UCl_4	590
Vanadium	V	1917
Vanadium dichloride	VCl_2	1027
Vanadium oxide	VO	2077
Vanadium pentoxide	V_2O_5	670
Xenon	Xe	−111.6
Ytterbium	Yb	823
Yttrium	Y	1504
Yttrium oxide	Y_2O_3	2227
Zinc	Zn	419.4
Zinc chloride	$ZnCl_2$	283
Zinc oxide	ZnO	1975
Zinc sulfide	ZnS	1745
Zirconium	Zr	1857
Zirconium dichloride	$ZrCl_2$	727
Zirconium oxide	ZrO_2	2715

Sources: Data from R. C. Weast (Ed.), *Handbook of Chemistry and Physics*, 55th Edn., CRC Press, Cleveland, 1974; R. E. Bolz, and G. L. Tuve (Eds.), *Handbook of Tables for Applied Engineering Science*, 2nd Edn., CRC Press, Cleveland, 1973, p. 479.

TABLE 2.23 Melting Points of Ceramics

Compound	T_m (K)
AgBr	703
AgCl	728
AgF	708
AgI	831
$AgNO_3$	483
Ag_2O	573
Ag_2SO_4	933
Ag_2S	1098
$AlBr_3$	371
Al_4C_3	2000
$AlCl_3$	465
AlF_3	1564
AlI	464
AlN	>2475
Al_2O_3	2322
$Al_2(SO_4)_3$	1043
Al_2S_3	1373
BBr_3	227
B_4C	2720
BCl_3	166
BF_3	146
BN	3000
B_2O_3	723
BS_4	663
BaB_4	2543
$BaBr_2$	1123
$BaCl_2$	1235
BaF_2	1627
BaI_2	1013
$Ba(NO_3)_2$	865
BaO	2283
$BaSO_4$	1853
BaS	1473
BeB_2	>2243
$BeBr_2$	793
Be_2C	>2375
$BeCl_2$	713
BeF_2	813
BeI_2	783
Be_3N_2	2513
BeO	2725
$BeSO_4$	848
$BiBr_3$	491
$BiCl_3$	507

(*Continued*)

TABLE 2.23 (*Continued*) Melting Points of Ceramics

Compound	T_m (K)
BiF_3	1000
BiI_3	681
Bi_2O_3	1098
$Bi(SO_4)_3$	678
Bi_2S_3	1020
$CaBr_2$	1003
$CaCl_2$	1055
CaF_2	1675
CaI_2	848
$Ca(NO_3)_2$	623
Ca_3N_2	1468
CaO	3183
$CaSO_4$	1723
$CdBr_2$	841
$CdCl_2$	841
CdF_2	1373
CdI_2	423
$Cd(NO_3)_2$	834
CdO	1773
$CdSO_4$	1273
CdS	2023
CeB_6	2463
$CeCl_3$	1095
CeF_2	1710
CeI_3	1025
CeO_2	>2873
CeS	2400
$Ce(SO_4)_2$	468
CrB_2	2123
Cr_3C_2	2168
CrN	1770
Cr_2O_3	>2603
$CrSi_2$	1843
CuBr	777
CuCl	695
CuF_2	1129
CuI	878
Cu_3N	573
Cu_2O	1508
Cu_4Si	1123
Cu_2S	1400
$FeBr_2$	955
Fe_3C	2110
$FeCl_2$	945

(*Continued*)

TABLE 2.23 (*Continued*) Melting Points of Ceramics

Compound	T_m (K)
FeF_3	>1275
Fe_2O_3	1864
$Fe_2(SO_4)_3$	753
FeS	1468
$InBr_3$	709
InCl	498
InF_3	1443
InI_3	483
In_2O_3	2183
In_2S_3	1323
KBr	1008
KCl	1043
KF	1131
KI	958
KNO_3	610
K_2O_3	703
K_2SO_4	1342
K_2S	1113
LiBr	823
LiCl	883
LiF	1119
LiI	722
$LiNO_3$	527
Li_3N	1118
Li_2O	>1975
Li_2SO_4	1132
Li_2S	1198
$MgBr_2$	984
$MgCl_2$	987
MgF_2	1535
MgI_2	<910
MgO	3098
Mg_2Si	1375
MgS	>2275
$MgSO_4$	1397
$MnCl_2$	923
MnF_2	1129
MnO	1840
MoB	2625
Mo_2C	2963
MoF_6	290
MoI_4	373
MoO_3	1068
$MoSi_2$	2553

(*Continued*)

TABLE 2.23 (*Continued*) Melting Points of Ceramics

Compound	T_m (K)
MoS_2	1458
NaBr	1023
NaC_2	973
NaCl	1073
NaF	1267
NaI	935
$NaNO_3$	583
Na_2N	573
Na_2SO_4	1157
Na_2S	1453
NbB	>2270
NbC	3770
NbN	2323
Nb_2O_5	1764
$NbSi_2$	2203
$NiBr_2$	1236
$NiCl_2$	1274
NiF_2	1273
NiI_2	1070
NiO	2257
$NiSO_4$	1121
NiS	1070
$PbBr_2$	643
$PbCl_2$	771
PbF_2	1095
PbI_2	675
$Pb(NO_3)_2$	743
PbO	1159
$PbSO_4$	1443
PbS	1387
$PtBr_2$	523
$PtCl_2$	854
PtI_2	633
PtS_2	508
$SbBr_3$	370
$SbCl_3$	346
SbF_3	565
SbI_3	443
Sb_2O_3	928
SbS_3	820
SiC	2970
SiF_4	183
Si_3N_4	2715
SiO_2	1978

(*Continued*)

TABLE 2.23 (*Continued*) Melting Points of Ceramics

Compound	T_m (K)
$SnBr_2$	488
$SnCl_2$	581
SnF_4	978
SnI_2	788
SnO	1353
$SnSO_4$	>635
SnS	1153
SrB_6	2508
$SrBr_2$	916
SrC_2	>1970
$SrCl_2$	1148
SrF_2	1736
SrI_2	593
$Sr(NO_3)_2$	643
SrO	2933
$SrSO_4$	1878
SrS	>2275
TaB	>2270
$TaBr_5$	538
TaC	3813
$TaCl_5$	489
TaF_5	370
Ta_2N	3360
Ta_2O_5	2100
$TaSi_2$	2670
TaS_4	>1575
$TeBr_2$	612
$TeCl_2$	448
TeO_2	1006
ThB_4	>2270
$ThBr_4$	883
ThC	2898
$ThCl_4$	1043
ThF_4	1375
ThN	2903
ThO_2	3493
ThS_2	2198
TiB_2	3253
$TiBr_4$	312
TiC	3433
$TiCl_4$	250
TiF_3	1475
TiI_2	873
TiN	3200

(*Continued*)

TABLE 2.23 (*Continued*) Melting Points of Ceramics

Compound	T_m (K)
TiO_2	2113
$TiSi_2$	1813
UB_2	>1770
UBr_4	789
UC	2863
UCl_4	843
UF_4	1233
UI_4	779
UN	3123
UO_2	3151
USi_2	1970
US_2	>1375
VB_2	2373
VC	3600
VCl_4	245
VF_3	>1075
VI_2	1048
VN	2593
V_2O_5	947
VSi_2	2023
V_2S_3	>875
WB	3133
WC	2900
WCl_6	548
WO_3	1744
WSi_2	2320
WS_2	1523
$ZnBr_2$	667
$ZnCl_2$	548
ZnF_2	1145
ZnI_2	719
ZnO	2248
$ZnSO_4$	873
ZrB_2	3313
$ZrBr_2$	>625
ZrC	3533
$ZrCl_2$	623
ZrF_4	873
ZrI_4	772
ZrN	3250
ZrO_2	3123
$Zr(SO_4)_2$	683
ZrS_2	1823

Source: Data from C. T. Lynch, (Ed.), *CRC Handbook of Materials Science*, Vol. 1, CRC Press, Boca Raton, FL, 1974, p. 348.

TABLE 2.24 Heat of Fusion for Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)	Heat of Fusion cal/g	Heat of Fusion cal/g mol
Actinium[227]	Ac	1050 ± 50	(11.0)	(3400)
Aluminum	Al	658.5	94.5	2550
Aluminum bromide	Al_2Br_6	87.4	10.1	5420
Aluminum chloride	Al_2Cl_6	192.4	63.6	19,600
Aluminum iodide	Al_2I_6	190.9	9.8	7960
Aluminum oxide	Al_2O_3	2045.0	(256.0)	(26,000)
Antimony	Sb	630	39.1	4770
Antimony pentachloride	$SbCl_5$	4.0	8.0	2400
Antimony tribromide	$SbBr_3$	96.8	9.7	3510
Antimony trichloride	$SbCl_3$	73.3	13.3	3030
Antimony trioxide	Sb_4O_6	655.0	(46.3)	(26,990)
Antimony trisulfide	Sb_4S_6	546.0	33.0	11,200
Argon	Ar	190.2	7.25	290
Arsenic	As	816.8	(22.0)	(6620)
Arsenic pentafluoride	AsF_5	80.8	16.5	2800
Arsenic tribromide	$AsBr_3$	30.0	8.9	2810
Arsenic trichloride	$AsCl_3$	–16.0	13.3	2420
Arsenic trifluoride	AsF_3	–6.0	18.9	2486
Arsenic trioxide	As_4O_6	312.8	22.2	8000
Barium	Ba	725	13.3	1830
Barium bromide	$BaBr_2$	846.8	21.9	6000
Barium chloride	$BaCl_2$	959.8	25.9	5370
Barium fluoride	BaF_2	1286.8	17.1	3000
Barium iodide	BaI_2	710.8	(17.3)	(6800)
Barium nitrate	$Ba(NO_3)_2$	594.8	(22.6)	(5900)
Barium oxide	BaO	1922.8	93.2	13,800
Barium phosphate	$Ba_3(PO_4)_2$	1727	30.9	18,600
Barium sulfate	$BaSO_4$	1350	41.6	9700
Beryllium	Be	1278	260.0	–
Beryllium bromide	$BeBr_2$	487.8	(26.6)	(4500)
Beryllium chloride	$BeCl_2$	404.8	(30)	(3000)
Beryllium oxide	BeO	2550.0	679.7	17,000
Bismuth	Bi	271	12.0	2505
Bismuth trichloride	$BiCl_3$	223.8	8.2	2600
Bismuth trifluoride	BiF_3	726.0	(23.3)	(6200)
Bismuth trioxide	Bi_2O_3	815.8	14.6	6800
Boron	B	2300	(490)	(5300)
Boron tribromide	BBr_3	–48.8	(2.9)	(700)
Boron trichloride	BCl_3	–107.8	(4.3)	(500)
Boron trifluoride	BF_3	–128.0	7.0	480
Boron trioxide	B_2O_3	448.8	78.9	5500
Bromine	Br_2	–7.2	16.1	2580
Bromine pentafluoride	BrF_5	–61.4	7.07	1355
Cadmium	Cd	320.8	12.9	1460
Cadmium bromide	$CdBr_2$	567.8	(18.4)	(5000)
Cadmium chloride	$CdCl_2$	567.8	28.8	5300

(*Continued*)

TABLE 2.24 (*Continued*) Heat of Fusion for Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)	Heat of Fusion cal/g	Heat of Fusion cal/g mol
Cadmium fluoride	CdF_2	1110	(35.9)	(5400)
Cadmium iodide	CdI_2	386.8	10.0	3660
Cadmium sulfate	$CdSO_4$	1000	22.9	4790
Calcium	Ca	851	55.7	2230
Calcium bromide	$CaBr_2$	729.8	20.9	4180
Calcium carbonate	$CaCO_3$	1282	(126)	(12,700)
Calcium chloride	$CaCl_2$	782	55	6100
Calcium fluoride	CaF_2	1382	52.5	4100
Calcium metasilicate	$CaSiO_3$	1512	115.4	13,400
Calcium nitrate	$Ca(NO_3)_2$	560.8	31.2	5120
Calcium oxide	CaO	2707	(218.1)	(12,240)
Calcium sulfate	$CaSO_4$	1297	49.2	6700
Carbon dioxide	CO_2	−57.6	43.2	1900
Carbon monoxide	CO	−205	7.13	199.7
Cyanogen	C_2N_2	−27.2	39.6	2060
Cyanogen chloride	CNCl	−5.2	36.4	2240
Cerium	Ce	775	27.2	2120
Cesium	Cs	28.3	3.7	500
Cesium chloride	CsCl	38.5	21.4	3600
Cesium nitrate	$CsNO_3$	406.8	16.6	3250
Chlorine	Cl_2	−103 ± 5	22.8	1531
Chromium	Cr	1890	62.1	3660
Chromium (II) chloride	$CrCl_2$	814	65.9	7700
Chromium (III) sesquioxide	Cr_2O_3	2279	27.6	4200
Chromium trioxide	CrO_3	197	37.7	3770
Cobalt	Co	1490	62.1	3640
Cobalt (II) chloride	$CoCl_2$	727	56.9	7390
Copper	Cu	1083	49.0	3110
Copper (II) chloride	$CuCl_2$	430	24.7	4890
Copper (I) chloride	CuCl	429	26.4	2620
Copper (l) cyanide	$Cu_2(CN)_2$	473	(30.1)	(5400)
Copper (I) iodide	CuI	587	(13.6)	(2600)
Copper (II) oxide	CuO	1446	35.4	2820
Copper (I) oxide	Cu_2O	1230	(93.6)	(13,400)
Copper (I) sulfide	Cu_2S	1129	62.3	5500
Dysprosium	Dy	1407	25.2	4100
Erbium	Er	1496	24.5	4100
Europium	Eu	826	16.4	2500
Europium trichloride	$EuCl_3$	622	(20.9)	(8000)
Fluorine	F_2	−219.6	6.4	244.0
Gadolinium	Gd	1312	23.8	3700
Gallium	Ga	29	19.1	1336
Germanium	Ge	959	(114.3)	(8300)
Gold	Au	1063	(15.3)	3030
Hafnium	Hf	2214	(34.1)	(6000)
Holmium	Ho	1461	24.8	4100

(*Continued*)

TABLE 2.24 (*Continued*) Heat of Fusion for Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)	Heat of Fusion	
			cal/g	cal/g mol
Hydrogen	H_2	−259.25	13.8	28
Hydrogen bromide	HBr	−86.96	7.1	575.1
Hydrogen chloride	HCl	−114.3	13.0	476.0
Hydrogen fluoride	HF	83.11	54.7	1094
Hydrogen iodide	HI	−50.91	5.4	686.3
Hydrogen nitrate	HNO_3	−47.2	9.5	601
Hydrogen oxide (water)	H_2O	0	79.72	1436
Deuterium oxide	D_2O	3.78	75.8	1516
Hydrogen peroxide	H_2O_2	−0.7	8.58	2920
Hydrogen selenite	H_2SeO_4	57.8	23.8	3450
Hydrogen sulfate	H_2SO_4	10.4	24.0	2360
Hydrogen sulfide	H_2S	−85.6	16.8	5683
Hydrogen sulfide, di−	H_2S_2	−89.7	27.3	1805
Hydrogen telluride	H_2Te	−49.0	12.9	1670
Indium	In	156.3	6.8	781
Iodine	I_2	112.9	14.3	3650
Iodine chloride (α)	ICl	17.1	16.4	2660
Iodine chloride (β)	ICl	13.8	13.3	2270
Iron	Fe	1530.0	63.7	3560
Iron carbide	Fe_3C	1226.8	68.6	12,330
Iron (III) chloride	Fe_2Cl_6	303.8	63.2	20,500
Iron (II) chloride	$FeCl_2$	677	61.5	7800
Iron (II) oxide	FeO	1380	(107.2)	(7700)
Iron oxide	Fe_3O_4	1596	142.5	33,000
Iron pentacarbonyl	$Fe(CO)_5$	−21.2	16.5	3250
Iron (II) sulfide	FeS	1195	56.9	5000
Lanthanum	La	920	17.4	2400
Lead	Pb	327.3	5.9	1224
Lead bromide	$PbBr_2$	487.8	11.7	4290
Lead chloride	$PbCl_2$	497.8	20.3	5650
Lead fluoride	PbF_2	823	7.6	1860
Lead iodide	PbI_2	412	17.9	5970
Lead molybdate	$PbMoO_4$	1065	70.8	(25,800)
Lead oxide	PbO	890	12.6	2820
Lead sulfate	$PbSO_4$	1087	31.6	9600
Lead sulfide	PbS	1114	17.3	4150
Lithium	Li	178.8	158.5	1100
Lithium bromide	LiBr	552	33.4	2900
Lithium chloride	LiCl	614	75.5	3200
Lithium fluoride	LiF	896	(91.1)	(2360)
Lithium hydroxide	LiOH	462	103.3	2480
Lithium iodide	LiI	440	(10.6)	(1420)
Lithium metasilicate	Li_2SiO_3	1177	80.2	7210
Lithium molybdate	Li_2MoO_4	705	24.1	4200
Lithium nitrate	$LiNO_3$	250	87.8	6060
Lithium orthosilicate	Li_4SiO_4	1249	60.5	7430

(*Continued*)

TABLE 2.24 (*Continued*) Heat of Fusion for Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)	Heat of Fusion	
			cal/g	cal/g mol
Lithium sulfate	Li_2SO_4	857	27.6	3040
Lithium tungstate	Li_2WO_4	742	(25.6)	(6700)
Lutetium	Lu	1651	26.3	4600
Magnesium	Mg	650	88.9	2160
Magnesium bromide	$MgBr_2$	711	45.0	8300
Magnesium chloride	$MgCl_2$	712	82.9	8100
Magnesium fluoride	MgF_2	1221	94.7	5900
Magnesium oxide	MgO	2642	459.0	18,500
Magnesium silicate	$MgSiO_3$	1524	146.4	14,700
Magnesium sulfate	$MgSO_4$	1327	28.9	3500
Manganese	Mn	1220	62.7	3450
Manganese dichloride	$MnCl_2$	650	58.4	7340
Manganese metasilicate	$MnSiO_3$	1274	(62.6)	(8200)
Manganese (II) oxide	MnO	1784	183.3	13,000
Manganese oxide	Mn_3O_4	1590	(170.4)	(39,000)
Mercury	Hg	−39	2.7	557.2
Mercury bromide	$HgBr_2$	241	10.9	3960
Mercury chloride	$HgCl_2$	276.8	15.3	4150
Mercury iodide	HgI_2	250	9.9	4500
Mercury sulfate	$HgSO_4$	850	(4.8)	(1440)
Molybdenum	Mo	2622	(68.4)	(6600)
Molybdenum dichloride	$MoCl_2$	726.8	3.58	6000
Molybdenum hexafluoride	MoF_6	17	11.9	2500
Molybdenum trioxide	MoO_3	795	(17.3)	(2500)
Neodymium	Nd	1020	11.8	1700
Neon	Ne	−248.6	3.83	77.4
Nickel	Ni	1452	71.5	4200
Nickel chloride	$NiCl_2$	1030	142.5	18.470
Nickel subsulfide	Ni_3S_2	790	25.81	5800
Niobium	Nb	2496	(68.9)	(6500)
Niobium pentachloride	$NbCl_5$	21.1	30 8	8400
Niobium pentoxide	Nb_2O_5	1511	91.0	24,200
Nitric oxide	NO	−163.7	18.3	549.5
Nitrogen	N_2	−210	6.15	172.3
Nitrogen tetroxide	N_2O_4	−13.2	60.2	5540
Nitrous oxide	N_2O	−90.9	35.5	1563
Osmium	Os	2700	(36.7)	(7000)
Osmium tetroxide (white)	OsO_4	41.8	9.2	2340
Osmium tetroxide (yellow)	OsO_4	55.8	15.5	4060
Oxygen	O_2	−218.8	3.3	106.3
Palladium	Pd	1555	38.6	4120
Phosphoric acid	H_3PO_4	42.3	25.8	2520
Phosphoric acid. hypo-	$H_4P_2O_6$	54.8	51.2	8300
Phosphorus acid, hypo-	H_3PO_2	17.3	35.0	2310
Phosphorus acid, ortho-	H_3PO_3	73.8	37.4	3070
Phosphorus oxychloride	$POCl_3$	1.0	20.3	3110

(*Continued*)

TABLE 2.24 (*Continued*) Heat of Fusion for Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)	Heat of Fusion	
			cal/g	cal/g mol
Phosphorus pentoxide	P_4O_{10}	569.0	60.1	17,080
Phosphorus trioxide	P_4O_6	23.7	15.3	3360
Phosphorus, yellow	P_4	44.1	4.8	600
Platinum	Pt	1770	24.1	4700
Potassium	K	63.4	14.6	574
Potassium borate, meta-	KBO_2	947	(69.1)	(5660)
Potassium bromide	KBr	742	42.0	5000
Potassium carbonate	K_2CO_3	897	56.4	7800
Potassium chloride	KCl	770	85.9	6410
Potassium chromate	K_2CrO_4	984	35.6	6920
Potassium cyanide	KCN	623	(53.7)	(3500)
Potassium dichromate	$K_2Cr_2O_7$	398	29.8	8770
Potassium fluoride	KF	875	111.9	6500
Potassium hydroxide	KOH	360	(35.3)	(1980)
Potassium iodide	Kl	682	24.7	4100
Potassium nitrate	KNO_3	338	78.1	2840
Potassium peroxide	K_2O_2	490	55.3	6100
Potassium phosphate	K_3PO_4	1340	41.9	8900
Potassium pyrophosphate	$K_4P_2O_7$	1092	42.4	14,000
Potassium sulfate	K_2SO_4	1074	46.4	8100
Potassium thiocyanate	KSCN	179	23.1	2250
Praseodymium	Pr	931	19.0	2700
Rhenium	Re	3167 ± 60	(42.4)	(7900)
Rhenium heptoxide	Re_2O_7	296	30.1	15,340
Rhenium hexafluoride	ReF_6	19.0	16.6	5000
Rubidium	Rb	38.9	6.1	525
Rubidium bromide	RbBr	677	22.4	3700
Rubidium chloride	RbCl	717	36.4	4400
Rubidium fluoride	RbF	833	39.5	4130
Rubidium iodide	Rbl	638	14.0	2990
Rubidium nitrate	$RbNO_3$	305	9.1	1340
Samarium	Sm	1072	17.3	2600
Scandium	Sc	1538	84.4	3800
Selenium	Se	217	15.4	1220
Selenium oxychloride	$SeOCl_3$	9.8	6.1	1010
Silane, hexafluoro-	Si_2F_6	−28.6	22.9	3900
Silicon	Si	1427	337.0	9470
Silicon dioxide (cristobalite)	SiO_2	1723	35.0	2100
Silicon tetrachloride	$SiCl_4$	−67.7	10.8	1845
Silver	Ag	961	25.0	2700
Silver bromide	AgBr	430	11.6	2180
Silver chloride	AgCl	455	22.0	3155
Silver cyanide	AgCN	350	20.5	2750
Silver iodide	AgI	557	9.5	2250
Silver nitrate	$AgNO_3$	209	16.2	2755
Silver sulfate	Ag_2SO_4	657	(13.7)	(4280)

(*Continued*)

TABLE 2.24 (*Continued*) Heat of Fusion for Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)	Heat of Fusion	
			cal/g	cal/g mol
Silver sulfide	Ag_2S	841	13.5	3360
Sodium	Na	97.8	27.4	630
Sodium borate, meta-	$NaBO_2$	966	134.6	8660
Sodium bromide	NaBr	747	59.7	6140
Sodium carbonate	Na_2CO_3	854	66.0	7000
Sodium chlorate	$NaClO_3$	255	49.7	5290
Sodium chloride	NaCl	800	123.5	7220
Sodium cyanide	NaCN	562	(88.9)	(4360)
Sodium fluoride	NaF	992	166.7	7000
Sodium hydroxide	NaOH	322	50.0	2000
Sodium iodide	NaI	662	35.1	5340
Sodium molybdate	Na_2MoO_4	687	17.5	3600
Sodium nitrate	$NaNO_3$	310	44.2	3760
Sodium peroxide	Na_2O_2	460	75.1	5860
Sodium phosphate, meta-	$NaPO_3$	988	(48.6)	(4960)
Sodium pyrophosphate	$Na_4P_2O_7$	970	(51.5)	(13,700)
Sodium silicate, aluminum-	$NaAlSi_3O_8$	1107	50.1	13,150
Sodium silicate, di-	$Na_2Si_2O_5$	884	46.4	8460
Sodium silicate, meta-	Na_2SiO_3	1087	84.4	10,300
Sodium sulfate	Na_2SO_4	884	41.0	5830
Sodium sulfide	Na_2S	920	15.4	(1200)
Sodium thiocyanate	NaSCN	323	54.8	4450
Sodium tungstate	Na_2WO_4	702	19.6	5800
Strontium	Sr	757	25.0	2190
Strontium bromide	$SrBr_2$	643	19.3	4780
Strontium chloride	$SrCl_2$	872	26.5	4100
Strontium fluoride	SrF_2	1400	34.0	4260
Strontium oxide	SrO	2430	161.2	16,700
Sulfur (monatomic)	S	119	9.2	295
Sulfur dioxide	SO_2	−73.2	32.2	2060
Sulfur trioxide (α)	SO_3	16.8	25.8	2060
Sulfur trioxide (β)	SO_3	32.3	36.1	2890
Sulfur trioxide (γ)	SO_3	62.1	79.0	6310
Tantalum	Ta	2996 ± 50	34.6–41.5	(7500)
Tantalum pentachloride	$TaCl_5$	206.8	25.1	9000
Tantalum pentoxide	Ta_2O_5	1877	108.6	48,000
Tellurium	Te	453	25.3	3230
Terbium	Tb	1356	24.6	3900
Thallium	Tl	302.4	5.0	1030
Thallium bromide, mono-	TlBr	460	21.0	5990
Thallium carbonate	Tl_2CO_3	273	9.5	4400
Thallium chloride, mono-	TICl	427	17.7	4260
Thallium iodide, mono-	TlI	440	9.4	3125
Thallium nitrate	$TINO_3$	207	8.6	2290
Thallium sulfate	Tl_2SO_4	632	10.9	5500
Thallium sulfide	Tl_2S	449	6.8	3000

(*Continued*)

TABLE 2.24 (*Continued*) Heat of Fusion for Elements and Inorganic Compounds

Compound	Formula	Melting Point (°C)	Heat of Fusion cal/g	Heat of Fusion cal/g mol
Thorium	Th	1845	(<19.8)	(<4600)
Thorium chloride	$ThCl_4$	765	61.6	22,500
Thorium dioxide	ThO_2	2952	1102.0	291,100
Thulium	Tm	1545	26.0	4400
Tin	Sn	231.7	14.4	1720
Tin bromide, di-	$SnBr_2$	231.8	(6.1)	(1720)
Tin bromide, tetra-	$SnBr_4$	29.8	6.8	3000
Tin chloride, di-	$SnCl_2$	247	16.0	3050
Tin chloride, tetra-	$SnCl_4$	−33.3	8.4	2190
Tin iodide, tetra-	SnI_4	143.4	(6.9)	(4330)
Tin oxide	SnO	1042	(46.8)	(6400)
Titanium	Ti	1800	(104.4)	(5000)
Titanium bromide, tetra-	$TiBr_4$	38	(5.6)	(2060)
Titanium chloride, tetra-	$TiCl_4$	−23.2	11.9	2240
Titanium dioxide	TiO_2	1825	(142.7)	(11,400)
Titanium oxide	TiO	991	219	14,000
Tungsten	W	3387	(45.8)	(8420)
Tungsten dioxide	WO_2	1270	60.1	13,940
Tungsten hexafluoride	WF_6	−0.5	6.0	1800
Tungsten tetrachloride	WCl_4	327	18.4	6000
Tungsten trioxide	WO_3	1470	60 1	13,940
Uranium[235]	U	~ 1133	20	3700
Uranium tetrachloride	UCl_4	590	27.1	10,300
Vanadium	V	1917	(70)	(4200)
Vanadium dichloride	VCl_2	1027	65.6	8000
Vanadium oxide	VO	2077	224.0	15,000
Vanadium pentoxide	V_2O_5	670	85.5	15,560
Xenon	Xe	−111.6	5.6	740
Ytterbium	Yb	823	12.7	2200
Yttrium	Y	1504	46.1	4100
Yttrium oxide	Y_2O_3	2227	110.7	25000
Zinc	Zn	419.4	24.4	1595
Zinc chloride	$ZnCl_2$	283	(406)	(5540)
Zinc oxide	ZnO	1975	54.9	4470
Zinc sulfide	ZnS	1745	(93.3)	(9100)
Zirconium	Zr	1857	(60)	(5500)
Zirconium dichloride	$ZrCl_2$	727	45.0	7300
Zirconium oxide	ZrO_2	2715	168.8	20,800

Source: Data from R. C. Weast (Ed.), *Handbook of Chemistry and Physics,* 55th Edn., CRC Press, Cleveland, 1974; R. E. Bolz and Tuve, G.L. (Eds.), *Handbook of Tables for Applied Engineering Science*, 2nd Edn., CRC Press, Cleveland, 1973.

Note: 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.

TABLE 2.25 Heats of Sublimation of Metals and Their Oxides

Metal	kcal/mol (25°C)	kJ/mol (25°C)
Al	78	326
Cu	81	338
Fe	100	416
Mg	113	473
Metal oxide		
FeO	122	509
MgO	145	605
α-TiO	143	597
TiO_2 (rutile)	153	639

Source: Data from *JANAF Thermochemical Tables,* 2nd Edn., National Standard Reference Data Series, Natl. Bur. Std. (U.S.), 1971, p. 37; and *Supplement* in *J. Phys. Chem. Ref. Data* 4 (1), 1–175, 1975.

TABLE 2.26 Thermodynamic Coefficients for Oxides

Oxide	Phase	*a*	*b* (cal/g · mol)	*c*	*d*	*A* (kcal/g · mol)	*B* (e.u.)
Ac_2O_3	Solid	(20.0)	(20.4)	–	–	(6.870)	(80.9)
	Liquid	(40)	–	–	–	(–19.767)	(180.5)
Ag_2O	Solid	13.26	7.04	–	–	4.266	48.56
Ag_2O_2	Solid	(16.4)	(12.2)	–	–	(5.432)	(76.7)
Al_2O_3	Solid	26.12	4.388	–	–7.269	10.422	142.03
	Liquid	(33)	–	–	–	(–11.655)	(174.1)
Am_2O_3	Solid	(20.0)	(15.6)	–	–	(6.657)	(81.6)
	Liquid	(38.5)	–	–	–	(–7.796)	(181.8)
AmO_2	Solid	(14.0)	(6.8)	–	–	(4.477)	(61.8)
As_2O_3	Solid, α	8.37	48.6	–	–	4.656	36.6
	Solid, β	8.37	48.6	–	–	0.556	28.4
	Liquid	(39)	–	–	–	(5.760)	(187.6)
	Gas	(21.5)	–	–	–	(–14.164)	(62.5)
AsO_2	Solid	(8.5)	(9.4)	–	–	(2.952)	(38.2)
	Liquid	(21)	–	–	–	(2.184)	(108.0)
As_2O_5	Solid	(31.1)	(16.4)	–	(–5.4)	(11.813)	(159.9)
Au_2O_3	Solid	(23.5)	(4.8)	–	–	(7.220)	(105.3)
B_2O_3	Solid	8.73	25.40	–	–1.31	4.171	45.04
	Liquid	30.50	–	–	–	7.822	161.59
Ba_2O	Solid	(20.0)	(2.2)	–	–	(6.061)	(91.1)
	Liquid	(22)	–	–	–	(1.769)	(96.8)
	Gas	(15)	–	–	–	(–25.51)	(29.0)
BaO	Solid	12.74	1.040	–	–1.984	4.510	57.2
	Liquid	(13.9)	–	–	–	(–9.341)	(57.5)
BaO_2	Solid	(13.6)	(2.0)	–	–	(4.144)	(59.6)
	Liquid	(21)	–	–	–	(3.241)	(99.0)
BeO	Solid	8.69	3.65	–	–3.13	3.803	48.99

(*Continued*)

TABLE 2.26 (*Continued*) Thermodynamic Coefficients for Oxides

Oxide	Phase	*a*	*b* (cal/g · mol)	*c*	*d*	*A* (kcal/g · mol)	*B* (e.u.)
BiO	Solid	(9.7)	(3.0)	–	–	(3.025)	(41.2)
	Liquid	(14)	–	–	–	(2.306)	(64.9)
	Gas	(8.9)	–	–	–	(−61.49)	(−1.8)
Bi_2O_3	Solid	23.27	11.05	–	–	7.429	99.7
	Liquid	(35.7)	–	–	–	(7.614)	(168.3)
CO	Gas	6.60	1.2	–	–	2.021	−9.34
CO_2	Gas	7.70	5.3	−0.83	–	2.490	−5.64
CaO	Solid	10.00	4.84	–	−1.08	3.559	49.5
CdO	Solid	9.65	2.08	–	–	2.970	42.5
Ce_2O_3	Solid	(−23.0)	(9.0)	–	–	(7.258)	(100.2)
	Liquid	(37)	–	–	–	(−2.591)	(178.5)
CeO_2	Solid	15.0	2.5	–	–	4.579	68.5
CoO	Solid	(9.8)	(2.2)	–	–	(3.020)	(46.0)
	Liquid	(15.5)	–	–	–	(−1.886)	(79.2)
Co_3O_4	Solid	(29.5)	(17.0)	–	–	(9.551)	(137.6)
Cr_2O_3	Solid	28.53	2.20	–	−3.736	9.857	145.9
CrO_2	Solid	(16.1)	(3.0)	–	(−3.0)	(5.946)	(82.8)
CrO_3	Solid	(18.1)	(4.0)	–	(−2.0)	(6.245)	(87.9)
	Liquid	(27)	–	–	–	(3.381)	(127.0)
	Gas	(20)	–	–	–	(−28.62)	(53.6)
Cs_2O	Solid	(16.51)	(5.4)	–	–	(5.160)	(72.6)
	Liquid	(22)	–	–	–	(3.205)	(99.0)
Cs_2O_2	Solid	(21.4)	(11.4)	–	–	(6.887)	(85.3)
	Liquid	(29.5)	–	–	–	(4.125)	(123.8)
Cs_2O_3	Solid	(24.0)	(22.6)	–	–	(8.160)	(96.5)
	Liquid	(35)	–	–	–	(2.148)	(142.2)
Cu_2O	Solid	(13.4)	(8.6)	–	–	(4.378)	(96.0)
	Liquid	(21.5)	–	–	–	(3.721)	(54.9)
CuO	Solid	14.34	6.2	–	–	4.551	61.11
	Liquid	(22)	–	–	–	(−4.339)	(98.91)
FeO	Solid	9.27	4.80	–	–	(2.977)	(43.8)
	Liquid	(14.5)	–	–	–	(−3.721)	(69.2)
Fe_3O_4	Solid, α	12.38	1.62	–	−0.38	3.826	58.3
	Solid, β	(14.5)	–	–	–	(−2.399)	(66.7)
Fe_2O_3	Solid, α	21.88	48.20	–	–	8.666	104.0
	Solid, β	48.00	–	–	–	12.652	238.3
	Solid, γ	23.49	18.6	–	−3.55	9.021	119.9
Ga_2O	Solid	36.00	–	–	–	11.979	187.6
	Liquid	31.71	1.8	–	–	8.467	159.7
	Gas	(13.8)	(8.6)	–	–	(4.497)	(58.7)
Ga_2O_3	Solid	(21.5)	–	–	–	(−0.559)	(94.1)
GeO	Liquid	(14)	–	–	–	(−28.06)	(22.3)
	Solid	11.77	25.2	–	–	(4.630)	(54.35)
	Gas	(35.5)	–	–	–	(−20.66)	(173.2)
GeO_2	Solid (α, β)	(10.4)	(2.6)	–	(−0.5)	(3.384)	(47.8)
	Liquid	(8.2)	(0.4)	–	(−0.2)	(−49.67)	(−20.2)

(*Continued*)

TABLE 2.26 (*Continued*) Thermodynamic Coefficients for Oxides

Oxide	Phase	*a*	*b* (cal/g · mol)	*c*	*d*	*A* (kcal/g · mol)	*B* (e.u.)
In_2O	Solid	(14.7)	(7.8)	–	–	(4.730)	(58.1)
	Liquid	(22)	–	–	–	(3.206)	(92.6)
	Gas	(15)	–	–	–	(−18.39)	(25.8)
InO	Solid	(10.0)	(3.2)	–	–	(3.124)	(43.4)
	Liquid	(14)	–	–	–	(1.615)	(64.9)
	Gas	(9.0)	–	–	–	(−68.38)	(−3.1)
In_2O_3	Solid	(22.6)	(6.0)	–	–	(7.005)	(100.5)
	Liquid	(35)	–	–	–	(−0.195)	(172.8)
Ir_2O_3	Solid	(21.8)	(14.4)	–	–	(7.140)	(102.0)
	Liquid	(35)	–	–	–	(0.706)	(170.3)
	Gas	(20)	(10)	–	–	(−57.73)	(54.8)
IrO_2	Solid	9.17	15.20	–	–	3.410	40.9
K_2O	Solid	(15.9)	(6.4)	–	–	(5.025)	(69.5)
	Liquid	(22)	–	–	–	(1.130)	(98.3)
K_2O_2	Solid	(20.8)	(5.4)	–	–	(6.442)	(93.1)
	Liquid	(29)	–	–	–	(4.127)	(134.2)
	Gas	(20)	–	–	–	(−57.07)	(41.7)
K_2O_3	Solid	(19.1)	(23.2)	–	–	(6.750)	(82.2)
	Liquid	(35.5)	–	–	–	(6.447)	(164.7)
	Gas	(20)	(5.0)	–	–	(−31.29)	(37.3)
KO_2	Solid	(15.0)	(12.0)	–	–	(5.006)	(61.1)
	Liquid	(24)	–	–	–	(3.424)	(105.5)
La_2O_3	Solid	28.86	3.076	–	−3.275	9.840	(130.7)
Li_2O	Solid	(11.4)	(5.4)	–	–	(3.639)	(57.5)
	Liquid	(21)	–	–	–	(−1.961)	(112.7)
Li_2O_2	Solid	(17.0)	(5.4)	–	–	(5.309)	(82.0)
MgO	Solid	10.86	1.197	–	−2.087	3.991	57.0
MgO_2	Solid	(12.1)	(2.4)	–	–	(3.714)	(49.2)
MnO	Solid	11.11	1.94	–	−0.88	3.689	50.10
	Liquid	(13.5)	–	–	–	(−8.543)	(58.02)
Mn_3O_4	Solid, α	34.64	10.82	–	−2.20	11.312	166.3
	Solid, β	50.20	–	–	–	17.376	260.4
	Liquid	(49)	–	–	–	(−17.86)	(233.4)
Mn_2O_3	Solid	24.73	8.38	–	−3.23	8.829	118.8
MnO_2	Solid	16.60	2.44	–	−3.88	6.359	84.8
MoO_2	Solid	(16.2)	(3.0)	–	(−3.0)	(5.973)	(80.4)
	Liquid	(23)	–	–	–	(−2.463)	(118.4)
MoO_3	Solid	13.6	13.5	–	–	4.655	62.83
	Liquid	(28.4)	–	–	–	(0.222)	(139.88)
	Gas	(18.1)	–	–	–	(−48.54)	(42.8)
N_2O	Gas	(10.92)	2.06	–	−2.04	4.032	11.40
Na_2O	Solid	15.70	5.40	–	–	4.921	73.7
	Liquid	(22)	–	–	–	(1.494)	(105.9)
Na_2O_2	Solid	(20.2)	(3.8)	–	–	(6.192)	(93.6)
NaO_2	Solid	(16.2)	(3.6)	–	–	(4.990)	(65.7)
	Liquid	(23)	–	–	–	(3.175)	(100.9)
	Gas	(15)	–	–	–	(−35.22)	(22.0)

(*Continued*)

TABLE 2.26 (*Continued*) Thermodynamic Coefficients for Oxides

Oxide	Phase	*a*	*b* (cal/g · mol)	*c*	*d*	*A* (kcal/g · mol)	*B* (e.u.)
NbO	Solid	(9.6)	(4.4)	–	–	(3.058)	(44.0)
NbO_2	Solid	(17.1)	(1.6)	–	(–2.8)	(6.109)	(84.6)
	Liquid	(24)	–	–	–	(1.033)	(127.2)
Nb_2O_5	Solid	21.88	28.2	–	–	7.776	100.3
	Liquid	(44.2)	–	–	–	(–24.09)	(201.6)
Nd_2O_3	Solid	28.99	5.760	–	(–4.159)	10.295	(133.9)
NiO	Solid	13.69	0.83	–	–2.915	5.097	70.67
	Liquid	(14.3)	–	–	–	(–7.861)	(67.91)
NpO_2	Solid	(17.7)	(3.2)	–	(–2.6)	(6.292)	(84.08)
Np_2O_5	Solid	(32.4)	(12.6)	–	–	(10.22)	(145.4)
OsO_2	Solid	(11.5)	(6.0)	–	–	(3.696)	(52.8)
OsO_4	Solid	(16.4)	(23.1)	–	(–2.4)	(6.726)	(67.0)
	Liquid	(33)	–	–	–	(6.612)	(143.0)
	Gas	16.46	8.60	–	–4.6	(–7.644)	(25.3)
P_2O_3	Liquid	(34.5)	–	–	–	(10.287)	(162.6)
	Gas	(153)	(10)	–	–	(–1.953)	(38.0)
PO_2	Solid	(11.3)	(5.0)	–	–	(3.591)	(54.4)
	Liquid	(20)	–	–	–	(3.640)	(95.9)
P_2O_5	Solid	8.375	5.40	–	–	4.897	30.3
	Gas	36.80	–	–	–	3.284	165.6
PaO_2	Solid	(14.4)	(2.6)	–	–	(4.409)	(65.0)
Pa_2O_5	Solid	(28.4)	(11.4)	–	–	(8.975)	(127.7)
	Liquid	(48)	–	–	–	(–0.800)	(241.1)
PbO	Solid, red	10.60	4.00	–	–	3.338	45.4
	Solid, yellow	9.05	6.40	–	–	2.454	36.4
	Liquid	(14.6)	–	–	–	1.788	65.7
	Gas	(8.1)	(0.4)	–	–	(–59.94)	(–11.0)
Pb_2O_4	Solid	(31.1)	(17.6)	–	–	(10.055)	(132.0)
PbO_2	Solid	12.7	7.80	–	–	4.133	56.4
PdO	Solid	3.30	14.2	–	–	1.615	(13.9)
PoO_2	Solid	(14.3)	(5.6)	–	–	(4.513)	(66.1)
	Liquid	(22)	–	–	–	(3.460)	(106.5)
Pr_2O_3	Solid	(29.0)	(4.0)	–	(–4.0)	(10.166)	(133.2)
	Liquid	(36)	–	–	–	(–6.298)	(168.3)
PrO_2	Solid	(17.6)	(3.4)	–	(–2.8)	(6.338)	(85.9)
PtO	Solid	(9.0)	(6.4)	–	–	(2.968)	(39.7)
Pt_3O_4	Solid	(30.8)	(17.4)	–	–	(9.957)	(139.7)
PtO_2	Solid	(11.1)	(9.6)	–	–	(3.736)	(49.6)
	Liquid	(21)	–	–	–	(3.785)	(101.5)
PuO	Solid	(12.0)	(2.4)	–	–	(3.685)	(49.1)
	Liquid	(14.5)	–	–	–	(–2.287)	(58.3)
	Gas	(8.9)	–	–	–	(–62.307)	(–5.3)
Pu_2O_3	Solid	(21.2)	(18.2)	–	–	(7.130)	(88.2)
	Liquid	(40)	–	–	–	(–5.691)	(187.2)
PuO_2	Solid	(17.1)	(3.4)	–	(–2.6)	(6.122)	(80.2)
	Liquid	(20.5)	–	–	–	(–10.62)	(92.2)

(*Continued*)

TABLE 2.26 (*Continued*) Thermodynamic Coefficients for Oxides

Oxide	Phase	*a*	*b* (cal/g · mol)	*c*	*d*	*A* (kcal/g · mol)	*B* (e.u.)
RaO	Solid	(10.5)	(2.0)	–	–	(3.220)	(43.4)
Rb_2O	Solid	(15.4)	(5.8)	–	–	(4.850)	(62.5)
	Liquid	(22)	–	–	–	(2.754)	(95.9)
Rb_2O_2	Solid	(20.9)	(8.0)	–	–	(6.587)	(94.0)
	Liquid	(29)	–	–	–	(3.273)	(133.2)
Rb_2O_3	Solid	(20.5)	(13.0)	–	–	(6.690)	(88.2)
	Liquid	(34)	–	–	–	(5.603)	(157.8)
RbO_2	Solid	(13.8)	(6.4)	–	–	(4.399)	(59.0)
	Liquid	(21)	–	–	–	(3.720)	(95.7)
ReO_2	Solid	(10.8)	(9.8)	–	–	(3.656)	(49.5)
	Liquid	(24.5)	–	–	–	(1.204)	(127.0)
ReO_3	Solid	(18.0)	(5.8)	–	–	(5.625)	(84.5)
	Liquid	29	–	–	–	(4.644)	(136.8)
Re_2O_7	Solid	(41.8)	(14.8)	–	(−3.0)	(14.127)	(200.3)
	Liquid	(65.7)	–	–	–	(9.203)	(314.7)
	Gas	(38.2)	–	–	–	(−25.97)	(109.3)
ReO_4	Solid	(21.4)	(10.8)	–	(−2.0)	(7.531)	(91.8)
	Liquid	(33)	–	–	–	(6.775)	(146.7)
	Gas	(16.5)	(8.6)	–	(−5.0)	(−8.118)	(30.6)
Rh_2O	Solid	15.59	6.47	–	–	4.936	(65.3)
RhO	Solid	(9.84)	(553)	–	–	(3.179)	(45.7)
Rh_2O_3	Solid	20.73	13.80	–	–	6.794	(99.2)
RuO_2	Solid	(11.4)	(6.0)	–	–	3.666	(54.2)
RuO_4	Solid	(20)	–	–	–	(5.963)	(81.5)
	Liquid	(33)	–	–	–	(6.663)	(144.9)
SO_2	Gas	11.4	1.414	–	−2.045	4.148	7.12
Sb_2O_3	Solid	19.10	17.1	–	–	6.455	84.5
	Liquid	(36)	–	–	–	(0.035)	(168.2)
	Gas	(20.8)	–	–	–	(−34.70)	(49.9)
SbO_2	Solid	11.30	8.1	–	–	3.725	51.6
Sb_2O_5	Solid	(22.4)	(23.6)	–	–	(7.723)	(104.8)
Sc_2O_3	Solid	23.17	5.64	–	–	7.159	1089
SeO	Solid	(9.1)	(3.8)	–	–	(2.882)	(42.0)
	Liquid	(15.5)	–	–	–	(0.490)	(77.5)
	Gas	8.20	0.50	–	−0.80	(−58.54)	(0.7)
SeO_2	Solid	(12.8)	(6.1)	–	(−0.2)	(4.150)	(59.9)
	Gas	(14.5)	–	–	–	(−20.45)	(26.4)
SiO	Solid	(7.3)	(2.4)	–	–	(2.283)	(35.8)
SiO_2	Solid, β	11.22	8.20	–	−2.70	4.615	57.83
	Solid, α	14.41	1.94	–	–	4.602	73.67
	Liquid	(20)	–	–	–	(9.649)	(111.08)
Sm_2O_3	Solid	(25.9)	(7.0)	–	–	(8.033)	(113.2)
	Liquid	(36)	–	–	–	(−6.431)	(166.3)
SnO	Solid	9.40	3.62	–	–	2.964	41.1
	Liquid	(14.5)	–	–	–	(0.141)	(68.1)
	Gas	(9.0)	–	–	–	(−69.76)	(−6.4)

(*Continued*)

TABLE 2.26 (*Continued*) Thermodynamic Coefficients for Oxides

Oxide	Phase	*a*	*b* (cal/g · mol)	*c*	*d*	*A* (kcal/g · mol)	*B* (e.u.)
SnO_2	Solid	17.66	2.40	–	−5.16	7.103	91.7
	Liquid	(22.5)	–	–	–	(0.304)	(117.7)
SrO	Solid	12.34	1.120	–	−1.806	4.335	58.7
SrO_2	Solid	(16.8)	(2.2)	–	(−3.0)	(6.113)	(83.3)
Ta_2O_5	Solid	29.2	10.0	–	–	9.151	135.2
	Liquid	(46)	–	–	–	(6.158)	(235.1)
TcO_2	Solid	(10.4)	(9.2)	–	–	(3.510)	(48.6)
	Liquid	(25)	–	–	–	(−5.946)	(132.7)
TcO_3	Solid	(19.4)	(5.2)	–	(−2.0)	(6.686)	(93.7)
Tc_2O_7	Solid	(39.1)	(18.6)	–	(−2.4)	(13.29)	(187.2)
	Liquid	(64)	–	–	–	(10.02)	(299.8)
	Gas	(25)	(28)	–	–	(−21.98)	(43.8)
TeO	Solid	(8.6)	(6.2)	–	–	(2.840)	(37.8)
	Liquid	(15.5)	–	–	–	(−0.448)	(72.3)
	Gas	(8.9)	–	–	–	(−62.16)	(−5.2)
TeO_3	Solid	13.85	6.87	–	–	4.435	63.97
	Liquid	(20)	–	–	–	(3.940)	(96.4)
TeO_2	Solid	(11.0)	(2.4)	–	–	(3.386)	(47.4)
	Liquid	(15)	–	–	–	(−6.561)	(66.9)
ThO_2	Solid	16.45	2.346	–	−2.124	5.721	80.03
TiO	Solid, α	10.57	3.60	–	−1.86	3.935	54.03
	Solid, β	11.85	3.00	–	–	4.108	61.71
Ti_2O_3	Solid, α	7.31	53.52	–	–	4.559	38.78
	Solid, β	34.68	1.30	–	−10.20	13.605	184.48
	Liquid	(37.5)	–	–	–	(−7.796)	(193.2)
Ti_3O_5	Solid, α	35.47	29.50	–	–	11.887	179.98
	Solid, β	41.60	8.00	–	–	10.230	202.80
	Liquid	(60)	–	–	–	(−18.701)	(306.4)
TiO_2	Solid	17.97	0.28	–	−4.35	6.829	92.92
	Liquid	(21.4)	–	–	–	(−2.610)	(111.08)
Ti_2O	Solid	(15.8)	(6.0)	–	(−0.3)	(5.078)	(68.2)
	Liquid	(22.1)	–	–	–	(2.651)	(96.0)
	Gas	(13.7)	–	–	–	(−20.94)	(18.0)
Ti_2O_3	Solid	(23.0)	(5.0)	–	–	(7.080)	(99.0)
	Liquid	(35.5)	–	–	–	(4.604)	(167.8)
UO	Solid	(10.6)	(2.0)	–	–	(3.249)	(45.0)
UO_2	Solid	19.20	1.62	–	−3.957	7.124	93.37
U_3O_8	Solid	(65)	(7.5)	–	(−10.9)	(23.37)	(312.7)
UO_3	Solid	22.09	2.54	–	−2.973	7.969	104.72
VO	Solid	11.32	1.61	–	−1.26	3.869	56.4
	Liquid	(14.5)	–	–	–	(−8.157)	(70.9)
V_2O_3	Solid	29.35	4.76	–	−5.42	10.780	148.12
	Liquid	(38)	–	–	–	(−6.028)	(193.4)
V_3O_4	Solid	(36)	(30)	–	–	(12.07)	(182.1)
	Liquid	(55.6)	–	–	–	(−54.72)	(249.1)
VO_2	Solid, α	14.96	–	–	–	4.460	72.92
	Solid, β	17.85	1.70	–	−3.94	5.680	89.09
	Liquid	25.50	–	–	–	2.962	135.87

(*Continued*)

TABLE 2.26 (*Continued*) Thermodynamic Coefficients for Oxides

Oxide	Phase	*a*	*b* (cal/g · mol)	*c*	*d*	*A* (kcal/g · mol)	*B* (e.u.)
V_2O_5	Solid	46.54	−390	–	−13.22	18.136	240.2
	Liquid	45.60	–	–	–	2.122	220.1
	Gas	(40)	–	–	–	(−73.90)	(149.6)
WO_2	Solid	(17.6)	(4.2)	–	(−4.0)	(6.772)	(88.8)
	Liquid	(24)	–	–	–	(−0.112)	(121.8)
WO_3	Solid	17.33	7.74	–	–	5.511	81.15
	Liquid	(30)	–	–	–	(−1.162)	(152.5)
	Gas	(18)	–	–	–	(−69.36)	(40.2)
Y_2O_3	Solid	(26.0)	(8.2)	–	(−2.2)	(8.846)	(122.3)
ZnO	Solid	11.71	1.22	–	−2.18	4.277	57.88
ZrO_2	Solid, α	16.64	1.80	–	−3.36	6.168	85.21
	Solid, β	17.80	–	–	–	4.270	89.96

Source: Data from R. C. Weast (Ed.), *Handbook of Chemistry and Physics,* 55th Edn., CRC Press, Cleveland, 1974, D-58.
Note: For discussion of these coefficients, please see Table 1.65, key to tables of thermodynamic coefficients.

TABLE 2.27 Vapor Pressure of Elements and Inorganic Compounds[a]

Compound	Formula	*a*	*b*	Temperature Range of Validity (°C)
Aluminum oxide	Al_2O_3	540,000	14.22	1840–2200 liq.
Ammonia	NH_3	31,211	9.9974	−127 to −78 sol.
Ammonium bromide	NH_4Br	90,208	9.9404	250–400 sol.
Ammonium chloride	NH_4Cl	83,486	10.0164	100–400 sol.
Ammonium cyanide	NH_4CN	41,484	9.978	7–17 sol.
Ammonium iodide	NH_4I	95,730	10.2700	300–400 sol.
Ammonium sulfhydrate	NH_4HS	46,025	10.7500	6–40 sol.
Antimony	Sb	189,000	9.051	1070–1325 liq.
Argon	Ar	7814.5	7.5741	−208 to −189 sol.
		6826	6.9605	−189 to −183 liq.
Arsenic	As	47,100	6.692	800–860 liq.
		133,000	10.800	440–815 sol.
Arsenous oxide	As_2O_3	111,350	12.127	100–315 sol.
		52,120	6.513	315–490 liq.
Barium	Ba	350,000	15.765	930–1130 liq.
Bismuth	Bi	200,000	8.876	1210–1420 liq.
Bismuth trichloride	$BiCl_3$	13,125	2.681	91–213 sol.
Cadmium	Cd	10,900	8.564	150–320.9 sol.
		99,900	7.897	500–840 liq.
Cadmium iodide	CdI_2	122,200	9.269	385–450 liq.
Cesium	Cs	73,400	6.949	200–350 liq.
Cesium chloride	CsCl	163,200	8.340	986–1295 liq.
Calcium	Ca	370,000	16.240	960–1110 liq.
Carbon	C	540,000	9.596	3880–4430 liq.
Carbon dioxide	CO_2	26,179.3	9.9082	−135 to −56.7 liq.

(*Continued*)

TABLE 2.27 (*Continued*) Vapor Pressure of Elements and Inorganic Compounds[a]

Compound	Formula	*a*	*b*	Temperature Range of Validity (°C)
Carbon monoxide	CO	6354	6.976	−220 to −206 liq.
Chlorine	Cl	29,293	9.950	−154 to −103 liq.
Cobalt	Co	309,000	7.571	2375 liq.
Copper	Cu	468,000	12.344	2100–2310 liq.
Cuprous chloride	Cu_2Cl_2	80,700	5.454	878–1369 liq.
Cyanogen	$(CN)_2$	32,437	9.6539	−72 to −28 sol.
		23,750	7.808	−32 to −6 liq.
Ferrous chloride	$FeCl_2$	135,200	8.33	700–390 sol.
Gold	Au	385,000	9.853	2315–2500 liq.
Hydriodic acid	HI	24,160	8.259	−97 to −51 sol.
		21,580	7.630	−50 to −34 liq.
Hydrobromic acid	HBr	22,420	8.734	−114 to −86 sol.
		17,960	7.427	−86 to −66 liq.
Hydrochloric acid	HCl	19,588	8.4430	−158 to −110 sol.
Hydrocyanic acid	HCN	27,830	7.7446	−8 to 27 liq.
Hydrofluoric acid	HF	25,180	7.370	−83 to 48 liq.
Hydrogen peroxide	H_2O_2	48,530	8.853	10–90 liq.
Hydrogen sulfide	H_2S	20,690	7.880	−110 to −83 sol.
Iron	Fe	309,000	7.482	2220–2450 liq.
Krypton	Kr	10,065	7.1770	−189 to −169 sol.
		9377	6.92387	−169 to −150 liq.
Lead	Pb	188,500	7.827	525–1325 liq.
Lead bromide	$PbBr_2$	118,000	7.827	735–918 liq.
Lead chloride	$PbCl_2$	141,900	8.961	500–950 liq.
Lithium bromide	LiBr	152,700	8.068	1010–1265 liq.
Lithium chloride	LiCl	155,900	7.939	1045–1325 liq.
Lithium fluoride	LiF	218,400	8.753	1398–1666 liq.
Lithium iodide	LiI	143,600	8.011	940–1140 liq.
Magnesium	Mg	260,000	12.993	900–1070 liq.
Manganese	Mn	267,000	9.300	1510–1900 liq.
Mercuric bromide	$HgBr_2$	79,800	10.181	111–235 sol.
		61,250	8.284	238–331 liq.
Mercuric chloride	$HgCl_2$	85,030	10.888	60–130 sol.
		78,850	10.094	130–270 sol.
		61,020	8.409	275–309 liq.
Mercuric iodide	HgI_2	82,340	10.057	100–250 sol.
		62,770	8.115	266–360 liq.
Mercury	Hg	73,000	10.383	−80 to −38.87 sol.
		58,700	7.752	400–1300 liq.
Molybdenum	Mo	680,000	10.844	1800–2240 sol.
Nitrogen	N_2	6881.3	7.66558	−215 to −210 sol.
Nitrogen dioxide	NO	16,423	10.048	−200 to −161 sol.
		13,040	8.440	−163.7 to −148 liq.
Nitrogen monoxide	N_2O	23,590	9.579	−144 to −90 sol.
		16,440	7.535	−90.1 to −88.7 liq.
Nitrogen pentoxide	N_2O_5	57,180	12.647	−30 to 30 sol.

(*Continued*)

TABLE 2.27 (*Continued*) Vapor Pressure of Elements and Inorganic Compounds[a]

Compound	Formula	*a*	*b*	Temperature Range of Validity (°C)
Nitrogen tetroxide	N_2O_4	55,160	13.400	−100 to −40 sol.
		45,440	11.214	−40 to −10 sol.
		33,430	8.814	−8 to 43.2 liq.
Nitrogen trioxide	N_2O_3	39,400	10.30	−25 to 0 liq.
Phosphorus (white)	P	63,123	9.6511	20–44.1 sol.
Phosphorus (violet)	P	108,510	11.0842	380–590 sol.
Platinum	Pt	486,000	7.786	1425–1765 sol.
Potassium	K	84,900	7.183	260–760 liq.
Potassium bromide	KBr	168,100	8.2470	906–1063 liq.
		163,800	7.936	1095–1375 liq.
Potassium chloride	KCl	174,500	8.3526	906–1105 liq.
		169,700	8.130	1116–1428 liq.
Potassium fluoride	KF	207,500	9.000	1278–1500 liq.
Potassium hydroxide	KOH	136,000	7.330	1170–1327 liq.
Potassium iodide	KI	157,600	8.0957	843–1028 liq.
		155,700	7.949	1063–1333 liq.
Rubidium	Rb	76,000	6.976	250–370 liq.
Rubidium chloride	RbCl	198,600	9.111	1142–1395 liq.
Silicon	Si	170,000	5.950	1200–1320 sol.
Silicon dioxide	SiO_2	506,000	13.43	1860–2230 liq.
Silver	Ag	250,000	8.762	1650–1950 liq.
Silver chloride	AgCl	185,500	8.179	1255–1442 liq.
Sodium	Na	103,300	7.553	180–883 liq.
Sodium bromide	NaBr	161,600	7.948	1138–1394 liq.
Sodium chloride	NaCl	180,300	8.3297	976–1155 liq.
		185,800	8.548	1156–1430 liq.
Sodium cyanide	NaCN	155,520	7.472	800–1360 liq.
Sodium fluoride	NaF	218,200	8.640	1562–1701 liq.
Sodium hydroxide	NaOH	132,000	7.030	1010–1042 liq.
Sodium iodide	NaI	165,100	8.371	1063–1307 liq.
Stannic chloride	$SnCl_4$	46,740	9.824	−52 to −38 liq.
Strontium	Sr	360,000	16.056	940–1140 liq.
Sulfur dioxide	SO_2	35,827	10.5916	−95 to −75 liq.
Sulfur trioxide	SO_3	43,450	10.022	24–48 liq.
Thallium	Tl	120,000	6.140	950–1200 liq.
Thallium chloride	TlCl	105,200	7.947	665–807 liq.
Tin	Sn	328,000	9.643	1950–2270 liq.
Tungsten	W	897,000	9.920	2230–2770 liq.
Zinc	Zn	133,000	9.200	250–491.4 sol.
		118,000	8.108	600–985 liq.

Source: Data compiled by J.S. Park from *CRC Handbook of Chemistry and Physics*, 71st Edn., D. R. Lide, (Ed.), CRC Press, Boca Raton, FL, 1990.

[a] The vapor pressure with respect to temperature may be represented by the following equation:

$$\log_{10} p = -0.05223a/T + b$$

where p is the pressure in mm of mercury of the saturated vapor at the absolute temperature T ($T = t$°C + 273.1). The values obtained by the use of the equation given above are valid within the temperature ranges indicated for each of the compounds.

3

Glasses

Physical Properties

TABLE 3.1 Density of Glasses

Class	Glass	Density (Mg/m^3)	Temperature Range of Validity
SiO_2 glass		2.201–2.211	Room temp.
	Stabilized	2.1977	Room temp.
	~1% wt. impurity	2.094	1935°C
	~1% wt. impurity	2.072	2048°C
	~1% wt. impurity	2.057	2114°C
	~1% wt. impurity	2.045	2165°C
	~1% wt. impurity	1.929	2322°C
	1300°C for 1 h then 1000°C for 70 h	2.201	
	1300°C for 1 h then 1100°C for 22 h	2.198	
	1300°C for 1 h then 1200°C for 7 h	2.201	
	1300°C for 1 h then 1400°C for 5 min	2.201	
SiO_2–Na_2O glass	5% wt. Na_2O	2.240	20°C
	10% wt. Na_2O	2.291	20°C
	14.86% wt. Na_2O	2.334	20°C
	19.55% wt. Na_2O	2.383	20°C
	25% wt. Na_2O	2.431	20°C
	29.20% wt. Na_2O	2.459	20°C
	35.25% wt. Na_2O	2.498	20°C
	39.66% wt. Na_2O	2.521	20°C
	49.20% wt. Na_2O	2.563	20°C
	20.1% wt. Na_2O	2.270	987°C
	20.1% wt. Na_2O	2.240	1249°C
	20.1% wt. Na_2O	2.220	1388°C
	30.1% wt. Na_2O	2.270	1004°C
	30.1% wt. Na_2O	2.230	1252°C
	30.1% wt. Na_2O	2.205	1400°C
	45.6% wt. Na_2O	2.260	1044°C
	45.6% wt. Na_2O	2.225	1243°C
	45.6% wt. Na_2O	2.190	1413°C
	50.2% wt. Na_2O	2.250	1075°C

(*Continued*)

TABLE 3.1 (*Continued*) Density of Glasses

Class	Glass	Density (Mg/m³)	Temperature Range of Validity
	50.2% wt. Na_2O	2.215	1259°C
	50.2% wt. Na_2O	2.180	1421°C
	55.4% wt. Na_2O	2.245	1105°C
	55.4% wt. Na_2O	2.205	1258°C
	55.4% wt. Na_2O	2.165	1412°C
	60.9% wt. Na_2O	2.250	1052°C
	60.9% wt. Na_2O	2.190	1243°C
	60.9% wt. Na_2O	2.145	1413°C
SiO_2–CaO glass	30% mol CaO	2.466	1700°C
	35% mol CaO	2.475	1700°C
	39.0% mol CaO	2.746	20°C
	40% mol CaO	2.542	1700°C
	42.5% mol CaO	2.555–2.568	1700°C
	44.6% mol CaO	2.835	20°C
	45% mol CaO	2.590–2.618	1700°C
	47.5% mol CaO	2.602–2.604	1700°C
	50.0% mol CaO	2.898	20°C
	50% mol CaO	2.615–2.617	1700°C
	52.5% mol CaO	2.612–2.640	1700°C
	52.9% mol CaO	2.918	20°C
	57.5% mol CaO	2.953	20°C
	57.5% mol CaO	2.641–2.644	1700°C
	60% mol CaO	2.661	1700°C
SiO_2–PbO glass	20.78% mol PbO	3.6711	Room temp.
	24.90% mol PbO	3.9606	Room temp.
	29.71% mol PbO	4.3558	Room temp.
	34.66% mol PbO	4.7437	Room temp.
	35.0% mol PbO	5.10	1270 K
	40.2% mol PbO	5.15	1270 K
	40.80% mol PbO	5.2543	Room temp.
	44.7% mol PbO	5.45	1270 K
	45.56% mol PbO	5.6416	Room temp.
	49.5% mol PbO	5.85	1270 K
	50.50% mol PbO	6.0473	Room temp.
	52.7% mol PbO	5.90	1270 K
	54.45% mol PbO	6.3322	Room temp.
	58.0% mol PbO	6.05	1270 K
	59.39% mol PbO	6.6894	Room temp.
	65.97% mol PbO	7.0810	Room temp.
	66.7% mol PbO	6.20	1270 K
	73.0% mol PbO	6.42	1270 K
	80.0% mol PbO	6.70	1270 K
	84.9% mol PbO	7.03	1270 K
	89.0% mol PbO	7.05	1270 K
	94.2% mol PbO	7.45	1270 K

(*Continued*)

TABLE 3.1 (*Continued*) Density of Glasses

Class	Glass	Density (Mg/m^3)	Temperature Range of Validity
SiO_2–Al_2O_3 glass	0.04% wt. Al_2O_3 for quintus quartz glass	2.2000	Room temp.
	0.10% wt. Al_2O_3 for Cab–O–Sil glass	2.2025	Room temp.
	0.37% wt. Al_2O_3 for IR vitreosil glass	2.2043	Room temp.
	0.38% wt. Al_2O_3 for Cab–O–Sil glass	2.1977	Room temp.
	0.38% wt. Al_2O_3 for quintus quartz glass	2.1982	Room temp.
	0.41% wt. Al_2O_3 for Cab–O–Sil glass	2.2047	Room temp.
	0.47% wt. Al_2O_3 for quintus quartz glass	2.2048	Room temp.
	0.64% wt. Al_2O_3 for I.R. vitreosil glass	2.2006	Room temp.
	0.77% wt. Al_2O_3 for quintus quartz glass	2.2027	Room temp.
	1.22% wt. Al_2O_3 for Cab–O–Sil glass	2.2095	Room temp.
	1.29% wt. Al_2O_3 for I.R. vitreosil glass	2.2072	Room temp.
	2.30% wt. Al_2O_3 for I.R. vitreosil glass	2.2081	Room temp.
	2.34% wt. Al_2O_3 for quintus quartz glass	2.1994	Room temp.
	2.70% wt. Al_2O_3 for Cab–O–Sil glass	2.2031	Room temp.
	5.22% wt. Al_2O_3 for quintus quartz glass	2.2118	Room temp.
	14.82% mol Al_2O_3	2.319	1707°C
	14.82% mol Al_2O_3	2.320	1813°C
	14.82% mol Al_2O_3	2.313	1907°C
	14.82% mol Al_2O_3	2.302	2008°C
	30.08% mol Al_2O_3	2.475	1758°C
	30.08% mol Al_2O_3	2.460	1858°C
	30.08% mol Al_2O_3	2.448	1909°C
	30.08% mol Al_2O_3	2.446	1975°C
	46.92% mol Al_2O_3	2.736	1755°C
	46.92% mol Al_2O_3	2.724	1803°C
	46.92% mol Al_2O_3	2.627	1859°C
	46.92% mol Al_2O_3	2.625	1910°C
	46.92% mol Al_2O_3	2.612	1959°C
	70.21% mol Al_2O_3	2.811	1966°C
	70.21% mol Al_2O_3	2.791	1995°C
SiO_2–B_2O_3 glass	35.1% mol B_2O_3	2.0436	25°C
	39.2% mol B_2O_3	2.0224	25°C
	44.2% mol B_2O_3	2.0031	25°C
	50.8% mol B_2O_3	1.9865	25°C
	53.10% mol B_2O_3	$1.892–0.0634 \times 10^{-3}$ T	1653 K < T < 1803 K
	58.4% mol B_2O_3	1.9608	25°C
	62.40% mol B_2O_3	$1.812–0.0475 \times 10^{-3}$ T	1553 K < T < 1733 K
	71.90% mol B_2O_3	$1.785–0.0705 \times 10^{-3}$ T	1303 K < T < 1683 K
	72.7% mol B_2O_3	1.9135	25°C
	82.50% mol B_2O_3	$1.737–0.0798 \times 10^{-3}$ T	1203 K < T < 1633 K
	83.2% mol B_2O_3	1.8838	25°C
	88.6% mol B_2O_3	1.8682	25°C

(*Continued*)

TABLE 3.1 (*Continued*) Density of Glasses

Class	Glass	Density (Mg/m^3)	Temperature Range of Validity
	90.00% mol B_2O_3	$1.680–0.0806 \times 10^{-3}$ T	1203 K < T < 1633 K
	92.6% mol B_2O_3	1.8599	25°C
	93.91% mol B_2O_3	$1.661–0.0825 \times 10^{-3}$ T	1243 K < T < 1623 K
	100% mol B_2O_3	1.8453	25°C
B_2O_3 glass		1.844–1.859	25°C
		1.693	411°C
		1.671	450°C
		1.648	500°C
		1.626	550°C
		1.609	600°C
		1.580	700°C
		1.559	800°C
		1.541	900°C
		1.528	1000°C
		1.518	1100°C
		1.509	1200°C
		1.503	1300°C
		1.498	1400°C
B_2O_3–CaO glass	28.8% mol CaO	2.475–2.483	25°C
	31.2% mol CaO	2.519–2.526	25°C
	31.2% mol CaO	2.334–2.341	900°C
	31.2% mol CaO	2.279–2.288	1000°C
	31.2% mol CaO	2.229–2.231	1100°C
	31.2% mol CaO	2.174	1200°C
	34.7% mol CaO	2.583–2.590	25°C
	34.7% mol CaO	2.309	1056°C
	34.7% mol CaO	2.280	1105°C
	37.1% mol CaO	2.622–2.629	25°C
	37.1% mol CaO	2.306	1105°C
	37.1% mol CaO	2.282	1153°C
	37.1% mol CaO	2.259	1200°C
	42.5% mol CaO	2.349	1145°C
	42.5% mol CaO	2.328	1193°C
	45.7% mol CaO	2.403	1106°C
	45.7% mol CaO	2.379	1156°C
	45.7% mol CaO	2.359	1207°C
	50.3% mol CaO	2.417	1156°C
	50.3% mol CaO	2.398	1199°C
B_2O_3–Na_2O glass	3% mol Na_2O	1.608	920°C
	3% mol Na_2O	1.601	1000°C
	3% mol Na_2O	1.587	1091°C
	6% mol Na_2O	1.705	907°C
	6% mol Na_2O	1.691	1000°C
	6% mol Na_2O	1.660	1141°C
	8.21% mol Na_2O	2.0112	Room temp.
	9% mol Na_2O	1.794	890°C

(*Continued*)

TABLE 3.1 (*Continued*) Density of Glasses

Class	Glass	Density (Mg/m^3)	Temperature Range of Validity
	9% mol Na_2O	1.773	1000°C
	9% mol Na_2O	1.740	1109°C
	10.33% mol Na_2O	2.0466	Room temp.
	12% mol Na_2O	1.872	901°C
	12% mol Na_2O	1.842	1000°C
	12% mol Na_2O	1.808	1106°C
	12.03% mol Na_2O	2.0752	Room temp.
	14.12% mol Na_2O	2.1053	Room temp.
	15% mol Na_2O	1.907	934°C
	15% mol Na_2O	1.886	1000°C
	15% mol Na_2O	1.848	1131°C
	16.34% mol Na_2O	2.0466	Room temp.
	18% mol Na_2O	1.976	882°C
	18% mol Na_2O	1.935	1000°C
	18% mol Na_2O	1.904	1097°C
	18.16% mol Na_2O	2.0752	Room temp.
	20.23% mol Na_2O	2.1053	Room temp.
	21% mol Na_2O	2.009	910°C
	21% mol Na_2O	1.971	1000°C
	21% mol Na_2O	1.921	1136°C
	22.07% mol Na_2O	2.2146	Room temp.
	24% mol Na_2O	2.054	891°C
	24% mol Na_2O	2.000	1000°C
	24% mol Na_2O	1.958	1106°C
	24.33% mol Na_2O	2.2493	Room temp.
	26.18% mol Na_2O	2.2835	Room temp.
	27% mol Na_2O	2.043	945°C
	27% mol Na_2O	1.992	1077°C
	27% mol Na_2O	1.954	1170°C
	28.17% mol Na_2O	2.3141	Room temp.
	30% mol Na_2O	2.059	916°C
	30% mol Na_2O	2.018	1000°C
	30% mol Na_2O	1.960	1094°C
	30.68% mol Na_2O	2.3488	Room temp.
	32.05% mol Na_2O	2.3591	Room temp.
	33% mol Na_2O	2.055	909°C
	33% mol Na_2O	2.008	1000°C
	33% mol Na_2O	1.963	1076°C
	34.20% mol Na_2O	2.3755	Room temp.
	36% mol Na_2O	2.075	885°C
	36% mol Na_2O	1.998	1000°C
	36% mol Na_2O	1.944	1081°C
	36% mol Na_2O	1.944	1081°C

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B,* O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.2 Thermal Conductivity of Glasses

Glass	Description	Thermal Conductivity	Units	Temperature Range of Validity
SiO_2 glass		0.00329	cal/cm s K	20°C
		0.59	W/m K	80°C
		0.67	W/m K	100°C
		0.88	W/m K	150°C
		1.10	W/m K	200°C
		1.28	W/m K	250°C
		1.32	W/m K	273.1°C
		1.36	W/m K	300°C
		1.43	W/m K	350°C
		1.50	W/m K	400°C
		1.62	W/m K	500°C
		1.72	W/m K	600°C
		1.80	W/m K	700°C
SiO_2–Na_2O glass	22% mol Na_2O	0.70	kcal/m h K	450°C
	22% mol Na_2O	0.90	kcal/m h K	850°C
	22% mol Na_2O	1.20	kcal/m h K	1050°C
	22% mol Na_2O	1.55	kcal/m h K	1250°C
	22% mol Na_2O	2.25	kcal/m h K	1500°C
	25% mol Na_2O	0.15	W/m K	35 K
	25% mol Na_2O	0.25	W/m K	60 K
	25% mol Na_2O	0.40	W/m K	80 K
	25% mol Na_2O	0.50	W/m K	100 K
	25% mol Na_2O	0.60	W/m K	140 K
	25% mol Na_2O	0.65	W/m K	150 K
	25% mol Na_2O	0.80	W/m K	190 K
	25% mol Na_2O	0.85	W/m K	240 K
	25% mol Na_2O	0.90	W/m K	280 K
	25% mol Na_2O	0.95	W/m K	300 K
	27% mol Na_2O	0.68	kcal/m h K	450°C
	27% mol Na_2O	0.85	kcal/m h K	850°C
	27% mol Na_2O	1.10	kcal/m h K	1050°C
	27% mol Na_2O	1.45	kcal/m h K	1250°C
	27% mol Na_2O	1.80	kcal/m h K	1500°C
	34.05% mol Na_2O	0.5	kcal/m h K	450°C
	34.05% mol Na_2O	0.75	kcal/m h K	850°C
	34.05% mol Na_2O	0.75	kcal/m h K	1050°C
	34.05% mol Na_2O	1.20	kcal/m h K	1250°C
	34.05% mol Na_2O	1.5	kcal/m h K	1500°C

(*Continued*)

TABLE 3.2 (*Continued*) Thermal Conductivity of Glasses

Glass	Description	Thermal Conductivity	Units	Temperature Range of Validity
SiO_2–PbO glass	51.9% mol PbO	0.00089	cal/cm s K	–150°C
	51.9% mol PbO	0.00100	cal/cm s K	–100°C
	51.9% mol PbO	0.00111	cal/cm s K	–50°C
	51.9% mol PbO	0.00123	cal/cm s K	0°C
	51.9% mol PbO	0.00134	cal/cm s K	50°C
	51.9% mol PbO	0.00146	cal/cm s K	100°C
	49.3% mol PbO	0.00130	cal/cm s K	40°C
	66.2% mol PbO	0.00112	cal/cm s K	40°C
B_2O_3 glass		0.5	mW/cm K	2 K
		0.75	mW/cm K	5 K
		1.5	mW/cm K	20 K
B_2O_3–Na_2O glass	3% mol Na_2O	1.7 + 0.0054 (T-900)	W/m K	1173–1373 K
	7% mol Na_2O	1.5 + 0.0045 (T-900)	W/m K	1173–1373 K
	11% mol Na_2O	1.25 + 0.0037 (T-900)	W/m K	1173–1373 K
	14% mol Na_2O	1.15 + 0.0020 (T-900)	W/m K	1173–1373 K
	19% mol Na_2O	1.0 + 0.0012 (T-900)	W/m K	1173–1373 K
	25% mol Na_2O	0.85 + 0.00075 (T-900)	W/m K	1173–1373 K
	31% mol Na_2O	0.9 + 0.00080 (T-900)	W/m K	1173–1373 K
B_2O_3–PbO glass	27.6% mol PbO	0.522 ± 0.022	W/m K	30°C
	31.9% mol PbO	0.483 ± 0.016	W/m K	30°C
	36.7% mol PbO	0.464 ± 0.010	W/m K	30°C
	42.1% mol PbO	0.433 ± 0.018	W/m K	30°C
	48.3% mol PbO	0.406 ± 0.020	W/m K	30°C
	55.5% mol PbO	0.381 ± 0.015	W/m K	30°C
	64.0% mol PbO	0.351 ± 0.011	W/m K	30°C

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.3 Thermal Expansion of Glasses

Glass	Composition	Thermal Expansion (/K)	Temperature Range of Validity
SiO_2 glass	Pure	3.50×10^{-7}	−60–20°C
		3.80×10^{-7}	−40–20°C
		4.00×10^{-7}	−20–20°C
		4.30×10^{-7}	0–20°C
		5.35×10^{-7}	20–100°C
		5.75×10^{-7}	20–150°C
		5.85×10^{-7}	20–200°C
		5.92×10^{-7}	20–250°C
		5.94×10^{-7}	20–300°C
		5.90×10^{-7}	20–350°C
SiO_2–B_2O_3 glass	39.2% mol B_2O_3	47.5×10^{-7}	0–100°C
	39.2% mol B_2O_3	44.9×10^{-7}	100–200°C
	39.2% mol B_2O_3	301×10^{-7}	390–410°C
	44.2% mol B_2O_3	49.8×10^{-7}	0–100°C
	44.2% mol B_2O_3	50.8×10^{-7}	100–200°C
	44.2% mol B_2O_3	450×10^{-7}	380–400°C
	50.8% mol B_2O_3	57.6×10^{-7}	0–100°C
	50.8% mol B_2O_3	54.8×10^{-7}	100–200°C
	50.8% mol B_2O_3	579×10^{-7}	350–370°C
	58.4% mol B_2O_3	71.9×10^{-7}	0–100°C
	58.4% mol B_2O_3	70.1×10^{-7}	100–200°C
	58.4% mol B_2O_3	694×10^{-7}	320–340°C
	72.7% mol B_2O_3	87.0×10^{-7}	0–100°C
	72.7% mol B_2O_3	89.7×10^{-7}	100–200°C
	72.7% mol B_2O_3	899×10^{-7}	300–320°C
	83.2% mol B_2O_3	111.4×10^{-7}	0–100°C
	83.2% mol B_2O_3	116.6×10^{-7}	100–200°C
	83.2% mol B_2O_3	970×10^{-7}	280–300°C
	88.6% mol B_2O_3	118.1×10^{-7}	0–100°C
	88.6% mol B_2O_3	126.0×10^{-7}	100–200°C
	88.6% mol B_2O_3	1023×10^{-7}	280–300°C
	94.0% mol B_2O_3	131.7×10^{-7}	0–100°C
	94.0% mol B_2O_3	141.9×10^{-7}	100–200°C
	94.0% mol B_2O_3	1200×10^{-7}	270–290°C
SiO_2–Al_2O_3 glass	13.9% mol Al_2O_3, 1000°C for 115 h	22.7×10^{-7}	20–900°C
	13.9% mol Al_2O_3, water quenching	17.2×10^{-7}	20–600°C
	17.4% mol Al_2O_3, 1000°C for 115 h	28.3×10^{-7}	20–800°C
	17.4% mol Al_2O_3, water quenching	20.7×10^{-7}	20–700°C
	3.1% mol Al_2O_3, 1000°C for 115 h	6.2×10^{-7}	20–980°C
	3.1% mol Al_2O_3, water quenching	6.2×10^{-7}	20–980°C
	5.4% mol Al_2O_3, 1130°C for 20 h	12.2×10^{-7}	20–350°C

(*Continued*)

TABLE 3.3 (*Continued*) Thermal Expansion of Glasses

Glass	Composition	Thermal Expansion (/K)	Temperature Range of Validity
	8.2% mol Al_2O_3, 1000°C for 115 h	14.5×10^{-7}	20–950°C
	8.2% mol Al_2O_3, water quenching	8.8×10^{-7}	20–800°C
SiO_2–CaO glass	30% mol CaO	$66 \pm 5 \times 10^{-6}$	1700°C
	35% mol CaO	$53 \pm 5 \times 10^{-6}$	1700°C
	40% mol CaO	$64 \pm 4 \times 10^{-6}$	1700°C
	42.5% mol CaO	$76 \pm 4 \times 10^{-6}$	1700°C
	45% mol CaO	$85–100 \pm 4 \times 10^{-6}$	1700°C
	47.5% mol CaO	$76 \pm 4 \times 10^{-6}$	1700°C
	50% mol CaO	$84–85 \pm 4 \times 10^{-6}$	1700°C
	52.5% mol CaO	$76–107 \pm 4 \times 10^{-6}$	1700°C
	55% mol CaO	$94–95 \pm 4 \times 10^{-6}$	1700°C
	57.5% mol CaO	$95 \pm 4 \times 10^{-6}$	1700°C
	60% mol CaO	$103 \pm 4 \times 10^{-6}$	1700°C
SiO_2–PbO glass	25.7% mol PbO	$51.45–52.23 \times 10^{-7}$	20–170°C
	30.0% mol PbO	$57.68–59.08 \times 10^{-7}$	20–170°C
	32.5% mol PbO	$60.62–62.31 \times 10^{-7}$	20–170°C
	33.2% mol PbO	$61.58–63.33 \times 10^{-7}$	20–170°C
	35.0% mol PbO	$63.99–66.17 \times 10^{-7}$	20–170°C
	37.5% mol PbO	$68.75–71.44 \times 10^{-7}$	20–170°C
	42.6% mol PbO	$75.16–78.58 \times 10^{-7}$	20–170°C
	45.8% mol PbO	$78.85–82.60 \times 10^{-7}$	20–170°C
	47.8% mol PbO	$83.03–87.03 \times 10^{-7}$	20–170°C
	49.8% mol PbO	$85.57–89.82 \times 10^{-7}$	20–170°C
	50% mol PbO	723×10^{-7}	1100°C
	53.8% mol PbO	$90.62–95.25 \times 10^{-7}$	20–170°C
	57.5% mol PbO	$95.64–100.45 \times 10^{-7}$	20–170°C
	59.0% mol PbO	$97.00–101.90 \times 10^{-7}$	20–170°C
	61.0% mol PbO	$100.66–105.58 \times 10^{-7}$	20–170°C
	61.75% mol PbO	$101.36–106.30 \times 10^{-7}$	20–170°C
	66.7% mol PbO	867×10^{-7}	1100°C
	67.7% mol PbO	$110.38–115.48 \times 10^{-7}$	20–170°C
SiO_2–Na_2O glass	20% mol Na_2O	6.7×10^{-5}	Liquidus temp. to 1400°C
	20% mol Na_2O, $T_g = 478$°C	120×10^{-7}	Below T_g
	20% mol Na_2O, $T_g = 478$°C	315×10^{-7}	Above T_g
	20.3% mol Na_2O	97.5×10^{-7}	Room temp. to 100°C
	20.3% mol Na_2O	99.3×10^{-7}	100–200°C
	20.3% mol Na_2O	100.6×10^{-7}	200–300°C
	20.3% mol Na_2O	106.9×10^{-7}	300–400°C
	24.0% mol Na_2O	109.7×10^{-7}	Room temp. to 100°C
	24.0% mol Na_2O	114.3×10^{-7}	100–200°C

(*Continued*)

TABLE 3.3 (*Continued*) Thermal Expansion of Glasses

Glass	Composition	Thermal Expansion (/K)	Temperature Range of Validity
	24.0% mol Na_2O	116.6×10^{-7}	200–300°C
	24.0% mol Na_2O	121.7×10^{-7}	300–400°C
	30% mol Na_2O, $T_g = 455$°C	152×10^{-7}	Below T_g
	30% mol Na_2O, $T_g = 455$°C	402×10^{-7}	Bbove T_g
	31.1% mol Na_2O	136.0×10^{-7}	Room temp. to 100°C
	31.1% mol Na_2O	142.5×10^{-7}	100–200°C
	31.1% mol Na_2O	148.3×10^{-7}	200–300°C
	31.1% mol Na_2O	160.0×10^{-7}	300–400°C
	33% mol Na_2O, $T_g = 445$°C	165×10^{-7}	Below T_g
	33% mol Na_2O, $T_g = 445$°C	465×10^{-7}	Above T_g
	33.3% mol Na_2O	17.2×10^{-5}	Liquidus temp. to 1400°C
	33.8% mol Na_2O	143.9×10^{-7}	Room temp. to 100°C
	33.8% mol Na_2O	153.6×10^{-7}	100–200°C
	33.8% mol Na_2O	159.1×10^{-7}	200–300°C
	33.8% mol Na_2O	173.6×10^{-7}	300–400°C
	37.2% mol Na_2O	152.1×10^{-7}	Room temp. to 100°C
	37.2% mol Na_2O	160.9×10^{-7}	100–200°C
	37.2% mol Na_2O	171.6×10^{-7}	200–300°C
	37.2% mol Na_2O	187.7×10^{-7}	300–400°C
	40% mol Na_2O	20.0×10^{-5}	Liquidus temp. to 1400°C
	40% mol Na_2O, $T_g = 421$°C	179×10^{-7}	Below T_g
	40% mol Na_2O, $T_g = 421$°C	500×10^{-7}	Above T_g
	45% mol Na_2O, $T_g = 417$°C	219×10^{-7}	Below T_g
	45% mol Na_2O, $T_g = 417$°C	574×10^{-7}	Above T_g
	50% mol Na_2O	23.7×10^{-5}	Liquidus temp. to 1400°C
B_2O_3 glass		$154.5–183 \times 10^{-7}$	0–100°C
		$154.5–169 \times 10^{-7}$	100–200°C
		$150 \pm 3–158 \pm 3 \times 10^{-7}$	20–200°C
B_2O_3–Na_2O glass	0.01% mol Na_2O	140×10^{-7}	–196–25°C
	0.01% mol Na_2O	149.3×10^{-7}	20–50°C
	0.01% mol Na_2O	149.0×10^{-7}	20–150°C
	4.4% mol Na_2O	94.6×10^{-7}	–196–25°C
	4.4% mol Na_2O	103.0×10^{-7}	20–50°C
	4.4% mol Na_2O	109.9×10^{-7}	20–150°C
	4.4% mol Na_2O	116.0×10^{-7}	20–250°C
	5% mol Na_2O, $T_g = 318$°C	115×10^{-7}	Below T_g
	5% mol Na_2O, $T_g = 318$°C	1400×10^{-7}	Above T_g
	8.7% mol Na_2O	98.8×10^{-7}	20–50°C
	8.7% mol Na_2O	100.5×10^{-7}	20–150°C
	8.7% mol Na_2O	105.3×10^{-7}	20–250°C

(*Continued*)

TABLE 3.3 (*Continued*) Thermal Expansion of Glasses

Glass	Composition	Thermal Expansion (/K)	Temperature Range of Validity
	10% mol Na_2O, T_g = 354°C	77×10^{-7}	Below T_g
	10% mol Na_2O, T_g = 354°C	1230×10^{-7}	Above T_g
	11.5% mol Na_2O	71.5×10^{-7}	–196–25°C
	11.5% mol Na_2O	88.7×10^{-7}	20–50°C
	11.5% mol Na_2O	94.9×10^{-7}	20–150°C
	11.5% mol Na_2O	97.9×10^{-7}	20–250°C
	13.7% mol Na_2O	69.3×10^{-7}	–196–25°C
	13.7% mol Na_2O	87.5×10^{-7}	20–50°C
	13.7% mol Na_2O	92.3×10^{-7}	20–150°C
	13.7% mol Na_2O	90.9×10^{-7}	20–250°C
	15% mol Na_2O, T_g = 407°C	69×10^{-7}	Below T_g
	15% mol Na_2O, T_g = 407°C	761×10^{-7}	Above T_g
	15.8% mol Na_2O	67.4×10^{-7}	–196–25°C
	15.8% mol Na_2O	80.7×10^{-7}	20–50°C
	15.8% mol Na_2O	87.8×10^{-7}	20–150°C
	15.8% mol Na_2O	93.3×10^{-7}	20–250°C
	15.8% mol Na_2O	97.9×10^{-7}	20–350°C
	16.2% mol Na_2O	65.9×10^{-7}	–196–25°C
	16.2% mol Na_2O	86.0×10^{-7}	20–50°C
	16.2% mol Na_2O	87.7×10^{-7}	20–150°C
	16.2% mol Na_2O	90.9×10^{-7}	20–250°C
	16.2% mol Na_2O	96.9×10^{-7}	20–350°C
	17.4% mol Na_2O	85.6×10^{-7}	20–50°C
	17.4% mol Na_2O	89.1×10^{-7}	20–150°C
	17.4% mol Na_2O	92.4×10^{-7}	20–250°C
	17.4% mol Na_2O	96.3×10^{-7}	20–350°C
	18.4% mol Na_2O	69.1×10^{-7}	–196–25°C
	18.4% mol Na_2O	86.2×10^{-7}	20–50°C
	18.4% mol Na_2O	89.2×10^{-7}	20–150°C
	18.4% mol Na_2O	94.1×10^{-7}	20–250°C
	18.4% mol Na_2O	96.2×10^{-7}	20–350°C
	19.6% mol Na_2O	86.8×10^{-7}	20–50°C
	19.6% mol Na_2O	91.2×10^{-7}	20–150°C
	19.6% mol Na_2O	95.3×10^{-7}	20–250°C
	19.6% mol Na_2O	99.6×10^{-7}	20–350°C
	20.0% mol Na_2O	87.6×10^{-7}	20–50°C
	20.0% mol Na_2O	91.6×10^{-7}	20–150°C
	20.0% mol Na_2O	97.6×10^{-7}	20–250°C
	20.0% mol Na_2O	101.3×10^{-7}	20–350°C
	20% mol Na_2O, T_g = 456°C	86×10^{-7}	Below T_g
	20% mol Na_2O, T_g = 456°C	586×10^{-7}	Above T_g

(*Continued*)

TABLE 3.3 (*Continued*) Thermal Expansion of Glasses

Glass	Composition	Thermal Expansion (/K)	Temperature Range of Validity
	22.5% mol Na_2O	71.9×10^{-7}	–196–25°C
	22.5% mol Na_2O	90.4×10^{-7}	20–50°C
	22.5% mol Na_2O	94.7×10^{-7}	20–150°C
	22.5% mol Na_2O	98.7×10^{-7}	20–250°C
	22.5% mol Na_2O	104.0×10^{-7}	20–350°C
	23.6% mol Na_2O	90.4×10^{-7}	20–50°C
	23.6% mol Na_2O	96.7×10^{-7}	20–150°C
	23.6% mol Na_2O	101.2×10^{-7}	20–250°C
	23.6% mol Na_2O	106.5×10^{-7}	20–350°C
	25% mol Na_2O, $T_g = 466°C$	95×10^{-7}	Below T_g
	25% mol Na_2O, $T_g = 466°C$	834×10^{-7}	Above T_g
	28.9% mol Na_2O	81.4×10^{-7}	–196–25°C
	28.9% mol Na_2O	102.1×10^{-7}	20–50°C
	28.9% mol Na_2O	107.4×10^{-7}	20–150°C
	28.9% mol Na_2O	112.8×10^{-7}	20–250°C
	28.9% mol Na_2O	117.1×10^{-7}	20–350°C
	30% mol Na_2O, $T_g = 468°C$	128×10^{-7}	Below T_g
	30% mol Na_2O, $T_g = 468°C$	1150×10^{-7}	Above T_g
B_2O_3–CaO glass	29.3% mol CaO	$54.9–56.4 \times 10^{-7}$	Room temp. to 100°C
	29.3% mol CaO	$60.2–60.8 \times 10^{-7}$	100–200°C
	29.3% mol CaO	$63.9–65.4 \times 10^{-7}$	200–300°C
	29.3% mol CaO	$71.3–71.6 \times 10^{-7}$	300–400°C
	29.3% mol CaO	$76.9–77.1 \times 10^{-7}$	400–500°C
	29.3% mol CaO	$80.9–86.8 \times 10^{-7}$	500–600°C
	31.4% mol CaO	$57.3–58.2 \times 10^{-7}$	Room temp. to 100°C
	31.4% mol CaO	$63.5–65.1 \times 10^{-7}$	100–200°C
	31.4% mol CaO	$67.4–68.1 \times 10^{-7}$	200–300°C
	31.4% mol CaO	$76.5–76.7 \times 10^{-7}$	300–400°C
	31.4% mol CaO	$79.2–81.0 \times 10^{-7}$	400–500°C
	31.4% mol CaO	$83.1–88.5 \times 10^{-7}$	500–600°C
	34.9% mol CaO	$60.1–66.2 \times 10^{-7}$	Room temp. to 100°C
	34.9% mol CaO	$67.5–67.6 \times 10^{-7}$	100–200°C
	34.9% mol CaO	$74.7–75.2 \times 10^{-7}$	200–300°C
	34.9% mol CaO	$77.8–78.5 \times 10^{-7}$	300–400°C
	34.9% mol CaO	$83.8–95.0 \times 10^{-7}$	400–500°C
	34.9% mol CaO	$91.8–92.1 \times 10^{-7}$	500–600°C
	37.1% mol CaO	$63.1–64.0 \times 10^{-7}$	Room temp. to 100°C
	37.1% mol CaO	$68.4–70.4 \times 10^{-7}$	100–200°C

(*Continued*)

TABLE 3.3 (*Continued*) Thermal Expansion of Glasses

Glass	Composition	Thermal Expansion (/K)	Temperature Range of Validity
	37.1% mol CaO	$74.6–75.8 \times 10^{-7}$	200–300°C
	37.1% mol CaO	$81.6–82.2 \times 10^{-7}$	300–400°C
	37.1% mol CaO	$86.9–87.6 \times 10^{-7}$	400–500°C
	37.1% mol CaO	$93.5–95.5 \times 10^{-7}$	500–600°C

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.4 Tensile Strength of Glass

Type	Glass	Tensile Strength (kg/mm²)	Temperature (°C)
SiO_2 glass	48 µm diameter fiber	49.6	
	56 µm diameter fiber	44.3	
	60 µm diameter fiber	42.3	
	65 µm diameter fiber	39.7	
	74 µm diameter fiber	36.5	
	78 µm diameter fiber	35.8	
	108 µm diameter fiber	28.8	
	112 µm diameter fiber	28.3	
	1.5 mm diameter rod, 0.5 g/mm² · s stress rate	5.84–7.08	
	1.5 mm diameter rod, 50 g/mm² · s stress rate	9.73 ± 2.13	
	1.5 mm diameter rod, 54 g/mm² · s stress rate	8.52 ± 2.52	
	Corning 7940 silica glass	5.6	100
	Corning 7940 silica glass	6.2	300
	Corning 7940 silica glass	6.6	500
	Corning 7940 silica glass	7.1	700
	Corning 7940 silica glass	7.6	900
SiO_2–Na_2O glass	6.0 µm diameter fiber, 19.5% mol Na_2O	173 ± 1.36	
	8.6 µm diameter fiber, 19.5% mol Na_2O	134 ± 1.34	
	25.7 µm diameter fiber, 19.5% mol Na_2O	92.5 ± 10.08	
	5 mm diameter rod, 20% mol Na_2O	15	
	3.6 µm diameter fiber, 25.5% mol Na_2O	142 ± 0.189	
	6.3 µm diameter fiber, 25.5% mol Na_2O	127 ± 0.259	
	12.8 µm diameter fiber, 25.5% mol Na_2O	103 ± 1.020	
	5.4 µm diameter fiber, 36.3% mol Na_2O	107.6 ± 0.308	
	8.6 µm diameter fiber, 36.3% mol Na_2O	98.0 ± 0.344	
	11.4 µm diameter fiber, 36.3% mol Na_2O	91.2 ± 1.480	
SiO_2–PbO glass	3.0 µm diameter fiber, 50% mol PbO	70.8	
	4.3 µm diameter fiber, 50% mol PbO	64	
	5.7 µm diameter fiber, 50% mol PbO	66–67.2	
	7.1 µm diameter fiber, 50% mol PbO	62–71.3	
	8.0 µm diameter fiber, 50% mol PbO	64.5	

(*Continued*)

TABLE 3.4 (*Continued*) Tensile Strength of Glass

Type	Glass	Tensile Strength (kg/mm^2)	Temperature (°C)
	11.4 μm diameter fiber, 50% mol PbO	51.9–56	
	17.2 μm diameter fiber, 50% mol PbO	43–51.6	
B_2O_3 glass	10–30 μm diameter fiber	60	
B_2O_3–Na_2O glass	10–30 μm diameter fiber, 10% mol Na_2O	102	
	10–30 μm diameter fiber, 20% mol Na_2O	137	
	10–30 μm diameter fiber, 30% mol Na_2O	152	

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.5 Microhardness of Glass

Class	Glass	Microhardness (kg/mm^2)
SiO_2	SiO_2 glass	Knoop
		500–679
	SiO_2–Na_2O glass	Vickers
	25% mol Na_2O	423 ± 4
	30% mol Na_2O	413 ± 3
	35% mol Na_2O	414 ± 4
	40% mol Na_2O	394 ± 2
	45% mol Na_2O	378 ± 2
	SiO_2–B_2O_3 glass	Vickers
	60% mol B_2O_3	328–345
	65% mol B_2O_3	293–297
	70% mol B_2O_3	251–279
	75% mol B_2O_3	237–269–345
	80% mol B_2O_3	239–271
	85% mol B_2O_3	239–267
	90% mol B_2O_3	231–257
	95% mol B_2O_3	227–253
B_2O_3	B_2O_3 glass	Vickers
		194–205
	B_2O_3–Na_2O glass	Vickers
	5% mol Na_2O	276
	10% mol Na_2O	292
	15% mol Na_2O	297
	20% mol Na_2O	380
	25% mol Na_2O	460
	30% mol Na_2O	503

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.6 Young's Modulus of Glass

Class	Glass	Young's Modulus (GPa)	Temperature
SiO_2 glass	SiO_2 glass	72.76–74.15	20°C
		79.87	998°C (annealing point)
		80.80	1096°C (straining point)
	SiO_2–Na_2O glass		
	15% mol Na_2O	64.4	Room temp.
	20% mol Na_2O	62.0	Room temp.
	25% mol Na_2O	56.9	–196°C
	25% mol Na_2O	61.4	Room temp.
	25% mol Na_2O	53.9	200–250°C
	30% mol Na_2O	60.5	Room temp.
	33% mol Na_2O	54.9	–196°C
	33% mol Na_2O	60.3	Room temp.
	33% mol Na_2O	51.0	200–250°C
	35% mol Na_2O	60.2	Room temp.
	40% mol Na_2O	51.9	–196°C
	40% mol Na_2O	46.1	200–250°C
	SiO_2–PbO glass		
	24.6% mol PbO	47.1	
	30.0% mol PbO	50.1	
	35.7% mol PbO	46.3	
	38.4% mol PbO	52.8	
	45.0% mol PbO	51.7	
	50.0% mol PbO	44.1	
	55.0% mol PbO	49.3	
	60.0% mol PbO	43.6	
	65.0% mol PbO	41.2	
SiO_2–B_2O_3 glass	60% mol B_2O_3	23.3	
	65% mol B_2O_3	22.5	
	70% mol B_2O_3	23.5	
	75% mol B_2O_3	24.1	
	80% mol B_2O_3	22.8	
	85% mol B_2O_3	21.2	
	90% mol B_2O_3	20.9	
	95% mol B_2O_3	21.2	
B_2O_3 glass	B_2O_3 glass	17.2–17.7	Room temp.
	B_2O_3–Na_2O glass		
	10% mol Na_2O	31.4	15°C
	20% mol Na_2O	43.2	15°C
	25% mol Na_2O	53.7	15°C
	33.3% mol Na_2O	59.4	15°C
	37% mol Na_2O	57.1	15°C

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.7 Bulk Modulus of Glass

Glass	Bulk Modulus (GPa)	Temperature (°C)
SiO_2 glass	31.01–37.62	
SiO_2–Na_2O glass		
15% mol Na_2O	33.8	Room temp.
20% mol Na_2O	34.8	Room temp.
25% mol Na_2O	36.5	Room temp.
30% mol Na_2O	38.2	Room temp.
33% mol Na_2O	40.1	Room temp.
35% mol Na_2O	39.8	Room temp.
SiO_2–PbO glass		
24.6% mol PbO	33.9	
30.0% mol PbO	25.6	
35.7% mol PbO	31.1	
38.4% mol PbO	25.1	
45.0% mol PbO	30.6	
50.0% mol PbO	30.5	
55.0% mol PbO	29.5	
60.0% mol PbO	33.1	
65.0% mol PbO	31.6	
B_2O_3–Na_2O glass		
10% mol Na_2O	23.2	15
20% mol Na_2O	33.6	15
25% mol Na_2O	39.2	15
33.3% mol Na_2O	44.4	15
37% mol Na_2O	42.1	15

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.8 Shear Modulus of Glass

Class	Glass	Shear Modulus (GPa)	Temperature
SiO_2 glass	SiO_2 glass	31.38	20°C
		33.57	998°C (annealing point)
		34.15	1096°C (straining point)
SiO_2–Na_2O glass	5% mol Na_2O	27.2	–100°C
	5% mol Na_2O	27.4	0°C
	5% mol Na_2O	27.6	80°C
	5% mol Na_2O	27.2	160°C
	7.5% mol Na_2O	26.9	–100–160°C
	15% mol Na_2O	27.2	Room temp.
	18% mol Na_2O	25.8	–100°C
	18% mol Na_2O	25.0	0°C
	18% mol Na_2O	24.8	80°C
	18% mol Na_2O	24.2	160°C
	20% mol Na_2O	25.8	Room temp.
	25% mol Na_2O	25.2	Room temp.
	30% mol Na_2O	24.5	Room temp.
	33% mol Na_2O	24.2	Room temp.
	35% mol Na_2O	24.1	Room temp.
SiO_2–PbO glass	24.6% mol PbO	20.4	
	30.0% mol PbO	21.4	
	35.7% mol PbO	18.5	
	38.4% mol PbO	23.0	
	45.0% mol PbO	21.2	
	50.0% mol PbO	17.5	
	55.0% mol PbO	20.2	
	60.0% mol PbO	17.0	
	65.0% mol PbO	16.1	
B_2O_3 glass	B_2O_3 glass	6.55	Room temp.
		6.29	250°C
		6.07	260°C
		5.78	270°C
		5.49	280°C
		5.15	290°C
		4.75	300°C
B_2O_3–Na_2O glass	10% mol Na_2O	12.3	15°C
	20% mol Na_2O	16.8	15°C
	25% mol Na_2O	21.1	15°C
	33.3% mol Na_2O	23.2	15°C
	37% mol Na_2O	22.4	15°C

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.9 Poisson's Ratio of Glass

Class	Composition	Poisson's Ratio	Temperature (°C)
SiO_2 glass		0.166–0.177	Room temp.
SiO_2–Na_2O glass	15% mol Na_2O	0.183	Room temp.
	20% mol Na_2O	0.203	Room temp.
	25% mol Na_2O	0.219	Room temp.
	30% mol Na_2O	0.236	Room temp.
	33% mol Na_2O	0.249	Room temp.
	35% mol Na_2O	0.248	Room temp.
SiO_2–PbO glass	24.6% mol PbO	0.249	
	30.0% mol PbO	0.174	
	35.7% mol PbO	0.252	
	38.4% mol PbO	0.150	
	45.0% mol PbO	0.219	
	50.0% mol PbO	0.259	
	55.0% mol PbO	0.222	
	60.0% mol PbO	0.281	
	65.0% mol PbO	0.283	
B_2O_3 glass		0.288–0.309	Room temp.
B_2O_3–Na_2O glass	5.5% mol Na_2O	0.279	
	10% mol Na_2O	0.2740	15
	15.4% mol Na_2O	0.271	
	20% mol Na_2O	0.2860	15
	22.8% mol Na_2O	0.272	
	25% mol Na_2O	0.2713	15
	29.8% mol Na_2O	0.274	
	33.3% mol Na_2O	0.2771	15
	37% mol Na_2O	0.2739	15
	37.25% mol Na_2O	0.292	

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.10 Viscosity of Glasses

Glass	Composition	Viscosity	Temperature (°C)
SiO_2 glass		12.6–14.4 log *P*	1100
		11.4–12.8 log *P*	1200
		10.4–11.83 log *P*	1300
		9.43–10.65 log *P*	1400
		8.54–9.52 log *P*	1500
		7.8–8.53 log *P*	1600
		7.1–7.65 log *P*	1700
		6.43–6.9 log *P*	1800
		5.88–6.2 log *P*	1900
		5.2–5.4 log *P*	2000
SiO_2–Na_2O glass	21.7% mol Na_2O	4.28 log *P*	900
	21.7% mol Na_2O	3.66 log *P*	1000
	21.7% mol Na_2O	3.17 log *P*	1100
	21.7% mol Na_2O	2.76 log *P*	1200
	21.7% mol Na_2O	2.40 log *P*	1300
	21.7% mol Na_2O	2.08 log *P*	1400
	23.8% mol Na_2O	3.88 log *P*	900
	23.8% mol Na_2O	3.28 log *P*	1000
	23.8% mol Na_2O	2.82 log *P*	1100
	23.8% mol Na_2O	2.44 log *P*	1200
	23.8% mol Na_2O	2.10 log *P*	1300
	23.8% mol Na_2O	1.84 log *P*	1400
	27.7% mol Na_2O	4.33 log *P*	800
	27.7% mol Na_2O	3.71 log *P*	900
	27.7% mol Na_2O	3.16 log *P*	1000
	27.7% mol Na_2O	2.69 log *P*	1100
	27.7% mol Na_2O	2.31 log *P*	1200
	27.7% mol Na_2O	1.98 log *P*	1300
	27.7% mol Na_2O	1.65 log *P*	1400
	31.7% mol Na_2O	4.17 log *P*	800
	31.7% mol Na_2O	3.45 log *P*	900
	31.7% mol Na_2O	2.92 log *P*	1000
	31.7% mol Na_2O	2.48 log *P*	1100
	31.7% mol Na_2O	2.12 log *P*	1200
	31.7% mol Na_2O	1.83 log *P*	1300
	31.7% mol Na_2O	1.59 log *P*	1400
	33.7% mol Na_2O	4.06 log *P*	800
	33.7% mol Na_2O	3.39 log *P*	900
	33.7% mol Na_2O	2.66 log *P*	1000
	33.7% mol Na_2O	2.20 log *P*	1100
	33.7% mol Na_2O	1.81 log *P*	1200
	33.7% mol Na_2O	1.52 log *P*	1300
	36.3% mol Na_2O	4.13 log *P*	800
	36.3% mol Na_2O	3.40 log *P*	900

(*Continued*)

TABLE 3.10 (*Continued*) Viscosity of Glasses

Glass	Composition	Viscosity	Temperature (°C)
	36.3% mol Na_2O	2.86 log *P*	1000
	36.3% mol Na_2O	2.42 log *P*	1100
	36.3% mol Na_2O	2.06 log *P*	1200
	36.3% mol Na_2O	1.76 log *P*	1300
	36.3% mol Na_2O	1.51 log *P*	1400
	38.9% mol Na_2O	3.91 log *P*	800
	38.9% mol Na_2O	3.20 log *P*	900
	38.9% mol Na_2O	2.63 log *P*	1000
	38.9% mol Na_2O	2.18 log *P*	1100
	38.9% mol Na_2O	1.78 log *P*	1200
	38.9% mol Na_2O	1.47 log *P*	1300
	41.9% mol Na_2O	3.56 log *P*	800
	41.9% mol Na_2O	2.83 log *P*	900
	41.9% mol Na_2O	2.29 log *P*	1000
	41.9% mol Na_2O	1.85 log *P*	1100
	41.9% mol Na_2O	1.50 log *P*	1200
	44.0% mol Na_2O	3.65 log *P*	800
	44.0% mol Na_2O	2.81 log *P*	900
	44.0% mol Na_2O	2.24 log *P*	1000
	44.0% mol Na_2O	1.80 log *P*	1100
	44.0% mol Na_2O	1.43 log *P*	1200
SiO_2–CaO glass	30.5% mol CaO	13.6 P	1700
	30.5% mol CaO	10.4 P	1750
	30.5% mol CaO	8.5 P	1800
	34.5% mol CaO	10.0 P	1650
	34.5% mol CaO	7.8 P	1700
	34.5% mol CaO	6.05 P	1750
	34.5% mol CaO	4.5 P	1800
	41.6% mol CaO	9.35 P	1500
	41.6% mol CaO	6.48 P	1550
	41.6% mol CaO	4.68 P	1600
	41.6% mol CaO	3.57 P	1650
	41.6% mol CaO	2.75 P	1700
	41.6% mol CaO	2.16 P	1750
	41.6% mol CaO	1.8 P	1800
	48.7% mol CaO	4.35 P	1500
	48.7% mol CaO	3.17 P	1550
	48.7% mol CaO	2.41 P	1600
	48.7% mol CaO	1.90 P	1650
	48.7% mol CaO	1.50 P	1700
	48.7% mol CaO	1.20 P	1750
	48.7% mol CaO	0.99 P	1800
	52.7% mol CaO	3.03 P	1500
	52.7% mol CaO	2.20 P	1550

(*Continued*)

TABLE 3.10 (*Continued*) Viscosity of Glasses

Glass	Composition	Viscosity	Temperature (°C)
	52.7% mol CaO	1.66 P	1600
	52.7% mol CaO	1.28 P	1650
	52.7% mol CaO	1.01 P	1700
	52.7% mol CaO	0.83 P	1750
	52.7% mol CaO	0.72 P	1800
	54.7% mol CaO	2.57 P	1500
	54.7% mol CaO	1.39 P	1550
	54.7% mol CaO	1.40 P	1600
	54.7% mol CaO	1.10 P	1650
	54.7% mol CaO	0.90 P	1700
	54.7% mol CaO	0.75 P	1750
	54.7% mol CaO	0.66 P	1800
	57.7% mol CaO	1.13 P	1600
	57.7% mol CaO	0.90 P	1650
	57.7% mol CaO	0.74 P	1700
	57.7% mol CaO	0.62 P	1750
	57.7% mol CaO	0.54 P	1800
SiO_2–PbO glass	35% mol PbO	7380 P	840
	35% mol PbO	1920 P	900
	35% mol PbO	620 P	960
	35% mol PbO	302 P	1020
	35% mol PbO	164 P	1080
	35% mol PbO	100.0 P	1140
	35% mol PbO	62.0 P	1200
	35% mol PbO	38.2 P	1260
	35% mol PbO	25.0 P	1320
	35% mol PbO	16.2 P	1380
	35% mol PbO	11.8 P	1440
	40% mol PbO	2970 P	780
	40% mol PbO	830 P	840
	40% mol PbO	329 P	900
	40% mol PbO	164 P	960
	40% mol PbO	91.0 P	1020
	40% mol PbO	51.8 P	1080
	40% mol PbO	31.8 P	1140
	40% mol PbO	20.4 P	1200
	40% mol PbO	13.5 P	1260
	40% mol PbO	10.2 P	1320
	46% mol PbO	2260 P	720
	46% mol PbO	494 P	780
	46% mol PbO	166 P	840
	46% mol PbO	85.0 P	900
	46% mol PbO	47.4 P	960
	46% mol PbO	29.4 P	1020

(*Continued*)

TABLE 3.10 (*Continued*) Viscosity of Glasses

Glass	Composition	Viscosity	Temperature (°C)
	46% mol PbO	18.6 P	1080
	46% mol PbO	12.7 P	1140
	46% mol PbO	8.8 P	1200
	46% mol PbO	6.3 P	1260
	46% mol PbO	5.2 P	1320
	46% mol PbO	4.9 P	1380
	50% mol PbO	21200 P	600
	50% mol PbO	1600 P	660
	50% mol PbO	292 P	720
	50% mol PbO	105 P	780
	50% mol PbO	43.8 P	840
	50% mol PbO	22.5 P	900
	50% mol PbO	13.9 P	960
	50% mol PbO	8.8 P	1020
	50% mol PbO	6.0 P	1080
	50% mol PbO	4.3 P	1140
	50% mol PbO	2.9 P	1200
	55% mol PbO	51.0 P	720
	55% mol PbO	22.4 P	780
	55% mol PbO	12.6 P	840
	55% mol PbO	7.10 P	900
	55% mol PbO	4.44 P	960
	55% mol PbO	3.00 P	1020
	55% mol PbO	2.06 P	1080
	55% mol PbO	1.40 P	1140
	55% mol PbO	0.98 P	1200
	60% mol PbO	37.6 P	660
	60% mol PbO	12.4 P	720
	60% mol PbO	5.8 P	780
	60% mol PbO	3.2 P	840
	60% mol PbO	2.2 P	900
	60% mol PbO	1.5 P	960
	60% mol PbO	1.00 P	1020
	60% mol PbO	0.7 P	1080
	64% mol PbO	5.2 P	720
	64% mol PbO	2.5 P	780
	64% mol PbO	1.23 P	840
	64% mol PbO	1.00 P	900
	64% mol PbO	0.70 P	960
	64% mol PbO	0.50 P	1020
	64% mol PbO	0.30 P	1080
	66.7% mol PbO	1.60 P	780
	66.7% mol PbO	1.00 P	840
	66.7% mol PbO	0.70 P	900

(*Continued*)

TABLE 3.10 (*Continued*) Viscosity of Glasses

Glass	Composition	Viscosity	Temperature (°C)
	66.7% mol PbO	0.50 P	960
	66.7% mol PbO	0.35 P	1020
	70% mol PbO	1.80 P	720
	70% mol PbO	1.17 P	780
	70% mol PbO	0.80 P	840
	70% mol PbO	0.40 P	900
	70% mol PbO	0.20 P	960
SiO_2–Al_2O_3 glass	37.1% mol Al_2O_3	5.8 P	1850
	37.1% mol Al_2O_3	4.1 P	1900
	37.1% mol Al_2O_3	3.1 P	1950
	37.1% mol Al_2O_3	2.5 P	2000
	37.1% mol Al_2O_3	2.2 P	2050
	37.1% mol Al_2O_3	1.9 P	2100
	46.9% mol Al_2O_3	3.3 P	1850
	46.9% mol Al_2O_3	2.4 P	1900
	46.9% mol Al_2O_3	1.8 P	1950
	46.9% mol Al_2O_3	1.5 P	2000
	46.9% mol Al_2O_3	1.3 P	2050
	46.9% mol Al_2O_3	1.2 P	2100
	70.2% mol Al_2O_3	0.9 P	1950
	70.2% mol Al_2O_3	0.8 P	2000
	70.2% mol Al_2O_3	0.7 P	2050
	70.2% mol Al_2O_3	0.6 P	2100
SiO_2–B_2O_3 glass	6.2% mol B_2O_3	33.0 kP	1763
	6.2% mol B_2O_3	26.6 kP	1783
	6.2% mol B_2O_3	16.9 kP	1815
	6.2% mol B_2O_3	13.1 kP	1840
	10.1% mol B_2O_3	13.3 kP	1727
	10.1% mol B_2O_3	11.2 kP	1730
	10.1% mol B_2O_3	10.9 kP	1736
	10.1% mol B_2O_3	11.4 kP	1738
	10.1% mol B_2O_3	11.0 kP	1740
	10.1% mol B_2O_3	9.07 kP	1757
	10.1% mol B_2O_3	8.57 kP	1768
	10.1% mol B_2O_3	7.78 kP	1775
	10.1% mol B_2O_3	6.54 kP	1778
	10.1% mol B_2O_3	5.83 kP	1792
	14.5% mol B_2O_3	3.51 kP	1691
	14.5% mol B_2O_3	3.37 kP	1693
	14.5% mol B_2O_3	2.63 kP	1720
	14.5% mol B_2O_3	2.45 kP	1725
	14.5% mol B_2O_3	1.92 kP	1752
	14.5% mol B_2O_3	1.85 kP	1757

(*Continued*)

TABLE 3.10 (*Continued*) Viscosity of Glasses

Glass	Composition	Viscosity	Temperature (°C)
	14.5% mol B_2O_3	1.47 kP	1778
	14.5% mol B_2O_3	1.45 kP	1783
	14.5% mol B_2O_3	1.17 kP	1797
	14.5% mol B_2O_3	1.14 kP	1800
	14.5% mol B_2O_3	1.12 kP	1802
	14.5% mol B_2O_3	1.00 kP	1812
	14.5% mol B_2O_3	0.97 kP	1816
	25.2% mol B_2O_3	127.0 kP	1303
	25.2% mol B_2O_3	89.8 kP	1329
	25.2% mol B_2O_3	67.4 kP	1355
	25.2% mol B_2O_3	44.5 kP	1376
	25.2% mol B_2O_3	32.0 kP	1418
	25.2% mol B_2O_3	21.9 kP	1444
	42.4% mol B_2O_3	−2.37 + 9823/T log *P*	1100–1460
	53.1% mol B_2O_3	−1.96 + 8239/T log *P*	1380–1530
	62.4% mol B_2O_3	−1.99 + 7687/T log *P*	1280–1460
	71.9% mol B_2O_3	−1.24 + 5740/T log *P*	1130–1410
	75.4% mol B_2O_3	119000 P	530
	75.4% mol B_2O_3	15230 P	630
	75.4% mol B_2O_3	3400 P	800
	79.7% mol B_2O_3	49500 P	530
	79.7% mol B_2O_3	9300 P	630
	79.7% mol B_2O_3	1400 P	800
	81.9% mol B_2O_3	11.61–14.06 log *P*	243–306
	82.5% mol B_2O_3	0.90 + 4576/T log *P*	1050–1360
	86.3% mol B_2O_3	17000 P	530
	86.3% mol B_2O_3	4000 P	630
	86.3% mol B_2O_3	425 P	800
	90.0% mol B_2O_3	0.42 + 3434/T log *P*	1030–1360
	90.4% mol B_2O_3	15300 P	530
	90.4% mol B_2O_3	4400 P	630
	90.4% mol B_2O_3	565 P	800
	93.1% mol B_2O_3	7150 P	530
	93.1% mol B_2O_3	2200 P	630
	93.1% mol B_2O_3	420 P	800
	93.91% mol B_2O_3	0.68 + 3655/T log *P*	1070–1350
	97.7% mol B_2O_3	6900 P	530
	97.7% mol B_2O_3	2730 P	630
	97.7% mol B_2O_3	410 P	800
B_2O_3 glass		9.799 log *P*	325
		8.602 log *P*	350
		7.602 log *P*	375

(*Continued*)

TABLE 3.10 (*Continued*) Viscosity of Glasses

Glass	Composition	Viscosity	Temperature (°C)
		6.415 log *P*	411
		5.484 log *P*	450
		4.611 log *P*	500
		4.029 log *P*	550
		3.561 log *P*	600
		2.959 log *P*	700
		2.549 log *P*	800
		2.245 log *P*	900
		2.000 log *P*	1000
		1.785 log *P*	1100
		1.603 log *P*	1200
		1.462 log *P*	1300
		1.335 log *P*	1400
		4.65 P	1829
		3.87 P	1863
B_2O_3–CaO glass	32.0% mol CaO	12.51 log *P*	646.5
	32.0% mol CaO	12.02 log *P*	654.8
	32.0% mol CaO	10.64 log *P*	674.8
	32.0% mol CaO	9.17 log *P*	697.2
	34.0% mol CaO	11.32 log *P*	656.1
	34.0% mol CaO	10.68 log *P*	667.1
	34.0% mol CaO	9.88 log *P*	681.3
	34.0% mol CaO	10.51 log *P*	671.3
	34.0% mol CaO	11.60 log *P*	653.6
	34.0% mol CaO	10.48 log *P*	668.9
	34.0% mol CaO	9.09 log *P*	691.5
	34.0% mol CaO	11.37 log *P*	657.2
	55.0% mol CaO	12.92 log *P*	650
	55.0% mol CaO	9.84 log *P*	700
	55.0% mol CaO	7.32 log *P*	750
	55.0% mol CaO	5.38 log *P*	800
	55.0% mol CaO	2.60 log *P*	900
	55.0% mol CaO	1.96 log *P*	950
	55.0% mol CaO	1.38 log *P*	1000
	55.0% mol CaO	0.96 log *P*	1050
	55.0% mol CaO	0.74 log *P*	1100
B_2O_3–Na_2O glass	5% mol Na_2O	7.83×10^{14} P	285
	5% mol Na_2O	5.86×10^{13} P	300
	5% mol Na_2O	1.99×10^{13} P	309
	9.9% mol Na_2O	3.371 log *P*	630
	9.9% mol Na_2O	3.095 log *P*	650
	9.9% mol Na_2O	2.586 log *P*	700
	9.9% mol Na_2O	2.181 log *P*	750
	9.9% mol Na_2O	1.884 log *P*	800

(*Continued*)

TABLE 3.10 (*Continued*) Viscosity of Glasses

Glass	Composition	Viscosity	Temperature (°C)
	9.9% mol Na_2O	1.647 log *P*	850
	9.9% mol Na_2O	1.569 log *P*	870
	10% mol Na_2O	1.28×10^{15} P	328
	10% mol Na_2O	1.41×10^{14} P	340
	10% mol Na_2O	2.06×10^{13} P	351
	12.8% mol Na_2O	3.566 log *P*	630
	12.8% mol Na_2O	3.257 log *P*	650
	12.8% mol Na_2O	2.695 log *P*	700
	12.8% mol Na_2O	2.252 log *P*	750
	12.8% mol Na_2O	1.923 log *P*	800
	12.8% mol Na_2O	1.661 log *P*	850
	12.8% mol Na_2O	1.574 log P	870
	15% mol Na_2O	1.44×10^{15} P	381
	15% mol Na_2O	1.65×10^{14} P	394
	15% mol Na_2O	2.75×10^{13} P	405
	15.1% mol Na_2O	3.825 log *P*	630
	15.1% mol Na_2O	3.457 log *P*	650
	15.1% mol Na_2O	2.818 log *P*	700
	15.1% mol Na_2O	2.319 log *P*	750
	15.1% mol Na_2O	1.942 log *P*	800
	15.1% mol Na_2O	1.652 log *P*	850
	15.1% mol Na_2O	1.560 log *P*	870
	17.5% mol Na_2O	4.050 log *P*	630
	17.5% mol Na_2O	3.623 log *P*	650
	17.5% mol Na_2O	2.881 log *P*	700
	17.5% mol Na_2O	2.332 log *P*	750
	17.5% mol Na_2O	1.931 log *P*	800
	17.5% mol Na_2O	1.633 log *P*	850
	17.5% mol Na_2O	1.545 log *P*	870
	19.7% mol Na_2O	4.110 log *P*	630
	19.7% mol Na_2O	3.712 log *P*	650
	19.7% mol Na_2O	2.945 log *P*	700
	19.7% mol Na_2O	2.324 log *P*	750
	19.7% mol Na_2O	1.875 log *P*	800
	19.7% mol Na_2O	1.540 log *P*	850
	19.7% mol Na_2O	1.435 log *P*	870
	20% mol Na_2O	5.19×10^{15} P	435
	20% mol Na_2O	1.31×10^{14} P	445
	20% mol Na_2O	1.57×10^{13} P	457
	21.9% mol Na_2O	4.185 log *P*	630
	21.9% mol Na_2O	3.746 log *P*	650
	21.9% mol Na_2O	2.951 log *P*	700
	21.9% mol Na_2O	2.324 log *P*	750

(*Continued*)

TABLE 3.10 (*Continued*) Viscosity of Glasses

Glass	Composition	Viscosity	Temperature (°C)
	21.9% mol Na_2O	1.810 log *P*	800
	21.9% mol Na_2O	1.506 log *P*	850
	21.9% mol Na_2O	1.392 log *P*	870
	24.0% mol Na_2O	4.050 log *P*	630
	24.0% mol Na_2O	3.598 log *P*	650
	24.0% mol Na_2O	2.824 log *P*	700
	24.0% mol Na_2O	2.228 log *P*	750
	24.0% mol Na_2O	1.782 log *P*	800
	24.0% mol Na_2O	1.455 log *P*	850
	24.0% mol Na_2O	1.344 log *P*	870
	25% mol Na_2O	6.67×10^{14} P	445
	25% mol Na_2O	1.29×10^{14} P	455
	25% mol Na_2O	1.31×10^{13} P	466
	26.4% mol Na_2O	3.865 log *P*	630
	26.4% mol Na_2O	3.448 log *P*	650
	26.4% mol Na_2O	2.679 log *P*	700
	26.4% mol Na_2O	2.086 log *P*	750
	26.4% mol Na_2O	1.684 log *P*	800
	26.4% mol Na_2O	1.395 log *P*	850
	26.4% mol Na_2O	1.300 log *P*	870
	30% mol Na_2O	2.12×10^{15} P	448
	30% mol Na_2O	8.06×10^{14} P	457
	30% mol Na_2O	1.02×10^{13} P	467

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.11 Internal Friction of SiO_2 Glass

Glass	Internal Friction	Temperature (°C)	Frequency (MHz)
SiO_2 glass	$4–80 \times 10^{-7}$	100	1.6
	$2–60 \times 10^{-7}$	200	1.6
	$2.5–30 \times 10^{-7}$	300	1.6
	$3.5–9 \times 10^{-7}$	400	1.6
	$4.5–5 \times 10^{-7}$	500	1.6
	$5.5–9 \times 10^{-7}$	600	1.6
	$8–15 \times 10^{-7}$	700	1.6
	$10.5–50 \times 10^{-7}$	800	1.6
	$13.5–95 \times 10^{-7}$	900	1.6
	$15–150 \times 10^{-7}$	1000	1.6

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.12 Volume Resistivity of Glass

Glass	Description	Resistivity	Temperature (°C)
SiO_2 glass		11.0–13.6 log Ω cm	250
		$3.16 \times 10^8 - 6.3 \times 10^{10}$ Ω cm	400
		6.3×10^7 Ω cm	500
		1.0×10^7 Ω cm	600
		3.6×10^6 Ω cm	700
		1.6×10^6 Ω cm	800
		8.0×10^5 Ω cm	900
		4.6×10^5 Ω cm	1000
		2.9×10^5 Ω cm	1100
		2.0×10^5 Ω cm	1200
		1.4×10^5 Ω cm	1300
		1.0×10^5 Ω cm	1400
		7.9×10^4 Ω cm	1500
	0.5 atm Ar pressure	4.6×10^4 Ω cm	1500
	0.5 atm Ar pressure	2.5×10^4 Ω cm	1600
	0.5 atm Ar pressure	1.0×10^4 Ω cm	1700
	0.5 atm Ar pressure	3.0×10^3 Ω cm	1800
	0.5 atm Ar pressure	1.0×10^3 Ω cm	1900
	0.5 atm Ar pressure	5.0×10^2 Ω cm	2000
	0.5 atm Ar pressure	2.0×10^2 Ω cm	2100
SiO_2–Na_2O glass	5% mol Na_2O	10.45–11.71 log Ω cm	150
	5% mol Na_2O	7.63 log Ω cm	250
	5% mol Na_2O	7.33–8.25 log Ω cm	300
	5% mol Na_2O	6.37 log Ω cm	350
	7.5% mol Na_2O	7.59 log Ω cm	150
	7.5% mol Na_2O	5.30 log Ω cm	300
	7.8% mol Na_2O	7.8×10^9 Ω cm	100
	10% mol Na_2O	7.35 log Ω cm	150
	10% mol Na_2O	6.14 log Ω cm	250
	10% mol Na_2O	5.18 log Ω cm	300
	10% mol Na_2O	4.96 log Ω cm	350
	10% mol Na_2O	1.03 log Ω cm	1500
	10% mol Na_2O	0.92 log Ω cm	1600
	13% mol Na_2O	6.90–6.96 log Ω cm	150
	13% mol Na_2O	4.77–4.79 log Ω cm	300
	15% mol Na_2O	5.44 log Ω cm	250
	15% mol Na_2O	4.32 log Ω cm	350
	15% mol Na_2O	0.61 log Ω cm	1400
	15% mol Na_2O	0.56 log Ω cm	1500
	15.1% mol Na_2O	1.4×10^8 Ω cm	100
	19.9% mol Na_2O	1.68 log Ω cm	600

(*Continued*)

TABLE 3.12 (*Continued*) Volume Resistivity of Glass

Glass	Description	Resistivity	Temperature (°C)
	19.9% mol Na_2O	1.34 log Ω cm	700
	19.9% mol Na_2O	0.96 log Ω cm	800
	19.9% mol Na_2O	0.76 log Ω cm	900
	19.9% mol Na_2O	0.61 log Ω cm	1000
	19.9% mol Na_2O	0.48 log Ω cm	1100
	19.9% mol Na_2O	0.38 log Ω cm	1200
	19.9% mol Na_2O	0.30 log Ω cm	1300
	20% mol Na_2O	6.45–6.80 log Ω cm	150
	20% mol Na_2O	4.85 log Ω cm	250
	20% mol Na_2O	4.36–4.64 log Ω cm	300
	20% mol Na_2O	3.80 log Ω cm	350
	24.8% mol Na_2O	0.52 log Ω cm	900
	24.8% mol Na_2O	0.38 log Ω cm	1000
	24.8% mol Na_2O	0.26 log Ω cm	1100
	24.8% mol Na_2O	0.17 log Ω cm	1200
	25% mol Na_2O	6.05 log Ω cm	150
	25% mol Na_2O	4.50 log Ω cm	250
	25% mol Na_2O	4.03 log Ω cm	300
	25% mol Na_2O	3.52 log Ω cm	350
	27% mol Na_2O	5.87 log Ω cm	150
	27% mol Na_2O	3.94 log Ω cm	300
	29.7% mol Na_2O	1.31 log Ω cm	550
	29.7% mol Na_2O	1.16 log Ω cm	600
	29.7% mol Na_2O	0.78 log Ω cm	700
	29.7% mol Na_2O	0.52 log Ω cm	800
	29.7% mol Na_2O	0.34 log Ω cm	900
	29.7% mol Na_2O	0.20 log Ω cm	1000
	29.7% mol Na_2O	0.08 log Ω cm	1100
	29.7% mol Na_2O	−0.02 log Ω cm	1200
	29.7% mol Na_2O	−0.10 log Ω cm	1300
	29.7% mol Na_2O	−0.16 log Ω cm	1400
	30% mol Na_2O	5.48–5.75 log Ω cm	150
	30% mol Na_2O	4.42 log Ω cm	250
	30% mol Na_2O	3.64–3.78 log Ω cm	300
	30% mol Na_2O	3.46 log Ω cm	350
	30.2% mol Na_2O	3.8×10^6 Ω cm	100
	33.3% mol Na_2O	5.06 log Ω cm	150
	33.3% mol Na_2O	3.34 log Ω cm	300
	34.7% mol Na_2O	0.12 log Ω cm	900
	34.7% mol Na_2O	0.00 log Ω cm	1000

(*Continued*)

TABLE 3.12 (*Continued*) Volume Resistivity of Glass

Glass	Description	Resistivity	Temperature (°C)
	34.7% mol Na_2O	−0.11 log Ω cm	1100
	34.7% mol Na_2O	−0.20 log Ω cm	1200
	34.7% mol Na_2O	−0.27 log Ω cm	1300
	34.7% mol Na_2O	−0.33 log Ω cm	1400
	35% mol Na_2O	3.85 log Ω cm	250
	35% mol Na_2O	2.92 log Ω cm	350
	36% mol Na_2O	4.89 log Ω cm	150
	36% mol Na_2O	3.22 log Ω cm	300
	39.5% mol Na_2O	0.91 log Ω cm	550
	39.5% mol Na_2O	0.67 log Ω cm	600
	39.5% mol Na_2O	0.33 log Ω cm	700
	39.5% mol Na_2O	0.13 log Ω cm	800
	39.5% mol Na_2O	0.00 log Ω cm	900
	39.5% mol Na_2O	−0.13 log Ω cm	1000
	39.5% mol Na_2O	−0.24 log Ω cm	1100
	39.5% mol Na_2O	−0.32 log Ω cm	1200
	39.5% mol Na_2O	−0.39 log Ω cm	1300
	39.5% mol Na_2O	−0.45 log Ω cm	1400
	40% mol Na_2O	4.58 log Ω cm	150
	40% mol Na_2O	3.59 log Ω cm	250
	40% mol Na_2O	2.97 log Ω cm	300
	40% mol Na_2O	2.66 log Ω cm	350
	44.2% mol Na_2O	1.4×10^5 Ω cm	100
	44.5% mol Na_2O	−0.38 log Ω cm	1100
	44.5% mol Na_2O	−0.46 log Ω cm	1200
	44.5% mol Na_2O	−0.52 log Ω cm	1300
	45% mol Na_2O	4.33 log Ω cm	150
	45% mol Na_2O	3.30 log Ω cm	250
	45% mol Na_2O	2.69 log Ω cm	300
	45% mol Na_2O	2.35 log Ω cm	350
	48% mol Na_2O	4.09 log Ω cm	150
	48% mol Na_2O	2.58 log Ω cm	300
	49.3% mol Na_2O	−0.47 log Ω cm	1100
	49.3% mol Na_2O	−0.56 log Ω cm	1200
	49.3% mol Na_2O	−0.61 log Ω cm	1300
	57.5% mol Na_2O	−0.52 log Ω cm	1100
	57.5% mol Na_2O	−0.61 log Ω cm	1200
	57.5% mol Na_2O	−0.67 log Ω cm	1300
SiO_2–PbO glass	30% mol PbO	12.94 log Ω cm	200
	30% mol PbO	10.44 log Ω cm	300
	33.8% mol PbO	16.14 log Ω cm	66

(*Continued*)

TABLE 3.12 (*Continued*) Volume Resistivity of Glass

Glass	Description	Resistivity	Temperature (°C)
	33.8% mol PbO	13.68 log Ω cm	135
	35% mol PbO	12.10 log Ω cm	200
	35% mol PbO	9.89 log Ω cm	300
	38.5% mol PbO	4.40 log Ω cm	700
	38.5% mol PbO	3.20 log Ω cm	800
	38.5% mol PbO	2.47 log Ω cm	900
	38.5% mol PbO	1.94 log Ω cm	1000
	38.5% mol PbO	1.56 log Ω cm	1100
	38.5% mol PbO	1.26 log Ω cm	1200
	38.5% mol PbO	1.04 log Ω cm	1300
	40% mol PbO	11.54 log Ω cm	200
	40% mol PbO	9.48 log Ω cm	300
	40.2% mol PbO	14.85 log Ω cm	78
	40.2% mol PbO	11.70 log Ω cm	175
	44.7% mol PbO	2.38 log Ω cm	800
	44.7% mol PbO	1.82 log Ω cm	900
	44.7% mol PbO	1.40 log Ω cm	1000
	44.7% mol PbO	1.15 log Ω cm	1100
	44.7% mol PbO	0.98 log Ω cm	1200
	44.7% mol PbO	0.82 log Ω cm	1300
	47.3% mol PbO	14.48 log Ω cm	79
	47.3% mol PbO	11.74 log Ω cm	149
	50% mol PbO	10.69 log Ω cm	200
	50% mol PbO	8.80–9.2 log Ω cm	300
	50.0% mol PbO	1.90 log Ω cm	800
	50.0% mol PbO	1.36 log Ω cm	900
	50.0% mol PbO	1.02 log Ω cm	1000
	50.0% mol PbO	0.80 log Ω cm	1100
	50.0% mol PbO	0.60 log Ω cm	1200
	51.4% mol PbO	14.52 log Ω cm	65
	51.4% mol PbO	11.59 log Ω cm	139
	51.6% mol PbO	1.62 log Ω cm	800
	51.6% mol PbO	1.20 log Ω cm	900
	51.6% mol PbO	0.92 log Ω cm	1000
	51.6% mol PbO	0.70 log Ω cm	1100
	51.6% mol PbO	0.54 log Ω cm	1200
	57.1% mol PbO	13.70 log Ω cm	77
	57.1% mol PbO	10.14 log Ω cm	172
	60% mol PbO	10.04 log Ω cm	200
	60% mol PbO	8.11 log Ω cm	300
	60% mol PbO	1.72 log Ω cm	650

(*Continued*)

TABLE 3.12 (*Continued*) Volume Resistivity of Glass

Glass	Description	Resistivity	Temperature (°C)
	60% mol PbO	1.74 log Ω cm	700
	60% mol PbO	1.07 log Ω cm	800
	60% mol PbO	0.76 log Ω cm	900
	60% mol PbO	0.40 log Ω cm	1000
	63.2% mol PbO	14.29 log Ω cm	57
	63.2% mol PbO	10.34 log Ω cm	159
	65% mol PbO	9.76 log Ω cm	200
	65% mol PbO	7.81 log Ω cm	300
	66.7% mol PbO	1.32 log Ω cm	700
	66.7% mol PbO	0.82 log Ω cm	800
	66.7% mol PbO	0.50 log Ω cm	900
	66.7% mol PbO	0.26 log Ω cm	1000
SiO_2–CaO glass	33.6% mol CaO	0.97 log Ω cm	1500
	33.6% mol CaO	0.93–0.94 log Ω cm	1560
	33.6% mol CaO	0.79–0.80 log Ω cm	1600
	41.3% mol CaO	0.82 log Ω cm	1519
	41.3% mol CaO	0.76 log Ω cm	1550
	41.3% mol CaO	0.67–0.68 log Ω cm	1600
	45.4% mol CaO	0.65 log Ω cm	1550
	45.4% mol CaO	0.58–0.59 log Ω cm	1585
	45.4% mol CaO	0.52 log Ω cm	1622
	50% mol CaO	12.2 log Ω cm	300
	50% mol CaO	8.70 log Ω cm	400
	51.4% mol CaO	0.48–0.49 log Ω cm	1500
	51.4% mol CaO	0.47 log Ω cm	1560
	51.4% mol CaO	0.38 log Ω cm	1618
	55.2% mol CaO	0.51–0.53 log Ω cm	1499
	55.2% mol CaO	0.42–0.43 log Ω cm	1550
	55.2% mol CaO	0.34 log Ω cm	1600
SiO_2–B_2O_3 glass	2.74% wt. B_2O_3	5.30 log Ω cm	900
	2.74% wt. B_2O_3	4.72 log Ω cm	1100
	2.74% wt. B_2O_3	4.40 log Ω cm	1300
	2.74% wt. B_2O_3	4.02 log Ω cm	1500
	2.74% wt. B_2O_3	3.76 log Ω cm	1700
	2.74% wt. B_2O_3	3.56 log Ω cm	1900
	5.48% wt. B_2O_3	5.64 log Ω cm	900
	5.48% wt. B_2O_3	5.16 log Ω cm	1100
	5.48% wt. B_2O_3	4.56 log Ω cm	1300
	5.48% wt. B_2O_3	4.30 log Ω cm	1500
	5.48% wt. B_2O_3	4.10 log Ω cm	1700
	5.48% wt. B_2O_3	3.94 log Ω cm	1900

(*Continued*)

TABLE 3.12 (*Continued*) Volume Resistivity of Glass

Glass	Description	Resistivity	Temperature (°C)
	10.75% wt. B_2O_3	5.74 log Ω cm	900
	10.75% wt. B_2O_3	5.08 log Ω cm	1100
	10.75% wt. B_2O_3	4.69 log Ω cm	1300
	10.75% wt. B_2O_3	4.40 log Ω cm	1500
	10.75% wt. B_2O_3	4.16 log Ω cm	1700
	10.75% wt. B_2O_3	3.98 log Ω cm	1900
	19.37% wt. B_2O_3	5.65 log Ω cm	900
	19.37% wt. B_2O_3	4.82 log Ω cm	1100
	19.37% wt. B_2O_3	4.48 log Ω cm	1300
	19.37% wt. B_2O_3	4.22 log Ω cm	1500
	19.37% wt. B_2O3	4.00 log Ω cm	1700
	19.37% wt. B_2O_3	3.84 log Ω cm	1900
SiO_2–Al_2O_3 glass	2.83% wt. Al_2O_3	5.74 log Ω cm	700
	2.83% wt. Al_2O_3	4.82 log Ω cm	900
	2.83% wt. Al_2O_3	4.29 log Ω cm	1100
	2.83% wt. Al_2O_3	3.94 log Ω cm	1300
	2.83% wt. Al_2O_3	3.67 log Ω cm	1500
	2.83% wt. Al_2O_3	3.46 log Ωcm	1700
	2.83% wt. Al_2O_3	3.28 log Ω cm	1900
	5.51% wt. Al_2O_3	5.34 log Ω cm	700
	5.51% wt. Al_2O_3	4.65 log Ω cm	900
	5.51% wt. Al_2O_3	4.15 log Ω cm	1100
	5.51% wt. Al_2O_3	3.76 log Ω cm	1300
	5.51% wt. Al_2O_3	3.56 log Ω cm	1500
	5.51% wt. Al_2O_3	3.36 log Ω cm	1700
	5.51% wt. Al_2O_3	3.20 log Ω cm	1900
	10.86% wt. Al_2O_3	5.38 log Ω cm	700
	10.86% wt. Al_2O_3	4.54 log Ω cm	900
	10.86% wt. Al_2O_3	4.02 log Ω cm	1100
	10.86% wt. Al_2O_3	3.74 log Ω cm	1300
	10.86% wt. Al_2O_3	3.52 log Ω cm	1500
	10.86% wt. Al_2O_3	3.34 log Ω cm	1700
	10.86% wt. Al_2O_3	3.20 log Ω cm	1900
B_2O_3 glass		7.6 log Ω cm	560
		7.3 log Ω cm	600
		6.9 log Ω cm	640
		6.6 log Ω cm	680
		6.2 log Ω cm	730
		5.8 log Ω cm	780
		5.5 log Ω cm	840
B_2O_3–Na_2O glass	3.63% mol Na_2O	2.70 log Ω cm	800
	3.63% mol Na_2O	2.30 log Ω cm	900
	3.63% mol Na_2O	2.00 log Ω cm	1000

(*Continued*)

TABLE 3.12 (*Continued*) Volume Resistivity of Glass

Glass	Description	Resistivity	Temperature (°C)
	10% mol Na_2O	14.20 log Ω cm	40
	10% mol Na_2O	13.21 log Ω cm	60
	10% mol Na_2O	12.40 log Ω cm	80
	10% mol Na_2O	11.61 log Ω cm	100
	12.1% mol Na_2O	2.43 log Ω cm	700
	12.1% mol Na_2O	1.89 log Ω cm	800
	12.1% mol Na_2O	1.48 log Ω cm	900
	16% mol Na_2O	15.89 log Ω cm	40
	16% mol Na_2O	15.08 log Ω cm	60
	16% mol Na_2O	14.32 log Ω cm	80
	16% mol Na_2O	13.58 log Ω cm	100
	17.3% mol Na_2O	1.39 log Ω cm	850
	17.3% mol Na_2O	1.18 log Ω cm	900
	17.3% mol Na_2O	0.89 log Ω cm	1000
	20% mol Na_2O	13.86 log Ω cm	40
	20% mol Na_2O	12.91 log Ω cm	60
	20% mol Na_2O	12.05 log Ω cm	80
	20% mol Na_2O	11.28 log Ω cm	100
	21.9% mol Na_2O	1.29 log Ω cm	800
	21.9% mol Na_2O	0.94 log Ω cm	900
	21.9% mol Na_2O	0.65 log Ω cm	1000
	27.5% mol Na_2O	1.00 log Ω cm	800
	27.5% mol Na_2O	0.70 log Ω cm	900
	30% mol Na_2O	11.90 log Ω cm	40
	30% mol Na_2O	10.14 log Ω cm	60
	30% mol Na_2O	9.43 log Ω cm	80
	30% mol Na_2O	8.82 log Ω cm	100
	32.8% mol Na_2O	1.02 log Ω cm	700
	32.8% mol Na_2O	0.60 log Ω cm	800
	32.8% mol Na_2O	0.40 log Ω cm	900
	40% mol Na_2O	10.48 log Ω cm	40
	40% mol Na_2O	9.73 log Ω cm	60
	40% mol Na_2O	9.08 log Ω cm	80
	40% mol Na_2O	8.46 log Ω cm	100
B_2O_3–CaO glass	33.3% mol CaO	14.40 log Ω cm	150
	33.3% mol CaO	13.92 log Ω cm	200
	33.3% mol CaO	13.50 log Ω cm	250
	33.3% mol CaO	13.16 log Ω cm	300
	33.3% mol CaO	3.10 log Ω cm	850
	33.3% mol CaO	2.25 log Ω cm	950
	33.3% mol CaO	1.52 log Ω cm	1050

(*Continued*)

TABLE 3.12 (*Continued*) Volume Resistivity of Glass

Glass	Description	Resistivity	Temperature (°C)
	33.3% mol CaO	1.10 log Ω cm	1150
	33.3% mol CaO	0.85 log Ω cm	1250
	40.0% mol CaO	2.97 log Ω cm	850
	40.0% mol CaO	2.06 log Ω cm	950
	40.0% mol CaO	1.40 log Ω cm	1050
	40.0% mol CaO	0.98 log Ω cm	1150
	40.0% mol CaO	0.75 log Ω cm	1250
	55.4% mol CaO	6.13 log Ω cm	750
	55.4% mol CaO	3.86 log Ω cm	850
	55.4% mol CaO	2.46 log Ω cm	950
	55.4% mol CaO	1.70 log Ω cm	1050
	55.4% mol CaO	1.22 log Ω cm	1150

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.13 Tangent Loss in Glass

Glass	Composition	Frequency	Tangent Loss (tan δ)	Temperature
SiO_2 glass	Pure	100 Hz	0.00002	25°C
		100 Hz	0.00052	200°C
		100 Hz	0.080	300°C
		100 Hz	1.0	400°C
		1 kHz	0.00002	25°C
		1 kHz	0.00012	200°C
		1 kHz	0.0072	300°C
		1 kHz	0.2	400°C
		10 kHz	0.00002	25°C
		10 kHz	0.00004	200°C
		10 kHz	0.00072	300°C
		10 kHz	0.022	400°C
		9.4 GHz	1.5×10^{-4}	20°C
		9.4 GHz	1.8×10^{-4}	200°C
		9.4 GHz	2.0×10^{-4}	400°C
		9.4 GHz	2.9×10^{-4}	600°C
		9.4 GHz	4.8×10^{-4}	800°C
		9.4 GHz	11×10^{-4}	1000°C
		9.4 GHz	25×10^{-4}	1200°C
		9.4 GHz	46×10^{-4}	1400°C
SiO_2–Na_2O glass	16% mol Na_2O	4.5×10^8 Hz	0.0058	20°C
	19.5% mol Na_2O	1 kHz	0.144	Room temp.
	19.5% mol Na_2O	3 kHz	0.0984	Room temp.
	19.5% mol Na_2O	5 kHz	0.0832	Room temp.

(*Continued*)

TABLE 3.13 (*Continued*) Tangent Loss in Glass

Glass	Composition	Frequency	Tangent Loss (tan δ)	Temperature
	19.5% mol Na_2O	10 kHz	0.0656	Room temp.
	19.5% mol Na_2O	30 kHz	0.0492	Room temp.
	19.5% mol Na_2O	50 kHz	0.0428	Room temp.
	19.5% mol Na_2O	100 kHz	0.0364	Room temp.
	19.5% mol Na_2O	300 kHz	0.0295	Room temp.
	20% mol Na_2O	4.5×10^8 Hz	0.0073	20°C
	22.2% mol Na_2O	4.5×10^8 Hz	0.0081	20°C
	24.4% mol Na_2O	1 kHz	0.2207	Room temp.
	24.4% mol Na_2O	3 kHz	0.1455	Room temp.
	24.4% mol Na_2O	5 kHz	0.1194	Room temp.
	24.4% mol Na_2O	10 kHz	0.0916	Room temp.
	24.4% mol Na_2O	30 kHz	0.0652	Room temp.
	24.4% mol Na_2O	50 kHz	0.0563	Room temp.
	24.4% mol Na_2O	100 kHz	0.0456	Room temp.
	24.4% mol Na_2O	300 kHz	0.0369	Room temp.
	28.6% mol Na_2O	4.5×10^8 Hz	0.0102	20°C
	29.4% mol Na_2O	1 kHz	0.4923	Room temp.
	29.4% mol Na_2O	3 kHz	0.3027	Room temp.
	29.4% mol Na_2O	5 kHz	0.2426	Room temp.
	29.4% mol Na_2O	10 kHz	0.1764	Room temp.
	29.4% mol Na_2O	30 kHz	0.1172	Room temp.
	29.4% mol Na_2O	50 kHz	0.0972	Room temp.
	29.4% mol Na_2O	100 kHz	0.0758	Room temp.
	29.4% mol Na_2O	300 kHz	0.0568	Room temp.
	34.3% mol Na_2O	1 kHz	0.10324	Room temp.
	34.3% mol Na_2O	3 kHz	0.6520	Room temp.
	34.3% mol Na_2O	5 kHz	0.5280	Room temp.
	34.3% mol Na_2O	10 kHz	0.3752	Room temp.
	34.3% mol Na_2O	30 kHz	0.2314	Room temp.
	34.3% mol Na_2O	50 kHz	0.1864	Room temp.
	34.3% mol Na_2O	100 kHz	0.1388	Room temp.
	34.3% mol Na_2O	300 kHz	0.0936	Room temp.
	36% mol Na_2O	4.5×10^8 Hz	0.0162	20°C
	39.3% mol Na_2O	10 kHz	0.6338	Room temp.
	39.3% mol Na_2O	30 kHz	0.3835	Room temp.
	39.3% mol Na_2O	50 kHz	0.3032	Room temp.
	39.3% mol Na_2O	100 kHz	0.2144	Room temp.
	39.3% mol Na_2O	300 kHz	0.1402	Room temp.
SiO_2–PbO glass	40% mol PbO	32 GHz	0.015	–150°C
	40% mol PbO	32 GHz	0.018	–100°C
	40% mol PbO	32 GHz	0.020	–50°C
	40% mol PbO	32 GHz	0.022	0°C

(*Continued*)

TABLE 3.13 (*Continued*) Tangent Loss in Glass

Glass	Composition	Frequency	Tangent Loss (tan δ)	Temperature
	40% mol PbO	32 GHz	0.024	50°C
	40% mol PbO	100 GHz	0.005	Room temp.
	40% mol PbO	1000 GHz	0.050	Room temp.
SiO_2–B_2O_3 glass	46.3% mol B_2O_3	10 GHz	0.0014	
SiO_2–Al_2O_3 glass	0.5% mol Al_2O_3	32 kHz	0.0025	50 K
	0.5% mol Al_2O_3	32 kHz	0.0021	100 K
	0.5% mol Al_2O_3	32 kHz	0.0026	150 K
B_2O_3 glass	B_2O_3 glass	1 MHz	0.0004	100°C
		1 MHz	0.0005	200°C
		1 MHz	0.0009	300°C
		32 kHz	0.00005	50 K
		32 kHz	0.00011	100 K
		32 kHz	0.0007	150 K
		32 kHz	0.0010	200 K
		32 kHz	0.0008	250 K
		32 kHz	0.0003	300 K
B_2O_3–Na_2O glass	8% mol Na_2O	1 MHz	0.0025	Room temp.
	10% mol Na_2O	1 MHz	0.0022	Room temp.
	10% mol Na_2O	1 kHz	0.0003	134.5°C
	10% mol Na_2O	1 kHz	0.0009	214°C
	10% mol Na_2O	1 kHz	0.0038	277°C
	10% mol Na_2O	1 kHz	0.0066	298°C
	12.5% mol Na_2O	1 kHz	0.0005	134.5°C
	12.5% mol Na_2O	1 kHz	0.0022	214°C
	12.5% mol Na_2O	1 kHz	0.0100	277°C
	12.5% mol Na_2O	1 kHz	0.0170	298°C
	15% mol Na_2O	1 kHz	0.0015	134.5°C
	15% mol Na_2O	1 kHz	0.0064	214°C
	15% mol Na_2O	1 kHz	0.0296	277°C
	15% mol Na_2O	1 kHz	0.0477	298°C
	16% mol Na_2O	1 MHz	0.0031	Room temp.
	20% mol Na_2O	1 kHz	0.0009	16°C
	20% mol Na_2O	1 kHz	0.0026	90.5°C
	20% mol Na_2O	1 kHz	0.0149	157°C
	20% mol Na_2O	1 kHz	0.0890	219°C
	20% mol Na_2O	1 kHz	0.2480	274°C
	25% mol Na_2O	1 kHz	0.0022	16°C
	25% mol Na_2O	1 MHz	0.0063	Room temp.
	25% mol Na_2O	1 kHz	0.0150	90.5°C
	25% mol Na_2O	1 kHz	0.1080	157°C

(*Continued*)

TABLE 3.13 (*Continued*) Tangent Loss in Glass

Glass	Composition	Frequency	Tangent Loss (tan δ)	Temperature
	28% mol Na_2O	1 MHz	0.0081	Room temp.
B_2O_3–CaO glass	33.3% mol CaO	2 MHz	0.001	25°C
	33.3% mol CaO	2 MHz	0.002	100°C
	33.3% mol CaO	2 MHz	0.0025	200°C
	33.3% mol CaO	2 MHz	0.0035	300°C
	33.3% mol CaO	2 MHz	0.0045	400°C
	33.3% mol CaO	2 MHz	0.0055	500°C
	33.3% mol CaO	2 MHz	0.007	550°C

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

TABLE 3.14 Electrical Permittivity of Glass

Glass	Composition	Frequency	Electrical Permittivity	Temperature (°C)
SiO_2 glass	Pure	100 Hz	4.0	25
		100 Hz	4.0	200
		100 Hz	4.0	300
		100 Hz	5.5	400
		1 kHz	4.0	25
		1 kHz	4.0	200
		1 kHz	4.0	300
		1 kHz	4.1	400
		10 kHz	4.0	25
		10 kHz	4.0	200
		10 kHz	4.0	300
		10 kHz	4.0	400
		9.4 GHz	3.81	20
		9.4 GHz	3.83	200
		9.4 GHz	3.84	400
		9.4 GHz	3.86	600
		9.4 GHz	3.88	800
		9.4 GHz	3.91	1000
		9.4 GHz	3.93	1200
		9.4 GHz	3.96	1400
		10 GHz	3.82	20
		10 GHz	3.82	220
		10 GHz	3.91	888
		10 GHz	3.98	1170

(*Continued*)

TABLE 3.14 (*Continued*) Electrical Permittivity of Glass

Glass	Composition	Frequency	Electrical Permittivity	Temperature (°C)
		10 GHz	4.05	1335
		10 GHz	4.07	1420
		10 GHz	4.09	1480
		10 GHz	4.11	1526
		10 GHz	4.12	1584
		10 GHz	4.15	1602
		10 GHz	4.12	1647
		10 GHz	4.04	1764
		10 GHz	4.05	1764
SiO_2–Na_2O glass	16% mol Na_2O	4.5×10^8 Hz	6.01	20
	19.5% mol Na_2O	1 kHz	9.40	Room temp.
	19.5% mol Na_2O	3 kHz	8.97	Room temp.
	19.5% mol Na_2O	5 kHz	8.56	Room temp.
	19.5% mol Na_2O	10 kHz	8.26	Room temp.
	19.5% mol Na_2O	30 kHz	8.00	Room temp.
	19.5% mol Na_2O	50 kHz	7.88	Room temp.
	19.5% mol Na_2O	100 kHz	7.74	Room temp.
	19.5% mol Na_2O	300 kHz	7.62	Room temp.
	20% mol Na_2O	4.5×10^8 Hz	6.48	20
	22.2% mol Na_2O	4.5×10^8 Hz	6.85	20
	24.4% mol Na_2O	1 kHz	11.62	Room temp.
	24.4% mol Na_2O	3 kHz	10.61	Room temp.
	24.4% mol Na_2O	5 kHz	10.21	Room temp.
	24.4% mol Na_2O	10 kHz	9.74	Room temp.
	24.4% mol Na_2O	30 kHz	9.30	Room temp.
	24.4% mol Na_2O	50 kHz	9.14	Room temp.
	24.4% mol Na_2O	100 kHz	8.91	Room temp.
	24.4% mol Na_2O	300 kHz	8.75	Room temp.
	28.6% mol Na_2O	4.5×10^8 Hz	7.62	20
	29.4% mol Na_2O	1 kHz	17.52	Room temp.
	29.4% mol Na_2O	3 kHz	14.23	Room temp.
	29.4% mol Na_2O	5 kHz	13.19	Room temp.
	29.4% mol Na_2O	10 kHz	12.08	Room temp.
	29.4% mol Na_2O	30 kHz	11.21	Room temp.
	29.4% mol Na_2O	50 kHz	10.86	Room temp.
	29.4% mol Na_2O	100 kHz	10.47	Room temp.
	29.4% mol Na_2O	300 kHz	10.15	Room temp.
	34.3% mol Na_2O	1 kHz	38.61	Room temp.

(*Continued*)

TABLE 3.14 (*Continued*) Electrical Permittivity of Glass

Glass	Composition	Frequency	Electrical Permittivity	Temperature (°C)
	34.3% mol Na_2O	3 kHz	21.30	Room temp.
	34.3% mol Na_2O	5 kHz	18.13	Room temp.
	34.3% mol Na_2O	10 kHz	15.22	Room temp.
	34.3% mol Na_2O	30 kHz	13.28	Room temp.
	34.3% mol Na_2O	50 kHz	12.57	Room temp.
	34.3% mol Na_2O	100 kHz	11.78	Room temp.
	34.3% mol Na_2O	300 kHz	11.14	Room temp.
	36% mol Na_2O	4.5×10^8 Hz	9.40	20
	39.3% mol Na_2O	10 kHz	22.08	Room temp.
	39.3% mol Na_2O	30 kHz	16.56	Room temp.
	39.3% mol Na_2O	50 kHz	15.06	Room temp.
	39.3% mol Na_2O	100 kHz	13.55	Room temp.
	39.3% mol Na_2O	300 kHz	12.43	Room temp.
SiO_2–PbO glass	40% mol PbO	32 GHz	4.25	–150
	40% mol PbO	32 GHz	4.30	–100
	40% mol PbO	32 GHz	4.40	–50
	40% mol PbO	32 GHz	4.45	0
	40% mol PbO	32 GHz	5.00	50
SiO_2–B_2O_3 glass	46.3% mol B_2O_3	10 GHz	3.55	
B_2O_3 glass	Pure	1 kHz	3.17	500
		1 kHz	3.21	550
		1 kHz	3.27	580
		3 kHz	3.15	500
		3 kHz	3.17	550
		3 kHz	3.18	580
		3 kHz	3.21	620
		3 kHz	3.25	650
		10 kHz	3.13	500
		10 kHz	3.14	550
		10 kHz	3.145	580
		10 kHz	3.15	620
		10 kHz	3.15	650
		10 kHz	3.16	700
		50 kHz	3.10	500
		50 kHz	3.12	550
		50 kHz	3.115	580
		50 kHz	3.05	620

(*Continued*)

TABLE 3.14 (*Continued*) Electrical Permittivity of Glass

Glass	Composition	Frequency	Electrical Permittivity	Temperature (°C)
		50 kHz	3.10	650
		50 kHz	3.09	700
		50 kHz	3.06	750
		50 kHz	3.04	800
B_2O_3–Na_2O glass	4.08% mol Na_2O	56.8 MHz	3.72	Room temp.
	7.35% mol Na_2O	56.8 MHz	4.20	Room temp.
	14.15% mol Na_2O	56.8 MHz	4.94	Room temp.
	17.31% mol Na_2O	56.8 MHz	5.27	Room temp.
	24.77% mol Na_2O	56.8 MHz	6.24	Room temp.
	31.98% mol Na_2O	56.8 MHz	7.03	Room temp.
	10% mol Na_2O	1 kHz	5.00	73
	10% mol Na_2O	1 kHz	5.05	134.5
	10% mol Na_2O	1 kHz	5.15	214
	10% mol Na_2O	1 kHz	5.45	277
	10% mol Na_2O	1 kHz	5.60	298
	12.5% mol Na_2O	1 kHz	5.45	73
	12.5% mol Na_2O	1 kHz	5.60	134.5
	12.5% mol Na_2O	1 kHz	5.75	214
	12.5% mol Na_2O	1 kHz	6.30	277
	12.5% mol Na_2O	1 kHz	6.65	298
	15% mol Na_2O	1 kHz	5.80	73
	15% mol Na_2O	1 kHz	6.00	134.5
	15% mol Na_2O	1 kHz	6.50	214
	15% mol Na_2O	1 kHz	7.80	277
	15% mol Na_2O	1 kHz	8.60	298
	20% mol Na_2O	1 kHz	6.15	16
	20% mol Na_2O	1 kHz	6.43	90.5
	20% mol Na_2O	1 kHz	7.45	157
	20% mol Na_2O	1 kHz	11.85	219
	20% mol Na_2O	1 kHz	31.00	274
	25% mol Na_2O	1 kHz	7.50	16
	25% mol Na_2O	1 kHz	8.90	90.5
	25% mol Na_2O	1 kHz	17.30	157

Source: Data compiled by J. S. Park from *Handbook of Glass Data, Part A and Part B*, O. V. Mazurin, M. V. Streltsina, and T. P. Shvaiko-Shvaikovskaya, Copyright 1983, Elsevier.

Chemical Properties

TABLE 3.15 Diffusion of Gas in Glass[a]

Diffusing Gas	Matrix Glass	$D_o \times 10^{-4}$ (cm²/s)	$\Delta H_{diffusion}$ (kJ/mol)
He	Vitreous silica	5.41	25.2
Ne	Vitreous silica	1.87	45.3
Ar	Vitreous silica	0.059	97
H_2	Vitreous silica	5.65	43.4
D_2	Vitreous silica	5.01	44.0
O_2	Vitreous silica	2.88	113
He	Corning 0120	28.9	44.2
He	Corning 3320	6.83	29.2
D_2	Corning 3320	1.45	38.7
He	Corning 7052	7.40	32.4
Ne	Corning 7052	22.0	63.4
D_2	Corning 7052	20.9	54.2
He	Corning 7740	4.55	26.8
Ne	Corning 7740	2.72	49.3
D_2	Corning 7740	13.8	48.7
He	Corning 7809	16.8	42.8
He	Corning 7900	4.53	22.9
D_2	Corning 7900	1.87	36.3
He	Corning 7971	6.63	25.3
Ne	Corning 7971	1.48	42.5
D_2	Corning 7971	2.65	37.5
He	Corning 8830	3.64	29.0

Source: Data from Shelby, J., *Handbook of Gas Diffusion in Solids and Melts,* ASM International, Materials Park, OH, 1996.

[a] The diffusion coefficient D at a temperature T (K) is given by the following:

$$D = D_o e^{-\Delta H/RT}$$

For D_o in m²/s, multiply values in cm²/s by 10^{-4}.

4

Polymers

Physical Properties

TABLE 4.1 Periodic Table of Elements in Polymeric Materials

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA																	VIIA
1 H	IIA											IIIA	IVA	VA	VIA	VIIA	
													6 C	7 N	8 O	9 F	
		IIIB	IVB	VB	VIB	VIIB	-----	VIII	-----	IB	IIB		14 Si				

TABLE 4.2 Periodic Table of Carbon Bond Lengths (Å)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA																	VIIA
H 1.06	IIA											IIIA	IVA	VA	VIA	VIIA	
	Be 1.93											B 1.56	C 1.2	N 1.47	O 1.43	F 1.55	
		IIIB	IVB	VB	VIB	VIIB	-----	VIII	-----	IB	IIB	Al 2.24	Si 1.8	P 1.87	S 1.81	Cl 1.7	
					Cr 1.92		Fe 1.94	Co 1.93	Ni 18.2				Ge 1.98	As 1.98	Se 1.98	Br 1.9	
					Mo 2.08				Pd 2.27			In 2.16	Sn 2.15	Sb 2.16	Te 2.05	I 2.1	
					W 2.06						Hg 2.07		Pb 2.29	Bi 2.30			

TABLE 4.3 Carbon Bond Lengths

Group No.	Element	At. No.	Sym.	Bond Length (Å)		Bond Type
1	Hydrogen	1	H	1.056	±1.115	
2	Beryllium	4	Be	1.93		
6	Chromium	24	Cr	1.92	±0.04	
	Molybdenum	42	Mo	2.08	±0.04	
	Tungsten	74	W	2.06	±0.01	
8	Iron	26	Fe	1.94	±0.02	
9	Cobalt	27	Co	1.93	±0.02	
10	Nickel	28	Ni	1.82	±0.03	
	Palladium	46	Pd	2.27	±0.04	
12	Mercury	80	Hg	2.07	±0.01	
13	Aluminum	13	Al	2.24	±0.04	
	Boron	5	B	1.56	±0.01	
	Indium	49	In	2.16	±0.04	
14	Carbon	6	C	1.20	±1.54	Alkyls (CH_3XH_3)
	Germanium	32	Ge	1.98	±0.03	Alkyls (CH_3XH_3)
	Lead	82	Pb	2.29	±0.05	Alkyls (CH_3XH_3)
	Silicon	14	Si	1.865	±0.008	Alkyls (CH_3XH_3)
				1.84	±0.01	Aryls (C_6H5XH_3)
				1.88	±0.01	Neg. Subst. (CH_3XCI_3)
	Tin	50	Sn	2.143	±0.008	Alkyls (CH_3XH_3)
				2.18	±0.02	Neg. Subst. (CH_3XCI_3)

(*Continued*)

TABLE 4.3 (*Continued*) Carbon Bond Lengths

Group No.	Element	At. No.	Sym.	Bond Length (Å)		Bond Type
15	Arsenic	33	As	1.98	±0.02	Paraffinic $(CH_3)_3X$
	Bismuth	83	Bi	2.30		Paraffinic $(CH_3)_3X$
	Nitrogen	7	N	1.47	±1.1	
	Phosphorus	15	P	1.87	±0.02	Paraffinic $(CH_3)_3X$
	Antimony	51	Sb	2.202	±0.016	Paraffinic $(CH_3)_3X$
16	Oxygen	8	O	1.43	±1.15	
	Sulfur	16	S	1.81	±1.55	
	Selenium	34	Se	1.98	±1.71	
	Tellurium	52	Te	2.05	±0.14	
17	Bromine	35	Br	1.937	±0.003	Paraffinic (monosubstituted) (CH_3X)
			Br	1.937	±0.003	Paraffinic (disubstituted) (CH_2X_2)
			Br	1.89	±0.01	Olefinic $(CH_2{:}CHX)$
				1.85	±0.01	Aromatic (C_6H_3X)
				1.79	±0.01	Acetylenic (HC:CX)
	Chlorine	17	Cl	1.767	±0.002	Paraffinic (monosubstituted) (CH_3X)
			Cl	1.767	±0.002	Paraffinic (disubstituted) (CH_2X_2)
			Cl	1.72	±0.01	Olefinic $(CH_2{:}CHX)$
				1.70	±0.01	Aromatic (C_6H_3X)
				1.79	±0.01	Acetylenic (HC:CX)
	Fluorine	9	F	1.831	±0.005	Paraffinic (monosubstituted) (CH_3X)
			F	1.334	±0.004	Paraffinic (disubstituted) (CH_2X_2)
			F	1.325	±0.1	Olefinic $(CH_2{:}CHX)$
				1.30	±0.01	Aromatic (C_6H_3X)
				1.635	±0.004	Acetylenic (HC:CX)
	Iodine	53	I	2.13	±0.1	Paraffinic (monosubstituted) (CH_3X)
			I	2.13	±0.1	Paraffinic (disubstituted) (CH_2X_2)
			I	2.092	±0.005	Olefinic $(CH_2{:}CHX)$
				2.05	±0.01	Aromatic (C_6H_3X)
				1.99	±0.02	Acetylenic (HC:CX)

Source: Data from D. R. Lide (Ed.), *CRC Handbook of Chemistry and Physics*, CRC Press, Boca Raton, 1990; L. E. Sutton (Ed.), *Tables of Interatomic Distances and Configuration in Molecules and Ions*, Spec. Publ. No. 11, Chemical Society, London, 1958.

TABLE 4.4 Carbon Bond Lengths in Polymers

Bond Type	Polymer Type	Bond Length (Å)	
Carbon–carbon Single bond	Paraffinic	1.541	±0.003
	In diamond (18°C)	1.54452	±0.00014
Partial double bond	1. Shortening of single bond in the presence of carbon–carbon double bond, for example, (CH_2), C_3CH_2; or of aromatic ring, for example, C_6H_5 CH_3	1.53	±0.01
	2. Shortening in the presence of a carbon oxygen double bond, for example, CH_3CHO	1.516	±0.005
	3. Shortening in the presence of two carbon oxygen double bonds, for example, $(CO_2H)_2$	1.49	±0.01
	4. Shortening in the presence of a carbon oxygen triple bond, for example, $CH_3C{:}CH$	1.460	±0.003
	5. In compounds with tendency to dipole formation, for example, C:C.C:N	1.44	±0.01
	6. In graphite (at 15°C)	1.4210	±0.0001
	7. In aromatic compounds	1.395	±0.003
	8. In the presence of a carbon–carbon triple bonds, for example, HC≡C−C≡CH	1.373	±0.004
Double bonds	1. Simple	1.337	±0.006
	2. Part triple bond, for example, $CH_2{:}C{:}CH_2$	1.309	±0.005
Triple bond	1. Simple, for example, C_2H_2	1.204	±0.002
	2. Conjugated, for example, $CH_3 \cdot (C{:}C)_2 \cdot H$ for example, C_5H_5N	1.206	±0.004
Carbon–hydrogen	1. Paraffinic		
	a. In methane	1.091	
	b. In monosubstituted carbon	1.101	
	c. In disubstituted carbon	1.073	
	d. In trisubstituted carbon	1.070	
	2. Olefinic, for example, $CH_2{:}CH_2$	1.07	±0.01
	3. Aromatic in C_6H_6	1.094	±0.006
	4. Acetylenic, for example, $CH_2{:}C.X$	1.056	±0.003
	5. Shortening in presence of a carbon oxygen triple bond, for example, CH_3CN	1.115	±0.004
	6. In small rings, for example, $(CH_2)_2S$	1.081	±0.007
Carbon–nitrogen			
Single bond	1. Paraffinic		
	a. Four covalent nitrogen	1.479	
	b. Three covalent nitrogen	1.472	
	2. In C–N•, for example, CH_3NO_2	1.475	±0.010
	3. Aromatic in $C_6H_5NHCOCH_3$	1.426	±0.012
	4. Shortened (partial double bond) in h. heterocyclic systems,	1.352	±0.005
	5. Shortened (partial double bond) in N–C•O, for example, $HCONH_2$	1.322	±0.003
Triple bond	a. In R.C:N	1.158	±0.002

Source: Data from D. R. Lide (Ed.), *CRC Handbook of Chemistry and Physics*, CRC Press, Boca Raton, 1990; L. E. Sutton (Ed.), *Tables of Interatomic Distances and Configuration in Molecules and Ions*, Spec. Publ. No. 11, Chemical Society, London, 1958.

TABLE 4.5 Bond Angle Values between Elements

Element	Bond	Compound	Bond Angle (°)		
B	H–B–H	B_2H_6	121.5	±	7.5
B	Br–B–Br	BBr_3	120	±	6
B	Cl–B–Cl	BCl_3	120	±	3
B	F–B–F	BF_3	120		
B	O–B–O	$B(OH)_3$	119.7		
N	B–N–B	$(BClNH)_3$	121		
N	F–N–F	NF_3	102.5	±	1.5
N	H–N–C	HNCS	130.25	±	0.25
N	H–N–N	N_3H	112.65	±	0.5
N	O–N–O	NO_2Cl	126	±	2
N	O–N–O	NO_2	134.1	±	0.25
O	O–O–H	H_2O_2	100	±	2
S	Br–S–Br	$SOBr_2$	96	±	2
S	F–S–F	SOF_2	92.8	±	1
S	O–S–O	SO_2	119.54		

Source: O. Kennard, In: R. C. Weast (Ed.), *Handbook of Chemistry and Physics*, 69th Edn., CRC Press, Boca Raton, FL, 1988, F–167.

TABLE 4.6 Specific Gravity of Polymers

Class	Polymer	Specific Gravity (ASTM D792)
ABS resins: Molded, extruded	Medium impact	1.05–1.07
	High impact	1.02–1.04
	Very high impact	1.01–1.06
	Low temperature impact	1.02–1.04
	Heat resistant	1.06–1.08
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	1.17–1.19
	General purpose, type II	1.18–1.20
	Moldings:	
	Grades 5, 6, 8	1.18–1.19
	High impact grade	1.12–1.16
	Thermoset carbonate	
	Allyl diglycol carbonate	1.32
	Alkyds: Molded	
	Putty (encapsulating)	2.05–2.15
	Rope (general purpose)	2.20–2.22
	Granular (high-speed molding)	2.21–2.24
	Glass reinforced (heavy duty parts)	2.02–2.10

(*Continued*)

TABLE 4.6 (*Continued*) Specific Gravity of Polymers

Class	Polymer	Specific Gravity (ASTM D792)
Cellulose acetate: Molded, extruded	ASTM grade:	
	H4-1	1.29–1.31
	H2-1	1.25–1.31
	MH-1, MH-2	1.24–1.31
	MS-1, MS-2	1.23–1.30
	S2-1	1.22–1.30
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	1.22
	MH	1.18–1.20
	S2	1.15–1.18
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	1.22
	3	1.20–1.21
	6	1.19
	Chlorinated polymers:	
	Chlorinated polyether	1.4
	Chlorinated polyvinyl chloride	1.54
	Polycarbonates:	
	Polycarbonate	1.2
	Polycarbonate (40% glass–fiber-reinforced)	1.51
	Chlorinated polymers	
	Chlorinated polyether	1.4
	Chlorinated polyvinyl chloride	1.54
	Polycarbonates	
	Polycarbonate	1.2
	Polycarbonate (40% glass–fiber-reinforced)	1.51
Diallyl phthalates: Molded	Orlon filled	1.31–1.35
	Dacron filled	1.40–1.65
	Asbestos filled	1.50–1.96
	Glass fiber filled	1.55–1.85
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	2.10–2.15
	Polytetrafluoroethylene (PTFE)	2.1–2.3
	Ceramic reinforced (PTFE)	2.2–2.4
	Fluorinated ethylene propylene (FEP)	2.12–2.17
	Polyvinylidene fluoride (PVDF)	1.77
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	1.15
	Cast flexible	1.14–1.18
	Molded	1.80–2.0

(*Continued*)

TABLE 4.6 (*Continued*) Specific Gravity of Polymers

Class	Polymer	Specific Gravity (ASTM D792)
	General purpose glass cloth laminate	1.8
	High strength laminate	1.84
	Filament wound composite	2.17–2.18
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides)	
	Cast, rigid	1.24
	Molded	1.7
	Glass cloth laminate	1.97
	Epoxy novolacs	
	Cast, rigid	1.22
	Glass cloth laminate	1.97
Melamines: Molded	Filler and type	
	Unfilled	1.48
	Cellulose electrical	1.43–1.50
	Glass fiber	1.8–2.0
	Alpha cellulose and mineral	1.5, 1.72 (mineral)
Nylons: Molded, extruded	Type 6	
	General purpose	1.12–1.14
	Glass fiber (30%) reinforced	1.35–1.42
	Cast	1.15
	Flexible copolymers	1.12–1.14
	Type 8	1.09
	Type 11	1.04
	Type 12	1.01
	6/6 Nylon	
	General purpose molding	1.13–1.15
	Glass–fiber-reinforced	1.37–1.47
	Glass fiber molybdenum disulfide filled	1.37–1.41
	General purpose extrusion	1.13–1.15
	6/10 Nylon	
	General purpose	1.07–1.09
	Glass fiber (30%) reinforced	1.3
Phenolics: Molded	Type and filler	
	General: woodflour and flock	1.32–1.46
	Shock: paper, flock, or pulp	1.34–1.46
	High shock: chopped fabric or cord	1.36–1.43
	Very high shock: glass fiber	1.75–1.90
Polyacetals	Homopolymer:	
	Standard	1.425
	20% Glass reinforced	1.56
	22% TFE reinforced	1.54

(*Continued*)

TABLE 4.6 (*Continued*) Specific Gravity of Polymers

Class	Polymer	Specific Gravity (ASTM D792)
	Copolymer:	
	Standard	1.41
	25% Glass reinforced	1.61
	High flow	1.41
Phenolics: Molded	Arc resistant—mineral	1.5–3.0
	Rubber phenolic—woodflour or flock	1.24–1.35
	Rubber phenolic—chopped fabric	1.30–1.35
	Rubber phenolic—asbestos	1.60–1.65
	ABS—polycarbonate alloy	1.14
	PVC—acrylic alloy	
	PVC—acrylic sheet	1.35
	PVC—acrylic injection molded	1.3
Polyimides	Unreinforced	1.19–1.47
	Glass reinforced	1.60–1.95
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	1.31
	Glass reinforced grades	1.52
	Glass reinforced self extinguishing	1.58
	General purpose grade	1.31
	Glass reinforced grade	1.45
	Asbestos-filled grade	1.46
Polyesters: Thermosets	Cast polyester	
	Rigid	1.12–1.46
	Flexible	1.06–1.25
Reinforced polyester moldings	High strength (glass fibers)	1.8–2.0
	Heat and chemical resistant (asbestos)	1.5–1.75
	Sheet molding compounds, general purpose	1.65–1.80
Phenylene oxides	SE-100	1.1
	SE-1	1.06
	Glass–fiber-reinforced	1.21–1.27
Phenylene oxides (Noryl)	Standard	1.24
	Glass–fiber-reinforced	1.41–1.55
	Polyarylsulfone	1.36
Polypropylene	General purpose	0.900–0.910
	High impact	0.900–0.910
	Asbestos filled	1.11–1.36
	Glass reinforced	1.04–1.22
	Flame retardant	1.2
Polyphenylene sulfide	Standard	1.34–1.35
	40% Glass reinforced	1.6–1.64

(*Continued*)

TABLE 4.6 (*Continued*) Specific Gravity of Polymers

Class	Polymer	Specific Gravity (ASTM D792)
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	0.910–0.925
	Melt index 6–26	0.918–0.925
	Melt index 200	0.91
	Type II—medium density (0.926–0.940)	
	Melt index 20	0.93
	Melt index 1.0–1.9	0.930–0.940
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	0.96
	Melt index 0.1–12.0	0.950–0.955
	Melt index 1.5–15	0.96
	High molecular weight	0.94
Olefin copolymers: Molded	EEA (ethylene ethyl acrylate)	0.93
	EVA (ethylene vinyl acetate)	0.94
	Ethylene butene	0.95
	Propylene–ethylene	0.91
	Ionomer	0.94
	Polyallomer	0.898–0.904
Polystyrenes: Molded	Polystyrenes	
	General purpose	1.04
	Medium impact	1.04–1.07
	High impact	1.04–1.07
	Glass fiber (30%) reinforced	1.29
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	1.04–1.07
	Glass fiber (30%) reinforced SAN	1.35
Polyvinyl chloride and copolymers: Molded, extruded	Nonrigid—general	1.20–1.55
	Nonrigid—electrical	1.16–1.40
	Rigid—normal impact	1.32–1.44
	Vinylidene chloride	1.68–1.75
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	1.88
	Granular (silica) reinforced silicones	1.86–2.00
	Woven glass fabric/silicone laminate	1.75–1.8
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	1.45–1.55
	Cellulose filled (ASTM type 2)	1.52
	Woodflour filled	1.45–1.49

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.7 Specific Heat of Polymers

Polymer Class	Polymer Subclass	Specific Heat (Btu/lb/°F)
ABS resins; Molded, extruded	Medium impact	0.36–0.38
	High impact	0.36–0.38
	Very high impact	0.36–0.38
	Low temperature impact	0.35–0.38
	Heat resistant	0.37–0.39
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	0.35
	General purpose, type II	0.35
	Moldings:	
	Grades 5, 6, 8	0.35
	High impact grade	0.34
Thermoset carbonate	Allyl diglycol carbonate	0.3
Cellulose acetate: Molded, extruded	ASTM grade:	
	H6-1	0.3–0.42
	H4-1	0.3–0.42
	H2-1	0.3–0.42
	MH-1, MH-2	0.3–0.42
	MS-1, MS-2	0.3–0.42
	S2-1	0.3–0.42
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	0.3–0.4
	MH	0.3–0.4
	S2	0.3–0.4
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	0.3–0.4
	3	0.3–0.4
	6	0.3–0.4
Chlorinated polyvinyl chloride	Chlorinated polyvinyl chloride	0.3
Polycarbonate	Polycarbonate	0.3
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	0.22
	Polytetrafluoroethylene (PTFE)	0.25
	Fluorinated ethylene propylene (FEP)	0.28
	Polyvinylidene fluoride (PVDF)	0.33
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	0.4–0.5
	High strength laminate	0.21
	Filament wound composite	0.24
Nylons: Molded, extruded	Type 6	
	General purpose	0.4
	Cast	0.4
	Type 8	0.4
	Type 11	0.58
	Type 12	0.28

(*Continued*)

TABLE 4.7 (*Continued*) Specific Heat of Polymers

Polymer Class	Polymer Subclass	Specific Heat (Btu/lb/°F)
	6/6 Nylon	
	General purpose molding	0.3–0.5
	General purpose extrusion	0.3–0.5
	6/10 Nylon	
	General purpose	0.3–0.5
Phenolics: Molded	Type and filler:	
	General: woodflour and flock	0.35–0.40
	Shock: paper, flock, or pulp	—
	High shock: chopped fabric or cord	0.30–0.35
	Very high shock: glass fiber	0.28–0.32
Phenolics: Molded	Arc resistant—mineral	0.27–0.37
	Rubber phenolic—woodflour or flock	0.33
	PVC—acrylic alloy	
	PVC—acrylic sheet	0.293
Polyimides	Unreinforced	0.31
	Unreinforced second value	0.25–0.35
	Glass reinforced	0.15–0.27
Polyacetals	Standard	0.35
	Copolymer:	
	Standard	0.35
	High flow	0.35
Polyesters: Thermosets	Cast polyester	
	Rigid	0.30–0.55
	Reinforced polyester moldings	
	High strength (glass fibers)	0.25–0.35
	Sheet molding compounds, general purpose	0.20–0.25
Phenylene oxides (Noryl)	Standard	0.24
Polypropylene:	General purpose	0.45
	High impact	0.45–0.48
Polyphenylene sulfide	Standard	0.26
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	0.53–0.55
	Melt index 6–26	0.53–0.55
	Melt index 200	0.53–0.55
	Type II—medium density (0.926–0.940)	
	Melt index 20	0.53–0.55
	Melt index 1.0–1.9	0.53–0.55
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	0.46–0.55

(*Continued*)

TABLE 4.7 (*Continued*) Specific Heat of Polymers

Polymer Class	Polymer Subclass	Specific Heat (Btu/lb/°F)
	Melt index 0.1–12.0	0.46–0.55
	Melt index 1.5–15	0.46–0.55
Polystyrenes: Molded	Polystyrenes	
	General purpose	0.30–0.35
	Medium impact	0.30–0.35
	High impact	0.30–0.35
	Glass fiber (30%) reinforced	0.256
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	0.33
Polyvinyl chloride and copolymers: Molded, extruded	Vinylidene chloride	0.32
Silicones: Molded, laminated	Woven glass fabric/silicone laminate	0.246

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

Note: To convert Btu/lb/°F to J/kg · K, multiply by 4186.9.

TABLE 4.8 Thermal Conductivity of Cryogenic Insulation

Class[a]	Cryogenic Insulation	Thermal Conductivity Range (mW/m · K)	Interspace Pressure (mm Hg)
1	Liquid and vapor shields	—	—
2	Multilayer	0.04–0.2	10^{-4}
3	Opacified powder	0.26–0.7	10^{-4}
4	Evacuated powder	1.0–2.0	10^{-4}
5	Vacuum flask	5.0	10^{-6}
6	Gas-filled powder	1.7–7.0	760
7	Expanded foam	5.0–35	760
8	Fiber blanket	35–45	760

Source: Data from R. E. Boltz and G. L. Tuve (Eds.), *Handbook of Tables for Applied Engineering Science,* 2nd Edn., CRC Press, Cleveland, 1973, p. 529.

Note: To convert mm Hg to N/m^2 multiply by 133.32.

[a] 1. Liquid and vapor shields—very low-temperature, valuable, or dangerous liquids such as helium or fluorine are often shielded by an intermediate cryogenic liquid or vapor container that must in turn be insulated by one of the methods described below.
2. Multilayer reflecting shields—foil or aluminized plastic alternated with paper-thin glass or plastic-fiber sheets; lowest conductivity, low density, and heat storage; good stability; minimum support structure.
3. Opacified evacuated powders—contain metallic flakes to reduce radiation; conform to irregular shapes.
4. Evacuated dielectric powders—very fine powders of low-conductivity adsorbent; moderate vacuum requirement; minimum fire hazard in oxygen.
5. Vacuum flasks (Dewar)—tight shield-space with highly reflecting walls and high vacuum; minimum heat capacity; rugged; small thickness.
6. Gas-filled powders—same powders as Class 4 but with air or inert gas; low cost; easy application; no vacuum requirement.
7. Expanded foams—very light foamed plastic; inexpensive; minimum weight but bulky; self-supporting.
8. Porous fiber blankets—blanket material of fine fibers, usually glass; minimum cost and easy installation but not an adequate insulation for most cryogenic applications.

TABLE 4.9 Thermal Conductivity of Cryogenic Supports

Insulation Support	Mean Thermal Conductivity[a] (W/mK)
Aluminum alloy	86
"K" Monel®	17
Stainless steel	9.3
Titanium alloy	6.1
Nylon	0.29
Teflon	0.24

Source: Data from R. E. Boltz and G. L. Tuve (Eds.), *Handbook of Tables for Applied Engineering Science,* 2nd Edn., CRC Press, Cleveland, 1973, p. 529.

[a] Range of validity is 20–300 K.

TABLE 4.10 Thermal Conductivity of Polymers

Class	Polymer	Thermal Conductivity (ASTM C177) Btu/(hft°F)
ABS resins: Molded, extruded	Medium impact	0.08–0.18
	High impact	0.12–0.16
	Very high impact	0.01–0.14
	Low temperature impact	0.08–0.14
	Heat resistant	0.12–0.20
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	0.12
	General purpose, type II	0.12
	Moldings:	
	Grades 5, 6, 8	0.12
	High impact grade	0.12
Thermoset carbonate	Allyl diglycol carbonate	1.45
Alkyds: Molded	Putty (encapsulating)	0.35–0.60
	Rope (general purpose)	0.35–0.60
	Granular (high-speed molding)	0.35–0.60
	Glass reinforced (heavy duty parts)	0.20–0.30
Cellulose acetate: Molded, extruded	ASTM grade:	
	H6-1	0.10–0.19
	H4-1	0.10–0.19
	H2-1	0.10–0.19
	MH-1, MH-2	0.10–0.19
	MS-1, MS-2	0.10–0.19
	S2-1	0.10–0.19
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	0.10–0.19
	MH	0.10–0.19
	S2	0.10–0.19

(*Continued*)

TABLE 4.10 (*Continued*) Thermal Conductivity of Polymers

Class	Polymer	Thermal Conductivity (ASTM C177) Btu/(hft°F)
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	0.10–0.19
	3	0.10–0.19
	6	0.10–0.19
Chlorinated polymers	Chlorinated polyether	0.91
	Chlorinated polyvinyl chloride	0.95
Polycarbonates	Polycarbonate	0.11
	Polycarbonate (40% glass–fiber-reinforced)	0.13
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	0.145
	Polytetrafluoroethylene (PTFE)	0.14
	Fluorinated ethylene propylene (FEP)	0.12
	Polyvinylidene fluoride (PVDF)	0.14
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	0.1–0.3
	Molded	0.1–0.5
	High strength laminate	2.35
Melamines: Molded	Filler and type	
	Cellulose electrical	0.17–0.20
	Glass fiber	0.28
Nylons: Molded, extruded	Type 6	
	General purpose	1.2–1.69
	Glass fiber (30%) reinforced	1.69–3.27
	Cast	1.2–1.7
	Type 11	1.5
	Type 12	1.7
	6/6 Nylon	
	General purpose molding	1.69–1.7
	Glass–fiber-reinforced	1.5–3.3
	General purpose extrusion	1.7
	6/10 Nylon	
	General purpose	1.5
	Glass fiber (30%) reinforced	3.5
Phenolics: Molded	Type and filler	
	General: woodflour and flock	0.097–0.3
	Shock: paper, flock, or pulp	0.1–0.16
	High shock: chopped fabric or cord	0.097–0.170
	Very high shock: glass fiber	0.2
Phenolics: Molded	Arc resistant—mineral	0.24–0.34
	Rubber phenolic—woodflour or flock	0.12
	Rubber phenolic—chopped fabric	0.05
	Rubber phenolic—asbestos	0.04
	ABS—polycarbonate alloy	2.46 (per ft)

(*Continued*)

TABLE 4.10 (*Continued*) Thermal Conductivity of Polymers

Class	Polymer	Thermal Conductivity (ASTM C177) Btu/(hft°F)
PVC: Acrylic alloy	PVC—acrylic sheet	1.01
	PVC—acrylic injection molded	0.98
Polyimides	Unreinforced	6.78
	Unreinforced second value	3.8
	Glass reinforced	3.59
Polyacetals	Homopolymer:	
	Standard	0.13
	Copolymer:	
	Standard	0.16
	High flow	1.6
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	0.36–0.55
Polyesters: Thermosets	Cast polyester	
	Rigid	0.10–0.12
	Reinforced polyester moldings	
	High strength (glass fibers)	1.32–1.68
Phenylene oxides	SE-100	1.1
	SE-1	1.5
	Glass–fiber-reinforced	1.15, 1.1
Phenylene oxides (Noryl)	Standard	1.8
	Polyarylsulfone	1.1
Polypropylene	General purpose	1.21–1.36
	High impact	1.72
	Polyphenylene sulfide:	
	Standard	2
	40% Glass reinforced	2
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	0.19
	Melt index 6–26	0.19
	Melt index 200	0.19
	Type II—medium density (0.926–0.940)	
	Melt index 20	0.19
	Melt index 1.0–1.9	0.19
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	0.19
	Melt index 0.1–12.0	0.19
	Melt index 1.5–15	0.19
	High molecular weight	0.19

(*Continued*)

TABLE 4.10 (*Continued*) Thermal Conductivity of Polymers

Class	Polymer	Thermal Conductivity (ASTM C177) Btu/(hft°F)
Polystyrenes: Molded	Polystyrenes	
	General purpose	0.058–0.090
	Medium impact	0.024–0.090
	High impact	0.024–0.090
	Glass fiber (30%) reinforced	0.117
Polyvinyl chloride and copolymers: Molded, extruded	Nonrigid—general	0.07–0.10
	Nonrigid—electrical	0.07–0.10
	Rigid—normal impact	0.07–0.10
	Vinylidene chloride	0.053
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	0.18
	Granular (silica) reinforced silicones	0.25–0.5
	Woven glass fabric/silicone laminate	0.075–0.125
Ureas: Molded	Alpha-cellulose filled (ASTM type l)	0.17–0.244

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

Note: To convert Btu/(hft°F) to W/mK, multiply by 1.7307.

TABLE 4.11 Thermal Expansion of Polymers

Type	Polymer	Thermal Expansion Coefficient ASTM D696 ($°F^{-1}$)
ABS resins: Molded, extruded	Medium impact	$3.2–4.8 \times 10^{-6}$
	High impact	$5.5–6.0 \times 10^{-6}$
	Very high impact	$5.0–6.0 \times 10^{-6}$
	Low temperature impact	$5.0–6.0 \times 10^{-6}$
	Heat resistant	$3.0–4.0 \times 10^{-6}$
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	4.5×10^{-6}
	General purpose, type II	4.5×10^{-6}
	Moldings:	
	Grades 5, 6, 8	$3–4 \times 10^{-6}$
	High impact grade	$4–6 \times 10^{-6}$
Thermoset carbonate	Allyl diglycol carbonate	6×10^{-5}
Alkyds: Molded	Putty (encapsulating)	1.3×10^{-5}
	Rope (general purpose)	1.3×10^{-5}
	Granular (high-speed molding)	1.3×10^{-5}
	Glass reinforced (heavy duty parts)	1.3×10^{-5}
Cellulose acetate: Molded, extruded	ASTM grade:	
	H6-1	$4.4–9.0 \times 10^{-5}$
	H4-1	$4.4–9.0 \times 10^{-5}$
	H2-1	$4.4–9.0 \times 10^{-5}$

(*Continued*)

TABLE 4.11 (*Continued*) Thermal Expansion of Polymers

Type	Polymer	Thermal Expansion Coefficient ASTM D696 (°F^{-1})
	MH-1, MH-2	$4.4–9.0 \times 10^{-5}$
	MS-1, MS-2	$4.4–9.0 \times 10^{-5}$
	S2-1	$4.4–9.0 \times 10^{-5}$
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	$6–9 \times 10^{-5}$
	MH	$6–9 \times 10^{-5}$
	S2	$6–9 \times 10^{-5}$
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	$6–9 \times 10^{-5}$
	3	$6–9 \times 10^{-5}$
	6	$6–9 \times 10^{-5}$
Chlorinated polymers	Chlorinated polyether	6.6×10^{-6}
	Chlorinated polyvinyl chloride	4.4×10^{-6}
Polycarbonates	Polycarbonate	3.75×10^{-6}
	Polycarbonate (40% glass–fiber-reinforced)	$1.0–1.1 \times 10^{-6}$
Diallyl phthalates: Molded	Orlon filled	5.0×10^{-5}
	Dacron filled	5.2×10^{-5}
	Asbestos filled	4.0×10^{-5}
	Glass fiber filled	$2.2–2.6 \times 10^{-5}$
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	3.88×10^{-5}
	Polytetrafluoroethylene (PTFE)	55×10^{-5}
	Ceramic reinforced (PTFE)	$1.7–2.0 \times 10^{-5}$
	Fluorinated ethylene propylene (FEP)	$8.3–10.5 \times 10^{-5}$
	Polyvinylidene fluoride (PVDF)	8.5×10^{-5}
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	3.3×10^{-5}
	Cast flexible	$3–5 \times 10^{-5}$
	Molded	$1–2 \times 10^{-5}$
	General purpose glass cloth laminate	$3.3–4.8 \times 10^{-6}$
	High strength laminate	$3.3–4.8 \times 10^{-6}$
	Filament wound composite	$2–6 \times 10^{-5}$
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides)	
	Molded	$1.7–2.2 \times 10^{-6}$
	Epoxy novolacs	
	Cast, rigid	$1.6–3.0 \times 10^{-6}$
Melamines: Molded	Filler and type	
	Cellulose electrical	$1.11–2.78 \times 10^{-5}$
	Glass fiber	0.82×10^{-5}

(*Continued*)

TABLE 4.11 (*Continued*) Thermal Expansion of Polymers

Type	Polymer	Thermal Expansion Coefficient ASTM D696 (°F^{-1})
Nylons: Molded, extruded		
Type 6 nylon	General purpose	4.8×10^{-5}
	Glass fiber (30%) reinforced	1.2×10^{-5}
	Cast	4.4×10^{-5}
	Type 11	5.5×10^{-5}
	Type 12	7.2×10^{-5}
6/6 Nylon	General purpose molding	$1.69–1.7 \times 10^{-5}$
	Glass–fiber-reinforced	$1.5–3.3 \times 10^{-5}$
	General purpose extrusion	1.7×10^{-5}
6/10 Nylon	General purpose	1.5×10^{-5}
	Glass fiber (30%) reinforced	3.5×10^{-5}
Phenolics: Molded	Type and filler	
	General: woodflour and flock	$1.66–2.50 \times 10^{-5}$
	Shock: paper, flock, or pulp	$1.6–2.3 \times 10^{-5}$
	High shock: chopped fabric or cord	$1.60–2.22 \times 10^{-5}$
	Very high shock: glass fiber	0.88×10^{-5}
	Rubber phenolic—woodflour or flock	$0.83–2.20 \times 10^{-5}$
	Rubber phenolic—chopped fabric	1.7×10^{-5}
	Rubber phenolic—asbestos	2.2×10^{-5}
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	6.12×10^{-5}
PVC: Acrylic	PVC—acrylic alloy	
	PVC—acrylic sheet	3.5×10^{-5}
Polyimides	Unreinforced	2.5×10^{-6}
	Unreinforced second value	$3.0–4.5 \times 10^{-6}$
	Glass reinforced	0.8×10^{-6}
Homopolymer	Standard	4.5×10^{-5}
	20% Glass reinforced	$2.0–4.5 \times 10^{-5}$
	22% TFE reinforced	4.5×10^{-5}
	Copolymer:	
	Standard	4.7×10^{-5}
	25% Glass reinforced	$2.2–4.7 \times 10^{-5}$
	High flow	4.7×10^{-5}
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	5.3×10^{-5}
	Glass reinforced grades	$2.7–3.3 \times 10^{-5}$
	Glass reinforced self extinguishing	3.5×10^{-5}
	General purpose grade	$4.9–13.0 \times 10^{-5}$
Polyesters: Thermosets	Cast polyester	
	Rigid	$3.9–5.6 \times 10^{-5}$
	Reinforced polyester moldings	
	High strength (glass fibers)	$13–19 \times 10^{-6}$

(*Continued*)

TABLE 4.11 (*Continued*) Thermal Expansion of Polymers

Type	Polymer	Thermal Expansion Coefficient ASTM D696 (°F^{-1})
Phenylene oxides	SE-100	3.8×10^{-5}
	SE-1	3.3×10^{-5}
	Glass–fiber-reinforced	$1.4–2.0 \times 10^{-5}$
	Phenylene oxides (Noryl)	
	Standard	3.1×10^{-5}
	Glass–fiber-reinforced	$1.2–1.6 \times 10^{-5}$
Polyarylsulfone	Polyarylsulfone	2.6×10^{-5}
Polypropylene	General purpose	$3.8–5.8 \times 10^{-5}$
	High impact	$4.0–5.9 \times 10^{-5}$
	Asbestos filled	$2–3 \times 10^{-5}$
	Glass reinforced	$1.6–2.4 \times 10^{-5}$
Polyphenylene sulfide	Standard	$3.0–4.9 \times 10^{-5}$
	40% Glass reinforced	4×10^{-5}
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	$8.9–11.0 \times 10^{-5}$
	Melt index 6–26	$8.9–11.0 \times 10^{-5}$
	Melt index 200	11×10^{-5}
	Type II—medium density (0.926–0.940)	
	Melt index 20	$8.3–16.7 \times 10^{-5}$
	Melt index 1.0–1.9	$8.3–16.7 \times 10^{-5}$
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	$8.3–16.7 \times 10^{-5}$
	Melt index 0.1–12.0	$8.3–16.7 \times 10^{-5}$
	Melt index 1.5–15	$8.3–16.7 \times 10^{-5}$
Polystyrenes: Molded	General purpose	$3.3–4.8 \times 10^{-5}$
	Medium impact	$3.3–4.7 \times 10^{-5}$
	High impact	$2.2–5.6 \times 10^{-5}$
	Glass fiber (30%) reinforced	1.8×10^{-5}
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	$3.6–3.7 \times 10^{-5}$
	Glass fiber (30%) reinforced SAN	1.6×10^{-5}
Polyvinyl chloride and copolymers: Molded, extruded	Rigid—normal impact	$2.8–3.3 \times 10^{-5}$
Vinylidene chloride	Vinylidene chloride	8.78×10^{-5}
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	$3.17–3.23 \times 10^{-5}$
	Granular (silica) reinforced silicones	$2.5–5.0 \times 10^{-5}$
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	$1.22–1.50 \times 10^{-5}$

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.12 Thermoplastic Polyester Softening with Temperature

Polymer	Flexural Modulus 10^6 psi	Tensile Strength 10^3 psi D638	212°F	302°F
Injection molding types:				
General purpose grade		7.5–8		
Glass reinforced grades		17–25	7	5.5
Glass reinforced grades	1.2–1.5		0.63	0.53

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.
Note: To convert psi to MPa, divide by 145.

TABLE 4.13 Tensile Strength of Polymers

Class	Polymer	Tensile Strength (ASTM D638) (10^3 psi)
ABS resins: Molded, extruded	Medium impact	6.3–8.0
	High impact	5.0–6.0
	Very high impact	4.5–6.0
	Low temperature impact	4–6
	Heat resistant	7.0–8.0
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	6–9
	General purpose, type II	8–10
	Moldings:	
	Grades 5, 6, 8	8.8–10.5
	High impact grade	5.5–8.0
Thermoset carbonate	Allyl diglycol carbonate	5–6
Alkyds: Molded	Putty (encapsulating)	4–5
	Rope (general purpose)	7–8
	Granular (high-speed molding)	3–4
	Glass reinforced (heavy duty parts)	5–9
Cellulose acetate: Molded, extruded	ASTM grade:	(Tensile strength at fracture)
	H4-1	7–8
	H2-1	5.8–7.2
	MH-1, MH-2	4.8–6.3
	MS-1, MS-2	3.9–5.3
	S2-1	3.0–4.4
Cellulose acetate butyrate	Molded, extruded	(Tensile strength at fracture)
	ASTM grade:	
	H4	6.9
	MH	5.0–6.0
	S2	3.0–4.0

(*Continued*)

TABLE 4.13 (*Continued*) Tensile Strength of Polymers

Class	Polymer	Tensile Strength (ASTM D638) (10^3 psi)
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	5.9–6.5
	3	5.1–5.9
	6	4
Chlorinated polymers	Chlorinated polyether	6
	Chlorinated polyvinyl chloride	7.3
Polycarbonates	Polycarbonate	9.5
	Polycarbonate (40% glass–fiber-reinforced)	18
Diallyl phthalates: Molded	Orlon filled	4.5–6
	Dacron filled	4.6–6.2
	Asbestos filled	4–6.5
	Glass fiber filled	5.5–11
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	4.6–5.7
	Polytetrafluoroethylene (PTFE)	2.5–6.5
	Ceramic reinforced (PTFE)	0.75–2.5
	Fluorinated ethylene propylene (FEP)	2.5–4.0
	Polyvinylidene fluoride (PVDF)	5.2–8.6
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	9.5–11.5
	Cast flexible	1.4–7.6
	Molded	8–11
	General purpose glass cloth laminate	50–58
	High strength laminate	160
	Filament wound composite	230–240 (hoop)
Epoxies: Molded, extruded	High-performance resins	
	Cycloaliphatic diepoxides	
	Cast, rigid	8–12
	Molded	5.2–5.3
	Glass cloth laminate	50–52
	Epoxy novolacs	
	Cast, rigid	9.6–12.0
	Glass cloth laminate	59.2
Melamines: Molded	Filler and type	
	Cellulose electrical	5–9
	Glass fiber	6–9
	Alpha cellulose and mineral	5–8
Nylons: Molded, extruded	Type 6	
	General purpose	9.5–12.5
	Glass fiber (30%) reinforced	21–24
	Cast	12.8
	Flexible copolymers	7.5–10.0

(*Continued*)

TABLE 4.13 (*Continued*) Tensile Strength of Polymers

Class	Polymer	Tensile Strength (ASTM D638) (10^3 psi)
	Type 12	7.1–8.5
	6/6 Nylon	
	General purpose molding	11.2–11.8
	Glass–fiber-reinforced	25–30
	Glass fiber molybdenum disulfide filled	19–22
	General purpose extrusion	1.26–8.6
	6/10 Nylon	
	General purpose	7.1–8.5
	Glass fiber (30%) reinforced	19
Phenolics: Molded	Phenolics: Molded	(ASTM D651)
	Type and filler	
	General: wood flour and flock	5.0–8.5
	Shock: paper, flock, or pulp	5.0–8.5
	High shock: chopped fabric or cord	5–9
	Very high shock: glass fiber	5–10
	Arc resistant—mineral	6
	Rubber phenolic—wood flour or flock	4.5–9
	Rubber phenolic—chopped fabric	3–5
	Rubber phenolic—asbestos	4
	ABS—polycarbonate alloy	8.2
Polyacetals	Homopolymer:	
	Standard	10
	20% glass reinforced	8.5
	22% TFE reinforced	6.9
	Copolymer:	
	Standard	8.8
	25% glass reinforced	18.5
	High flow	8.8
Polyesters: Thermosets	Cast polyester	
	Rigid	5–15
	Flexible	1–8
Reinforced polyester moldings	High strength (glass fibers)	5–10
	Heat and chemical resistant (asbestos)	4–6
	Sheet molding compounds, general purpose	15–17
Polyarylsulfone	Polyarylsulfone	13
Polypropylene	General purpose	4.5–6.0

(*Continued*)

TABLE 4.13 (*Continued*) Tensile Strength of Polymers

Class	Polymer	Tensile Strength (ASTM D638) (10^3 psi)
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	(ASTM D412)
	Melt index 0.3–3.6	1.4–2.5
	Melt index 6–26	1.4–2.0
	Melt index 200	0.9–1.1
	Type II—medium density (0.926–0.940)	
	Melt index 20	2
	Melt index 1.0–1.9	2.3–2.4
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	4.4
	Melt index 0.1–12.0	2.9–4.0
	Melt index 1.5–15	4.4
	High molecular weight	5.4
Olefin copolymers: Molded	EEA (ethylene ethyl acrylate)	0.2
	EVA (ethylene vinyl acetate)	0.36
	Ethylene butane	0.35
Propylene–ethylene	Propylene–ethylene	0.4
	Ionomer	0.4
	Polyallomer	3–4.3
Polystyrenes	Polystyrenes: Molded	
	General purpose	5.0–10
	Medium impact	4.0–6.0
	High impact	3.3–5.1
	Glass fiber (30%) reinforced	14
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	8.3–12.0
	Glass fiber (30%) reinforced SAN	18
Polyvinyl chloride and copolymers	Polyvinyl chloride and copolymers: Molded, extruded	D412
	Nonrigid—general	1–3.5
	Nonrigid—electrical	2–3.2
	Rigid—normal impact	5.5–8
	Vinylidene chloride	4–40
Silicones	Silicones: Molded, laminated	(ASTM D651)
	Fibrous (glass) reinforced silicones	6.5
	Granular (silica) reinforced silicones	4–6
	Woven glass fabric/silicone laminate	30–35
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	5–10

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

Note: To convert psi to MPa, divide by 145.

TABLE 4.14 Yield Strength of Polymers

Class	Polymer	Yield Strength (ASTM D638) (10^3 psi)
Chlorinated polyether	Chlorinated polyether	5.9
Polycarbonate	Polycarbonate	8.5
Nylons: Molded, extruded	Type 6	
	General purpose	8.5–12.5
	Cast	12.8
	Flexible copolymers	7.5–10.0
	Type 8	3.9
	Type 11	8.5
	Type 12	5.5–6.5
	6/6 Nylon	
	General purpose molding	8.0–11.8
	Glass–fiber-reinforced	25
	General purpose extrusion	8.6–12.6
	6/10 Nylon	
	General purpose	7.1–8.5
ABS—polycarbonate alloy	ABS—polycarbonate alloy	8.2
PVC: Acrylic alloy	PVC—acrylic sheet	6.5
	PVC—acrylic injection molded	5.5
Polyimides	Unreinforced	7.5
	Unreinforced second value	5
	Glass reinforced	28
Polyacetals	Homopolymer:	
	Standard	10
	Copolymer:	
	Standard	8.8
	25% Glass reinforced	18.5
	High flow	8.8
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	7.5–8
	Glass reinforced grades	17–25
	Glass reinforced self extinguishing	17
	General purpose grade	8.2
	Glass reinforced grade	14
	Asbestos-filled grade	12
Phenylene oxides	SE-100	7.8
	SE-1	9.6
	Glass–fiber-reinforced	14.5–17.0
Phenylene oxides (Noryl)	Standard	10.2
	Glass–fiber-reinforced	17–19
	Polyarylsulfone	8–12

(Continued)

TABLE 4.14 (*Continued*) Yield Strength of Polymers

Class	Polymer	Yield Strength (ASTM D638) (10^3 psi)
Polypropylene	Polypropylene:	
	General purpose	4.5–6.0
	High impact	2.8–4.3
	Asbestos filled	3.3–8.2
	Glass reinforced	7–11
	Flame retardant	3.6–4.2
Polyphenylene sulfide:	Standard	9.511
	40% Glass reinforced	20–21
Polystyrenes: Molded	Polystyrenes	
	General purpose	5.0–10
	Medium impact	3.7–6.0
	High impact	2.8–5.3
	Glass fiber (30%) reinforced	14
Styrene acrylonitrile (SAN)	Glass fiber (30%) reinforced SAN	18

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.
Note: To convert psi to MPa, divide by 145.

TABLE 4.15 Compressive Yield Strength of Polymers

Class	Polymer	Compressive Yield Strength (ASTM D690 or D695) (0.1% offset, 1000 psi)
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	12–14
	General purpose, type II	14–18
	Moldings:	
	Grades 5, 6, 8	14.5–17
	High impact grade	7.3–12.0
Cellulose acetate: Molded, extruded	ASTM grade:	
	H4-1	6.5–10.6
	H2-1	4.3–9.6
	MH-1, MH-2	4.4–8.4
	MS-1, MS-2	3.2–7.2
	S2-1	3.15–6.1
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	8.8
	MH	5.3–7.1
	S2	2.6–4.3

(*Continued*)

TABLE 4.15 (*Continued*) Compressive Yield Strength of Polymers

Class	Polymer	Compressive Yield Strength (ASTM D690 or D695) (0.1% offset, 1000 psi)
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	6.2–7.3
	3	4.9–5.8
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	2
	Polytetrafluoroethylene (PTFE)	0.7–1.8
	Ceramic reinforced (PTFE)	1.4–1.8
	Fluorinated ethylene propylene (FEP)	1.6
	Polyvinylidene fluoride (PVDF)	12.8–14.2
Nylons: Molded, extruded	Type 6	
	General purpose	9.7
	Glass fiber (30%) reinforced	19–20
	Cast	14
	6/6 Nylon	
	General purpose molding	4.9
	Glass–fiber-reinforced	20–24
	General purpose extrusion	4.9
	6/10 Nylon	
	General purpose	3.0
	Glass fiber (30%) reinforced	18
Polyacetals	Homopolymer:	
	Standard	5.2
	20% Glass reinforced	5.2
	22% TFE reinforced	4.5
	Copolymer:	
	Standard	4.5
	High flow	4.5
Polypropylene	General purpose	5.5–6.5
	High impact	4.4
	Asbestos filled	7
	Glass reinforced	6.5–7
Polyvinyl chloride and copolymers: Molded, extruded	Rigid—normal impact	10–11
Vinylidene chloride	Vinylidene chloride	75–85

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

Note: To convert from psi to MPa, divide by 145.

TABLE 4.16 Flexural Strength of Polymers

Class	Polymer	Flexural Strength (ASTM D790) (10^3 psi)
ABS resins: Molded, extruded	Medium impact	9.9–11.8
	High impact	7.5–9.5
	Very high impact	6.0–9.8
	Low temperature impact	5–8
	Heat resistant	11.0–12.0
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	12–14
	General purpose, type II	15–17
	Moldings:	
	Grades 5, 6, 8	15–16
	High impact grade	8.7–12.0
Alkyds: Molded	Putty (encapsulating)	8–11
	Rope (general purpose)	19–20
	Granular (high-speed molding)	7–10
	Glass reinforced (heavy duty parts)	12–17
Cellulose acetate: Molded, extruded	ASTM grade:	
	H4-1	8.1–11.15 (yield)
	H2-1	6.0–10.0 (yield)
	MH-1, MH-2	4.4–8.65 (yield)
	MS-1, MS-2	3.8–7.1 (yield)
	S2-1	3.5–5.7 (yield)
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	9 (yield)
	MH	5.6–6.7 (yield)
	S2	2.5–3.95 (yield)
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	6.8–7.9 (yield)
	3	5.6–6.2 (yield)
Chlorinated polymers	Chlorinated polyether	5 (0.1% offset)
	Chlorinated polyvinyl chloride	14.5
Polycarbonates	Polycarbonate	13.5
	Polycarbonate (40% glass–fiber-reinforced)	27
Diallyl phthalates: Molded	Orlon filled	7.5–10.5
	Dacron filled	9–11.5
	Asbestos filled	8–10
	Glass fiber filled	10–18
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	3.5 (0.1% offset)
	Fluorinated ethylene propylene (FEP)	3 (0.1% offset)
	Polyvinylidene fluoride (PVDF)	8.6–10.8 (0.1% offset)

(*Continued*)

TABLE 4.16 (*Continued*) Flexural Strength of Polymers

Class	Polymer	Flexural Strength (ASTM D790) (10^3 psi)
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	14–18
	Cast flexible	1.2–12.7
	Molded	19–22
	General purpose glass cloth laminate	80–90
	High strength laminate	165–177
	Filament wound composite	180–170
Epoxies: Molded, extruded	High-performance resins	
	Cycloaliphatic diepoxides	
	Cast, rigid	11–16
	Molded	10–12
	Glass cloth laminate	70–72
	Epoxy novolacs	
	Cast, rigid	12–13
	Glass cloth laminate	84–89
Melamines: Molded	Filler and type	
	Unfilled	9.5–14
	Cellulose electrical	6–15
	Glass fiber	14–18
	Alpha cellulose and mineral	11–16, 8–10 (mineral)
Nylons: Molded, extruded	Type 6	
	General purpose	Unbreakable
	Glass fiber (30%) reinforced	26–34
	Cast	16.5
	Flexible copolymers	3.4–16.4
	6/6 Nylon	
	General purpose molding	Unbreakable
	Glass–fiber-reinforced	26–35
	Glass fiber molybdenum disulfide filled	26–28
	6/10 Nylon	
	General purpose	8
	Glass fiber (30%) reinforced	23
Phenolics: Molded	Type and filler	
	General: wood flour and flock	8.5–12
	Shock: paper, flock, or pulp	8.0–11.5
	High shock: chopped fabric or cord	8–15
	Very high shock: glass fiber	10–45
	Arc resistant—mineral	10–13
	Rubber phenolic—wood flour or flock	7–12
	Rubber phenolic—chopped fabric	7
	Rubber phenolic—asbestos	7

(*Continued*)

TABLE 4.16 (*Continued*) Flexural Strength of Polymers

Class	Polymer	Flexural Strength (ASTM D790) (10^3 psi)
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	14.3
PVC: Acrylic alloy	PVC—acrylic sheet	10.7
	PVC—acrylic injection molded	8.7
Polyimides	Unreinforced	6.6–11
	Glass reinforced	56
Polyacetals	Homopolymer:	
	Standard	14.1
	Copolymer:	
	Standard	13
	25% Glass reinforced	28
	High flow	13
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	12.8
	Glass reinforced grades	22–24
	Glass reinforced self extinguishing	23
	General purpose grade	12
	Glass reinforced grade	19
	Asbestos-filled grade	19
Polyesters: Thermosets	Cast polyester	
	Rigid	8–24
	Flexible	4–16
Reinforced polyester moldings	High strength (glass fibers)	6–26
	Heat and chemical resistant (asbestos)	10–13
	Sheet molding compounds, general purpose	26–32
Phenylene oxides	SE-100	12.8
	SE-1	13.5
	Glass–fiber-reinforced	20.5–22
Phenylene oxides (Noryl)	Standard	15.4
	Glass–fiber-reinforced	25–28
Polyarylsulfone	Polyarylsulfone	16.1–17.2
Polypropylene	General purpose	6–7 (yield)
	High impact	4.1 (yield)
	Asbestos filled	7.5–9 (yield)
	Glass reinforced	8–11 (yield)
Polyphenylene sulfide	Standard	20
	40% Glass reinforced	37
Polystyrenes: Molded	Polystyrenes	
	General purpose	10–15
	Glass fiber (30%) reinforced	17

(*Continued*)

TABLE 4.16 (*Continued*) Flexural Strength of Polymers

Class	Polymer	Flexural Strength (ASTM D790) (10^3 psi)
Styrene acrylonitrile (SAN)	Glass fiber (30%) reinforced SAN	22
Polyvinyl chloride and copolymers	Molded, extruded:	
	Rigid—normal impact	11–16
	Vinylidene chloride	15–17
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	16–19
	Granular (silica) reinforced silicones	6–10
	Woven glass fabric/silicone laminate	33–47
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	8–18
	Cellulose filled (ASTM type 2)	7.5–13
	Woodflour filled	7.5–12.0

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

Note: To convert from psi to MPa, divide by 145.

TABLE 4.17 Hardness of Polymers

Class	Polymer	Hardness (ASTM D785) (Rockwell)
ABS resins: Molded, extruded	Medium impact	R108–115
	High impact	R95–113
	Very high impact	R85–105
	Low temperature impact	R75–95
	Heat resistant	R107–116
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	M80–90
	General purpose, type II	M96–102
	Moldings:	
	Grades 5, 6, 8	M80–103
	High impact grade	M38–45
Thermoset carbonate	Allyl diglycol carbonate	M95–100 (Barcol)
Alkyds: Molded	Putty (encapsulating)	60–70 (Barcol)
	Rope (general purpose)	70–75 (Barcol)
	Granular (high-speed molding)	60–70 (Barcol)
	Glass reinforced (heavy duty parts)	70–80 (Barcol)
Cellulose acetate: Molded, extruded	ASTM grade:	
	H4-1	R103–120
	H2-1	R89–112
	MH-1, MH-2	R74–104
	MS-1, MS-2	R54–96
	S2-1	R49–88

(*Continued*)

TABLE 4.17 (*Continued*) Hardness of Polymers

Class	Polymer	Hardness (ASTM D785) (Rockwell)
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	R114
	MH	R80–100
	S2	R23–42
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	100–109
	3	92–96
	6	57
	Chlorinated polymers	
	Chlorinated polyether	R100
	Chlorinated polyvinyl chloride	R118
Polycarbonates	Polycarbonate	M70
	Polycarbonate (40% glass–fiber-reinforced)	M97
Diallyl phthalates: Molded	Orlon filled	M108
	Asbestos filled	M107
	Glass fiber filled	M108
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	R110–115
	Polytetrafluoroethylene (PTFE)	52D
	Ceramic reinforced (PTFE)	R35–55
	Fluorinated ethylene propylene (FEP)	57–58D
	Polyvinylidene fluoride (PVDF)	109–110R
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	106M
	Cast flexible	50–100M
	Molded	75–80 (Barcol)
	General purpose glass cloth laminate	115–117M
	High strength laminate	70–72 (Barcol)
	Filament wound composite	98–120M
Epoxies: Molded, extruded	High-performance resins	
	Cycloaliphatic diepoxides	
	Cast, rigid	107–112
	Molded	94–96D
	Glass cloth laminate	75–80
Melamines: Molded	Filler and type	
	Unfilled	E110
	Cellulose electrical	M115–125
Nylons: Molded, extruded	Type 6	
	General purpose	R118–120
	Glass fiber (30%) reinforced	R93–121
	Cast	R116
	Flexible copolymers	R72–119

(*Continued*)

TABLE 4.17 (*Continued*) Hardness of Polymers

Class	Polymer	Hardness (ASTM D785) (Rockwell)
	Type 11	R100–108
	Type 12	R106
	6/6 Nylon	
	General purpose molding	R118–120, R108
	Glass–fiber-reinforced	E60–80
	Glass fiber molybdenum disulfide filled	M95–100
	General purpose extrusion	R118–108
	6/10 Nylon	
	General purpose	R111
	Glass fiber (30%) reinforced	E40–50
Phenolics: Molded	Type and filler	
	General: wood flour and flock	E85–100
	Shock: paper, flock, or pulp	E85–95
	High shock: chopped fabric or cord	E80–90
	Very high shock: glass fiber	E50–70
	Arc resistant—mineral	M105–115
	Rubber phenolic—wood flour or flock	M40–90
	Rubber phenolic—chopped fabric	M57
	Rubber phenolic—asbestos	M50
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	R118
PVC: Acrylic alloy	PVC—acrylic sheet	R105
	PVC—acrylic injection molded	R104
Polyimide	Glass reinforced	114E
Polyacetals	Homopolymer:	
	Standard	M94
	20% Glass reinforced	M90
	22% TFE reinforced	M78
	Copolymer:	
	Standard	M80
	25% Glass reinforced	M79
	High flow	M80
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	R117
	Glass reinforced grades	R118–M90
	Glass reinforced self extinguishing	R119
	General purpose grade	R117
	Glass reinforced grade	R117–M85
	Asbestos-filled grade	M85
Polyesters: Thermosets	Cast polyester	
	Rigid	35–50 (Barcol)
	Flexible	6–40 (Barcol)

(*Continued*)

TABLE 4.17 (*Continued*) Hardness of Polymers

Class	Polymer	Hardness (ASTM D785) (Rockwell)
	Reinforced polyester moldings	
	High strength (glass fibers)	60–80 (Barcol)
	Heat and chemical resistant (asbestos)	40–70 (Barcol)
	Sheet molding compounds, general purpose	45–60 (Barcol)
Phenylene oxides	SE-100	R115
	SE-1	R119
	Glass–fiber-reinforced	L106, L108
Phenylene oxides (Noryl)	Standard	R120
	Glass–fiber-reinforced	M84
Polyarylsulfone	Polyarylsulfone	M85–110
Polypropylene	General purpose	R80–100
	High impact	R28–95
	Asbestos filled	R90–110
	Glass reinforced	R90–115
	Flame retardant	R60–105
Polyphenylene sulfide	Standard	R120–124
	40% Glass reinforced	R123
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	C73, D50–52 (Shore)
	Melt index 6–26	C73, D47–53 (Shore)
	Melt index 200	D45 (Shore)
	Type II—medium density (0.926–0.940)	
	Melt index 20	D55 (Shore)
	Melt index 1.0–1.9	D55–56 (Shore)
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	D68–70 (Shore)
	Melt index 0.1–12.0	D60–70 (Shore)
	Melt index 1.5–15	D68–70 (Shore)
	High molecular weight	D60–65 (Shore)
Olefin copolymers: Molded	EEA (ethylene ethyl acrylate)	D35 (Shore)
	EVA (ethylene vinyl acetate)	D36 (Shore)
	Ethylene butane	D65 (Shore)
	Propylene–ethylene ionomer	D60 (Shore)
Polystyrenes: Molded	Polystyrenes	
	General purpose	M72
	Medium impact	M47–65
	High impact	M3–43
	Glass fiber (30%) reinforced	M85–95
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	M75–85
	Glass fiber (30%) reinforced SAN	M90–123

(*Continued*)

TABLE 4.17 (*Continued*) Hardness of Polymers

Class	Polymer	Hardness (ASTM D785) (Rockwell)
Polyvinyl chloride and copolymers: Molded, extruded	Rigid—normal impact	R110–120
	Vinylidene chloride	M50–65
	Polyvinyl chloride and copolymers: Molded, extruded:	(ASTM D676)
	Nonrigid—general	A50–100 (Shore)
	Nonrigid—electrical	A78–100 (Shore)
	Rigid—normal impact	D70–85 (Shore)
	Vinylidene chloride	>A95 (Shore)
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	M87
	Granular (silica) reinforced silicones	M71–95
	Woven glass fabric/silicone laminate	75 (Barcol)
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	E94–97, M116–120
	Woodflour filled	M116–120

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, Ohio, 1988.

TABLE 4.18 Coefficient of Static Friction for Polymers

Class	Polymer	Coefficient of Static Friction (Against Self) (Dimensionless)
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	0.2
Polycarbonates	Polycarbonate	0.52
Nylons: Molded, extruded	Type 6	
	Cast	0.32 (dynamic)
	6/6 Nylon general purpose molding	0.04–0.13
Polyacetals	Homopolymer: Standard	0.1–0.3 (against steel)
	20% Glass reinforced	0.1–0.3 (against steel)
	22% TFE reinforced	0.05–0.15 (against steel)
	Copolymer: Standard	0.15 (against steel)
	25% Glass reinforced	0.15 (against steel)
	High flow	0.15 (against steel)
Polyester: Thermoplastic		(ASTM D1894)
	Injection moldings: general purpose grade	0.17
	Glass reinforced grades	0.16
	Glass reinforced self extinguishing	0.16
	Injection moldings: general purpose grade	0.13 (against steel)
	Glass reinforced grades	0.14 (against steel)
	Glass reinforced self extinguishing	0.14 (against steel)
Phenylene oxides (Noryl)	Standard	0.67
Polyarylsulfone	Polyarylsulfone	0.1–0.3

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, Ohio, 1988.

TABLE 4.19 Abrasion Resistance of Polymers

Class	Polymer	Abrasion Resistance (Taber, CS–17 Wheel, ASTM D1044) (mg/1000 cycles)
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	0.008 (g/cycle)
	Polyvinylidene fluoride (PVDF)	0.0006–0.0012 (g/cycle)
Polycarbonates	Polycarbonate	10
	Polycarbonate (40% glass–fiber-reinforced)	40
Nylons: Molded, extruded	Type 6	
	General purpose	5
	Cast	2.7
	6/6 Nylon	
	General purpose molding	3–8
	General purpose extrusion	3–5
PVC: Acrylic alloy	PVC—acrylic sheet	0.073 (CS-10 wheel)
	PVC—acrylic injection molded	0.0058 (CS-10 wheel)
Polyimides	Unreinforced	0.08
	Unreinforced second value	0.004
	Glass reinforced	20
Polyacetals	Homopolymer: Standard	14–20
	20% glass reinforced	33
	22% TFE reinforced	9
	Copolymer: Standard	14
	25% glass reinforced	40
	High flow	14
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	6.5
	Glass reinforced grades	9–50
	Glass reinforced self extinguishing	11
Phenylene oxides	SE-100	100
	SE-1	20
	Glass–fiber-reinforced	35
Phenylene oxides (Noryl)	Standard	20
Polyarylsulfone	Polyarylsulfone	40
Polystyrenes: Molded	Glass fiber (30%) reinforced	164

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.20 Impact Strength of Polymers

Class	Polymer	Impact Strength (Izod Notched, ASTM D256) (ftlb/in.)
ABS resins: Molded, extruded	Medium impact	2.0–4.0
	High impact	3.0–5.0
	Very high impact	5.0–7.5
	Low temperature impact	6–10
	Heat resistant	2.0–4.0
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	0.4
	General purpose, type II	0.4
	Moldings:	
	Grades 5, 6, 8	0.2–0.4
	High impact grade	0.8–2.3
Thermoset carbonate	Allyl diglycol carbonate	0.2–0.4
alkyds: Molded	Putty (encapsulating)	0.25–0.35
	Rope (general purpose)	2.2
	Granular (high-speed molding)	0.30–0.35
	Glass reinforced (heavy duty parts)	8–12
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	3
	MH	4.4–6.9
	S2	7.5–10.0
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	1.7–2.7
	3	3.5–5.6
	6	9.4
Chlorinated polymers	Chlorinated polyether	0.4 (D758)
	Chlorinated polyvinyl chloride	6.3
Polycarbonate	Polycarbonate	12–16
Diallyl phthalates: Molded	Orlon filled	0.5–1.2
	Dacron filled	1.7–5.0
	Asbestos filled	0.30–0.50
	Glass fiber filled	0.5–15.0
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	3.50–3.62
	Polytetrafluoroethylene (PTFE)	2.0–4.0
	Fluorinated ethylene propylene (FEP)	No break
	Polyvinylidene fluoride (PVDF)	3.0–10.3
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	0.2–0.5
	Cast flexible	0.3–0.2
	Molded	0.4–0.5

(*Continued*)

TABLE 4.20 (*Continued*) Impact Strength of Polymers

Class	Polymer	Impact Strength (Izod Notched, ASTM D256) (ftlb/in.)
	General purpose glass cloth laminate	12–15
	High strength laminate	60–61
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides)	
	Cast, rigid	0.5
	Molded	0.3–0.5
	Epoxy novolacs	
	Cast, rigid	13–17
Melamines: Molded	Filler and type	
	Cellulose electrical	0.27–0.36
	Glass fiber	0.5–12.0
	Alpha cellulose and mineral	0.30–0.35, 0.2 (mineral)
Nylons: Molded, extruded	Type 6	
	General purpose	0.6–1.2
	Glass fiber (30%) reinforced	2.2–3.4
	Cast	1.2
	Flexible copolymers	1.5–19
	Type 8	>16
	Type 11	3.3–3.6
	Type 12	1.2–4.2
	6/6 Nylon	(ASTM D638)
	General purpose molding	0.55–1.0, 2.0
	Glass–fiber-reinforced	2.5–3.4
	General purpose extrusion	1.3
	6/10 Nylon	
	General purpose	0.6–1.6
	Glass fiber (30%) reinforced	3.4
Phenolics: Molded	Type and filler	
	General: wood flour and flock	0.24–0.50
	Shock: paper, flock, or pulp	0.4–1.0
	High shock: chopped fabric or cord	0.6–8.0
	Very high shock: glass fiber	10–33
	Arc resistant—mineral	0.30–0.45
	Rubber phenolic—wood flour or flock	0.34–1.0
	Rubber phenolic—chopped fabric	2.0–2.3
	Rubber phenolic—asbestos	0.3–0.4
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	10 (ASTM D638)
PVC—acrylic alloy	PVC—acrylic sheet	15
	PVC—acrylic injection molded	15
Polyimides	Unreinforced	0.5
	Unreinforced second value	0.5
	Glass reinforced	17

(*Continued*)

TABLE 4.20 (*Continued*) Impact Strength of Polymers

Class	Polymer	Impact Strength (Izod Notched, ASTM D256) (ftlb/in.)
Polyacetals		(ASTM D638)
	Homopolymer:	
	Standard	1.4
	20% glass reinforced	0.8
	22% TFE reinforced	0.7
	Copolymer:	
	Standard	1.3
	25% glass reinforced	1.8
	High flow	1
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	1.0–1.2
	Glass reinforced grades	1.3–2.2
	Glass reinforced self extinguishing	1.8
	General purpose grade	1
	Glass reinforced grade	1
	Asbestos-filled grade	0.5
Polyesters: Thermosets	Cast polyester	
	Rigid	0.18–0.40
	Flexible	4
	Reinforced polyester moldings	
	High strength (glass fibers)	1–10
	Heat and chemical resistant (asbestos)	0.45–1.0
	Sheet molding compounds, general purpose	5–15
Phenylene oxides		(ASTM D638)
	SE-100	5
	SE-1	5
	Glass–fiber-reinforced	2.3
Phenylene oxides (Noryl)	Standard	1.2–1.3
	Glass–fiber-reinforced	1.8–2.0
Polyarylsulfone	Polyarylsulfone	1.6–5.0
Polypropylene	General purpose	0.4–2.2
	High impact	1.5–12
	Asbestos filled	0.5–1.5
	Glass reinforced	0.5–2
	Flame retardant	2.2
Polyphenylene sulfide	Standard	0.3
	40% glass reinforced	1.09

(*Continued*)

TABLE 4.20 (*Continued*) Impact Strength of Polymers

Class	Polymer	Impact Strength (Izod Notched, ASTM D256) (ftlb/in.)
Polyethylenes: Molded, extruded	Type III–higher density (0.941–0.965)	
	Melt index 0.2–0.9	4.0–14
	Melt index 0.1–12.0	0.4–6.0
	Melt index 1.5–15	1.2–2.5
	High molecular weight	>20
Olefin copolymers: Molded	Ethylene butene	0.4
	Propylene–ethylene	1.1
	Ionomer	9–14
	Polyallomer	1.5
Polystyrenes: Molded	Polystyrenes	(ASTM D638)
	General purpose	0.2–0.4
	Medium impact	0.5–1.2
	High impact	0.8–1.8
	Glass fiber (30%) reinforced	2.5
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	0.29–0.54
	Glass fiber (30%) reinforced SAN	1.35–3.0
Polyvinyl chloride and copolymers: Molded, extruded	Nonrigid—general	Variable
	Nonrigid—electrical	Variable
	Rigid—normal impact	0.5–10
	Vinylidene chloride	2–8
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	10
	Granular (silica) reinforced silicones	0.34
	Woven glass fabric/silicone laminate	10–25
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	0.20–0.35
	Cellulose filled (ASTM type 2)	0.20–0.275
	Wood flour filled	0.25–0.35

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

Note: To convert ft-lb/in. to Nm/m, multiply by 53.38.

TABLE 4.21 Modulus of Elasticity in Tension for Polymers

Class	Polymer	Modulus of Elasticity in Tension (ASTM D638) (10^5 psi)
ABS resins: Molded, extruded	Medium impact	3.3–4.0
	High impact	2.6–3.2
	Very high impact	2.0–3.1
	Low temperature impact	2.0–3.1
	Heat resistant	3.5–4.2

(*Continued*)

TABLE 4.21 (*Continued*) Modulus of Elasticity in Tension for Polymers

Class	Polymer	Modulus of Elasticity in Tension (ASTM D638) (10^5psi)
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	3.5–4.5
	General purpose, type II	4.0–5.0
	Moldings:	
	Grades 5, 6, 8	3.5–5.0
	High impact grade	2.3–3.3
Chlorinated polymers	Chlorinated polyether	1.5
	Chlorinated polyvinyl chloride	3.7
Polycarbonates	Polycarbonate	3.45
	Polycarbonate (40% glass–fiber-reinforced)	17
Diallyl phthalates: Molded	Orlon filled	6
	Asbestos filled	12
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	1.9–3.0
	Polytetrafluoroethylene (PTFE)	0.38–0.65
	Ceramic reinforced (PTFE)	1.5–2.0
	Fluorinated ethylene propylene (FEP)	0.5–0.7
	Polyvinylidene fluoride (PVDF)	1.7–2
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	4.5
	Cast flexible	0.5–2.5
	Molded:	
	General purpose glass cloth laminate	33–36
	High strength laminate	57–58
	Filament wound composite	72–64
	High-performance resins	
	Cycloaliphatic diepoxides	
	Cast, rigid	4–5
	Molded	
	Glass cloth laminate	32–33
	Epoxy novolacs	
	Cast, rigid	4.8–5.0
	Glass cloth laminate	27.5
Melamines: Molded	Unfilled	
	Cellulose electrical	10–11
Phenolics: Molded	Type and filler	
	General: wood flour and flock	8–13
	Shock: paper, flock, or pulp	8–12
	High shock: chopped fabric or cord	9–14
	Very high shock: glass fiber	30–33
	Arc resistant—mineral	10–30

(*Continued*)

TABLE 4.21 (*Continued*) Modulus of Elasticity in Tension for Polymers

Class	Polymer	Modulus of Elasticity in Tension (ASTM D638) (10^5psi)
	Rubber phenolic—wood flour or flock	4–6
	Rubber phenolic—chopped fabric	3.5–6
	Rubber phenolic—asbestos	5–9
Polyesters: Thermosets	Cast polyester	
	Rigid	1.5–6.5
	Flexible	0.001–0.10
	Reinforced polyester moldings	
	High strength (glass fibers)	16–20
	Heat and chemical resistant (asbestos)	12–15
	Sheet molding compounds, general purpose	15–20
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	0.21–0.27
	Melt index 6–26	0.20–0.24
Polystyrenes: Molded	Polystyrenes	D638
	General purpose	4.6–5.0
	Medium impact	2.6–4.7
	High impact	1.50–3.80
	Glass fiber (30%) reinforced	12.1
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	4.0–5.2
	Glass fiber (30%) reinforced SAN	17.5
Polyvinyl chloride and copolymers		ASTM D412
	Molded, extruded	
	Nonrigid—general	0.004–0.03
	Nonrigid—electrical	0.01–0.03
	Rigid—normal impact	3 5–4.0
	Vinylidene chloride	0.7–2.0
Silicones: Molded, laminated		ASTM D651
	Woven glass fabric/silicone laminate	28
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	13–16
	Woodflour filled	11–14

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

Note: To convert psi to MPa, divide by 145.

TABLE 4.22 Modulus of Elasticity in Compression for Polymers

Polymer	Modulus of Elasticity in Compression (ASTM D638) (10^5 psi)
Fluorocarbons: Molded, extruded	
Polytrifluorochloroethylene (PTFCE)	1.8
Polytetrafluoroethylene (PTFE)	0 70–0.90
Ceramic reinforced (PTFE)	1.5–2.0
Fluorinated ethylene propylene (FEP)	0.6–0.8
Polyvinylidene fluoride (PVDF)	1.7–2

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

Note: To convert from psi to MPa, divide by 145.

TABLE 4.23 Modulus of Elasticity in Flexure for Polymers

Polymer Class	Polymer	Modulus of Elasticity in Flexure (ASTM D790) (10^5 psi)
ABS resins: Molded, extruded	Medium impact	3.5–4.0
	High impact	2.5–3.2
	Very high impact	2.0–3.2
	Low temperature impact	2.0–3.2
	Heat resistant	3.5–4.2
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	3.5–4.5
	General purpose, type II	4.0–5.0
	Moldings:	
	Grades 5, 6, 8	3.5–5.0
	High impact grade	2.7–3.6
Thermoset carbonate	Allyl diglycol carbonate	2.5–3.3
Alkyds: Molded	Rope (general purpose)	22–27
	Granular (high-speed molding)	22–27
	Glass reinforced (heavy duty parts)	22–28
Cellulose acetate: Molded, extruded	ASTM grade:	(ASTM D747)
	H4-1	2.0–2.55
	H2-1	1.50–2.35
	MH-1, MH-2	1.50–2.15
	MS-1, MS-2	1.25–1.90
	S2-1	1.05–1.65
Cellulose acetate butyrate: Molded, extruded		(ASTM D747)
	ASTM grade:	
	H4	1.8
	MH	1.20–1.40
	S2	0.70–0.90

(*Continued*)

TABLE 4.23 (*Continued*) Modulus of Elasticity in Flexure for Polymers

Polymer Class	Polymer	Modulus of Elasticity in Flexure (ASTM D790) (10^5 psi)
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	1.7–1.8
	3	1.45–1.55
	6	1.1
Chlorinated polymers	Chlorinated polyether	1.3 (0.1% offset)
	Chlorinated polyvinyl chloride	3.85
Polycarbonates	Polycarbonate	3.4
	Polycarbonate (40% glass–fiber-reinforced)	12
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	2.0–2.5
	Polytetrafluoroethylene (PTFE)	0.6–1.1
	Ceramic reinforced (PTFE)	4.64
	Fluorinated ethylene propylene (FEP)	0.8
	Polyvinylidene fluoride (PVDF)	1.75–2.0
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	4.5–5.4
	Cast flexible	0.36–3.9
	Molded	15–25
	General purpose glass cloth laminate	36–39
	High strength laminate	53–55
	Filament wound composite	69–75
Epoxies: Molded, extruded	High-performance resins	
	(cycloaliphatic diepoxides)	
	Cast, rigid	4–5
	Glass cloth laminate	28–31
	Epoxy novolacs	
	Cast, rigid	4.4–4.8
	Glass cloth laminate	32–35
Melamines: Molded	Filler and type	
	Unfilled	10–13
	Cellulose electrical	10–13
	Glass fiber	24
Nylons: Molded, extruded	Type 6	
	General purpose	1.4–3.9
	Glass fiber (30%) reinforced	1.0–1.4
	Cast	5.05
	Flexible copolymers	0.92–3.2
	Type 8	0.4
	Type 11	1.51
	6/6 Nylon	
	General purpose molding	1.75–4.5
	Glass–fiber-reinforced	10–18

(*Continued*)

TABLE 4.23 (*Continued*) Modulus of Elasticity in Flexure for Polymers

Polymer Class	Polymer	Modulus of Elasticity in Flexure (ASTM D790) (10^5 psi)
	Glass fiber molybdenum disulfide filled	11–13
	General purpose extrusion	1.75–4.1
	6/10 Nylon	
	General purpose	1.6–2.8
	Glass fiber (30%) reinforced	8.5
Phenolics: Molded	Type and filler	
	General: wood flour and flock	8–12
	Shock: paper, flock, or pulp	8–12
	High shock: chopped fabric or cord	9–13
	Very high shock: glass fiber	30–33
	Arc resistant—mineral	10–30
	Rubber phenolic—wood flour or flock	4–6
	Rubber phenolic—chopped fabric	3.5
	Rubber phenolic—asbestos	5
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	4
PVC: acrylic alloy	PVC—acrylic sheet	4
	PVC—acrylic injection molded	3
Polyimides	Unreinforced	7
	Unreinforced second value	5
	Glass reinforced	38.4
Polyacetals	Homopolymer:	
	Standard	4.1
	20% Glass reinforced	8.8
	22% TFE reinforced	4
	Copolymer:	
	Standard	3.75
	25% Glass reinforced	11
	High flow	3.75
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	3.4
	Glass reinforced grades	12–15
	Glass reinforced self extinguishing	12
	General purpose grade	33
	Glass reinforced grade	87
	Asbestos-filled grade	90
Polyesters: Thermosets	Cast polyester	
	Rigid	1–9
	Flexible	0.001–0.39
	Reinforced polyester moldings	
	High strength (glass fibers)	15–25
	Sheet molding compounds, general purpose	15–18

(*Continued*)

TABLE 4.23 (*Continued*) Modulus of Elasticity in Flexure for Polymers

Polymer Class	Polymer	Modulus of Elasticity in Flexure (ASTM D790) (10^5 psi)
Phenylene oxides	SE-100	3.6
	SE-1	3.6
	Glass–fiber-reinforced	7.4–10.4
Phenylene oxides (Noryl)	Standard	3.9
	Glass–fiber-reinforced	12, 15.5
Polyarylsulfone	Polyarylsulfone	4
Polypropylene	General purpose	1.7–2.5
	High impact	1.0–2.0
	Asbestos filled	3.4–6.5
	Glass reinforced	4–8.2
	Flame retardant	1.9–6.1
Polyphenylene sulfide	Standard	5.5–6.0
	40% Glass reinforced	17–22
Polyethylenes: Molded, extruded		(ASTM D747)
	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	0.13–0.27
	Melt index 6–26	0.12–0.3
	Melt index 200	0.1
	Type II—medium density (0.926–0.940)	
	Melt index 20	0.35–0.5
	Melt index 1.0–1.9	0.35–0.5
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	1.3–1.5
	Melt index 0.1–12.0	0.9–0.25
	Melt index 1.5–15	1.5
	High molecular weight	0.75
Olefin Copolymers: Molded	Ethylene butane	165 (psi)
	Propylene–ethylene	140 (psi)
	Polyallomer	0.7–1.3
Polystyrenes: Molded	Polystyrenes:	
	General purpose	4–5
	Medium impact	3.5–5.0
	High impact	2.3–4.0
	Glass fiber (30%) reinforced	12
Styrene acrylonitrile (SAN)	Glass fiber (30%) reinforced SAN	14.5
Polyvinyl chloride and copolymers: Molded, extruded	Rigid—normal impact	3.8–5.4
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	25
	Granular (silica) reinforced silicones	14–17
	Woven glass fabric/silicone laminate	26–32

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

Note: To convert from psi to MPa, divide by 145.

TABLE 4.24 Total Elongation of Polymers

Class	Polymer	Elongation (in 51 mm) (ASTM D638) (%)
ABS resins: Molded, extruded	Medium impact	5–20
	High impact	5–50
	Very high impact	20–50
	Low temperature impact	30–200
	Heat resistant	20
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	2–7
	General purpose, type II	2–7
	Moldings:	
	Grades 5, 6, 8	3–5
	High impact grade	>25
	Chlorinated polymers	
	Chlorinated polyether	130
Polycarbonates	Polycarbonate	110
	Polycarbonate (40% glass–fiber-reinforced)	0–5
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	125–175
	Polytetrafluoroethylene (PTFE)	250–350
	Ceramic reinforced (PTFE)	10–200
	Fluorinated ethylene propylene (FEP)	250–330
	Polyvinylidene fluoride (PVDF)	200–300
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	4.4
	Cast flexible	1.5–60
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides)	
	Cast, rigid	2–5
	Epoxy novolacs	
	Glass cloth laminate	2.2–4.8
Melamines: Molded	Cellulose electrical	0.6
Nylons: Molded, extruded	Type 6	
	General purpose	30–100
	Glass fiber (30%) reinforced	2.2–3.6
	Cast	20
	Flexible copolymers	200–320
	Type 8	400
	Type 11	100–120
	Type 12	120–350
	6/6 Nylon	
	General purpose molding	15–300
	Glass–fiber-reinforced	1.8–2.2
	Glass fiber molybdenum disulfide filled	3

(*Continued*)

TABLE 4.24 (*Continued*) Total Elongation of Polymers

Class	Polymer	Elongation (in 51 mm) (ASTM D638) (%)
	General purpose extrusion	90–240
	6/10 Nylon	
	General purpose	85–220
	Glass fiber (30%) reinforced	1.9
Phenolics: Molded	Type and filler	
	General: wood flour and flock	0.4–0.8
	High shock: chopped fabric or cord	0.37–0.57
	Very high shock: glass fiber	0.2
	Rubber phenolic: wood flour or flock	0.75–2.25
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	110
PVC: Acrylic alloy	PVC—acrylic sheet	>100
	PVC—acrylic injection molded	150
Polyimides	Unreinforced	<1
	Unreinforced second value	1.2
	Glass reinforced	<1
Polyacetals	Homopolymer:	
	Standard	25
	20% Glass reinforced	7
	22% TFE reinforced	12
	Copolymer:	
	Standard	60–75
	25% Glass reinforced	3
	High flow	40
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	300
	Glass reinforced grades	1–5
	Glass reinforced self extinguishing	5
	General purpose grade	250
	Glass reinforced grade	<5
	Asbestos-filled grade	<5
Polyesters: Thermosets	Cast polyester	
	Rigid	1.7–2.6
	Flexible	25–300
Reinforced polyester moldings	High strength (glass fibers)	0.3–0.5
Phenylene oxides	SE-100	50
	SE-1	60
	Glass–fiber-reinforced	4–6
Phenylene oxides (Noryl)	Standard	50–100
Polyarylsulfone	Polyarylsulfone	15–40

(*Continued*)

TABLE 4.24 (*Continued*) Total Elongation of Polymers

Class	Polymer	Elongation (in 51 mm) (ASTM D638) (%)
Polypropylene	General purpose	100–600
	High impact	30–>200
	Asbestos filled	3–20
	Glass reinforced	2–4
	Flame retardant	3–15
Polyphenylene sulfide	Standard	3
	40% glass reinforced	3–9
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	(ASTM D412)
	Melt index 0.3–3.6	500–725
	Melt index 6–26	125–675
	Melt index 200	80–100
	Type II—medium density (0.926–0.940)	
	Melt index 20	200
	Melt index 1.0–1.9	200–425
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	700–1000
	Melt index 0.1–12.0	50–1000
	Melt index 1.5–15	100–700
	High molecular weight	400
Olefin copolymers: Molded	EEA (ethylene ethyl acrylate)	650
	EVA (ethylene vinyl acetate)	650
	Ethylene butane	20
	Ionomer	450
	Polyallomer	300–400
Polystyrenes: Molded	General purpose	1.0–2.3
	Medium impact	3.0–40
	Glass fiber (30%) reinforced	1.1
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	0.5–4.5
	Glass fiber (30%) reinforced SAN	1.4–1.6
Polyvinyl chloride and copolymers: Molded, extruded	Nonrigid—general	200–450
	Nonrigid—electrical	220–360
	Rigid—normal impact	1–10
	Vinylidene chloride	15–30
Silicones: Molded, laminated		(ASTM D651)
	Fibrous (glass) reinforced silicones	<3
	Granular (silica) reinforced silicones	<3
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	1

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.25 Elongation at Yield for Polymers

Class	Polymer	Elongation at Yield (ASTM D638) (%)
Chlorinated polyether	Chlorinated polyether	15
Polycarbonates	Polycarbonate	5
Nylons: Molded, extruded	Type 6	
	Cast	5
	Type 12	5.8
	6/6 Nylon:	
	General purpose molding	5–25
	General purpose extrusion	5–30
	6/10 Nylon:	
	General purpose	5–30
Polyacetals	Homopolymer:	
	Standard	12
	Copolymer:	
	Standard	12
	25% Glass reinforced	3
	High flow	12
Phenylene oxides (Noryl)	Standard	5.6
	Glass–fiber-reinforced	1.6–2
Polyarylsulfone	Polyarylsulfone	6.5–13
Polypropylene	General purpose	9–15
	High impact	7–13
	Asbestos filled	5
Polyphenylene sulfide	Standard	1.6
	40% Glass reinforced	1.25
Polystyrenes: Molded	General purpose	1.0–2.3
	Medium impact	1.2–3.0
	High impact	1.5–2.0
	Glass fiber (30%) reinforced	1.1
Styrene acrylonitrile (SAN)	Glass fiber (30%) reinforced SAN	1.4–1.6

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.26 Volume Resistivity of Polymers

Polymer	Type	Volume Resistivity (ASTM D257) (Ω · cm)
ABS resins: Molded, extruded	Medium impact	$2–4 \times 10^{15}$
	High impact	$1–4 \times 10^{15}$
	Very high impact	$1–4 \times 10^{15}$
	Low temperature impact	$1–4 \times 10^{15}$
	Heat resistant	$1–5 \times 10^{15}$
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	$>10^{15}$
	General purpose, type II	$>10^{15}$
	Moldings:	
	Grades 5, 6, 8	$>10^{14}$
	High impact grade	2.0×10^{16}
Thermoset carbonate alkyds: Molded	Allyl diglycol carbonate	4×10^{14}
	Putty (encapsulating)	10^{14}
	Rope (general purpose)	10^{14}
	Granular (high-speed molding)	$10^{14}–10^{15}$
	Glass reinforced (heavy duty parts)	10^{14}
Cellulose acetate: Molded, extruded	ASTM grade:	
	H6-1	$10^{10}–10^{13}$
	H4-1	$10^{10}–10^{13}$
	H2-1	$10^{10}–10^{13}$
	MH-1, MH-2	$10^{10}–10^{13}$
	MS-1, MS-2	$10^{10}–10^{13}$
	S2-1	$10^{10}–10^{13}$
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	$10^{11}–10^{14}$
	MH	$10^{11}–10^{14}$
	S2	$10^{11}–10^{14}$
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	$10^{11}–10^{14}$
	3	$10^{11}–10^{14}$
	6	$10^{11}–10^{14}$
Chlorinated polymers	Chlorinated polyether	1.5×10^{16}
	Chlorinated polyvinyl chloride	$1 \times 10^{15}–2 \times 10^{16}$
Polycarbonates	Polycarbonate	2.1×10^{16}
	Polycarbonate (40% glass–fiber-reinforced)	1.4×10^{15}
Diallyl phthalates: Molded	Orlon filled	$6 \times 10^{4}–6 \times 10^{6}$
	Dacron filled	$10^{2}–2.5 \times 10^{4}$
	Asbestos filled	$10^{2}–5 \times 10^{3}$
	Glass fiber filled	$10^{4}–5 \times 10^{4}$

(*Continued*)

TABLE 4.26 (*Continued*) Volume Resistivity of Polymers

Polymer	Type	Volume Resistivity (ASTM D257) (Ω · cm)
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	10^{18}
	Polytetrafluoroethylene (PTFE)	$>10^{18}$
	Ceramic reinforced (PTFE)	10^{15}
	Fluorinated ethylene propylene (FEP)	$>2 \times 10^{18}$
	Polyvinylidene fluoride (PVDF)	5×10^{14}
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	6.1×10^{15}
	Cast flexible	9.1×10^{5}–6.7×10^{9}
	Molded	1–5×10^{15}
	High strength laminate	6.6×10^{7}–10^{9}
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides)	
	Cast, rigid	2.10×10^{14}
	Molded	1.4–5.5×10^{14}
	Epoxy novolacs	
	Cast, rigid	$>10^{16}$
Melamines: Molded	Filler and type	
	Cellulose electrical	10^{12}–10^{13}
	Glass fiber	1–7×10^{11}
	Alpha cellulose and mineral	10^{12}
Nylons: Molded, extruded	Type 6	
	General purpose	4.5×10^{13}
	Glass fiber (30%) reinforced	2.8×10^{14}–1.5×10^{15}
	Cast	2.6×10^{14}
	Type 8	1.5×10^{11}
	Type 11	2×10^{13}
	Type 12	10^{14}–10^{15}
	6/6 Nylon	
	General purpose molding	10^{14}–10^{15}
	Glass–fiber-reinforced	2.6–5.5×10^{15}
	General purpose extrusion	10^{15}
	6/10 Nylon	
	General purpose	10^{15}
Phenolics: Molded	Type and filler	
	General: wood flour and flock	10^{9}–10^{13}
	Shock: paper, flock, or pulp	1–50×10^{11}
	High shock: chopped fabric or cord	$>10^{10}$
	Very high shock: glass fiber	10^{10}–10^{11}

(*Continued*)

TABLE 4.26 (*Continued*) Volume Resistivity of Polymers

Polymer	Type	Volume Resistivity (ASTM D257) (Ω · cm)
	Arc resistant—mineral	10^{10}–10^{12}
	Rubber phenolic—wood flour or flock	10^{8}–10^{11}
	Rubber phenolic—chopped fabric	10^{11}
	Rubber phenolic—asbestos	10^{11}
	ABS—polycarbonate alloy	2.2×10^{16}
	PVC—acrylic alloy	
	PVC—acrylic Sheet	$1–5 \times 10^{13}$
	PVC—acrylic injection molded	5×10^{15}
Polyimides	Unreinforced	4×10^{15}
	Glass reinforced	9.2×10^{15}
Polyacetals	Homopolymer:	
	Standard	1×10^{15}
	20% Glass reinforced	5×10^{14}
	Copolymer:	
	Standard	1×10^{14}
	25% Glass reinforced	1.2×10^{14}
	High flow	1.0×10^{14}
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	$1–4 \times 10^{16}$
	Glass reinforced grades	$3.2–3.3 \times 10^{16}$
	Glass reinforced self extinguishing	3.4×10^{16}
	General purpose grade	2×10^{15}
	Asbestos-filled grade	3×10^{14}
Polyesters: Thermosets	Cast polyester	
	Rigid	10^{13}
	Flexible	10^{12}
	Reinforced polyester moldings	
	High strength (glass fibers)	$1 \times 10^{12}–1 \times 10^{13}$
	Heat and chemical resistant (asbestos)	$1 \times 10^{12}–1 \times 10^{13}$
	Sheet molding compounds, general purpose	$6.4 \times 10^{15}–2.2 \times 10^{16}$
Phenylene oxides	Phenylene oxides	
	SE-100	10^{17}
	SE-1	10^{17}
	Glass–fiber-reinforced	10^{17}
Phenylene oxides (Noryl)	Standard	5×10^{16}
	Glass–fiber-reinforced	10^{17}
Polyarylsulfone	Polyarylsulfone	$3.2–7.71 \times 10^{16}$
Polypropylene	General purpose	$>10^{17}$
	High impact	10^{17}
	Asbestos filled	1.5×10^{15}
	Glass reinforced	1.7×10^{16}
	Flame retardant	$4 \times 10^{16}–10^{17}$

(*Continued*)

TABLE 4.26 (*Continued*) Volume Resistivity of Polymers

Polymer	Type	Volume Resistivity (ASTM D257) ($\Omega \cdot cm$)
Polyphenylene sulfide	40% Glass reinforced	4.5×10^{14}
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	10^{17}–10^{19}
	Melt index 6–26	10^{17}–10^{19}
	Melt index 200	10^{17}–10^{19}
	Type II—medium density (0.926–0.940)	
	Melt index 20	$>10^{15}$
	Melt index 1.0–1.9	$>10^{15}$
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	$>10^{15}$
	Melt index 0.1–12.0	$>10^{15}$
	Melt index 1.5–15	$>10^{15}$
	High molecular weight	$>10^{15}$
Olefin copolymers: Molded	EEA (ethylene ethyl acrylate)	2.4×10^{15}
	EVA (ethylene vinyl acetate)	0.15×10^{15}
	Ionomer	10×10^{15}
	Polyallomer	$>10^{16}$
Polystyrenes: Molded	Polystyrenes	
	General purpose	$>10^{16}$
	Medium impact	$>10^{16}$
	High impact	$>10^{16}$
	Glass fiber (30%) reinforced	3.6×10^{16}
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	$>10^{16}$
	Glass fiber (30%) reinforced SAN	4.4×10^{16}
Polyvinyl chloride and copolymers: Molded, extruded	Nonrigid—general	$1–700 \times 10^{12}$
	Nonrigid—electrical	$4–300 \times 10^{11}$
	Rigid—normal impact	10^{14}–10^{16}
	Vinylidene chloride	10^{14}–10^{16}
	Silicones: Molded, laminated	(Dry)
	Fibrous (glass) reinforced silicones	9×10^{14}
	Granular (silica) reinforced silicones	5×10^{14}
	Woven glass fabric/silicone laminate	$2–5 \times 10^{14}$
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	$0.5–5 \times 10^{11}$
	Cellulose filled (ASTM type 2)	$5–8 \times 10^{10}$

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook*, Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.27 Dissipation Factor for Polymers

Class	Polymer	Dissipation Factor (ASTM D150) 60 Hz	10^6 Hz
ABS Resins: Molded, extruded	Medium impact	0.003–0.006	0.008–0.009
	High impact	0.005–0.007	0.007–0.015
	Very high impact	0.005–0.010	0.008–0.016
	Low temperature impact	0.005–0.01	0.008–0.016
	Heat resistant	0.030–0.040	0.005–0.015
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:		
	General purpose, type I	0.05–0.06	0.02–0.03
	General purpose, type II	0.05–0.06	0.02–0.03
	Moldings:		
	Grades 5, 6, 8	0.04–0.06	0.02–0.03
	High impact grade	0.03–0.04	0.01–0.02
Thermoset carbonate	Allyl diglycol carbonate	0.03–0.04	0.1–0.2
alkyds: Molded	Putty (encapsulating)	0.030–0.045	0.016–0.020
	Rope (general purpose)	0.019	0.023
	Granular (high-speed molding)	0.030–0.040	0.017–0.020
	Glass reinforced (heavy duty parts)	0.02–0.03	0.015–0.022
Cellulose acetate: Molded, extruded	ASTM grade:		
	H4-1	0.01–0.06	0.01–0.10
	H2-1	0.01–0.06	0.01–0.10
	MH-1, MH-2	0.01–0.06	0.01–0.10
	MS-1, MS-2	0.01–0.06	0.01–0.10
	S2-1	0.01–0.06	0.01–0.10
Cellulose acetate butyrate: Molded, extruded	ASTM grade:		
	H4	0.01–0.04	0.02–0.05
	MH	0.01–0.04	0.02–0.05
	S2	0.01–0.04	0.02–0.05
Cellulose acetate propionate: Molded, extruded	ASTM grade:		
	1	0.01–0.04	0.02–0.05
	3	0.01–0.04	0.02–0.05
	6	0.01–0.04	0.02–0.05
Chlorinated polymers	Chlorinated polymers		
	Chlorinated polyether	0.011	0.011
	Chlorinated polyvinyl chloride	0.0189–0.0208	0.02
Polycarbonates	Polycarbonate	0.0009	0.01
	Polycarbonate (40% glass–fiber-reinforced)	0.006	0.007
Diallyl phthalates: Molded	Orlon filled	0.023–0.015 (dry)	0.045–0.040 (wet)
	Dacron filled	0.004–0.016 (dry)	0.009–0.017 (wet)
	Asbestos filled	0.05–0.03 (dry)	0.154–0.050 (wet)
	Glass fiber filled	0.004–0.015 (dry)	0.012–0.020 (wet)

(*Continued*)

TABLE 4.27 (*Continued*) Dissipation Factor for Polymers

Class	Polymer	Dissipation Factor (ASTM D150)	
		60 Hz	10^6 Hz
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	0.02	0.007–0.010
	Polytetrafluoroethylene (PTFE)	0.0002	0.0002
	Ceramic reinforced (PTFE)	0.0005–0.0015	0.0005–0.0015
	Fluorinated ethylene propylene (FEP)	0.0003	0.0003
	Polyvinylidene fluoride (PVDF)	0.05	0.184
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)		
	Cast rigid	0.0074	0.032
	Cast flexible	0.0048–0.0380	0.0369–0.0622
	Molded	0.011–0.018	0.013–0.020
	General purpose glass cloth laminate	0.004–0.006	0.024–0.026
	High strength laminate	—	0.010–0.017
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides)		
	Cast, rigid	0.0055–0.0074	0.029–0.028
	Molded	0.0071–0.025	—
	Glass cloth laminate	—	0.0158
	Epoxy novolacs		
	Cast, rigid	0.001–0.007	—
Melamines: Molded	Filler and type		
	Unfilled	0.048–0.162	0.031–0.040
	Cellulose electrical	0.026–0.192	0.032–0.12
	Glass fiber	0.14–0.23	0.020–0.03
	Alpha cellulose	—	0.028
	Mineral	—	0.030
Nylons: Molded, extruded	Type 6		
	General purpose	0.06–0.014	0.03–0.04
	Glass fiber (30%) reinforced	0.022–0.008	0.019–0.015
	Cast	0.015	0.05
	Flexible copolymers	0.007–0.010	0.010–0.015
	Type 8	0.19	0.08
	Type 11	0.03	0.02
	Type 12	0.04 (10^3 Hz)	
	6/6 Nylon		
	General purpose molding	0.014–0.04	0.04
	Glass–fiber-reinforced	0.009–0.018	0.017–0.018
	6/10 Nylon general purpose	0.04	
Phenolics: Molded	Type and filler		
	General: wood flour and flock	0.05–0.30	0.03–0.07
	Shock: paper, flock, or pulp	0.08–0.35	0.03–0.07
	High shock: chopped fabric or cord	0.08–0.45	0.03–0.09

(*Continued*)

TABLE 4.27 (*Continued*) Dissipation Factor for Polymers

Class	Polymer	Dissipation Factor (ASTM D150)	
		60 Hz	10^6 Hz
	Very high shock: glass fiber	0.02–0.03	0.02
	Arc resistant—mineral	0.13–0.16	0.1
	Rubber phenolic—wood flour or flock	0.15–0.60	0.1–0.2
	Rubber phenolic—chopped fabric	0.5	0.09
	Rubber phenolic—asbestos	0.15	0.13
	ABS—polycarbonate alloy	0.0026	0.0059
PVC: Acrylic alloy	PVC—acrylic sheet	0.076	0.094
	PVC—acrylic injection molded	0.037	0.031
Polyimides	Unreinforced	0.003	0.011
	Glass reinforced	0.0034	0.0055
Polyacetals	Homopolymer:		
	Standard	0.0048	0.0048
	20% Glass reinforced	0.0047	0.0036
	Copolymer:		
	Standard	0.001 (100 Hz)	0.006
	25% Glass reinforced	0.003 (100 Hz)	0.006
	High flow	0.001 (100 Hz)	0.006
Polyester: Thermoplastic	Injection moldings:		
	General purpose grade	0.002 (10^3 Hz)	
	Glass reinforced grades	0.002–0.003 (10^3 Hz)	
	Glass reinforced self extinguishing	0.002 (10^3 Hz)	
	General purpose grade	0.023 (10^3 Hz)	
	Asbestos-filled grade	0.015 (10^3 Hz)	
Polyesters: Thermosets	Cast polyester rigid	0.003–0.04	0.006–0.04
	Flexible	0.01–0.18	0.02–0.06
Reinforced polyester moldings	Sheet molding compounds, general purpose	0.0087–0.04	0.0086–0.022
Phenylene oxides	SE-100	0.0007	0.0024
	SE-1	0.0007	0.0024
	Glass–fiber-reinforced	0.0009	0.0015
	Phenylene oxides (Noryl) standard	0.0008	0.0034
	Glass–fiber-reinforced	0.0019	0.0049
Polyarylsulfone	Polyarylsulfone	0.0017–0.003	0.0056–0.012
Polypropylene	General purpose	0.0005–0.0007	0.0002–0.0003
	High impact	<0.0016	0.0002–0.0003
	Asbestos filled	0.007	0.002
	Glass reinforced	0.002	0.003
	Flame retardant	0.0007–0.017	0.0006–0.003
Polyphenylene sulfide	Standard	—	0.0007
	40% Glass reinforced	—	0.0014–0.0041

(*Continued*)

TABLE 4.27 (*Continued*) Dissipation Factor for Polymers

		Dissipation Factor (ASTM D150)	
Class	Polymer	60 Hz	10^6 Hz
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)		
	Melt index 0.3–3.6	<0.0005	
	Melt index 6–26	<0.0005	
	Melt index 200	<0.0005	
	Type II—medium density (0.926–0.940)		
	Melt index 20	<0.0005	
	Melt index 1.0–1.9	<0.0005	
	Type III—higher density (0.941–0.965)		
	Melt index 0.2–0.9	<0.0005	
	Melt index 0.1–12.0	<0.0005	
	Melt index 1.5–15	<0.0005	
	High molecular weight	<0.0005	
Olefin copolymers: Molded	EEA (ethylene ethyl acrylate)	0.001	
	EVA (ethylene vinyl acetate)	0.003	
	Ionomer	0.003	
	Polyallomer	>0.0005	
Polystyrenes: Molded	Polystyrenes general purpose	0.0001–0.0003	0.0001–0.0005
	Medium impact	0.0004–0.002	0.0004–0.002
	High impact	0.0004–0.002	0.0004–0.002
	Glass fiber (30%) reinforced	0.005	0.002
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	>0.006	0.007–0.010
	Glass fiber (30%) reinforced SAN	0.005	0.009
Polyvinyl chloride and copolymers	Molded, extruded		
	Nonrigid—general	0.05–0.15	
	Nonrigid—electrical	0.08–0.11	
	Rigid—normal impact	0.020–0.03	
	Vinylidene chloride	0.03–0.15	
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	0.01	0.004
	Granular (silica) reinforced silicones	0.002–0.004	0.001–0.004
	Woven glass fabric/silicone laminate	0.02	0.002
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	0.035–0.043	0.028–0.032
	Cellulose filled (ASTM type 2)	0.042–0.044	0.027–0.029
	Woodflour filled	0.035–0.040	0.028–0.032

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), and *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.28 Dielectric Strength of Polymers

Class	Polymer	Dielectric Strength (Short Time, ASTM D149) (V/mil)
ABS Resins: Molded, extruded	Medium impact	385
	High impact	350–440
	Very high impact	300–375
	Low temperature impact	300–415
	Heat resistant	360–400
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	450–530
	General purpose, type II	450–500
	Moldings:	
	Grades 5, 6, 8	400
	High impact grade	400–500
Cellulose acetate: Molded, extruded	ASTM grade:	
	H6-1	250–600
	H4-1	250–600
	H2-1	250–600
	MH-1, MH-2	250–600
	MS-1, MS-2	250–600
	S2-1	250–600
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	250–400
	MH	250–400
	S2	250–400
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	300–450
	3	300–450
	6	300–450
Chlorinated polymers	Chlorinated polyether	400
	Chlorinated polyvinyl chloride	1250–1550
Polycarbonates	Polycarbonate	400
	Polycarbonate (40% glass–fiber-reinforced)	475
Diallyl phthalates: Molded	Orlon filled	400 (dry)
		375 (wet)
	Dacron filled	376–400 (dry)
		360–391 (wet)
	Asbestos filled	350–450 (dry)
		300–400 (wet)
	Glass fiber filled	350–430 (dry)
		300–420 (wet)

(*Continued*)

TABLE 4.28 (*Continued*) Dielectric Strength of Polymers

Class	Polymer	Dielectric Strength (Short Time, ASTM D149) (V/mil)
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	530–600
	Polytetrafluoroethylene (PTFE)	1000–2000
	Ceramic reinforced (PTFE)	300–400
	Fluorinated ethylene propylene (FEP)	2100
	Polyvinylidene fluoride (PVDF)	260
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides) Molded	280–400 (step)
	Epoxy novolacs	
	Cast, rigid	444
Melamines: Molded	Filler and type cellulose electrical	350–400
	Glass fiber	250–300
	Alpha cellulose and mineral	375
Nylons: Molded, extruded	Type 6	
	General purpose	385–400
	Glass fiber (30%) reinforced	400–450
	Cast	380
	Flexible copolymers	440
	Type 8	340
	Type 11	425
	Type 12	840
	6/6 Nylon	
	General purpose molding	385
	Glass–fiber-reinforced	400–480
	Glass fiber molybdenum disulfide filled	300–400
	General purpose extrusion	
	6/10 Nylon	
	General purpose	470
Phenolics: Molded	Type and filler	
	General: wood flour and flock	200–425
	Shock: paper, flock, or pulp	250–350
	High shock: chopped fabric or cord	200–350
	Very high shock: glass fiber	375–425
	Arc resistant—mineral	350–425
	Rubber phenolic—wood flour or flock	250–375
	Rubber phenolic—chopped fabric	250
	Rubber phenolic—asbestos	350
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	500
PVC: Acrylic alloy	PVC—acrylic sheet	>429
	PVC—acrylic injection molded	400

(*Continued*)

TABLE 4.28 (*Continued*) Dielectric Strength of Polymers

Class	Polymer	Dielectric Strength (Short Time, ASTM D149) (V/mil)
Polyimides	Unreinforced second value	310
	Glass reinforced	300
Polyacetals	Homopolymer:	
	Standard	500
	20% Glass reinforced	500
	Copolymer:	
	Standard	500
	25% Glass reinforced	580
	High flow	500
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	590
	Glass reinforced grades	560–750
	Glass reinforced self extinguishing	750
	General purpose grade	420–540
	Glass reinforced grade	—
	Asbestos-filled grade	580
Polyesters: Thermosets	Cast polyester	
	Rigid	300–400
	Flexible	300–400
	Reinforced polyester moldings	
	High strength (glass fibers)	200–400
	Heat and chemical resistant (asbestos)	350
	Sheet molding compounds, general purpose	400–440
Phenylene oxides	SE-100	400 (1/8 in.)
	SE-1	500 (1/8 in.)
	Glass–fiber-reinforced	1020 (1/32 in.)
Phenylene oxides (Noryl)	Standard	425
	Glass–fiber-reinforced	480
Polyarylsulfone	Polyarylsulfone	350–383
Polypropylene	General purpose	650 (125 mil)
	High impact	450–650
	Asbestos filled	450
	Glass reinforced	317–475
	Flame retardant	485–700
Polyphenylene sulfide	Standard	450–595
	40% Glass reinforced	490
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	480
	Melt index 6–26	480
	Melt index 200	480

(*Continued*)

TABLE 4.28 (*Continued*) Dielectric Strength of Polymers

Class	Polymer	Dielectric Strength (Short Time, ASTM D149) (V/mil)
	Type II—medium density (0.926–0.940)	
	Melt index 20	480
	Melt index 1.0–1.9	480
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	480
	Melt index 0.1–12.0	480
	Melt index 1.5–15	480
	High molecular weight	480
Olefin copolymers: Molded	EEA (ethylene ethyl acrylate)	550
	EVA (ethylene vinyl acetate)	525
	Ionomer	1000
	Polyallomer	500–650
Polystyrenes: Molded	Polystyrenes	
	General purpose	>500
	Medium impact	>425
	High impact	300–650
	Glass fiber (30%) reinforced	396
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	400–500
	Glass fiber (30%) reinforced SAN	515
Polyvinyl chloride and copolymers: Molded, extruded	Nonrigid—electrical	24–500
	Rigid—normal impact	725–1400
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	280 (in oil)
	Granular (silica) reinforced silicones	380 (in oil)
	Woven glass fabric/silicone laminate	725
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	300–400
	Cellulose filled (ASTM type 2)	340–370
	Woodflour filled	300–400

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.29 Step Dielectric Strength of Polymers

Class	Polymer	Dielectric Strength, Step by Step ASTM D149 (V/mil) (Dry)	(Wet)
Thermoset carbonate	Allyl diglycol carbonate	290	
Alkyds: Molded	Putty (encapsulating)	300–350	
	Rope (general purpose)	290	
	Granular (high-speed molding)	300–350	
	Glass reinforced (heavy duty parts)	300–350	
Diallyl phthalates: Molded	Orlon filled	350	325
	Dacron filled	350–410	350–361
	Asbestos filled	300–400	250–350
	Glass fiber filled	300–420	275–420
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)		
	Cast rigid	>400	
	Cast flexible	400–410	
	Molded	360–400	
	General purpose glass cloth laminate	450–550	
	High strength laminate	650–750	
	High-performance resins		
	cycloaliphatic diepoxides		
	Molded	280–400	
Polyesters: Thermosets	Cast polyester		
	Rigid	300–400	
	Flexible	300–400	
	Reinforced polyester moldings		
	High strength (glass fibers)	200–400	
	Heat and chemical resistant (asbestos)	350	
	Sheet molding compounds, general purpose	400–440	

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.30 Dielectric Constant of Polymers

Polymer	Type	Dielectric Constant (ASTM D150)	
		60 Hz	10^6 Hz
ABS resins: Molded, extruded	Medium impact	2.8–3.2	2.75–3.0
	High impact	2.8–3.2	2.7–3.0
	Very high impact	2.8–3.5	2.4–3.0
	Low temperature impact	2.5–3.5	2.4–3.0
	Heat resistant	2.7–3.5	2.8–3.2
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:		
	General purpose, type I	3.5–4.5	2.7–3.2
	General purpose, type II	3.5–4.5	2.7–3.2
	Moldings:		
	Grades 5, 6, 8	3.5–3.9	2.7–2.9
	High impact grade	3.5–3.9	2.5–3.0
Thermoset carbonate	Allyl diglycol carbonate	4.4	3.5–3.8
Alkyds: Molded	Putty (encapsulating)	5.4–5.9	4.5–4.7
	Rope (general purpose)	7.4	6.8
	Granular (high-speed molding)	5.7–6.3	4.8–5.1
	Glass reinforced (heavy duty parts)	5.2–6.0	4.5–5.0
Cellulose acetate: Molded, extruded	ASTM grade:		
	H6-1	3.5–7.5	3.2–7.0
	H4-1	3.5–7.5	3.2–7.0
	H2-1	3.5–7.5	3.2–7.0
	MH-1, MH-2	3.5–7.5	3.2–7.0
	MS-1, MS-2	3.5–7.5	3.2–7.0
	S2-1	3.5–7.5	3.2–7.0
Cellulose acetate butyrate: Molded, extruded	ASTM grade:		
	H4	3.5–6.4	3.2–6.2
	MH	3.5–6.4	3.2–6.2
	S2	3.5–64	3.2–6.2
Cellulose acetate propionate:; Molded, extruded	ASTM grade:		
	1	3.7–4.0	3.4–3.7
	3	3.7–4.0	3.4–3.7
	6	3.7–4.0	3.4–3.7
Chlorinated polymers	Chlorinated polyether	3.1	2.92
	Chlorinated polyvinyl chloride	3.08	3.2–3.6
Polycarbonates	Polycarbonate	3.17	2.96
	Polycarbonate (40% glass–fiber-reinforced)	3.8	3.58
Diallyl phthalates: Molded	Orlon filled	3.9 (dry), 3.3 (wet)	4.1 (d), 3.4 (w)
	Dacron filled	3.7–3.8 (d), 3.5–3.6 (w)	3.9 (d), 3.7 (w)
	Asbestos filled	5.2 (d), 4.5 (w)	6.5 (d), 4.8 (w)

(*Continued*)

TABLE 4.30 (*Continued*) Dielectric Constant of Polymers

Polymer	Type	Dielectric Constant (ASTM D150)	
		60 Hz	10^6 Hz
	Glass fiber filled	4.1–4.5 (d), 3.5–4.5 (w)	4.6 (d), 4.4 (w)
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	2.6–2.7	
	Polytetrafluoroethylene (PTFE)		
	0.01 in thickness	2.1	
	Ceramic reinforced (PTFE)	2.9–3.6	
	Fluorinated ethylene propylene (FEP)		
	0.01 in thickness	2.1	
	Polyvinylidene fluoride (PVDF)		
	0.125 in thickness	10	
Epoxies: Cast, molded, reinforced	Standard epoxies		
	Diglycidyl ethers of bisphenol A		
	Cast rigid	4.02	3.42
	Cast flexible	4.43–4.79	2.78–3.52
	Molded	4.4–5.4	4.1–4.6
	General purpose glass cloth laminate	5.3–5.4	4.7–4.8
	High strength laminate	—	4.8–5.2
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides)		
	Cast, rigid	3.96–4.02	3.53–3.58
	Molded	4.7–5.7	4.3–4.8
	Glass cloth laminate	—	5.1
	Epoxy novolacs		
	Cast, rigid	3.34–3.39	—
	Glass cloth laminate	4.41–4.43	—
Melamines: Molded	Filler and type		
	Unfilled	7.9–11.0	6.3–7.3
	Cellulose electrical	6.2–7.7	5.2–6.0
	Glass fiber	7.0–11.1	6.0–7.9
Alpha cellulose	Alpha cellulose	—	6.4–8.1
	Mineral	—	5.6
Nylons: Molded, extruded	Type 6		
	General purpose	4.0–5.3	3.6–3.8
	Glass fiber (30%) reinforced	4.6–5.6	3.9–5.4
	Cast	4	3.3
	Flexible copolymers	3.2–4.0	3.0–3.6
	Type 8	9.3	4
	Type 11	3.3 (10^3 Hz)	—
	Type 12	3.6 (10^3 Hz)	—

(*Continued*)

TABLE 4.30 (*Continued*) Dielectric Constant of Polymers

Polymer	Type	Dielectric Constant (ASTM D150) 60 Hz	10^6 Hz
	6/6 Nylon		
	General purpose molding	4	3.6
	Glass–fiber-reinforced	40–44	3.5–4.1
	6/10 Nylon		
	General purpose	3.9	3.5
Phenolics: Molded	Type and filler		
	General: wood flour and flock	5.0–9.0	4.0–7.0
	Shock: paper, flock, or pulp	5.6–11.0	4.5–7.0
	High shock: chopped fabric or cord	6.5–15.0	4.5–7.0
	Very high shock: glass fiber	7.1–7.2	4.6–6.6
	Arc resistant—mineral	7.4	5
	Rubber phenolic—wood flour or flock	9–16	5
	Rubber phenolic—chopped fabric	15	5
	Rubber phenolic—asbestos	15	5
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	2.74	2.69
PVC: Acrylic alloy	PVC—acrylic sheet	3.86	3.44
	PVC—acrylic injection molded	4	3.4
Polyimides	Unreinforced	4.12	3.96
	Glass reinforced	4.84	4.74
Polyacetals	Homopolymer:		
	Standard	3.7	3.7
	20% Glass reinforced	4	4.0
	Copolymer:		
	Standard	3.7 (100 Hz)	3.7
	25% Glass reinforced	3.9 (100 Hz)	3.9
	High flow	3.7 (100 Hz)	3.7
Polyester: Thermoplastic	Injection moldings:		
	General purpose grade	3.1–3.3	—
	Glass reinforced grades	3.7–4.2	—
	Glass reinforced self extinguishing	3.7–3.8	—
	General purpose grade	3.16	—
	Asbestos-filled grade	3.5–4.2	—
Polyesters: Thermosets	Cast polyester		
	Rigid	2.8–4.4	2.8–4.4
	Flexible	3.18–7.0	3.7–6.1
	Reinforced polyester moldings sheet molding compounds, general purpose	4.62–5.0	4.55–4.75
Phenylene oxides	SE-100	2.65	2.64
	SE-1	2.69	2.68
	Glass–fiber-reinforced	2.93	2.92

(*Continued*)

TABLE 4.30 (*Continued*) Dielectric Constant of Polymers

Polymer	Type	Dielectric Constant (ASTM D150)	
		60 Hz	10^6 Hz
Phenylene oxides (Noryl)	Standard	3.06–3.15	3.03–3.10
	Glass–fiber-reinforced	3.55	3.41
Polyarylsulfone	Polyarylsulfone	3.51–3.94	3.54–3.7
Polypropylene	General purpose	2.20–2.28	2.23–2.24
	High impact	2.20–2.28	2.23–2.27
	Asbestos filled	2.75	2.6–3.17
	Glass reinforced	2.3–2.5	2–2.25
	Flame retardant	2.46–2.79	2.45–2.70
Polyphenylene sulfide	Standard	—	3.22–3.8
	40% Glass reinforced	—	3.88
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)		
	Melt index 0.3–3.6	2.3	–
	Melt index 6–26	2.3	–
	Melt index 200	2.3	–
	Type II—medium density (0.926–0.940)		
	Melt index 20	2.3	–
	Melt index 1.0–1.9	2.3	–
	Type III—higher density (0.941–0.965)		
	Melt index 0.2–0.9	2.3	–
	Melt index 0.1–12.0	2.3	–
	Melt index 1.5–15	2.3	–
	High molecular weight	2.3	–
Olefin copolymers: Molded	EEA (ethylene ethyl acrylate)	2.8	
	EVA (ethylene vinyl acetate)	3.16	
	Ionomer	2.4	
	Polyallomer	2.3	
Polystyrenes: Molded	Polystyrenes		
	General purpose	2.45–2.65	2.45–2.65
	Medium impact	2.45–4.75	2.4–3.8
	High impact	2.45–4.75	2.5–4.0
	Glass fiber (30%) reinforced	3.1	3
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	2.6–3.4	2.6–3.02
	Glass fiber (30%) reinforced SAN	3.5	3.4–3.6
Polyvinyl chloride and copolymers	Molded, extruded		
	Nonrigid—general	5.5–9.1	
	Nonrigid—electrical	6.0–8.0	
	Rigid—normal impact	2.3–3.7	
	Vinylidene chloride	3–5	

(*Continued*)

TABLE 4.30 (*Continued*) Dielectric Constant of Polymers

		Dielectric Constant (ASTM D150)	
Polymer	Type	60 Hz	10^6 Hz
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	4.34	4.28
	Granular (silica) reinforced silicones	4.1–4.5	3.4–4.3
	Woven glass fabric/silicone laminate	3.9–4.2	3.8–397
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	7.0–9.5	6.4–6.9
	Cellulose filled (ASTM type 2)	7.2–7.3	6.4–6.5
	Woodflour filled	7.0–9.5	6.4–6.9

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science,* Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), and *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.31 Dielectric Breakdown of Polymers: Short Time

		Dielectric Breakdown, Short Time (kV)	
Polymer	Type	(Dry)	(Wet)
Diallyl phthalates: Molded	Orlon filled	65–75	60–65
	Dacron filled	65	60
	Asbestos filled	55–80	55
	Glass fiber filled	63–70	45–65

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science,* Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.32 Dielectric Breakdown of Polymers: Step by Step

		Dielectric Breakdown, Step by Step (kV)	
Polymer	Type	(Dry)	(Wet)
Diallyl phthalates: Molded	Orlon filled	55–60	46–60
	Dacron filled	60	55
	Asbestos filled	38–70	39–60
	Glass fiber filled	55–65	45–65

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.33 Arc Resistance of Polymers

Polymer	Type	Arc Resistance (ASTM D495) (s)
Acrylics: Cast, molded, extruded	Cast resin sheets, Rods:	
	General purpose, type I	No track
	General purpose, type II	No track
	Moldings:	
	Grades 5, 6, 8	No track
	High impact grade	No track
Thermoset carbonate	Allyl diglycol carbonate	185
Alkyds: Molded	Putty (encapsulating)	180
	Rope (general purpose)	180
	Granular (high-speed molding)	180
	Glass reinforced (heavy duty parts)	180
Polycarbonates	Polycarbonate	120 (tungsten electrode)
	Polycarbonate (40% glass–fiber-reinforced)	120 (tungsten electrode)
Diallyl phthalates: Molded	Orlon filled	85–115
	Dacron filled	105–125
	Asbestos filled	125–140
	Glass fiber filled	125–140
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	>360
	Polytetrafluoroethylene (PTFE)	>200
	Ceramic reinforced (PTFE)	0
	Fluorinated ethylene propylene (FEP)	>165
	Polyvinylidene fluoride (PVDF)	50–60
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	100
	Cast flexible	75–98
	Molded	135–190
	General purpose glass cloth laminate	130–180
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides)	
	Molded	180–185
	Epoxy novolacs	
	Cast, rigid	120
Melamines: Molded	Filler and type	
	Unfilled	100–145
	Cellulose electrical	70–135
	Glass fiber	180–186
	Alpha cellulose and mineral	125
Nylons: Molded, extruded	Type 6	
	Glass fiber (30%) reinforced	92–81
	6/6 Nylon	

(*Continued*)

TABLE 4.33 (*Continued*) Arc Resistance of Polymers

Polymer	Type	Arc Resistance (ASTM D495) (s)
	General purpose molding	120
	Glass–fiber-reinforced	100–148
	Glass fiber molybdenum disulfide filled	135
	General purpose extrusion	120
	6/10 Nylon	
	General purpose	120
Phenolics: Molded	Type and filler	
	General: wood flour and flock	5–60
	Shock: paper, flock, or pulp	5–60
	High shock: chopped fabric or cord	5–60
	Very high shock: glass fiber	60
	Arc resistant—mineral	180
	Rubber phenolic—wood flour or flock	7–20
	Rubber phenolic—chopped fabric	10–20
	Rubber phenolic—asbestos	5–20
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	96
PVC: Acrylic alloy	PVC—acrylic sheet	80
	PVC—acrylic injection molded	25
Polyimides	Unreinforced	152
	Glass reinforced	50–180
Polyacetals	Homopolymer:	
	Standard	129
	20% Glass reinforced	188
	Copolymer:	
	Standard	240
	25% Glass reinforced	136
	High flow	240
Polyester: Thermoplastics	Injection moldings:	
	General purpose grade	190
	Glass reinforced grades	130
	Glass reinforced self extinguishing	80
	General purpose grade	125
	Asbestos-filled grade	108
Polyesters: Thermosets	Cast polyester	
	Rigid	115–135
	Flexible	125–145
	Reinforced polyester moldings high strength (glass fibers)	130–170
	Sheet molding compounds, general purpose	130–180
Phenylene oxides	SE-100	75
	SE-1	75
	Glass–fiber-reinforced	120

(*Continued*)

TABLE 4.33 (*Continued*) Arc Resistance of Polymers

Polymer	Type	Arc Resistance (ASTM D495) (s)
Phenylene oxides (Noryl)	Standard	122
	Glass–fiber-reinforced	114
Polyarylsulfone	Polyarylsulfone	67–81
Polypropylene	General purpose	125–136
	High impact	123–140
	Asbestos filled	121–125
	Glass reinforced	73–77
	Flame retardant	15–40
Polyphenylene sulfide	40% Glass reinforced	34
Polystyrenes	Molded	
	General purpose	60–135
	Medium impact	20–135
	High impact	20–100
	Glass fiber (30%) reinforced	28
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	100–150
	Glass fiber (30%) reinforced SAN	65
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	240
	Granular (silica) reinforced silicones	250–310
	Woven glass fabric/silicone laminate	225–250
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	100–135
	Cellulose filled (ASTM type 2)	85–110
	Woodflour filled	80–110

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.34 Transparency of Polymers

Polymer	Type	Transparency (Visible Light) (ASTM D791) (%)
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	(0.125 in.)
	General purpose, type I	91–92
	General purpose, type II	91–92
	Moldings:	
	Grades 5, 6, 8	>92
	High impact grade	90
Thermoset carbonate	Allyl diglycol carbonate	89–92
Alkyds: Molded	Putty (encapsulating)	Opaque
	Rope (general purpose)	Opaque
	Granular (high-speed molding)	Opaque
	Glass reinforced (heavy duty parts)	Opaque
Cellulose acetate: Molded, extruded	ASTM grade:	
	H6-1	75–90
	H4-1	75–90
	H2-1	80–90
	MH-1, MH-2	80–90
	MS-1, MS-2	80–90
	S2-1	80–95
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	75–92
	MH	80–92
	S2	85–95
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	80–92
	3	80–92
	6	80–92
Chlorinated polymers	Chlorinated polyether	Opaque
	Chlorinated polyvinyl chloride	Opaque
Polycarbonates	Polycarbonate	75–85
	Polycarbonate (40% glass–fiber-reinforced)	Translucent
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	80–92
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	
	Cast flexible	90
	Molded	85
	General purpose glass cloth laminate	Opaque
	High strength laminate	Opaque
	Filament wound composite	Opaque
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides)	
	Cast, rigid	

(*Continued*)

TABLE 4.34 (*Continued*) Transparency of Polymers

Polymer	Type	Transparency (Visible Light) (ASTM D791) (%)
	Molded	Opaque
	Glass cloth laminate	Opaque
	Epoxy novolacs	
	Glass cloth laminate	Opaque
Melamines: Molded	Filler and type	
	Unfilled	Good
	Cellulose electrical	Opaque
Nylons: Molded, extruded	6/6 Nylon	
	General purpose molding	Translucent
	Glass–fiber-reinforced	Opaque
	Glass fiber molybdenum disulfide filled	Opaque
	General purpose extrusion	Opaque
	6/10 Nylon	
	General purpose	Opaque
	Glass fiber (30%) reinforced	Opaque
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	Opaque
PVC: Acrylic alloy	PVC—acrylic sheet	Opaque
	PVC—acrylic injection molded	Opaque
Polyimides	Unreinforced	Opaque
	Unreinforced second value	Opaque
	Glass reinforced	Opaque
Polyesters: Thermosets	Reinforced polyester moldings	
	High strength (glass fibers)	Opaque
	Heat and chemical resistant (asbestos)	Opaque
	Sheet molding compounds, general purpose	Opaque
Phenylene oxides	SE-100	Opaque
	SE-1	Opaque
	Glass–fiber-reinforced	Opaque
Phenylene oxides (Noryl)	Glass–fiber-reinforced	Opaque
Polypropylene	General purpose	Translucent–opaque
	High impact	Translucent–opaque
	Asbestos filled	Opaque
	Glass reinforced	Opaque
	Flame retardant	Opaque
Polyphenylene sulfide	Standard	Opaque
	40% Glass reinforced	Opaque
Polystyrenes: Molded	General purpose	Transparent
	Medium impact	Opaque
	High impact	Opaque
	Glass fiber (30%) reinforced	Opaque

(*Continued*)

TABLE 4.34 (*Continued*) Transparency of Polymers

Polymer	Type	Transparency (Visible Light) (ASTM D791) (%)
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	Transparent
	Glass fiber (30%) reinforced SAN	Opaque
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	Opaque
	Granular (silica) reinforced silicones	Opaque
	Woven glass fabric/silicone laminate	Opaque
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	21.8
	Cellulose filled (ASTM type 2)	Opaque
	Woodflour filled	Opaque

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook*, Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.35 Refractive Index of Polymers

Polymer	Type	Refractive Index (ASTM D542) (n_D)
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	1.485–1.500
	General purpose, type II	1.485–1.495
	Moldings:	
	Grades 5, 6, 8	1.489–1.493
	High impact grade	1.49
Thermoset carbonate	Allyl diglycol carbonate	1.5
Cellulose acetate: Molded, extruded	ASTM grade:	
	H6-1	1.46–1.50
	H4-1	1.46–1.50
	H2-1	1.46–1.50
	MH-1, MH-2	1.46–1.50
	MS-1, MS-2	1.46–1.50
	S2-1	1.46–1.50
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	(D543)
	H4	1.46–1.49
	MH	1.46–1.49
	S2	1.46–1.49
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	1.46–1.49
	3	1.46–1.49
	6	1.46–1.49
Polycarbonate	Polycarbonate	1.586
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	1.43
	Polytetrafluoroethylene (PTFE)	1.35
	Fluorinated ethylene propylene (FEP)	1.34
	Polyvinylidene fluoride (PVDF)	1.42

(*Continued*)

TABLE 4.35 (*Continued*) Refractive Index of Polymers

Polymer	Type	Refractive Index (ASTM D542) (n_D)
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast flexible	1.61
	Molded	1.61
Polyacetals	Homopolymer:	
	Standard	Opaque
	20% Glass reinforced	Opaque
	22% TFE reinforced	Opaque
	Copolymer:	
	Standard	Opaque
	25% Glass reinforced	Opaque
	High flow	Opaque
Polyesters: Thermosets	Cast polyester	
	Rigid	1.53–1.58
	Flexible	1.50–1.57
Phenylene oxides (Noryl)	Standard	1.63
Polyarylsulfone	Polyarylsulfone	1.651
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	1.51
	Melt index 6–26	1.51
	Melt index 200	1.51
	Type II—medium density (0.926–0.940)	
	Melt index 20	1.51
	Melt index 1.0–1.9	1.51
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	1.54
	Melt index 0.1–12.0	1.54
	Melt index 1.5–15	1.54
Polystyrenes: Molded	Polystyrenes	
	General purpose	1.6
	Medium impact	Opaque
	High impact	Opaque
	Glass fiber (30%) reinforced	Opaque
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	1.565–1.569
	Glass fiber (30%) reinforced SAN	Opaque
Polyvinyl chloride and copolymers: Molded, extruded	Vinylidene chloride	1.60–1.63

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

Chemical Properties

TABLE 4.36 Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
H–H	104.207	±0.001
H–D	105.030	±0.001
D–D	106.010	±0.001
H–Li	56.91	±0.01
H–Be	54	
H–B	79	±1
H–C	80.9	
H–N	75	±4
H–O	102.34	±0.30
H–F	135.9	±0.3
H–Na	48	±5
H–Mg	47	±12
H–Al	68	±2
H–Si	71.4	±1.2
H–P	82	±7
H–S	82.3	±2.9
H–Cl	103.1	
H–K	43.8	±3.5
H–Ca	40.1	
H–Cr	67	±12
H–Mn	56	±7
H–Ni	61	±7
H–Cu	67	±2
H–Zn	20.5	±0.5
H–Ga	68	±5
H–Ge	76.8	±0.2
H–As	65	±3
H–Se	73	±1
H–Br	87.4	±0.5
H–Rb	40	±5
H–Sr	39	±2
H–Ag	59	±1
H–Cd	16.5	±0.1
H–In	59	±2
H–Sn	63	±1
H–Te	64	±1

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
H–I	71.4	±0.2
H–Cs	42.6	±0.9
H–Ba	42	±4
H–Yb	38	±1
H–Pt	84	±9
H–Au	75	±3
H–Hg	9.5	
H–Ti	45	±2
H–Pb	42	±5
H–Bi	59	±7
Li–Li	24.55	±0.14
Li–O	78	±6
Li–F	137.5	±1
Li–Cl	111.9	±2
Li–Br	100.2	±2
Li–I	84.6	±2
Be–Be	17	
Be–O	98	±7
Be–F	136	±2
Be–S	89	±14
Be–Cl	92.8	±2.2
Be–Au	~67C	
B–B	~67	±5
B–N	93	±12
B–O	192.7	±1.2
B–F	180	±3
B–S	138.8	±2.2
B–Cl	119	
B–Se	110	±4
B–Br	101	±5
B–Ru	107	±5
B–Rh	114	±5
B–Pd	79	±5
B–Te	85	±5
B–Ce	~100	
B–Ir	123	±4

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
B–Pt	114	±4
B–Au	82	±4
B–Th	71	
C–C	144	±5
C–N	184	±1
C–O	257.26	±0.77
C–F	128	±5
C–Si	104	±5
C–P	139	±23
C–S	175	±7
C–Cl	93	
C–Ti	~128	
C–V	133	
C–Ge	110	±5
C–Se	139	±23
C–Br	67	±5
C–Ru	152	±3
C–Rh	139	±2
C–I	50	±5
C–Ce	109	±7
C–Ir	149	±3
C–Pt	146	±2
C–U	111	±7
N–N	226.8	±1.5
N–O	150.8	±0.2
N–F	62.6	±0.8
N–Al	71	±23
N–Si	105	±9
N–P	148	±5
N–S	~120	±6
N–Cl	93	±12
N–Ti	111	
N–As	116	±23
N–Se	105	±23
N–Br	67	±5
N–Sb	72	±12

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
N–I	~0.38	
N–Xe	55	
N–Th	138	±1
N–U	127	±1
O–O	118.86	±0.04
O–F	56	±9
O–Na	61	±4
O–Mg	79	±7
O–Al	116	±5
O–Si	184	±3
O–P	119.6	±3
O–S	124.69	±0.03
O–Cl	64.29	±0.03
O–K	57	±8
O–Ca	84	±7
O–Sc	155	±5
O–Ti	158	±8
O–V	154	±5
O–Cr	110	±10
O–Mn	96	±8
O–Fe	96	±5
O–Co	88	±5
O–Ni	89	±5
O–Cu	82	±15
O–Zn	≤66	
O–Ga	68	±15
O–Ge	158.2	±3
O–As	115	±3
O–Se	101	
O–Br	56.2	±0.6
O–Rb	(61)	±20
O–Sr	93	±6
O–Y	162	±5
O–Zr	181	±10
O–Nb	189	±10
O–Mo	115	±12

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
O–Ru	115	±15
O–Rh	90	±15
O–Pd	56	±7
O–Ag	51	±20
O–Cd	≤67	
O–In	≤77	
O–Sn	127	±2
O–Sb	89	±20
O–Fe	93.4	±2
O–I	47	±7
O–Xe	9	±5
O–Cs	67	±8
O–Ba	131	±6
O–La	188	±5
O–Ce	188	±6
O–Pr	183.7	
O–Nd	168	±8
O–Sm	134	±8
O–Eu	130	±10
O–Gd	162	±6
O–Tb	165	±8
O–Dy	146	±10
O–Ho	149	±10
O–Er	147	±10
O–Tm	122	±15
O–Yb	98	±15
O–Lu	159	±8
O–Hf	185	±10
O–Ta	183	±15
O–W	156	±6
O–Os	<142	
O–Ir	≤94	
O–Pt	83	±8
O–Pb	90.3	±1.0
O–Bi	81.9	±1.5
O–Th	192	±10

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
O–U	182	±8
O–Np	172	±7
O–Pu	163	±15
O–Cm	≤134	
F–F	37.5	±2.3
F–Na	114	±1
F–Mg	110	±1
F–Al	159	±3
F–Si	116	±12
F–P	105	±23
F–Cl	59.9	±0.1
F–K	118.9	±0.6
F–Ca	125	±5
F–Sc	141	±3
F–Ti	136	±8
F–Cr	104.5	±4.7
F–Mn	101.2	±3.5
F–Ni	89	±4
F–Cu	88	±9
F–Ga	138	±4
F–Ge	116	±5
F–Br	55.9	
F–Rb	116.1	±1
F–Sr	129.5	±1.6
F–Y	144	±5
Mg–I	~68	
Mg–Au	59	±23
Al–Al	44	
Al–P	52	±3
Al–S	79	
Al–Cl	119.0	±1
Al–Br	103.1	
Al–I	88	
Al–Au	65	
Al–U	78	±7
Si–Si	76	±5
Si–S	148	±3
Si–Cl	105	±12
Si–Fe	71	±6
Si–Co	66	±4

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
Si–Ni	76	±4
Si–Ge	72	±5
Si–Se	127	±4
Si–Br	82	±12
Si–Ru	95	±5
Si–Rh	95	±5
Si–Pd	75	±4
Si–Te	121	±9
Si–Ir	110	±5
Si–Pt	120	±5
Si–Au	75	±3
P–P	117	±3
F–Ag	84.7	±3.9
F–Cd	73	±5
F–In	121	±4
F–Sn	111.5	±3
F–Sb	105	±23
F–I	≤64.9	
F–Xe	11	
F–Cs	119.6	±1
F–Ba	140.3	±1.6
F–Nd	130	±3
F–Sm	126.9	±4.4
F–Eu	126.1	±4.4
F–Gd	141.1	±6.5
F–Hg	31	±9
F–Tl	106.4	±4.6
F–Pb	85	±2
F–Bi	62	
F–Pu	129	±7
Na–Na	18.4	
Na–Cl	97.5	±0.5
Na–K	15.2	±0.7
Na–Br	86.7	±1
Na–Rb	14	±1
Na–I	72.7	±1
Mg–Mg	2.044	±0.001
Mg–S	56	
Mg–Cl	76	±3
Mg–Br	75	±23

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
P–S	70	
P–Ga	56	
P–W	73	±1
P–Th	90	
S–S	101.9	±2.5
S–Ca	75	±5
S–Sc	114	±3
S–Mn	72	±4
S–Fe	78	
S–Cu	72	±12
S–Zn	49	±3
S–Ge	131.7	±0.6
S–Se	91	±5
S–Sr	75	±5
S–Y	127	±3
S–Cd	48	
S–In	69	±4
S–Sn	111	±1
S–Te	81	±5
S–Ba	96	±5
S–La	137	±3
S–Ce	137	±3
S–Pr	122.7	
S–Nd	113	±4
S–Eu	87	±4
S–Gd	126	±4
S–Ho	102	±4
S–Lu	121	±4
S–Au	100	±6
S–Hg	51	
S-Pb	82.7	±0.4
S–Bi	75.4	±1.1
S–U	135	±2
Cl–Cl	58.066	±0.001
Cl–K	101.3	±0.5
Cl–Ca	95	±3
Cl–Sc	79	
Cl–Ti	26	±2
Cl–Cr	87.5	±5.8
Cl–Mn	86.2	±2.3

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
Cl–Fe	≈84	
Cl–Ni	89	±5
Cl–Cu	84	±6
Cl–Zn	54.7	±4.7
Cl–Ga	114.5	
Cl–Ge	≈103	
Cl–Br	52.3	±0.2
Cl–Rb	100.7	±1
Cl–Sr	97	±3
Cl–Y	82	±23
Cl–Ag	75	±9
Cl–Cd	49.9	
Cl–In	103.3	
Cl–Sn	99	±4
Cl–Sb	86	±12
Cl–I	50.5	±0.1
Cl–Cs	106.2	±1
Cl–Ba	106	±3
Cl–Au	82	±2
Cl–Hg	24	±2
Cl–Ti	89.0	±0.5
Cl–Pb	72	±7
Cl–Bi	72	±1
Cl–Ra	82	±18
Ar–Ar	0.2	
K–K	12.8	
K–Br	90.9	±0.5
K–I	76.8	±0.5
Ca–I	70	±23
Ca–Au	18	
Sc–Sc	25.9	±5
Ti–Ti	34	±5
V–V	58	±5
Cr–Cr	<37	
Cr–Cu	37	±5
Cr–Ge	41	±7
Cr–Br	78.4	±5
Cr–I	68.6	±5.8
Cr–Au	51.3	±3.5
Mn–Mn	4	±3

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
Mn–Se	48	±3
Mn–Br	75.1	±23
Mn–I	67.6	±2.3
Mn–Au	44	±3
Fe–Fe	24	±5
Fe–Ge	50	±7
Fe–Br	59	±23
Fe–Au	45	±4
Co–Co	40	±6
Co–Cu	39	±5
Co–Ge	57	±6
Co–Au	51	±3
Ni–Ni	55.5	±5
Ni–Cu	48	±5
Ni–Ge	67.3	±4
Ni–Br	86	±3
Ni–I	70	±5
Ni–Au	59	±5
Cu–Cu	46.6	±2.2
Cu–Ge	49	±5
Cu–Se	70	±9
Cu–Br	79	±65
Cu–Ag	41.6	±2.2
Cu–Sn	42.3	±4
Cu–Te	42	±9
Cu–I	47	±5
Cu–Au	55.4	±2.2
Zn–Zn	7	
Zn–Se	33	±3
Zn–Te	28.1	±4.3
Zn–I	33	±7
Ga–Ga	3	±3
Ga–As	50.1	±0.3
Ga–Br	101	±4
Ga–Ag	4	±3
Ga–Te	60	±6
Ga–I	81	±2
Ga–Au	51	±23
Ge–Ge	65.8	±3
Ge–Se	113.0	±2.0

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
Ge–Br	61	±7
Ge–Te	93	±2
Ge–Au	70	±23
As–As	91.7	
As–Se	23	
Se–Se	79.5	±0.1
Se–Cd	~75	
Se–In	59	±4
Se–Sn	95.9	±1.4
Se–Te	64	±2
Se–La	114	±4
Se–Nd	92	±4
Se–Eu	72	±4
Se–Gd	103	±4
Se–Ho	80	±4
Se–Lu	100	±4
Se–Pb	72.4	±1
Se–Bi	67.0	±1.5
Bi–Br	46.336	±0.001
Br–Rb	90.4	±1
Br–Ag	70	±7
Br–Cd	~38	
Br–In	93	
Bi–Sn	47	±23
Br–Sb	75	±14
Br–I	42.8	±0.1
Br–Cs	96.5	±1
Br–Hg	17.3	
Br–Ti	79.8	±0.4
Br–Pb	59	±9
Br–Bi	63.9	±1
Rb–Rb	12.2	
Rb–I	76.7	±1
Sr–Au	63	±23
Y–Y	38.3	
Y–La	48.3	
Pd–Pd	17	
Pd–Au	34.2	±5
Ag–Ag	41	±2
Ag–Sn	32.5	±5

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
Ag–Te	70	±23
Ag–I	56	±7
Ag–Au	48.5	±2.2
Cd–Cd	2.7	±0.2
Cd–I	33	±5
In–In	23.3	±2.5
In–Sb	36.3	±2.5
In–Te	52	±4
In–I	80	
Sn–Sn	46.7	±4
Sn–Te	76	±1
Sn–Au	58.4	±4
Sb–Sb	71.5	±1.5
Sb–Te	61	±4
Sb–Bi	60	±1
Te–Te	63.2	±0.2
Te–La	91	±4
Te–Nd	73	±4
Te–Eu	58	±4
Te–Gd	82	±4
Te–Ho	62	±4
Te–Lu	78	±4
Te–Au	59	±16
Te–Pb	60	±3
Te–Bi	56	±3
I–I	36.460	±0.002
I–Cs	82.4	±1
I–Hg	9	
I–Ti	65	±2
I–Pb	47	±9
I–Bi	52	±1
Xe–Xe	~0.7	
Cs–Cs	11.3	
Ba–Au	38	±14
La–Au	80	±5

(*Continued*)

TABLE 4.36 (*Continued*) Bond Strengths in Diatomic Molecules[a]

Molecule	Kcal/mol	
Ce–Ce	66	±1
Ce–Au	76	±4
Pr–Au	74	±5
Nd–Au	70	±6
Au–Au	52.4	±2.2
Au–Pb	31	±23
Au–U	76	±7
Hg–Hg	4.1	±0.5
Hg–Tl	1	
Tl–Tl	15.4	±4
Pb–Pb	24	±5
Pb–Bi	32	±5
Bi–Bi	45	±2
Po–Po	44.4	±2.3
At–At	19	
Th–Th	<69	

Source: Data from J. A. Kerr, M. J. Parsonage, and A. F. Trotman–Dickenson. In: R. C. Weast (Ed.), *Handbook of Chemistry and Physics,* 55th Edn., CRC Press, Cleveland, 1974, F–204; J. A. Kerr. In: D. R. Lide (Ed.), *CRC Handbook of Chemistry and Physics*, 71st Edn., CRC Press, Boca Raton, 1990, 9-86–9-89.

Note: To convert kcal to KJ, multiply by 4.184.

[a] The strength of a chemical bond, D $(R - X)$, often known as the bond dissociation energy, is defined as the heat of the reaction: $RX \rightarrow R + X$. It is given by: $D(R - X) = \Delta H_f°(R) + \Delta H_f°(X) - \Delta H_f°(RX)$. Some authors list bond strengths for 0K, but here the values for 298 K are given because more thermodynamic data are available for this temperature. Bond strengths, or bond dissociation energies, are not equal to, and may differ considerable from, mean bond energies derived solely from thermochemical data on molecules and atoms.

The values in this table have usually been measured spectroscopically or by mass spectrometric analysis of hot gases effusing from a Knudsen cell.

TABLE 4.37 Bond Strengths of Polyatomic Molecules[a]

Molecule	Kcal/mol Value	Kcal/mol Error
H–CH	102	±2
H–CH_2	110	±2
H–CH_3	104	±1
H–ethynyl	128	±5
H–vinyl	≥108	±2
H–C_2H_5	98	±1
H–propargyl	93.9	±1.2
H–allyl	89	±1
H–cyclopropyl	100.7	±1
H–n–C_3H_7	98	±1
H–i–C_3H_7	95	±1
H–cyclobutyl	96.5	±1
H–cyclopropylcarbinyl	97.4	±1.6
H–methallyl	83	±1
H–s–C_4H_9	95	±1
H–t–C_4H_9	92	±1.2
H–cyclopentadien–1,3–yl–5	81.2	±1.2
H–pentadien–1,4–yi–3	80	±1
H–OH	119	±1
H–OCH_3	103.6	±1
H–OC_2H_5	103.9	±1
H–$OC(CH_3)_3$	104.7	±1
H–OC_6H_5	88	±5
H–O_2H	90	±2
H–O_2CCH_3	112	±4
H–$O_2CC_2H_3$	110	±4
H–O_2Cn–C_3H_7	103	±4
H–ONO	78.3	±0.5
H–ONO_2	101.2	±0.5
H–SH	90	±2
H–SCH	≥88	
H–SiH_3	94	±3
H–$Si(CH_3)_3$	90	±3
BH_3–BH_3	35	
HC•CH	230	±2
H_2C•CH_2	172	±2
H_3C–CH_3	88	±2
CH_3–$C(CH_3)_2CH$:CH_2	69.4	
$C_6H_5CH_2$–C_2H_5	69	±2
$C_6H_5CH(CH_3)$–CH_3	71	

(*Continued*)

TABLE 4.37 (*Continued*) Bond Strengths of Polyatomic Molecules[a]

Molecule	Kcal/mol	
	Value	Error
$C_6H_5CH_2$–n–C_3H_7	67	±2
CH_3–CH_2CN	72.7	±2
CH_3–$C(CH_3)_2CN$	70.2	±2
$C_6H_5C(CH_3)(CN)$–CH_3	59.9	
NC–CN	128	±1
$C_6H_5CH_2CO$–$CH_2C_6H_5$	65.4	
C_6H_5CO–CF_3	73.8	
CH_3CO–$COCH_3$	67.4	±2.3
$C_6H_5CH_2$–COOH	68.1	
$C_6H_5CH_2$–O_2CCH_3	67	
C_6H_5CO–COC_6H_5	66.4	
$C_6H_5CH_2$–$O_2CC_6H_5$	69	
$(C_6H_5CH_2)_2CH$–COOH	59.4	
CH_2F–CH_2F	88	±2
CF_2=CF_2	76.3	±3
CF_3–CF_3	96.9	±2
$C_6H_5CH_2$–NH_2	71.9	±1
C_6H_5NH–CH_3	67.7	
$C_6H_5CH_2$–$NHCH_3$	68.7	±1
$C_6H_5N(CH_2)$–CH_3	65.2	
$C_6H_5CH_2$–$N(CH_3)_2$	60.9	±1
CF_3–NF_2	65	±2.5
CH_2•N_2	≤41.7	±1
CH_3N:N–CH_3	52.5	
C_2H_5N:N–C_2H_5	50.0	
i–C_3H_7N:N–i–C_3H_7	47.5	
n–C_4H_9N:N–n–C_4H_9	50.0	
i–C_4H_9N:N–i–C_4H_9	49.0	
s–C_4H_9N:N–s–C_4H_9	46.7	
t–C_4H_9N:N–t–C_4H_9	43.5	
$C_6H_5CH_2N$:N–$C_6H_5CH_2$	37.6	
CF_3N:N–CF_3	55.2	
C_2H_5–NO_2	62	
O•CO	127.2	±0.1
CH_3–O_2SCH_3	66.8	
Allyl–O_2SCH_3	49.6	
$C_6H_5CH_2$–O_2SCH_3	52.9	
C_6H_5S–CH_3	60	
$C_6H_5CH_2$–SCH_3	53.8	
F–CH_3	103	±3

(*Continued*)

TABLE 4.37 (*Continued*) Bond Strengths of Polyatomic Molecules[a]

	Kcal/mol	
Molecule	Value	Error
Cl–CN	97	±1
$Cl–COC_6H_5$	74	±3
$Cl–CF_3$	86.1	±0.8
$Cl–CCl_2F$	73	±2
$Cl–C_2F_5$	82.7	±1.7
$Br–CH_3$	70.0	±1.2
Br–CN	83	±1
$Br–COC_6H_5$	64.2	
$Br–CF_3$	70.6	±1.0
$Br–CBr_3$	56.2	±1.8
$Br–C_2F_5$	68.7	±1.5
$Br–n–C_3F$	66.5	±2.5
$I–CH_3$	56.3	±1
1–norbornyl	62.5	±2.5
I–CN	73	±1
$I–CF_3$	53.5	±2
$CH_3–Ga(CH_3)_2$	59.5	
$CH_3–CdCH_3$	54.4	
$CH_3–HgCH_3$	57.5	
$C_2H_5–HgC_2H_5$	43.7	±1
$n–C_3H_7–Hg\ n–C_3H_7$	47.1	
$i–C_3H_7–Hg\ i–C_3H_7$	40.7	
$C_6H_5–HgC_6H_5$	68	
$CH_3–Tl(CH_3)_2$	36.4	±0.6
$CH_3–Pb(CH_3)_3$	49.4	±1
$NH_2–NH_2$	70.8	±2
$NH_2–NHCH_3$	64.8	
$NH_2–N(CH_3)_2$	62.7	
$NH_2–NHC_6H_5$	51.1	
$NO–NO_2$	9.5	±0.5
$NO_2–NO_2$	12.9	±0.5
$NF_2–NF_2$	21	±1
$O–N_2$	40	
O–NO	73	
$HO–N:CHCH_3$	49.7	
$Cl–NF_2$	≈32	
HO–OH	51	±1
$CH_3O–OCH_3$	36.9	±1
$HO–OC(CH_3)_3$	42.5	
$C_2H_5O–OC_2H_5$	37.3	±1.2

(*Continued*)

TABLE 4.37 (*Continued*) Bond Strengths of Polyatomic Molecules[a]

Molecule	Kcal/mol Value	Error
$n–C_3H_7O–O\ n–C_3H_7$	37.2	±1
$i–C_3H_7O–O\ i–C_3H_7$	37.0	±1
$s–C_4H_9O–O\ s–C_4H_9$	36.4	±1
$t–C_4H_9O–O\ t–C_4H_9$	37.4	±1
$(CH_3)_3CCH_2O–OCH_2C(CH_3)_3$	36.4	±1
$O–O_2ClF$	58.4	
$CH_3CO_2–O_2CCH_3$	30.4	±2
$C_2H_5CO_2–O_2CC_2H_5$	30.4	±2
$n–C_3H_7CO_2–O_2Cn–C_3H_7$	30.4	±2
O–SO	132	±2
$F–OCF_3$	43.5	±0.5
Cl–OH	60	±3
O–ClO	59	±3
Br–OH	56	±3
I–OH	56	±3
$ClO_3–ClO_4$	58.4	
$O=PF_3$	130	±5
$O=PCl_3$	122	±5
$O=PBr_3$	119	±5
$SiH_3–SiH_3$	81	±4
$(CH_3)_3Si–Si(CH_3)_3$	80.5	

Source: Data from J. A. Kerr, M. J. Parsonage, and A. F. Trotman–Dickenson, In: R. C. Weast (Ed.), *Handbook of Chemistry and Physics,* 55th Edn., CRC Press, Cleveland, 1974, F–213.

Note: To convert kcal to KJ, multiply by 4.184.

[a] The values refer to a temperature of 298 K and have mostly been determined by kinetic methods. Some have been calculated from formation of the species involved according to equations:

$$D(R - X) = \Delta H_f^\circ(R^\bullet) + \Delta H_f^\circ(X^\bullet) - \Delta H_f^\circ(RX) \quad \text{or}$$

$$D(R - X) = 2\Delta H_f^\circ(R^\bullet) - \Delta H_f^\circ(RR)$$

TABLE 4.38 Water Absorption of Polymers

Polymer	Type	Water Absorption in 24 h (ASTM D570) (%)
ABS resins: Molded, extruded	Medium impact	0.2–0.4
	High impact	0.2–0.45
	Very high impact	0.2–0.45
	Low temperature impact	0.2–0.45
	Heat resistant	0.2–0.4
Acrylics: Cast, molded, extruded	Cast resin sheets, rods:	
	General purpose, type I	0.3–0.4
	General purpose, type II	0.2–0.4
	Moldings:	
	Grades 5, 6, 8	0.3–0.4
	High impact grade	0.2–0.4
Thermoset carbonate	Allyl diglycol carbonate	0.2
Alkyds: Molded	Putty (encapsulating)	0.10–0.15
	Rope (general purpose)	0.05–0.08
	Granular (high-speed molding)	0.08–0.12
	Glass reinforced (heavy duty parts)	0.007–0.10
Cellulose acetate: Molded, extruded	ASTM grade:	
	H4-1	1.7–2.7
	H2-1	1.7–2.7
	MH-1, MH-2	1.8–4.0
	MS-1, MS-2	2.1–4.0
	S2-1	2.3–4.0
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	2
	MH	1.3–1.6
	S2	0.9–1.3
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	1.6–2.0
	3	1.3–1.8
	6	1.6
Chlorinated polymers	Chlorinated polyether	0.01
	Chlorinated polyvinyl chloride	0.11
Polycarbonates	Polycarbonate	0.15
	Polycarbonate (40% glass–fiber-reinforced)	0.08
Diallyl phthalates: Molded		(122°F, 48 h), %
	Orlon filled	0.2–0.5
	Dacron filled	0.2–0.5
	Asbestos filled	0.4–0.7
	Glass fiber filled	0.2–0.4

(*Continued*)

TABLE 4.38 (*Continued*) Water Absorption of Polymers

Polymer	Type	Water Absorption in 24 h (ASTM D570) (%)
Fluorocarbons: Molded, extruded	Polytrifluorochloroethylene (PTFCE)	0
	Polytetrafluoroethylene (PTFE)	0.01
	Ceramic reinforced (PTFE)	>0.2
	Fluorinated ethylene propylene (FEP)	<0.01
	Polyvinylidene fluoride (PVDF)	0.03–0.06
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	0.1–0.2
	Cast flexible	0.4–0.1
	Molded	0.3–0.8
	General purpose glass cloth laminate	0.05–0.07
	High strength laminate	0.05
	Filament wound composite	0.05–0.07
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides)	
	Molded	0.11–0.2
	Glass cloth laminate	0.04–0.06
	Epoxy novolacs	
	Cast, rigid	0.1–0.7
Melamines: Molded	Filler and type	
	Unfilled	0.2–0.5
	Cellulose electrical	0.27–0.80
	Glass fiber	0.09–0.60
	Alpha cellulose and mineral	0.3–0.5
Nylons: Molded, extruded	Type 6	
	General purpose	1.3–1.9
	Glass fiber (30%) reinforced	0.9–1.2
	Cast	0.6
	Flexible copolymers	0.8–1.4
	Type 8	9.5
	Type 11	0.4
	Type 12	0.25
	6/6 Nylon	
	General purpose molding	1.5
	Glass–fiber-reinforced	0.8–0.9
	Glass fiber molybdenum disulfide filled	0.5–0.7
	General purpose extrusion	1.5
	6/10 Nylon	
	General purpose	0.4
	Glass fiber (30%) reinforced	0.2

(*Continued*)

TABLE 4.38 (*Continued*) Water Absorption of Polymers

Polymer	Type	Water Absorption in 24 h (ASTM D570) (%)
Phenolics: Molded	Type and filler	
	General: wood flour and flock	0.3–0.8
	Shock: paper, flock, or pulp	0.4–1.5
	High shock: chopped fabric or cord	0.4–1.75
	Very high shock: glass fiber	0.1–1.0
	Arc resistant—mineral	0.5–0.7
	Rubber phenolic—wood flour or flock	0.5–2.0
	Rubber phenolic—chopped fabric	0.5–2.0
	Rubber phenolic—asbestos	0.10–0.50
ABS: Polycarbonate alloy	ABS—polycarbonate alloy	0.21
PVC: Acrylic alloy	PVC—acrylic sheet	0.06
	PVC—acrylic injection molded	0.13
Polyimides	Unreinforced	0.47
	Unreinforced second value	0.24–0.40
	Glass reinforced	0.2
Polyacetals	Homopolymer:	
	Standard	0.25
	20% Glass reinforced	0.25
	22% TFE reinforced	0.2
	Copolymer:	
	Standard	0.22
	25% Glass reinforced	0.29
	High flow	0.22
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	0.08
	Glass reinforced grades	0.06–0.07
	Glass reinforced self extinguishing	0.07
	General purpose grade	0.09
	Glass reinforced grade	0.07
	Asbestos-filled grade	0.1
Polyesters: Thermosets	Cast polyester	
	Rigid	0.20–0.60
	Flexible	0.12–2.5
	Reinforced polyester moldings	
	High strength (glass fibers)	0.5–0.75
	Heat and chemical resistant (asbestos)	0.25–0.50
	Sheet molding compounds, general purpose	0.15–0.25
Phenylene oxides	SE-100	0.07
	SE-1	0.07
	Glass–fiber-reinforced	0.06

(*Continued*)

TABLE 4.38 (*Continued*) Water Absorption of Polymers

Polymer	Type	Water Absorption in 24 h (ASTM D570) (%)
Phenylene oxides (Noryl)	Standard	0.22
	Glass–fiber-reinforced	0.22, 0.18
Polyarylsulfone	Polyarylsulfone	0.4
Polypropylene	General purpose	<0.01–0.03
	High impact	<0.01–0.02
	Asbestos filled	0.02–0.04
	Glass reinforced	0.02–0.05
	Flame retardant	0.02–0.03
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	<0.01
	Melt index 6–26	<0.01
	Melt index 200	<0.01
	Type II—medium density (0.926–0.940)	
	Melt index 20	<0.01
	Melt index 1.0–1.9	<0.01
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	<0.01
	Melt index 0.1–12.0	<0.01
	Melt index 1.5–15	<0.01
	High molecular weight	<0.01
Polystyrenes: Molded	General purpose	0.30–0.2
	Medium impact	0.03–0.09
	High impact	0.05–0.22
	Glass fiber (30%) reinforced	0.07
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	0.20–0.35
	Glass fiber (30%) reinforced SAN	0.15
Polyvinyl chloride and copolymers	Molded, extruded	(ASTM D635)
	Nonrigid—general	0.2–1.0
	Nonrigid—electrical	0.40–0.75
	Rigid—normal impact	0.03–0.40
	Vinylidene chloride	>0.1
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	0.1–0.15
	Granular (silica) reinforced silicones	0.08–0.1
	Woven glass fabric/silicone laminate	0.03–0.05
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	0.4–0.8

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science,* Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

TABLE 4.39 Flammability of Polymers

Polymer	Type	Flammability (ASTM D635) (ipm)
ABS resins: Molded, extruded	Medium impact	1.0–1.6
	High impact	1.3–1.5
	Very high impact	1.3–1.5
	Low temperature impact	1.0–1.5
	Heat resistant	1.3–2.0
Acrylics: Cast, molded, extruded		(0.125 in.)
	Cast resin sheets, rods:	
	General purpose, type I	0.5–2.2
	General purpose, type II	0.5–1.8
	Moldings:	
	Grades 5, 6, 8	0.9–1.2
	High impact grade	0.8–1.2
Thermoset carbonate	Allyl diglycol carbonate	0.35
Alkyds: Molded	Putty (encapsulating)	Nonburning
	Rope (general purpose)	Self extinguishing
	Granular (high-speed molding)	Self extinguishing
	Glass reinforced (heavy duty parts)	Nonburning
Cellulose acetate: Molded, extruded	ASTM grade:	
	H6-1	0.5–2.0
	H4-1	0.5–2.0
	H2-1	0.5–2.0
	MH-1, MH-2	0.5–2.0
	MS-1, MS-2	0.5–2.0
	S2-1	0.5–2.0
Cellulose acetate butyrate: Molded, extruded	ASTM grade:	
	H4	0.5–1.5
	MH	0.5–1.5
	S2	0.5–1.5
Cellulose acetate propionate: Molded, extruded	ASTM grade:	
	1	0.5–1.5
	3	0.5–1.5
	6	0.5–1.5
Chlorinated polymers	Chlorinated polyether	Self extinguishing
	Chlorinated polyvinyl chloride	Nonburning
Polycarbonates	Polycarbonate	Self extinguishing
	Polycarbonate (40% glass–fiber-reinforced)	Self extinguishing
Diallyl phthalates: Molded		Ignition time
	Orlon filled	68 s
	Dacron filled	84–90 s

(*Continued*)

TABLE 4.39 (*Continued*) Flammability of Polymers

Polymer	Type	Flammability (ASTM D635) (ipm)
	Asbestos filled	70 s
	Glass fiber filled	70–400 s
Fluorocarbons; Molded, Extruded	Polytrifluorochloroethylene (PTFCE)	Noninflammable
	Polytetrafluoroethylene (PTFE)	Noninflammable
	Ceramic reinforced (PTFE)	Noninflammable
	Fluorinated ethylene propylene (FEP)	Noninflammable
	Polyvinylidene fluoride (PVDF)	Self extinguishing
Epoxies: Cast, molded, reinforced	Standard epoxies (diglycidyl ethers of bisphenol A)	
	Cast rigid	0.3–0.34
	Cast flexible	—
	Molded	Self extinguishing
	General purpose glass cloth laminate	Slow burn to self extinguishing
	High strength laminate	Self extinguishing
	Filament wound composite	Self extinguishing
Epoxies: Molded, extruded	High-performance resins (cycloaliphatic diepoxides)	
	Cast, rigid	Self extinguishing
	Molded	Self extinguishing
	Glass cloth laminate	Self extinguishing
Melamines: Molded	Filler and type	
	Unfilled	Self extinguishing
	Cellulose electrical	Self extinguishing
	Glass fiber	Self extinguishing
	Alpha cellulose and mineral	Self extinguishing
Nylons: Molded, extruded	Type 6	
	General purpose	Self extinguishing
	Glass fiber (30%) reinforced	Slow burn
	Cast	Self extinguishing
	Flexible copolymers	Slow burn, 0.6
	Type 8	Self extinguishing
	Type 11	Self extinguishing
	6/6 Nylon	
	General purpose molding	Self extinguishing
	Glass–fiber-reinforced	Slow burn
	Glass fiber molybdenum disulfide filled	Slow burn
	General purpose extrusion	Self extinguishing
	6/10 Nylon	
	General purpose	Self extinguishing
	Glass fiber (30%) reinforced	Slow burn

(*Continued*)

TABLE 4.39 (*Continued*) Flammability of Polymers

Polymer	Type	Flammability (ASTM D635) (ipm)
Phenolics: Molded	Type and filler	
	General: wood flour and flock	Self extinguishing
	Shock: paper, flock, or pulp	Self extinguishing
	High shock: chopped fabric or cord	Self extinguishing
	Very high shock: glass fiber	Self extinguishing
	Arc resistant—mineral	Self extinguishing
	Rubber phenolic—wood flour or flock	Self extinguishing
	Rubber phenolic—chopped fabric	Self extinguishing
	Rubber phenolic—asbestos	Self extinguishing
ABS: Polycarbonate alloy	ABS: Polycarbonate alloy	0.9
PVC: Acrylic alloy	PVC—acrylic sheet	Nonburning
	PVC—acrylic injection molded	Nonburning
Polyimides	Polyimides	
	Unreinforced	IBM Class A
	Unreinforced second value	IBM Class A
	Glass reinforced	UL SE-0
Polyacetals	Homopolymer:	
	Standard	1.1
	20% Glass reinforced	0.8
	22% TFE reinforced	0.8
	Copolymer:	
	Standard	1.1
	25% Glass reinforced	1
	High flow	1.1
Polyester: Thermoplastic	Injection moldings:	
	General purpose grade	Slow burn
	Glass reinforced grades	Slow burn
	Glass reinforced self extinguishing	Self extinguishing
	General purpose grade	Slow burn
	Glass reinforced grade	Slow burn
Polyesters: Thermosets	Cast polyester	
	Rigid	0.87 to self extinguishing
	Flexible	Slow burn to self extinguishing
Reinforced polyester moldings	High strength (glass fibers)	Self extinguishing
	Heat and chemical resistant (asbestos)	Self extinguishing
	Sheet molding compounds, general purpose	Self extinguishing

(*Continued*)

TABLE 4.39 (*Continued*) Flammability of Polymers

Polymer	Type	Flammability (ASTM D635) (ipm)
Phenylene oxides	SE-100	Self extinguishing
	SE-1	Self extinguishing
	Glass–fiber-reinforced	Self extinguishing
Phenylene oxides (Noryl)	Standard	Self extinguishing
	Glass–fiber-reinforced	Self extinguishing
Polyarylsulfone	Polyarylsulfone	Self extinguishing
Polypropylene	General purpose	0.7–1
	High impact	1
	Asbestos filled	1
	Glass reinforced	1
	Flame retardant	Self extinguishing
Polyphenylene sulfide	Standard	Nonburning
	40% Glass reinforced	Nonburning
Polyethylenes: Molded, extruded	Type I—lower density (0.910–0.925)	
	Melt index 0.3–3.6	1
	Melt index 6–26	1
	Melt index 200	1
	Type II—medium density (0.926–0.940)	
	Melt index 20	1
	Melt index 1.0–1.9	1
	Type III—higher density (0.941–0.965)	
	Melt index 0.2–0.9	1
	Melt index 0.1–12.0	1
	Melt index 1.5–15	1
	High molecular weight	1
Polystyrenes: Molded	Polystyrenes	
	General purpose	1.0–1.5
	Medium impact	0.5–2.0
	High impact	0.5–1.5
Styrene acrylonitrile (SAN)	Styrene acrylonitrile (SAN)	0.8
Polyvinyl chloride and copolymers: Molded, extruded	Nonrigid—general	Self extinguishing
	Nonrigid—electrical	Self extinguishing
	Rigid—normal impact	Self extinguishing
	Vinylidene chloride	Self extinguishing
Silicones: Molded, laminated	Fibrous (glass) reinforced silicones	Nonburning
	Granular (silica) reinforced silicones	Nonburning
	Woven glass fabric/silicone laminate	0.12
Ureas: Molded	Alpha-cellulose filled (ASTM type 1)	Self extinguishing
	Cellulose filled (ASTM type 2)	Self extinguishing
	Woodflour filled	Self extinguishing

Source: Data compiled by J. S. Park from C. T. Lynch, *CRC Handbook of Materials Science*, Vol. 3, CRC Press, Boca Raton, FL, 1975; C. A. Dostal (Ed.), *Engineered Materials Handbook,* Vol. 2, Engineering Plastics, ASM International, Metals Park, OH, 1988.

5

Composites

Physical Properties

TABLE 5.1 Density of 55MSI[a] Graphite/6061 Aluminum Composites

	Reinforcement Content (vol%)	Fiber Orientation	Density (Mg/m^3)
55MSI Graphite/6061 aluminum composites	34	0°	2.35
55MSI Graphite/6061 aluminum composites	34	90°	2.35

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.

[a] xxMSI is a code defining the modulus of elasticity for the reinforcing graphite fiber having a value of xx millions of pounds per square inch.

TABLE 5.2 Density of Graphite Fiber-Reinforced Metals

Composite	Fiber Content (vol%)	Density (lb/in^3)
Graphite[a]/lead	41	0.270
Graphite[b]/lead	35	0.280
Graphite[a]/zinc	35	0.191
Graphite[a]/magnesium	42	0.064

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.

Note: To convert lb/in^3 to Mg/m^3, multiply by 27.68.

[a] Thornel 75 fiber.

[b] Courtaulds HM fiber.

TABLE 5.3 Density of Si_3N_4 Composites

Matrix	Dispersed Phase[a]	Density (Mg/m^3)
Si_3N_4 + 6 wt.% Y_2O_3	None	3.26
Si_3N_4 + 6 wt.% Y_2O_3	TiC	3.81
	(Ti, W)C	4.55
	WC	7.70
	TaC	6.87
	HfC	5.74
	SiC	3.24
Al_2O_3	TiC	4.28

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 169.

[a] Containing 30 vol% of metal carbide dispersoid (2 μm average particle diameter).

TABLE 5.4 Specific Heat of Fiberglass-Reinforced Plastics

Class	Material	Glass Fiber Content (wt.%)	Specific Heat (Btu/lb-°F)
Glass–fiber-reinforced thermosets	Sheet molding compound (SMC)	15–30	0.30–0.35
	Bulk molding compound (BMC)	15–35	0.30–0.35
	Preform/mat (compression molded)	25–50	0.30–0.33
	Cold press molding—polyester	20–30	0.30–0.33
	Spray-up—polyester	30–50	0.30–0.34
	Filament wound—epoxy	30–80	0.23–0.25
	Rod stock—polyester	40–80	0.22–0.25
	Molding compound—phenolic	5–25	0.20–0.30
Glass–fiber-reinforced thermoplastics	Nylon	6–60	0.30–0.35
	Polystyrene	20–35	0.23–0.35

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 106.

Note: To convert Btu/lb-°F to J/kg · K, multiply by 4186.9.

TABLE 5.5 Thermal Conductivity of SiC Whisker-Reinforced Ceramics

Composite	Thermal Conductivity (W/m · K)	
	At 22°C	At 600°C
Alumina	36 ± 5	12 ± 3
Alumina with 20 vol% SiC whiskers	32	16
SiC	95	50
Mullite with 20 vol% SiC whiskers	7.2	—

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 173.

TABLE 5.6 Thermal Conductivity of Fiberglass-Reinforced Plastics

Class	Material	Glass Fiber Content (wt.%)	Thermal Conductivity (Btu · in/ft² · h · °F)
Glass–fiber-reinforced thermosets	Sheet molding compound (SMC)	15–30	1.3–1.7
	Bulk molding compound (BMC)	15–35	1.3–1.7
	Preform/mat (compression molded)	25–50	1.3–1.8
	Cold press molding—polyester	20–30	1.3–1.8
	Spray-up—polyester	30–50	1.2–1.6
	Filament wound—epoxy	30–80	1.92–2.28
	Rod stock—polyester	40–80	1.92–2.28
	Molding compound—phenolic	5–25	1.1–2.0
Glass–fiber-reinforced thermoplastic	Thermoplastic polyester	20–35	1.3

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 106.

Note: To convert (Btu · in/ft^2 · h · °F) to (W/m · K), multiply by 0.144.

TABLE 5.7 Thermal Expansion of Graphite Magnesium Castings[a]

Fiber Type	Fiber Content	Fiber Orientation	Casting	Fiber Preform Method	Coefficient of Thermal Expansion (10^{-6}/K)
P75	40%	±16°	Hollow cylinder	Filament wound	1.3
	Plus 9%	90°	Hollow cylinder	Filament wound	1.3
P100	40%	±16°	Hollow cylinder	Filament wound	−0.07
P55	40%	0°	Plate	Prepreg	2.3
	30%	0° plus	Plate	Prepreg	4.5
	10%	90°	Plate	Prepreg	4.5

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.

[a] Pitch-base fibers.

TABLE 5.8 Thermal Expansion of SiC Whisker-Reinforced Ceramics

Composite	Linear Coefficient of Thermal Expansion at 22–1100°C (10^{-6}/K)
Alumina	7.8–8.2
Alumina with 20 vol% SiC whiskers	7.35
Alumina with 30 vol% SiC whiskers	6.70
Alumina with 60 vol% SiC whiskers	5.82
SiC	4.8
Mullite with 20 vol% SiC whiskers	5.60

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 173.

TABLE 5.9 Thermal Expansion of Silicon Carbide[a] SCS-2-Al

Fiber Orientation	No. of Plies	Coefficient of Thermal Expansion (10^{-6}/K)
0°	6, 8, 12	6.6
90°	6, 12, 40	21.3

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 149.

[a] "Silicon Carbide SCS" is the brand name of a SiC fiber produced by Specialty Materials, Inc. The SiC is deposited on a carbon monofilament core and is coated with a carbon-rich outer layer.

TABLE 5.10 Heat-Deflection Temperature of Carbon- and Glass-Reinforced Engineering Thermoplastics

Class	Resin Type	Composition	Heat-Deflection Temperature (°C)
Amorphous	Acrylonitrile butadiene styrene (ABS)	30% glass fiber	105
		30% carbon fiber	105
	Nylon	30% glass fiber	140
		30% carbon fiber	145
	Polycarbonate	30% glass fiber	150
		30% carbon fiber	150
	Polyetherimide	30% glass fiber	215
		30% carbon fiber	215
	Polyphenylene oxide (PPO)	30% glass fiber	155
		30% carbon fiber	155
	Polysulfone	30% glass fiber	185
		30% carbon fiber	185
	Styrene–maleic anhydride (SMA)	30% glass fiber	120
	Thermoplastic polyurethane	30% glass fiber	170
Crystalline	Acetal	30% glass fiber	165
		20% carbon fiber	160
	Nylon 66%	30% glass fiber	255
		30% carbon fiber	257
	Polybutylene terephthalate (PBT)	30% glass fiber	210
		30% carbon fiber	210
	Polyethylene terephthalate (PET)	30% glass fiber	225
	Polyphenylene sulfide (PPS)	30% glass fiber	260
		30% carbon fiber	265

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, pp. 111–112.

TABLE 5.11 Tensile Strength of Fiberglass-Reinforced Plastics

Class	Material	Glass Fiber Content (wt.%)	Tensile Strength at Yield (ksi)
Glass–fiber-reinforced thermosets	Sheet molding compound (SMC)	15–30	8–20
	Bulk molding compound (BMC)	15–35	4–10
	Preform/mat (compression molded)	25–50	25–30
	Cold press molding—polyester	20–30	12–20
	Spray-up—polyester	30–50	9–18
	Filament wound—epoxy	30–80	80–250
	Rod stock—polyester	40–80	60–180
	Molding compound—phenolic	5–25	7–17
Glass–fiber-reinforced thermoplastics	Acetal	20–40	9–18
	Nylon	6–60	13–33

(*Continued*)

TABLE 5.11 (*Continued*) Tensile Strength of Fiberglass-Reinforced Plastics

Class	Material	Glass Fiber Content (wt.%)	Tensile Strength at Yield (ksi)
	Polycarbonate	20–40	12–25
	Polyethylene	10–40	6.5–11
	Polypropylene	20–40	5.5–10.5
	Polystyrene	20–35	10–15
	Polysulfone	20–40	13–20
	ABS (acrylonitrile butadiene styrene)	20–40	11–16
	PVC (polyvinyl chloride)	15–35	14–18
	Polyphenylene oxide (modified)	20–40	15–22
	SAN (styrene acrylonitrile)	20–40	13–18
	Thermoplastic polyester	20–35	14–19

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 106.
Note: To convert ksi to MPa, multiply by 6.89.

TABLE 5.12 Tensile Strength of Carbon- and Glass-Reinforced Engineering Thermoplastics

Class	Resin Type	Composition	Tensile Strength (MPa)
Amorphous	Acrylonitrile butadiene styrene (ABS)	30% glass fiber	100
		30% carbon fiber	130
	Nylon	30% glass fiber	148
		30% carbon fiber	207
	Polycarbonate	30% glass fiber	128
		30% carbon fiber	165
	Polyetherimide	30% glass fiber	197
		30% carbon fiber	234
	Polyphenylene oxide (PPO)	30% glass fiber	145
		30% carbon fiber	159
	Polysulfone	30% glass fiber	124
		30% carbon fiber	159
	Styrene–maleic anhydride (SMA)	30% glass fiber	103
	Thermoplastic polyurethane	30% glass fiber	57
Crystalline	Acetal	30% glass fiber	134
		20% carbon fiber	81
	Nylon 66	30% glass fiber	179
		30% carbon fiber	241
	Polybutylene terephthalate (PBT)	30% glass fiber	134
		30% carbon fiber	152
	Polyethylene terephthalate (PET)	30% glass fiber	159
	Polyphenylene sulfide (PPS)	30% glass fiber	138
		30% carbon fiber	186

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, pp. 111–112.

TABLE 5.13 Strength of Graphite Fiber-Reinforced Metals

Composite	Fiber Content (vol%)	Strength (ksi)
Graphite[a]/lead	41	104
Graphite[b]/lead	35	72
Graphite[a]/zinc	35	110.9
Graphite[a]/magnesium	42	65

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.

Note: To convert ksi to MPa, multiply by 6.89.

[a] Thornel 75 fiber.

[b] Courtaulds HM fiber.

TABLE 5.14 Tensile Strength of Graphite/Magnesium Castings[a]

Fiber Type	Fiber Content	Fiber Orientation	Casting	Fiber Preform Method	Tensile Strength (GPa)	Tensile Strength, 90° (GPa)
P75	40%	±16°	Hollow cylinder	Filament wound	0.45	0.061
	Plus 9%	90°	Hollow cylinder	Filament wound	0.45	0.061
P100	40%	±16°	Hollow cylinder	Filament wound	0.56	0.38
P55	40%	0°	Plate	Prepreg	0.48	0.02
	30%	0° plus	Plate	Prepreg	0.28	0.010
	10%	90°	Plate	Prepreg	0.28	0.010
	20%	0° plus	Plate	Prepreg	8.45	0.24
	20%	90°	Plate	Prepreg	8.45	0.24

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.

[a] Pitch-base fibers.

TABLE 5.15 Tensile Strength of Graphite/Aluminum Composites

Composite	Fiber Loading (vol%)	Wire Diameter (mm)	Tensile Strength (MPa)
VS0054/201 Al	48–52	0.64 (2-strand)	1035–1070
GY70SE/201 Al	37–38	0.71 (8-strand)	793–827

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.

TABLE 5.16 Tensile Strength of Graphite/Aluminum Composites

Thornel Fiber	Longitudinal Tensile Strength (MPa)	Transverse Tensile Strength (MPa)
P55	517–621	28–48
P75	621–724	28–48
P100	552–834	28 to ~48

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.

TABLE 5.17 Tensile Strength of Silicon Carbide[a] SCS-2-Al

Fiber Orientation	No. of Plies	Tensile Strength (MPa)
0°	6, 8, 12	1462
90°	6, 12, 40	86.2
$[0°/90°/0°/90°]_s$	8	673
$[0°_2/90°/0°]_s$	8	1144
$[90°_2/0°/90°]_s$	8	341.3
±45°	8, 12, 40	309.5
$[0°/\pm45°/0°]_{s+2s}$	8, 16	800.0
$[0°/\pm45°/90°]_s$	8	572.3

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 149.

[a] "Silicon Carbide SCS" is the brand name of a SiC fiber produced by Specialty Materials, Inc. The SiC is deposited on a carbon monofilament core and is coated with a carbon-rich outer layer.

TABLE 5.18 Ultimate Tensile Strength of Investment Cast Silicon Carbide[a] SCS-Al

Fiber Orientation	Fiber (vol%)	Ultimate Tensile Strength (MPa)	Range of Measurement (%)
$0°_3/90°_6/0°_3$	33	458.5	75
$90°_3/0°_6/90°_3$	33	584.0	95
0°	34	1034.2	85

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 149.

[a] "Silicon Carbide SCS" is the brand name of a SiC fiber produced by Specialty Materials, Inc. The SiC is deposited on a carbon monofilament core and is coated with a carbon-rich outer layer.

TABLE 5.19 Ultimate Tensile Strength of Silicon Carbide–Aluminum Alloy Composites[a]

		Ultimate Tensile Strength (MPa)	
Material	Fiber (vol%)	Base	Reinforced
Pure aluminum	11	59	235
6061–T6	16	300	441
2024–T4	20	470	565

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 149.

[a] Room temperature.

TABLE 5.20 Tensile Strength of SiC Whisker-Reinforced Aluminum Alloy

Fiber Content (vol%)	Tensile Strength		
	MPa	Standard Deviation	Range of Measurement
0	297	1.8	3.5
12	359	33.6	85.6
16	374	8.0	23.0
20	383.6	15.2	38.8

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 150.

TABLE 5.21 Ultimate Tensile Strength of Aluminum Alloy Reinforced with SiC Whiskers versus Temperature

Fiber (vol%)	Ultimate Tensile Strength (MPa) 350°C	300°C	250°C
Polycrystalline Alumina			
0	55	70	115
0.05	63	88	134
0.12	74	—	—
0.20	112	155	198
SiC Whiskers			
0	55	70	115
0.12	124	180	226
0.16	147	—	—
0.20	184	235	284

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 150.

TABLE 5.22 Ultimate Tensile Strength of Reinforced Aluminum Alloy versus Temperature

Fiber	Vol%	Ultimate Tensile Strength (MPa) 350°C	300°C	250°C
Polycrystalline alumina	0	55	70	115
	5	63	88	134
	12	74	—	—
	20	112	155	198
SiC whiskers	0	55	70	115
	12	124	180	226
	16	147	—	—
	20	184	235	284

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 154.

TABLE 5.23 Tensile Strength of Polycrystalline Alumina-Reinforced Aluminum Alloy

Fiber Content (vol%)	Tensile Strength MPa	Standard Deviation	Range of Measurement
0	297	1.8	3.5
5	282	6.5	15.1
12	273	19.6	49.6
20	312	16.0	42.3

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 154.

TABLE 5.24 Tensile Strength of Boron/Aluminum Composites[a]

Matrix	Fiber Orientation	Tensile Strength (MPa)
Al-6061	0°	1515
	90°	138
Al-2024	0°	1550
	90°	214

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 157.

[a] These samples contain 48% Avco (142 μm) boron. Longitudinal tensile specimens are 152 mm × 7.9 mm × 6 ply. Transverse tensile bars are 152 mm × 12.7 mm × 6 ply.

TABLE 5.25 Compressive Strength of Fiberglass-Reinforced Plastic

Class	Material	Glass Fiber Content (wt.%)	Compressive Strength (ksi)
Glass–fiber-reinforced thermosets	Sheet molding compound (SMC)	15–30	15–30
	Bulk molding compound (BMC)	15–35	20–30
	Preform/mat (compression molded)	25–50	15–30
	Spray-up—polyester	30–50	15–25
	Filament wound—epoxy	30–80	45–70
	Rod stock—polyester	40–80	30–70
	Molding compound—phenolic	5–25	14–35
Glass–fiber-reinforced thermoplastics	Acetal	20–40	11–17
	Nylon	6–60	13–24
	Polycarbonate	20–40	14–24
	Polyethylene	10–40	4–8
	Polypropylene	20–40	6–8
	Polystyrene	20–35	13.5–19
	Polysulfone	20–40	21–26
	ABS (acrylonitrile butadiene styrene)	20–40	12–22
	PVC (polyvinyl chloride)	15–35	13.4–16.8
	Polyphenylene oxide (modified)	20–40	18–20
	SAN (styrene acrylonitrile)	20–40	12–23
	Thermoplastic polyester	20–35	16–18

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 106.

Note: To convert ksi to MPa, multiply by 6.89.

TABLE 5.26 Ultimate Compressive Strength of Investment Cast Silicon Carbide[a] SCS-Al

Fiber Orientation	Fiber (vol%)	Ultimate Compressive Strength (MPa)	Compressive Modulus (GPa)
$0°_3/90°_6/0°_3$	33	1378 9	—
$90°_3/0°_6/90°_3$	33	1378.9	—
0°	34	1896.1	186.2

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 149.

[a] "Silicon Carbide SCS" is the brand name of a SiC fiber produced by Specialty Materials, Inc. The SiC is deposited on a carbon monofilament core and is coated with a carbon-rich outer layer.

TABLE 5.27 Yield Strength of SiC Whisker-Reinforced Aluminum Alloy

Fiber Content (vol%)	Yield Strength (0.2%)		
	MPa	Standard Deviation	Range of Measurement
0	210	3.8	9.5
0.12	266.5	4.2	10.6
0.16	264.5	0.6	1.6
0.20	298	4.0	10.2

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 150.

TABLE 5.28 Yield Strength of Reinforced Aluminum Alloy versus Temperature

Fiber	Vol%	Yield Strength (MPa)		
		350°C	300°C	250°C
Polycrystalline alumina	0	35	—	70
	5	54	79	112
	12	68	—	—
	20	110	154	186
SiC whiskers	0	35	—	70
	12	94	153	197
	16	120	—	—
	20	163	207	268

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 154.

TABLE 5.29 Yield Strength of Polycrystalline Alumina-Reinforced Aluminum Alloy

	Yield Strength (0.2%)		
Fiber Content (vol%)	MPa	Standard Deviation	Range of Measurement
0	210	3.8	9.5
5	232	4.2	10.4
12	251.5	14.6	38.3
20	282.5	11.3	25.2

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 154.

TABLE 5.30 Flexural Strength of Fiberglass-Reinforced Plastics

Class	Material	Glass Fiber Content (wt.%)	Flexural Strength (ksi)
Glass–fiber-reinforced thermosets	Sheet molding compound (SMC)	15–30	18–30
	Bulk molding compound (BMC)	15–35	10–20
	Preform/mat (compression molded)	25–50	10–40
	Cold press molding—polyester	20–30	22–37
	Spray-up—polyester	30–50	16–28
	Filament wound—epoxy	30–80	100–270
	Rod stock—polyester	40–80	100–180
	Molding compound—phenolic	5–25	18–24
Glass–fiber-reinforced thermoplastics	Acetal	20–40	15–28
	Nylon	6–60	7–50
	Polycarbonate	20–40	17–30
	Polyethylene	10–40	7–12
	Polypropylene	20–40	7–11
	Polystyrene	20–35	10–17
	Polysulfone	20–40	21–27
	ABS (acrylonitrile butadiene styrene)	20–40	23–26
	PVC (polyvinyl chloride)	15–35	20–25
	Polyphenylene oxide (modified)	20–40	17–31
	SAN (styrene acrylonitrile)	20–40	15–21
	Thermoplastic polyester	20–35	19–29

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 106.

Note: To convert ksi to MPa, multiply by 6.89.

TABLE 5.31 Hardness of Si_3N_4 and Al_2O_3 Composites

Matrix	Dispersed Phase	Knoop Hardness (GPa)
Si_3N_4 + 6 wt.% Y_2O_3	None	13.4 ± 0.3
Si_3N_4 + 6 wt.% Y_2O_3	TiC	15.21 ± 0.3
	(Ti, W) C	14.06 ± 0.3
	WC	14.4 ± 0.4
	TaC	12.6 ± 0.2
	HfC	14.1 ± 0.4
	SiC	13.6 ± 0.2
Al_2O_3	TiC	17.2 ± 0.2

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 169.

Note: Containing 30 vol% of metal carbide dispersoid (2 μm average particle diameter).

TABLE 5.32 Impact Strength of Fiberglass-Reinforced Plastics

Class	Material	Glass Fiber Content (wt.%)	Izod Impact Strength (ft · lb/in. of notch)
Glass–fiber-reinforced thermosets	Sheet molding compound (SMC)	15–30	8–22
	Bulk molding compound (BMC)	15–35	2–10
	Preform/mat (compression molded)	25–50	10–20
	Cold press molding–polyester	20–30	9–12
	Spray-up—polyester	30–50	4–12
	Filament wound—epoxy	30–80	40–60
	Rod stock—polyester	40–80	45–60
	Molding compound—phenolic	5–25	1–8
Glass–fiber-reinforced thermoplastics	Acetal	20–40	0.8–2.8
	Nylon	6–60	0.8–4.5
	Polycarbonate	20–40	1.5–3.5
	Polyethylene	10–40	1.2–4.0
	Polypropylene	20–40	1–4
	Polystyrene	20–35	0.4–4.5
	Polysulfone	20–40	1.3–2.5
	ABS (acrylonitrile butadiene styrene)	20–40	1–2.4
	PVC (polyvinyl chloride)	15–35	0.8–1.6
	Polyphenylene oxide (modified)	20–40	1.6–2.2
	SAN (styrene acrylonitrile)	20–40	0.4–2.4
	Thermoplastic polyester	20–35	1.0–2.7

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 106.

Note: To convert ft · lb/in. of notch to J/cm of notch, multiply by 0.534.

TABLE 5.33 Impact Strength of Carbon- and Glass-Reinforced Engineering Thermoplastics

Class	Resin Type	Composition	Impact Strength, Notched/ Unnotched (J/cm)
Amorphous	Acrylonitrile butadiene styrene (ABS)	30% glass fiber	0.75/3.5
		30% carbon fiber	0.59/2.4
	Nylon	30% glass fiber	0.64/3.7
		30% carbon fiber	0.64/4.3
	Polycarbonate	30% glass fiber	2.0/9.34
		30% carbon fiber	0.96/5.34
	Polyetherimide	30% glass fiber	0.75/5.60
		30% carbon fiber	0.75/6.67
	Polyphenylene oxide (PPO)	30% glass fiber	1.2/5.1
		30% carbon fiber	0.53/3.0
	Polysulfone	30% glass fiber	0.96/7.5
		30% carbon fiber	0.64/3.5
	Styrene–maleic anhydride (SMA)	30% glass fiber	0.59/2.4
	Thermoplastic polyurethane	30% glass fiber	5.1/15
Crystalline	Acetal	30% glass fiber	0.96/4.8
		20% carbon fiber	0.53/1.6
	Nylon 66	30% glass fiber	1.5/11
		30% carbon fiber	0.80/6.4
	Polybutylene terephthalate (PBT)	30% glass fiber	1.4/9.1
		30% carbon fiber	0.64/3.5
	Polyethylene terephthalate (PET)	30% glass fiber	1.0/–
	Polyphenylene sulfide (PPS)	30% glass fiber	0.75/4.5
		30% carbon fiber	0.59/2.9

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, pp. 111–112.

TABLE 5.34 Fracture Toughness of Si_3N_4 and Al_2O_3 Composites

Matrix	Dispersed Phase	Fracture Toughness (K_{Ic}), (MPa $\sqrt{m}$)
Si_3N_4 + 6 wt.% Y_2O_3	None	4.8 ± 0.3
Si_3N_4 + 6 wt.% Y_2O_3	TiC	4.4 ± 0.5
	(Ti, W) C	3.5 ± 0.3
	WC	5.2 ± 0.4
	TaC	4.6 ± 0.4
	HfC	3.6 ± 0.2
	SiC	3.65 ± 0.5
Al_2O_3	TiC	3.2 ± 0.4

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 169.

Note: Containing 30 vol% of metal carbide dispersoid (2 μm average particle diameter).

TABLE 5.35 Tensile Modulus of Fiberglass-Reinforced Plastics

Class	Material	Glass Fiber Content (wt.%)	Tensile Modulus (10^5 psi)
Glass–fiber-reinforced thermosets	Sheet molding compound (SMC)	15–30	16–25
	Bulk molding compound (BMC)	15–35	16–25
	Preform/mat (compression molded)	25–50	9–20
	Spray-up—polyester	30–50	8–l8
	Filament wound—epoxy	30–80	40–90
	Rod stock—polyester	40–80	40–60
	Molding compound—phenolic	5–25	26–29
Glass–fiber-reinforced thermoplastics	Acetal	20–40	8–15
	Nylon	6–60	2–20
	Polycarbonate	20–40	7.5–17
	Polyethylene	10–40	4–9
	Polypropylene	20–40	4.5–9
	Polystyrene	20–35	8.4–12.1
	Polysulfone	20–40	15
	ABS (acrylonitrile butadiene styrene)	20–40	6–10
	PVC (polyvinyl chloride)	15–35	10–18
	Polyphenylene oxide (modified)	20–40	9.5–15
	SAN (styrene acrylonitrile)	20–40	9–18.5
	Thermoplastic polyester	20–35	13–15.5

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 106.

Note: To convert from psi to MPa, divide by 145.

TABLE 5.36 Tensile Modulus of Graphite/Aluminum Composites

Composite	Fiber Loading (vol%)	Wire Diameter (mm)	Tensile Modulus (GPa)
VS0054/201 Al	48–52	0.64 (2-strand)	345
GY70SE/201 Al	37–38	0.71 (8-strand)	207

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.

TABLE 5.37 Tensile Modulus of Investment Cast Silicon Carbide[a] SCS–Al

Fiber Orientation	Fiber (vol%)	Tensile Modulus (GPa)	Range of Measurement (%)
$0°_3/90°_6/0°_3$	33	122.0	107
$90°_3/0°_6/90°_3$	33	124.8	110
0°	34	172.4	100

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 149.

[a] "Silicon Carbide SCS" is the brand name of a SiC fiber produced by Specialty Materials, Inc. The SiC is deposited on a carbon monofilament core and is coated with a carbon-rich outer layer.

TABLE 5.38 Tensile Modulus of Silicon Carbide[a] SCS-2-Al

Fiber Orientation	No. of Plies	Tensile Modulus (GPa)
0°	6, 8, 12	204.1
90°	6, 12, 40	118.0
$[0°/90°/0°/90°]_s$	8	136.5
$[0°_2/90°/0°]_s$	8	180.0
$[90°_2/0°/90°]_s$	8	96.5
±45°	8, 12, 40	94.5
$[0°/\pm45°/0°]_{s+2s}$	8, 16	146.2
$[0°/\pm45°/90°]_s$	8	127.0

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 149.

[a] "Silicon Carbide SCS" is the brand name of a SiC fiber produced by Specialty Materials, Inc. The SiC is deposited on a carbon monofilament core and is coated with a carbon-rich outer layer.

TABLE 5.39 Modulus of Elasticity of 55MSI[a] Graphite/6061 Aluminum Composites

Material	Reinforcement Content (vol%)	Fiber Orientation	Modulus of Elasticity (GPa)
55MSI graphite/6061 aluminum composites	34	0°	182.2 ± 6.6
55MSI graphite/6061 aluminum composites	34	90°	33

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.

[a] xxMSI is a code defining the modulus of elasticity for the reinforcing graphite fiber having a value of xx millions of pounds per square inch.

TABLE 5.40 Modulus of Elasticity of Graphite/Magnesium Castings[a]

Fiber Type	Fiber Content (%)	Fiber Orientation	Casting	Fiber Preform Method	Modulus of Elasticity, 0° (GPa)	Modulus of Elasticity, 90° (GPa)
P75	40	±16°	Hollow cylinder	Filament wound	179	86
P100	40	±16°	Hollow cylinder	Filament wound	228	30
P55	40	0°	Plate	Prepreg	159	21
	30	0° plus	Plate	Prepreg	83	34
	20	0° plus	Plate	Prepreg	90	90

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.
[a] Pitch-base fibers.

TABLE 5.41 Modulus of Elasticity of Graphite/Aluminum Composites

Thornel Fiber	Longitudinal Modulus of Elasticity (GPa)	Transverse Modulus of Elasticity (GPa)
P55	207–221	28–41
P75	276–296	28–41
P100	379–414	28–41

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.

TABLE 5.42 Modulus of Elasticity of Graphite Fiber-Reinforced Metals

Composite	Fiber Content (vol%)	Modulus of Elasticity (10^6 psi)
Graphite[a]/lead	41	29.0
Graphite[b]/lead	35	17.4
Graphite[a]/zinc	35	16.9
Graphite[a]/magnesium	42	26.6

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.
Note: To convert from psi to MPa, divide by 145.
[a] Thornel 75 fiber.
[b] Courtaulds HM fiber.

TABLE 5.43 Modulus of Elasticity of SiC Whisker-Reinforced Aluminum Alloy

	Modulus of Elasticity		
Fiber Content (vol%)	GPa	Standard Deviation	Range of Measurement
0	71.9	4.5	13
12	95.3	1.6	6
16	90.0	3.7	9
20	111.0	5.0	13

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 150.

TABLE 5.44 Modulus of Elasticity of Polycrystalline Alumina-Reinforced Aluminum Alloy

	Modulus of Elasticity		
Fiber Content (vol%)	GPa	Standard Deviation	Range of Measurement
0	71.9	4.5	13
5	78.4	2.3	6
12	83.0	7.8	21
20	95.2	2.7	7

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 154.

TABLE 5.45 Modulus of Elasticity of Boron/Aluminum Composites[a]

Matrix	Fiber Orientation	Modulus of Elasticity (GPa)
Al-6061	0°	207
	90°	138
Al-2024	0°	207
	90°	145

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 157.

[a] These samples contain 48% Avco (142 µm) boron. Longitudinal tensile specimens are 152 mm × 7.9 mm × 6 ply. Transverse tensile bars are 152 mm × 12.7 mm × 6 ply.

TABLE 5.46 Flexural Modulus of Fiberglass-Reinforced Plastics

Class	Material	Glass Fiber Content (wt.%)	Flexural Modulus (10^5 psi)
Glass–fiber-reinforced thermosets	Sheet molding compound (SMC)	15–30	14–20
	Bulk molding compound (BMC)	15–35	14–20
	Preform/mat (compression molded)	25–50	13–18
	Cold press molding–polyester	20–30	13–19
	Spray-up—polyester	30–50	10–12
	Filament wound—epoxy	30–80	50–70
	Rod stock—polyester	40–80	40–60
	Molding compound—phenolic	5–25	30
Glass–fiber-reinforced thermoplastics	Acetal	20–40	8–13
	Nylon	6–60	2–28
	Polycarbonate	20–40	7.5–15
	Polyethylene	10–40	2.1–6
	Polypropylene	20–40	3.5–8.2
	Polystyrene	20–35	8–12
	Polysulfone	20–40	8–15
	ABS (acrylonitrile butadiene styrene)	20–40	9.2–15
	PVC (polyvinyl chloride)	15–35	9–16
	Polyphenylene oxide (modified)	20–40	8–15
	SAN (styrene acrylonitrile)	20–40	8.0–18
	Thermoplastic polyester	20–35	8.7–15

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 106.
Note: To convert from psi to MPa, divide by 145.

TABLE 5.47 Flexural Modulus of Carbon- and Glass-Reinforced Engineering Thermoplastics

Class	Resin Type	Composition	Flexural Modulus (GPa)
Amorphous	Acrylonitrile butadiene styrene (ABS)	30% glass fiber	7.6
		30% carbon fiber	12.4
	Nylon	30% glass fiber	7.9
		30% carbon fiber	15.2
	Polycarbonate	30% glass fiber	8.3
		30% carbon fiber	13.1
	Polyetherimide	30% glass fiber	8.6
		30% carbon fiber	17.2
	Polyphenylene oxide (PPO)	30% glass fiber	9.0
		30% carbon fiber	11.7
	Polysulfone	30% glass fiber	8.3
		30% carbon fiber	14.5

(*Continued*)

TABLE 5.47 (*Continued*) Flexural Modulus of Carbon- and Glass-Reinforced Engineering Thermoplastics

Class	Resin Type	Composition	Flexural Modulus (GPa)
	Styrene–maleic anhydride (SMA)	30% glass fiber	9.0
	Thermoplastic polyurethane	30% glass fiber	1.3
Crystalline	Acetal	30% glass fiber	9.7
		20% carbon fiber	9.3
	Nylon 66	30% glass fiber	9.0
		30% carbon fiber	20.0
	Polybutylene terephthalate (PBT)	30% glass fiber	9.7
		30% carbon fiber	15.9
	Polyethylene terephthalate (PET)	30% glass fiber	9.0
	Polyphenylene sulfide (PPS)	30% glass fiber	11.0
		30% carbon fiber	16.9

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, pp. 111–112.

TABLE 5.48 Modulus of Rupture for Si_3N_4 and Al_2O_3 Composites

Matrix	Dispersed Phase	Modulus of Rupture (MPa)		
		RT	1000°C	1200°C
Si_3N_4 + 6 wt.% Y_2O_3	None	110.9 ± 1.6	88.3 ± 3.5	49.2 ± 5.0
Si_3N_4 + 6 wt.% Y_2O_3	TiC	80.6 ± 5.9	120.4 ± 12.2	64.4 ± 2.9
	(Ti, W) C	75.5 ± 3.2	86 ± 0	52.9 ± 0.5
	WC	89.1 ± 31.8	136.4 ± 1.6	55.7 ± 0.5
	TaC	86.2 ± 7.3	124.5 ± 16.0	43.2 ± 2.0
	HfC	86 ± 0.8	—	68.6 ± 0.5
	SiC	97.6 ± 8.5	94.0 ± 4.9	52.3 ± 3.2
Al_2O_3	TiC	72.2 ± 13.0	69.4 ± 4.3	57.0 ± 4.1

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 169.

Note: Containing 30 vol% of metal carbide dispersoid (2 μm average particle diameter).

TABLE 5.49 Poisson's Ratio of Silicon Carbide[a] SCS-2-Al

Fiber Orientation	No. of Plies	Poisson's Ratio
0°	6, 8, 12	0.268
90°	6, 12, 40	0.124
±45°	8, 12, 40	0.395

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 149.

[a] "Silicon Carbide SCS" is the brand name of a SiC fiber produced by Specialty Materials, Inc. The SiC is deposited on a carbon monofilament core and is coated with a carbon-rich outer layer.

TABLE 5.50 Ultimate Tensile Elongation of Fiberglass-Reinforced Plastics

Class	Material	Glass Fiber Content (wt.%)	Ultimate Tensile Elongation (%)
Glass–fiber-reinforced thermosets	Sheet molding compound (SMC)	15–30	0.3–1.5
	Bulk molding compound (BMC)	15–35	0.3–5
	Preform/mat (compression molded)	25–50	1–2
	Cold press molding—polyester	20–30	1–2
	Spray-up—polyester	30–50	1.0–1.2
	Filament wound—epoxy	30–80	1.6–2.8
	Rod stock—polyester	40–80	1.6–2.5
	Molding compound—phenolic	5–25	0.25–0.6
Glass–fiber-reinforced thermoplastics	Acetal	20–40	2
	Nylon	6–60	2–10
	Polycarbonate	20–40	2
	Polyethylene	10–40	1.5–3.5
	Polypropylene	20–40	1–3
	Polystyrene	20–35	1.0–1.4
	Polysulfone	20–40	2–3
	ABS (acrylonitrile butadiene styrene)	20–40	3–3.4
	PVC (polyvinyl chloride)	15–35	2–4
	Polyphenylene oxide (modified)	20–40	1.7–5
	SAN (styrene acrylonitrile)	20–40	1.1–1.6
	Thermoplastic polyester	20–35	1–5

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 106.

TABLE 5.51 Total Strain of Silicon Carbide[a] SCS-2-Al

Fiber Orientation	No. of Plies	Total Strain
0°	6, 8, 12	0.89
90°	6, 12, 40	0.08
$[0°/90°/0°/90°]_s$	8	0.90
$[0°_2/90°/0°]_s$	8	0.92
$[90°_2/0°/90°]_s$	8	1.01
±45°	8, 12, 40	10.6
$[0°/\pm 45°/0°]_{s+2s}$	8, 16	0.86
$[0°/\pm 45°/90°]_s$	8	1.0

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 149.

[a] "Silicon Carbide SCS" is the brand name of a SiC fiber produced by Specialty Materials, Inc. The SiC is deposited on a carbon monofilament core and is coated with a carbon-rich outer layer.

TABLE 5.52 Strength Density Ratio of Graphite Fiber-Reinforced Metals

Composite	Fiber Content (vol%)	Strength/Density (10^6 in.)
Graphite[a]/lead	41	0.385
Graphite[b]/lead	35	0.260
Graphite[a]/zinc	35	0.580
Graphite[a]/magnesium	42	1.016

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.
[a] Thornel 75 fiber.
[b] Courtaulds HM fiber.

TABLE 5.53 Modulus Density Ratio of Graphite Fiber-Reinforced Metals

Composite	Fiber Content (vol%)	Modulus/Density (10^6 in.)
Graphite[a]/lead	41	107.0
Graphite[b]/lead	35	62.3
Graphite[a]/zinc	35	88.5
Graphite[a]/magnesium	42	393.7

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 148.
[a] Thornel 75 fiber.
[b] Courtaulds HM fiber.

Chemical Properties

TABLE 5.54 Flammability of Fiberglass-Reinforced Plastics

Class	Material	Glass Fiber Content (wt.%)	Flammability (UL94)
Glass–fiber-reinforced thermosets	Sheet molding compound (SMC)	15–30	5V
	Bulk molding compound (BMC)	15–35	5V
	Preform/mat (compression molded)	25–50	V–0
	Cold press molding—polyester	20–30	V–0
	Spray-up—polyester	30–50	V–0
	Filament wound—epoxy	30–80	V–0
	Rod stock—polyester	40–80	V–0
	Molding compound—phenolic	5–25	V–0
Glass–fiber-reinforced thermoplastics	Acetal	20–40	HB
	Nylon	6–60	V–0
	Polycarbonate	20–40	V–0
	Polyethylene	10–40	V–0
	Polypropylene	20–40	V–0
	Polystyrene	20–35	V–0
	Polysulfone	20–40	V–0
	ABS (acrylonitrile butadiene styrene)	20–40	V–0

(*Continued*)

TABLE 5.54 (*Continued*) Flammability of Fiberglass-Reinforced Plastics

Class	Material	Glass Fiber Content (wt.%)	Flammability (UL94)
	PVC (polyvinyl chloride)	15–35	V–0
	Polyphenylene oxide (modified)	20–40	V–0
	SAN (styrene acrylonitrile)	20–40	V–0
	Thermoplastic polyester	20–35	V–0

Source: Data from Michael Bauccio (Ed.), *ASM Engineering Materials Reference Book,* Second Edn., ASM International, Materials Park, OH, 1994, p. 106.

6

Semiconductors

Physical Properties

TABLE 6.1 Periodic Table of Elements in Semiconducting Materials

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
IA																	VIIA
	IIA											IIIA	IVA	VA	VIA	VIIA	
															8 O		
		IIIB	IVB	VB	VIB	VIIB	-----	VIII	-----	IB	IIB	13 Al	14 Si	15 P	16 S		
											30 Zn	31 Ga	32 Ge	33 As	34 Se		
											48 Cd	49 In	50 Sn	51 Sb	52 Te		
											80 Hg						

Chemical Properties

TABLE 6.2 Diffusion in Semiconductors[a]

Semiconductor	Diffusing Element	D_o (cm²/s)	ΔE (eV)	Temperature Range of Validity (°C)
Aluminum antimonide (AlSb)	Al		~1.8	
	Cu	3.5×10^{-3}	0.36	150–500
	Sb		~1.5	
	Zn	0.33 ± 0.15	1.93 ± 0.04	660–860
Cadmium selenide (CdSe)	Se	2.6×10^{-3}	1.55	700–1800
Cadmium sulfide (CdS)	Ag	$2.5 \times 10^{+1}$	1.2	250–500
	Cd	3.4	2.0	750–1000
	Cu	1.5×10^{-3}	0.76	450–750
Cadmium telluride (CdTe)	Au	$6.7 \times 10^{+1}$	2.0	600–1000
	In	4.1×10^{-1}	1.6	450–1000
Calcium ferrate (III) ($CaFe_2O_4$)	Ca	30	3.7	
	Fe	0.4	3.1	
α-Calcium metasilicate ($CaSiO_3$)	Ca	$7.4 \times 10^{+4}$	4.8	
Gallium antimonide (GaSb)	Ga	$3.2 \times 10^{+3}$	3.15	650–700
	In	1.2×10^{-7}	0.53	400–650
	Sb	$3.4 \times 10^{+4}$	3.44	650–700
		$8.7 \times 10^{+2}$	1.13	470–570
	Sn	2.4×10^{-5}	0.80	320–570
	Te	3.8×10^{-4}	1.2	400–650
Gallium arsenide (GaAs)	Ag	2.5×10^{-3}	1.5	
		4×10^{-4}	0.8 ± 0.05	500–1160
	As	4×10^{21}	10.2 ± 1.2	1200–1250
	Au	10^{-3}	1.0 ± 0.2	740–1024
	Cd	0.05 ± 0.04	2.43 ± 0.06	868–1149
		50×10^{-2}[b]	2.8[b]	
	Cu	0.03	0.52	100–600
	Ga	$1 \times 10^{+7}$	5.60 ± 0.32	1125–1250
	Li	0.53	1.0	250–400
	Mg	1.4×10^{-4}	1.89	
		2.3×10^{-2}	2.6	740–1024
		2.6×10^{-2}[b]	2.7[b]	
		6.5×10^{-1}[b]	2.49[b]	
		8.5×10^{-3}	1.7	740–1024
	S	1.2×10^{-4}	1.8	
		1.6×10^{-5}[b]	1.63[b]	

(*Continued*)

TABLE 6.2 (*Continued*) Diffusion in Semiconductors[a]

Semiconductor	Diffusing Element	D_o (cm²/s)	ΔE (eV)	Temperature Range of Validity (°C)
		2.6×10^{-5}	1.86	
		4×10^{3}	4.04 ± 0.15	1000–1200
	Se	3×10^{3}	4.16 ± 0.16	1000–1200
	Sn	3.8×10^{-2}[b]	2.7	
		6×10^{-4}	2.5	1069–1215
	Zn	2.5×10^{-1}[b]	3.0[b]	
		3.0×10^{-7}	1.0	
		6.0×10^{-7}	0.6	
		15 ± 7	2.49 ± 0.05	800
Gallium phosphide (GaP)	Zn	1.0	2.1	700–1300
Germanium (Ge)	Ag	4.4×10^{-2}	1.0	700–900
	As	6.3	2.4	600–850
	Au	2.2×10^{-2}	2.5	
	B	1.6×10^{-9}	4.6	600–850
	Cu	1.9×10^{-4}	0.18	600–850
	Fe	1.3×10^{-1}	1.1	750–850
	Ga	$4.0 \times 10^{+1}$	3.1	600–850
	Ge	$8.7 \times 10^{+1}$	3.2	750–920
	He	6.1×10^{-3}	0.69	750–850
	In	3×10^{-2}	2.4	600–850
	Li	1.3×10^{-4}	0.47	200–600
	Ni	8×10^{-1}	0.9	700–875
	P	2.5	2.5	600–850
	Pb	–	3.6	600–850
	Sb	4.0	2.4	600–850
	Sn	1.7×10^{-2}	1.9	600–850
	Zn	$1.0 \times 10^{+1}$	2.5	600–850
Indium antimonide (InSb)	Ag	1.0×10^{-7}	0.25	
	Au	7×10^{-4}[b]	0.32[b]	140–510
	Cd	1.0×10^{-5}[b]	1.1[b]	250–500
		1.23×10^{-9}	0.52	442–519
		1.26	1.75	
		1.3×10^{-4}	1.2	360–500
	Co	2.7×10^{-11}	0.39	
		10^{-7}	0.25	440–510
	Cu	3.0×10^{-5}	0.37	
		9.0×10^{-4}[b]	1.08[b]	
	Fe	10^{-7}	0.25	440–510
	Hg	4.0×10^{-6}[b]	1.17[b]	

(*Continued*)

TABLE 6.2 (*Continued*) Diffusion in Semiconductors[a]

Semiconductor	Diffusing Element	D_o (cm²/s)	ΔE (eV)	Temperature Range of Validity (°C)
	In	0.05	1.81	450–500
		1.8×10^{-9}	0.28	
	Ni	10^{-7}	0.25	440–510
	Sb	0.05	1.94	450–500
		1.4×10^{-6}	0.75	
	Sn	5.5×10^{-8}	0.75	390–512
	Te	1.7×10^{-7}	0.57	300–500
	Zn	0.5	1.35	360–500
		1.6×10^{-6}	2.3 ± 0.3	360–500
		5.5	1.6	360–500
	Polycrystal	1.7×10^{-7}	0.85	390–512
		$5.3 \times 10^{+7}$ [b]	2.61	
	Zinc (high concentration)	$6.3 \times 10^{+8}$	2.61	
		8.7×10^{-10} [b]	0.7[b]	
	Conc. 2.2×10^{20} cm^{-3}	9.0×10^{-10}	~0	
	Single crystal	1.4×10^{-7}	0.86	390–512
Indium arsenide (InAs)	Cd	4.35×10^{-4}	1.17	600–900
	Cu		0.52[b]	
	Ge	3.74×10^{-6}	1.17	600–900
	Mg	1.98×10^{-6}	1.17	600–900
	S	6.78	2.20	600–900
	Se	12.55	2.20	600–900
	Sn	1.49×10^{-6}	1.17	600–900
	Te	3.43×10^{-5}	1.28	600–900
	Zn	3.11×10^{-3}	1.17	600–900
Indium phosphide (InP)	In	$1 \times 10^{+5}$	3.85	850–1000
	P	$7 \times 10^{+10}$	5.65	850–1000
Iron oxide (Fe_3O_4)	Fe	5.2	2.4	
Lead metasilicate ($PbSiO_3$)	Pb	85	2.6	
Lead orthosilicate ($PbSiO_4$)	Pb	8.2	2.0	
Mercury selenide (HgSe)	Sb	6.3×10^{-5}	0.85	540–630
Nickel aluminate ($NiAl_2O_4$)	Cr	1.17×10^{-3}	2.2	
	Fe	1.33	3.5	
Nickel chromate (III) ($NiCr_2O_4$)	Cr	0.74	3.1	
	Cr	2.03×10^{-5}	1.9	
	Fe	1.35×10^{-3}	2.6	
	Ni	0.85	3.2	

(*Continued*)

TABLE 6.2 (*Continued*) Diffusion in Semiconductors[a]

Semiconductor	Diffusing Element	D_o (cm²/s)	ΔE (eV)	Temperature Range of Validity (°C)
Selenium (Se) (amorphous)	Fe	1.1×10^{-5}	0.38	300–400
	Ge	9.4×10^{-6}	0.39	300–400
	In	5.2×10^{-6}	0.32	300–400
	Sb	2.8×10^{-8}	0.29	300–400
	Se	7.6×10^{-10}	0.14	300–400
	Sn	4.8×10^{-8}	0.39	300–400
	Te	5.4×10^{-6}	0.53	300–400
	Tl	1.4×10^{-6}	0.35	300–400
	Zn	3.8×10^{-7}	0.29	300–400
Silicon (Si)	Al	8.0	3.5	1100–1400
	Ag	2×10^{-3}	1.6	1100–1350
	As	3.2×10^{-1}	3.5	1100–1350
	Au	1.1×10^{-3}	1.1	800–1200
	B	$1.0 \times 10^{+1}$	3.7	950–1200
	Bi	$1.04 \times 10^{+3}$	4.6	1100–1350
	Cu	4×10^{-1}	1.0	800–1100
	Fe	6.2×10^{-3}	0.86	1000–1200
	Ga	3.6	3.5	1150–1350
	H_2	9.4×10^{-3}	0.47	1000–1200
	He	1.1×10^{-1}	0.86	1000–1200
	In	$1.65 \times 10^{+1}$	3.9	1100–1350
	Li	9.4×10^{-3}	0.78	100–800
	P	$1.0 \times 10^{+1}$	3.7	1100–1350
	Sb	5.6	3.9	1100–1350
	Tl	$1.65 \times 10^{+1}$	3.9	1100–1350
Silicon carbide (SiC)	Al	2.0×10^{-1}	4.9	1800–2250
	B	$1.6 \times 10^{+1}$	5.6	1850–2250
	Cr	2.3×10^{-1}	4.8	1700–1900
Sulfur (S)	S	$2.8 \times 10^{+13}$	2.0	>100
Tin zinc oxide ($SnZn_2O_4$)	Sn	$2 \times 10^{+5}$	4.7	
	Zn	37	3.3	
Zinc aluminate ($ZnAl_2O_4$)	Zn	$2.5 \times 10^{+2}$	3.4	
Zinc chromate (III) ($ZnCr_2O_4$)	Cr	8.5	3.5	
	Zn	60	3.7	
Zinc ferrate (III) ($ZnFe_2O_4$)	Fe	$8.5 \times 10^{+2}$	3.5	
	Zn	$8.8 \times 10^{+2}$	3.7	
Zinc selenide (ZnSe)	Cu	1.7×10^{-5}	0.56	200–570

(*Continued*)

TABLE 6.2 (*Continued*) Diffusion in Semiconductors[a]

Semiconductor	Diffusing Element	D_o (cm²/s)	ΔE (eV)	Temperature Range of Validity (°C)
Zinc sulfide (ZnS)	Zn	$1.0 \times 10^{+16}$	6.50	>1030
		$1.5 \times 10^{+4}$	3.25	940–1030
		3.0×10^{-4}	1.52	<940

Source: Data from R. E. Bolz and G. L. Tuve (Eds.), *Handbook of Tables for Applied Engineering Science,* 2nd Edn., CRC Press, Cleveland, 1973, pp. 251.

[a] The diffusion coefficient D at a temperature T(K) is given by the following

$$D = D_o e^{-\Delta E/kT}$$

For D_o in m²/s, multiply values in cm²/s by 10^{-4}.

[b] Values obtained at the low concentration limit.

II

Advanced Materials

7

Low-Dimensional Carbons and Two-Dimensional Nanomaterials

Physical Properties

TABLE 7.1 Energies and Bond Lengths at Nanotube/Diamond Interfaces[a]

Nanotube Type	Interface Energy (J/m^2)	Average Energy per Atom (eV) Diamond	Average Energy per Atom (eV) Nanotube	Interface Bond Lengths (Å)
		Zigzag Nanotube and the (111) Diamond Faucet		
(6,0)	0.53	−7.45	−6.84(−7.1)	1.525
(12,0)	0.74	−7.44	−7.0(−7.32)	1.525(6), 1.529(6)
(18,0)	0.75	−7.43	−7.04(−7.36)	1.52(12), 1.537(6)
(24,0)	0.78	−7.42	−7.05(−7.37)	1.52(12), 1.547(6), 1.519(6)
(8,0)	1.04	−7.38	−6.85(−7.22)	1.51(3), 1.53(4), 1.69(1)
(9,0)	0.58	−7.48	−6.95(−7.26)	1.52(6), 1.53(3)
(10,0)	0.61	−7.45	−6.99(−7.28)	1.53(6), 1.55(4)
(7,0)	15 d.b.[b]	−7.43	−6.92(−7.17)	1.51(4), 1.57(2), 1 d.b.[b]
		−5.5 d.b.[b]	−4.57 d.b.[b]	
		Armchair Nanotube and a Pentaparticle		
(5,5)[c]	5(0.9)	−6.85(−7.0)	−6.2(−7.45)	1.6(1.6)
		Zigzag Nanotube and the (100) Diamond Faucet		
(6,0)	1.7	−7.4	−6.7	1.52(2), 1.57(2), 1.63(2)
(8,0)	1.2	−7.47	−6.83	1.47(2), 1.54(4), 1.62(2)
(12,0)[d]	1.6	−7.0	−7.0	1.48(2), 1.52(4), 1.57(4)

Source: Data from O. A. Shenderova, D. Areshkin, and D. W. Brenner, *Mater. Res.*, 6(1), 11–17, 2002. With permission.

[a] Values in parentheses for bond lengths correspond to the number of bonds of the given length at the interface. In the column "Nanotube," the value in parentheses corresponds to energy per atom in relaxed single nanotube (reference point for the interface energy calculations).

[b] d.b.—dangling bond.

[c] Values in parentheses correspond to a structure with hydrogen atoms attached to the (5,5) nanotube atoms near the interface to decrease the energy.

[d] (12,0) nanotube was attached to the dimerized diamond surface (Figure 2).

TABLE 7.2 Thermal Properties of Low-Dimensional Carbons

	Thermal Conductivity (W/m K)	Thermal Stability
Single-wall carbon nanotube[a]	3000	>700°C (in air) 2800°C (in vacuum)
Multiwall carbon nanotube[a]	3000	>700°C (in air) 2800°C (in vacuum)
Graphene[b]	~5000	

Source: [a]Data from Y. T. Ong et al. *Braz. J. Chem. Eng.*, 27, 227–242, 2010.
[b]Data from X. Huang et al. *Small*, 7, 1876–1902, 2011.

TABLE 7.3 Mechanical Properties of Low-Dimensional Carbons

	Diameter (nm)	Specific Surface Area (m^2/g)	Specific Gravity (Mg/m^3)	Elastic Modulus (TPa)	Strength (GPa)	Bending Modulus (GPa)	Tensile Strength (GPa)	Breaking Strength (N/m)	Fracture Strength (GPa)
Single-wall carbon nanotube	~0.4 to >3	~400–900	0.8	~1	50–500	$K_{(n,n)}$ (armchair): 963.44 $K_{(n,0)}$ (zigzag): 911.64 $K_{(2n,n)}$: 935.48	13–53		
Multiwall carbon nanotube	~1.4 to >100	~200–400	1.8	~0.3–1	10–60		11–150		
Graphene		2630		1			~1100	42	130

Source: Data from Y. T. Ong et al. *Braz. J. Chem. Eng.*, 27, 227–242, 2010; X. Huang, Z. Zeng, and H. Zhang, *Chem. Soc. Rev.*, 42, 1934, 2013; S. K. Lee, H. Kim, and B. S. Shim, *Carbon Lett.*, 14, 63–75, 2013.

TABLE 7.4 Mechanical Properties of Nano-Crystalline Diamond Thin Films

	Nano-Crystalline Diamond (NCD)				Ultra Nano-Crystalline Diamond
Property	Grown with High Methane NCD	Bias-Enhanced Growth NCD	Grown with Modified Gas Chemistry	Highest Quality NCD	UNCD
Growth chemistry	H_2/CH_4	H_2/CH_4	N_2/CH_4	H_2/CH_4	Ar/CH_4
Young's modulus (GPa)	500–900	–	–	1120	980
Hardness (GPa)	80	35–75	–	–	98
Macroscopic friction coefficient	0.02–0.05	–	0.02–0.05	0.02–0.05	0.02–0.05
Surface roughness (nm)	50–100	15–30	20–30	5–30 (depending on film thickness)	5–25 (depending on nucleation density and thickness)
Grain size (nm)	50–100	–	5–15	5–100 (depending on film thickness)	2–5
Bonding character	Up to 50% sp^2	20%–40% sp^2	10%–15% sp^2	<0.1% sp^2	2%–5% sp^2

Source: Data from J. E. Butler and A. V. Sumant, *Chem. Vap. Deposition*, 14, 145–160, 2008. With permission.

TABLE 7.5 Properties of Ultra Nano-Crystalline Diamond (UNCD) and Nano-Crystalline Diamond (NCD) Thin Films

Property	Ultra Nano-Crystalline Diamond (UNCD)	Nano-Crystalline Diamond (NCD)
Bonding character	2%–5% sp^2	<0.1% sp^2
Density (Mg/m^3)	3.300	3.510
Young's modulus (GPa)	980	1120
Hardness (GPa)	98	–
Macroscopic friction coefficient	0.02–0.05	0.02–0.05
Macroscopic wear rate (mm^3/N m)	1.8×10^{-8}	–
Adhesion energy (mJ/m^2) (measured using AFM with diamond tip against surface)	10	–
Surface roughness (nm)	5–10	5–25
Fracture toughness (MPa $m^{1/2}$)	4.7–7.2	–
Grain size (nm)	2–5	5–100
Sound velocity (m/s)	15,700	17,980
Thermal conductivity (W/m K)	12	1370
Film stress (MPa)	100	–100 to 300 controllable
Deposition temperature (°C)	400–800	450–950
UV–vis transmission	Semi-opaque	Transparent
Electrical resistivity (undoped)	–	$>10^{13}$ Ω/cm^2
Electrical conductivity (doped with nitrogen)	140–260 Ω^{-1} cm^{-1}	200 Ω^{-1} cm^{-1}
Electrical mobility (doped with nitrogen)	5–10 cm^2/V s	–
Electrical mobility (doped with $10^{17}/cm^3$ boron)	90 cm^2/V s	10–90 cm^2/V s
Electrical conductivity (doped with $>10^{21}/cm^3$ boron)	10 Ω^{-1} cm^{-1}	Superconducting at $T < 1.6$ K

Source: Data from J. E. Butler and A. V. Sumant, *Chem. Vap. Deposition*, 14, 145–160, 2008. With permission; D. M. Gruen, *Ann. Rev. Mater. Sci*., 29, 211, 1999; A. V. Sumant et al., *Adv. Mater*., 17, 1039, 2005; A. V. Sumant et al., *Phys. Rev. B*, 73, 235439, 2007; H. D. Espinosa et al., J. *Appl. Phys*., 94, 6076, 2003; S. Bhattacharyya et al., *Appl. Phys. Lett*., 79, 1441, 2001; Y. Show et al., *Chem. Mater*., 15, 879, 2003; M. Nesladek et al., *Diamond Relat. Mater*., 15, 607, 2006.

Additional data from A. V. Sumant et al., *Mater. Res. Symp. Proc*., Vol. 657, MRS, Warendale, PA, 2000, p. 5; *26th Int. Conf. Metall. Coat. Thin Films*, A. Erdemir et al., p. 565, Copyright 1999, Elsevier; M. A. Angadi et al., *J. Appl. Phys*., 99, 114301, 2006; X. Xiao et al., *J. Appl. Phys*., 96, 2232, 2004; H. D. Espinosa and B. Peng, *J. Microelectromech. Syst*., 14, 153, 2005; L. M. Trolio et al., *Third Int. Conf. Appl. Diamond Films Relat. Mater*., Gaithersburg, MD, 1995, p. 133; J. Philip et al., *J. Appl. Phys*., 93, 2164, 2003; M. Bevilacqua et al., *J. Appl. Phys*., 107, 033716, 2010; J. J. Mares et al., *Diamond Relat. Mater*., 16, 1, 2007; M. Dipalo et al., *Phys. Status Solidi A*, 203, 3036, 2006.

TABLE 7.6 Electronic Properties of Low-Dimensional Carbons

	Magnetic Susceptibility (EMU/g)	Resistivity (μΩ cm)	Fermi Velocity (m/s)	Band Gap E_g (eV)	Current Density (A/cm²)	Electrical Conductivity (Ω^{-1} cm^{-1})	Carrier Mobility at Room Temperature (cm²/V s)	Electron Effective Mass (m^*/m_e)	Electron Saturation Velocity (cm/s)
Single-wall carbon nanotube	22×10^6 (perpendicular to plane) 0.5×10^6 (parallel to plane)	5–50	8×10^5	0.5	10^7	–	–	–	–
Multiwall carbon nanotube	–	5–50	–	–	1.32×10^7	1.85×10^3	–	–	–
Graphene	–	–	–	0	$>10^8$	–	$\sim 2 \times 10^5$ (at 300 K)	0	$\sim 4 \times 10^7$

Source: Data from Xiao-Lin Xie, Yiu-Wing Mai, and Xing-Ping Zhou, *Mater. Sci. Eng. R*, 49, 89–112, 2005. Additional data from Y. Ando et al., *Int. J. Inorg. Mater.*, 11, 77–82, 1999; S. K. Lee, H. Kim, and B. S. Shim, *Carbon Lett.*, 14, 63–75, 2013; Hongjie Dai, *Acc. Chem. Res.*, 35, 1035–1044, 2002; H. Hibino, Graphene Research at NTT Group, Japan.

TABLE 7.7 Electrical Properties of Two-Dimensional Nanomaterials

	Surface Charge Density (cm^{-2})	Carrier Mobility (cm²/V · s)	Band Overlap (meV)	Electrical Conductivity	Band Gap (eV)	Room-Temperature Mobility (cm^{-2}s^{-1})
MoS_2	10^{12}–10^{13}	0.5–3	–	–	1.29	200
Few layer graphene	7.2×10^{12}	3000–10,000	4–6	–	–	–
BN	–	–	–	Insulating	–	–
$NbSe_2$	10^{12}–10^{13}	0.5–3	–	–	–	–
$Bi_2Sr_2CaCu_2O_x$	–	–	–	Insulating	–	–
Graphene	10^{13}	2000–5000	–	–	–	~10,000

Source: Data from J. Brivio, D. T. L. Alexander, and A. Kis, *Nano Lett.*, 11, 5148–5153, 2011; K. S. Novoselov et al., *Science*, 306, 666–669, 2004; K. S. Novoselov et al., *Proc. Natl. Acad. Sci. U.S.A*, 102(30), 10451–10453, 2005; X. Huang et al., *Small*, 7, 1876–1902, 2011; S. Bertolazzi, J. Brivio, and A. Kis, *ACS Nano*, 5, 9703–9709, 2011; K. F. Mak et al., *Phys. Rev. Lett.*, 105, 136805, 2010; K. F. Mak et al., *Nat. Mater.*, 12, 207, 2013.

TABLE 7.8 Resistivity of $Ta_xMo_{1-x}S_2$ Phases and Corresponding Pyridine Intercalation Compounds and Polyethylene Oxide (PEO) Nanocomposites

Compound	Resistivity at 298 K (Ω cm)
$Ta_xMo_{1-x}S_2$	
$x = 0$	1.7×10^{5}
$x = 0.55$	1.4×10^{-3}
$x = 0.75$	5.0×10^{-3}
$x = 0.90$	6.3×10^{-4}
$x = 1.00$	10^{-3}–10^{4}
$Ta_{0.55}Mo_{0.45}S_2$	1.4×10^{-3}
$Ta_{0.55}Mo_{0.45}S_2 \cdot 0.32Py$	2.7×10^{-1}
$Ta_{0.75}Mo_{0.25}S_2 \cdot 0.41Py$	2.3×10^{-2}
$Ta_{0.90}Mo_{0.10}S_2 \cdot 0.46Py$	3.8×10^{-2}
$Ta_{0.90}Mo_{0.10}S_2 \cdot 1.8PEO$	1.93
$Ta_{0.90}Mo_{0.10}S_2 \cdot 2.2PEO$	208.5

Source: Data from N. Lara et al., *J. Braz. Chem. Soc.*, 23(3), 415–425, 2012.

Chemical Properties

TABLE 7.9 Triple Point and Critical Point[a] for C_{60}

		GEMC				
	SCOZA	$N = 300$	$N = 600$	$N = 1500$	NVT MC	Ab Initio
T_t (K)	1388	–	1500–1700	–	1880	1885.2
ρ_t (nm^{-3})	1.03	–	0.91–1.0	–	0.74	0.8447
T_c (K)	1957	1924	1927	1941	1980	2012
ρ_c (nm^{-3})	0.432	0.39	0.40	0.42	0.44	0.468

Source: Data from M. C. Abramo et al., *Europhys. Lett.*, 54, 468–474, 2001; E. Scholl-Paschinger and G. Kahl, *Europhys. Lett.*, 63(4), 538–544, 2003. With permission.

[a] Calculated using the Girifalco potential in the Self-Consistent Ornstein-Zernike Approximation (SCOZA), Gibbs Ensemble Monte Carlo (GEMC) simulation (for different particle numbers *N*), number-volume-temperature Monte Carlo (NVT MC) simulation, and *ab initio* calculations.

TABLE 7.10 Solution of Single-Wall Nanotubes (SWNT) and Multiwall Nanotubes (MWNT) in Various Solvents

Solute	Solvent (Mixture Ratio)	Dispersion Limit (mg/mL)	Surface Tension (Room Temperature and Pressure) (mJ/m^2)	Chi Value (χ)
Single-wall nanotubes (SWNT)	CHP/NEP (5:1)	0.232	38.4	–0.348
	CHP	0.16	38.8	–0.3
	NMP/N8P	0.058	38.4	–0.15
	NMP	0.0216	40.1	–0.0746
	BASF BASIONIC BC01 (1-ethyl-3-methylimidazolium acetate)	–	42.17	0.345
Multiwall nanotubes (MWNT)	NMP	0.0138	40.1	0.0771

Source: Data from J. Hamilton and P. Streich, Method and apparatus for identifying and characterizing material solvents and composite matrices and methods of using same, U.S. Patent Number US 2013/0075650 A1, March 28, 2013.

8

MAX Phases*

Physical Properties

TABLE 8.1 $M_{n+1}AX_n$ Phases

		413 Phases			
Nb_4AlC_3	Ta_4AlC_3	Ta_4GaC_3	Ti_4AlN_3	V_4AlC_3	–
		312 Phases			
Ta_3AlC_2	Ti_3AlC_2	Ti_3AlCN	Ti_3GeC_2	Ti_3SiC_2	Ti_3SnC_2
		211 Phases			
Cr_2AlC	Cr_2GaC	Cr_2GaN	Cr_2GeC	Hf_2InC	Hf_2PbC
Hf_2SC	Hf_2SnC	Hf_2SnN	Hf_2TlC	Mo_2GaC	Nb_2AlC
Nb_2AsC	Nb_2GaC	Nb_2InC	Nb_2PC	Nb_2SnC	Sc_2InC
Ta_2AlC	Ta_2GaC	Ti_2AlC	Ti_2AlN	Ti_2CdC	Ti_2GaC
Ti_2GaN	Ti_2GeC	Ti_2InC	Ti_2InN	Ti_2PbC	Ti_2SC
Ti_2SnC	Ti_2TlC	V_2AlC	V_2AsC	V_2GaC	V_2GaN
V_2GeC	V_2PC	Zr_2InC	Zr_2InN	Zr_2PbC	Zr_2SC
Zr_2SnC	Zr_2TlC	Zr_2TlN	–	–	–

TABLE 8.2 Density, Shear Modulus (G), Young's Modulus (E), Poisson's Ratio (ν), and Longitudinal and Shear Sound Velocities for MAX Phases

Solid	Density (Mg/m^3)	G (GPa)	E (GPa)	ν	v_L (m/s)	v_s (m/s)	Comments and References
			413 Phases				
Ti_4AlN_3	4.7	127	310	0.22	8685	5201	Finkel et al. (2000)
Nb_4AlC_3	7.0	127	306	0.20	7000	4270	Du et al. (2009) and Hu et al. (2008c)
Nb_4AlC_3	7.0	149	365	0.22	7770 (avg.)	4675 (avg.)	Parallel to basal planes; Hu et al. (2011b)
Nb_4AlC_3	7.0	153	353	0.15	–	–	Perpendicular to basal planes; Hu et al. (2011b)
β-Ta_4AlC_3	13.2	132	324	0.23	5400	3150	Hu et al. (2007)

(*Continued*)

* MAX Phases are defined as the family of carbides and nitrides that exhibit a layered structure at the atomic scale and a laminated structure at the microscopic scale. The name specifically comes from the formula $M_{n+1}AX_n$, where M is an early transition metal, A is one of the elements 13-16, and X is carbon and/or nitrogen. A review of these materials and their characteristics is provided in Radovic and Barsoum (2013).

TABLE 8.2 (*Continued*) Density, Shear Modulus (*G*), Young's Modulus (*E*), Poisson's Ratio (ν), and Longitudinal and Shear Sound Velocities for MAX Phases

Solid	Density (Mg/m³)	*G* (GPa)	*E* (GPa)	ν	v_L (m/s)	v_s (m s)	Comments and References
			312 Phases				
Ti_3SiC_2	405	139	343	0.20	9100	5570	Finkel et al. (2004) and Radovic et al. (2006)
Ti_3GeC_2	506	142	343	0.19	9230	5063	Finkel et al. (2004)
$Ti_3(Si, Ge)C_2$	5.02	137	322	0.18	8400	5650	Finkel et al. (2004)
Ti_3AlC_2	4.2	124	294	0.20	8880	5440	Radovic et al. (2006)
Ti_3AlCN	4.5	137	330	0.21	9092	5514	Radovic et al. (2008)
			211 Phases				
Ti_2AlC	4.1	118	277	0.19	8500	5400	Hettinger et al. (2005)
$Ti_2AlC_{0.5}N_{0.5}$	4.2	123	290	0.18	8670	5407	Radovic et al. (2008)
Ti_2AlN-a	4.25	150	285	0.18	8533	5328	Radovic et al. (2008)
Ti_2AlN-b	4.3	112	277	0.16	4700	5100	Radovic et al. (2008)
Ti_2SC	4.6	125	290	0.16	8200	5200	Scabarozi et al. (2008a)
Ti_2SC	4.62	129	293	0.16	8180	5248	Shamma et al. (2011)
V_2AlC	4.8	116	235	0.20	7000	4913	Hettinger et al. (2005)
V_2AlC	–	–	283	–	–	–	Hu et al. (2008a)
Cr_2AlC	5.24	105	245	0.20	6200	4450	Hettinger et al. (2005)
Cr_2AlC	5.1	116	288	0.24	7550	4770	Tian et al. (2007)
Cr_2AlC	–	121	285	0.18	–	–	Lin et al. (2007b)
Cr_2AlC	5.2	–	282	–	–	–	Ying et al. (2011b)
Cr_2GeC	6.9	80	208	0.29	6300	3422	Amini et al. (2008)
Nb_2AlC	6.3	117	286	0.21	7165	4306	Hettinger et al. (2005)
Nb_2AlC	6.44	–	294	–	6750	–	Zhang, W. et al. (2009)
Nb_2SnC	8.0	–	216	–	5200	–	El-Raghy et al. (2000)
Ta_2AlC	11.46	121	292	0.2	5350	3250	Hu et al. (2008b)
Hf_2SnC	11.2	–	237	–	4600	4600	El-Raghy et al. (2000)
Zr_2SnC	6.9	–	–	178	–	5080	El-Raghy et al. (2000)

Source: Barsoum, M. W. *MAX Phases: Properties of Machinable Ternary Carbides and Nitrides*. 2013. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

TABLE 8.3 Thermal Conductivities (in W/m K) for MAX and MX Phases at 300 and 1300 K[a]

	K_{th}		300 K		1300 K		
Phase	300	1300	κ_e	κ_{ph}	κ_e	κ_{ph}	References
			413 Phases				
$Ti_4AlN_{2.9}$	12	20	3(25%)	9(75%)	10(50%)	10(50%)	Barsoum et al. (2000d)
Ta_4AlC_3	38	26	19(50%)	19(50%)	20(77%)	6(23%)	Hu et al. (2007)
Nb_4AlC_3	13	20	10(77%)	3(23%)	13(65%)	7(35%)	Hu et al. (2008c)
			312 Phase				
Ti_3SiC_2	37	33	33(90%)	≈4(10%)	32(97%)	≈1(3%)	Barsoum et al. (1999)
			211 Phases				
Ti_2AlC	46	36	20(43%)	26(57%)	20(55%)	16(45%)	Barsoum et al. (2002b)
TiNbAlC	17	24	9(53%)	8(47%)	20(83%)	4(17%)	Barsoum et al. (2002b)
Nb_2AlC	23	27	16[b](70%)	7[b](30%)	20(74%)	>4(26%)	Barsoum et al. (2002b)
Nb_2SnC	17	30	12[b](72%)	5[b](28%)	25(82%)	5(18%)	Barsoum et al. (2000b)
Ta_2AlC	28	26	28(100%)	–	26(100%)	–	Hu et al. (2008b)
Cr_2AlC	19	16[c]	10(53%)	9(47%)	12(75%)	4[c](25%)	Tian et al. (2006)
Zr_2SC	≈38	≈30	–	–	–	–	Opeka et al. (2011)
			MX Phases				
TiC_x	33.5	39	–	–	24(62%)	15(38%)	Lengauer et al. (1995)
$TiC_{0.96}$	14.4	33.4	–	–	–	–	Taylor (1961)
$TiN_{0.99}$	27.4	45.3	29.4[d]	–	–	–	Lengauer et al. (1995)
NbC_x	14	–	21[d]	–	–	–	Pierson (1996)

Source: Barsoum, M. W. *MAX Phases: Properties of Machinable Ternary Carbides and Nitrides*. 2013. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

[a] The percent contributions of phonon (κ_{ph}) and electronic (κ_e) to total (κ_{th}) are shown in parentheses.

[b] Assuming $L_0 = 1.5 \times 10^{-8}$ W Ω/K^2.

[c] Extrapolated.

[d] Implies $L_0 < 4.5 \times 10^{-8}$ W Ω/K^2.

TABLE 8.4 Thermal Expansion Coefficients of MAX Phases[a,b]

Phase	α_a (μK^{-1})	α_c (μK^{-1})	α_c/α_a	α_{avg} (μK^{-1})	$\alpha_{dilatometric}$ (μK^{-1})	<γ>[c]	References
				413 Phases			
$Ti_4AlN_{2.9}$	8.3(2)	8.3(9)	1.0	8.3(5)	9.7(2)	1.33	Scabarozi et al. (2009)
	9.6(1)	8.8(1)	0.9	9.4(1)	–	–	Rawn et al. (2000)
Nb_4AlC_3	–	–	–	–	7.2	–	Hu et al. (2008b)
Nb_4AlC_3	–	–	–	–	6.7	–	Hu et al. (2009)
Ta_4AlC_3	–	–	–	–	8.2 ± 0.3	–	Hu et al. (2007)
				312 Phases			
Ti_3SiC_2	8.9(1)	10.0(2)	1.1	9.3(2)	9.1(5)	1.64	Scabarozi et al. (2009)
	8.4(1)	9.3(10)	1.1	8.7(4)	9.1(2)	–	Manoun et al. (2005)
	8.6(1)	9.7(1)	1.1	9.1(2)	9.1(2)	–	Barsoum et al. (1999)
	8.9(1)	9.4(1)	1.1	9.2	–	–	Lane et al. (2010)
Ti_3AlCN	6.0(2)	11.3(2)	1.9	7.8(2)	7.5(5)	–	Scabarozi et al. (2009)
Ti_3GeC_2	8.1(2)	9.7(2)	1.2	8.6(2)	7.8(2)	1.46	Scabarozi et al. (2009)

(*Continued*)

TABLE 8.4 (*Continued*) Thermal Expansion Coefficients of MAX Phases[a,b]

Phase	α_a (μK^{-1})	α_c (μK^{-1})	α_c/α_a	α_{avg} (μK^{-1})	$\alpha_{dilatometric}$ (μK^{-1})	<γ>[c]	References
Ti_3GeC_2	8.5(1)	9.1(1)	1.1	8.7(1)	–	–	Lane et al. (2010)
Ti_3SiGeC_2	8.8(6)	11.1(3)	1.3	9.6(5)	–	–	Scabarozi et al. (2009)
Ti_3AlC_2	8.3(1)	11.1(1)	1.3	9.2(1)	–	1.34	Scabarozi et al. (2009)
					9.0(2)	–	Tzenov and Barsoum (2000)
Ti_3AlC_2	8.5	10.2	1.2	9.2	–	–	Pang et al. (2010)
				211 Phases			
Ti_2AlN	10.6(2)	9.75(2)	0.9	10.3(2)	8.8(2)	1.52	Scabarozi et al. (2009)
	8.6(2)	7.0(5)	0.8	8.1(5)	–	–	Barsoum (2000)
	12.75	11.5	0.9	9.7	–	–	Lane et al. (2011)
	10.0	9.0			–	–	Barsoum et al. (2000a)
Ti_2AlCN	8.4(1)	8.8(1)	1.0	8.5(1)	7.9(5)	–	Scabarozi et al. (2009)
Ti_2AlC	7.1(3)	10.0(5)	1.42	8.1(5)	8.8(2)	–	Barsoum (2000)
	8.6	9.2	1.1	8.8	–	–	Lane et al. (2013)
Ti_2SnC	–	–	–	–	10	–	El-Raghy et al. (2000)
Ti_2GeC	10.3	8.6	0.84	9.7	–	–	N.J. Lane (private communication)
Ti_2InC	–	–	–	–	9.5	–	Barsoum et al. (2002a)
Ti_2SC	8.6(1)	8.7(2)	1.0	8.7(1)	9.3(6)	1.40	Scabarozi et al. (2009)
	8.5(5)	8.8(2)	1.04	8.6(6)	–	–	Kulkarni et al. (2009)
V_2AlC	9.1(2)	10.0(7)	1.1	9.4(10)	9.4(5)	1.44	Scabarozi et al. (2009)
	9.3(5)	9.5(4)	1.0	9.4(5)	–	–	Kulkarni et al. (2009)
V_2GeC	6.9(1)	15.8(3)	2.3	9.9(2)	9.4(6)	1.63	Scabarozi et al. (2009)
V_2AsC	7.2(1)	14.0(1)	1.9	9.5(1)	–	1.69	Scabarozi et al. (2009)
Cr_2GeC	12.9(1)	17.6(2)	1.4	14.5(2)	9.5(5)	2.38	Scabarozi et al. (2009)
	14.3	17.2	1.2	15.3	–	–	Cabioch et al. (2013)
	12.3	14.4	1.2	13.0	–	–	Lane et al. (2011)
Cr_2AlC	12.8(3)	12.1(1)	0.9	12.6(2)	12.8(5)	1.99	Scabarozi et al. (2009)
	13.3	11.7	0.9	12.8	13.3	–	Cabioch et al. (2013)
	–	–	–	–	13	–	Tian et al. (2006)
	–	–	–	–	13	–	Lin et al. (2007b)
	–	–	–	–	13	–	Zhou et al. (2009)
Nb_2AlC	8.8(2)	6.8(3)	0.8	8.1(2)	7.5(2)	1.56	Scabarozi et al. (2009), Barsoum (2000)
				–	8.7(2)	–	Barsoum et al. (2002b), and
				–	8.1	–	Zhang et al. (2009)
Nb_2AsC	2.9(1)	10.6(1)	2.6	5.5(1)	7.3(5)	1.40	Scabarozi et al. (2009)
Nb_2SnC	6.6(4)	14.5(2)	2.2	9.3(3)	7.8(2)	1.72	Scabarozi et al. (2009) and El-Raghy et al. (2000)
Hf_2InC	7.2(1)	7.6(2)	1.0	7.3(2)	7.6(2)	1.07	Scabarozi et al. (2009) and Barsoum et al. (2002a)
Hf_2PbC	–	–	–	–	8.3	–	El-Raghy et al. (2000)
Hf_2SnC	–	–	–	–	8.1	–	El-Raghy et al. (2000)
Ta_2AlC	–	–	–	–	8.0	1.66	Hu et al. (2008b)
Zr_2SnC	–	–	–	–	8.3	–	El-Raghy et al. (2000)

(*Continued*)

TABLE 8.4 (*Continued*) Thermal Expansion Coefficients of MAX Phases[a,b]

Phase	α_a (μK⁻¹)	α_c (μK⁻¹)	α_c/α_a	α_{avg} (μK⁻¹)	$\alpha_{dilatometric}$ (μK⁻¹)	$<\gamma>$[c]	References
Zr_2PbC	–	–	–	–	8.2	–	El-Raghy et al. (2000)
Zr_2SC	–	–	–	–	8.8	–	Opeka et al. (2011)

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[a] Obtained from high-temperature x-ray and neutron diffraction.

[b] Numbers in parentheses are estimated standard deviations for the last significant figure.

[c] Average Grüneisen parameter.

TABLE 8.5 Room Temperature Breaking Stress of MAX Phases

Compound	Grain Size[a] (μm)	Load[b]	σ (MPa)	References
		413 Phases		
$Ti_4AlN_{2.9}$	20D	4-Flex	350 ± 15	Procopio et al. (2000)
$Ti_4AlN_{2.9}$	20D	Comp	475 ± 15	Procopio et al. (2000)
Nb_4AlC_3	50D; 17W	3-Flex	350 ± 40	Hu et al. (2008c)
Nb_4AlC_3	21D; 9W	3-Flex	45 ± 7	Hu et al. (2009)
Nb_4AlC_3	50D; 17W	Comp	500 ± 50	Hu et al. (2008c)
Nb_4AlC_3	50D; 17W	Shear	120 ± 40	Hu et al. (2008c)
Ta_4AlC_3	10D; 3W	3-Flex	370 ± 20	Hu et al. (2007)
Ta_4AlC_3	10D; 3W	Comp	800 ± 100	Hu et al. (2007)
Ta_4AlC_3	10D; 3W	Shear	250 ± 20	Hu et al. (2007)
		312 Phases		
Ti_3SiC_2	≈100D	4-Flex	260 ± 20	Barsoum and El-Raghy (1996)
Ti_3SiC_2	100D	4-Flex	320	El-Raghy et al. (1999)
Ti_3SiC_2	5	4-Flex	600	El-Raghy et al. (1999)
Ti_3SiC_2	10–20D	3-Flex	410 ± 25	Gao et al. (1999)
Ti_3SiC_2	26D; 12W	4-Flex	300	Li et al. (2001)
Ti_3SiC_2	20–50D; 5–8W	3-Flex	390 ± 10	Bao et al. (2004)
$Ti_3Si(Al)C_2$	15 ± 12D; 4 ± 2	3-Flex	460 ± 25	Wan et al. (2008)
$Ti_3Si(Al)C_2$	50 ± 40D; 16 ± 10	3-Flex	306 ± 15	Wan et al. (2008)
Ti_3SiC_2	≈100D	Comp	580 ± 20	Barsoum and El-Raghy (1996)
Ti_3SiC_2	44 ± 40	Comp	710	Barsoum et al. (1997a)
Ti_3SiC_2	100D	Comp	720	El-Raghy et al. (1999)
Ti_3SiC_2	5	Comp	1050	El-Raghy et al. (1999)
Ti_3SiC_2	20–50D; 5–8W	Comp	750 ± 80[c]	Bao et al. (2004)
Ti_3SiC_2	20–50D; 5–8W	Comp	840 ± 80[d]	Bao et al. (2004)
Ti_3SiC_2	20–50D	Comp	935	Zhang and Sun (2005)
Ti_3SiC_2	20–50D; 5–8W	Shear	138 ± 12	Bao et al. (2004)
Ti_3SiC_2	3–5	Tensile	225	Radovic et al. (2000)
Ti_3SiC_2	100–200D	Tensile	200	Radovic et al. (2000)
Ti_3SiC_2	3–5	Tensile	300	Radovic et al. (2000)
Ti_3AlC_2	≈20D	3-Flex	340	Wang and Zhou (2002a)
Ti_3AlC_2	30 ± 10D; 6 ± 2W	3-Flex	320 ± 12	Wan et al. (2008)

(*Continued*)

TABLE 8.5 (*Continued*) Room Temperature Breaking Stress of MAX Phases

Compound	Grain Size[a] (μm)	Load[b]	σ (MPa)	References
Ti_3AlC_2	75 ± 25D; 20 ± 10W	3-Flex	170 ± 13	Wan et al. (2008)
Ti_3AlC_2	20–30	Comp	560 ± 20	Tzenov and Barasoum (2000)
Ti_3AlC_2	10–30D	Comp	760	Wang and Zhou (2002a)
Ti_3AlC_2	60–100D; 10–4W	Comp	545	Bei et al. (2013)
$Ti_3Al_{0.8}Sn_{0.2}C_2$	10–80D; 2–15W	Comp	840	Bei et al. (2013)
Ti_3GeC_2	FG	Comp	1270	Barsoum et al. (1997a)
Ti_3GeC_2	46 ± 25	Comp	467 ± 12	Ganguly et al. (2004)
$Ti_3Ge_{3/4}Si_{1/4}C_2$	70 ± 60	Comp	670 ± 10	Ganguly et al. (2004)
$Ti_3Ge_{1/2}Si_{1/2}C_2$	40 ± 30	Comp	540 ± 10	Ganguly et al. (2004)
Ti_3GeC_2	46 ± 25	Flex	217 ± 4	Ganguly et al. (2004)
$Ti_3Ge_{1/2}Si_{1/2}C_2$	40 ± 30	Flex	254 ± 15	Ganguly et al. (2004)
		211 Phases		
Ti_2AlC	100–200D	Comp	≈390	Barsoum et al. (1997a)
Ti_2AlC	25D	Comp	540	Barsoum et al. (2000a)
Ti_2AlC	75D; 15W	3-Flex	275	Wang and Zhou (2002b)
Ti_2AlN	100–200	Comp	≈470	Barsoum et al. (1997a)
Ti_2AlN	100D	Comp	380 ± 30	Barsoum et al. (2000a)
$Ti_2AlC_{0.5}N_{0.5}$	25D	Comp	800 ± 80	Barsoum et al. (2000a)
Ti_2SC	3–5	Comp	1400	Amini et al. (2007)
Ti_2GeC	–	Comp	≈1750	Barsoum et al. (1997a)
TiNbAlC	15D	4-Flex	350 ± 15	Salama et al. (2002)
TiNbAlC	45D	4-Flex	310 ± 10	Salama et al. (2002)
V_2AlC	49D; 19W	3-Flex	263 ± 23	Hu et al. (2008a)
V_2AlC	108D; 37W	3-Flex	290 ± 6	Hu et al. (2008a)
V_2AlC	119D; 47W	3-Flex	270 ± 12	Hu et al. (2008a)
V_2AlC	405D; 106W	3-Flex	61 ± 15	Hu et al. (2008a)
V_2AlC	49D; 19W	Comp	740 ± 90	Hu et al. (2008a)
V_2AlC	108D; 37W	Comp	600 ± 30	Hu et al. (2008a)
V_2AlC	119D; 47W	Comp	530 ± 12	Hu et al. (2008a)
V_2AlC	405D; 106W	Comp	390 ± 16	Hu et al. (2008a)
Cr_2AlC	≈40D; 10W	3-Flex	378	Tian et al. (2006)
Cr_2AlC	5	3-Flex	480 ± 30	Tian et al. (2007)
Cr_2AlC	5.5 ± 3	4-Flex	555 ± 11	Tian et al. (2009)
Cr_2AlC	10	3-Flex	500	Zhou et al. (2009)
Cr_2AlC	2	3-Flex	510 ± 15	Li et al. (2011)
Cr_2AlC	35	3-Flex	310 ± 10	Li et al. (2011)
Cr_2AlC	10–40	3-Flex	470 ± 30	Ying et al. (2011b)
Cr_2AlC	5	Comp	1160 ± 25	Tian et al. (2007)
Cr_2AlC	10–40	Comp	950 ± 25	Ying et al. (2011b)
Cr_2AlC	10	Comp	630	Zhou et al. (2009)
Cr_2GeC	20 ± 10D; 10 ± 5W	Comp	770	Amini et al. (2008)
Nb_2AlC	15D	4-Flex	415 ± 20	Salama et al. (2002)
Nb_2AlC	17D	3-Flex	480 ± 40	Zhang et al. (2009)
Nb_2AlC	17D	4-Flex	440 ± 30	Zhang et al. (2009)
Zr_2SC	10	3-Flex	275 ± 10	Opeka et al. (2011)

(*Continued*)

TABLE 8.5 (*Continued*) Room Temperature Breaking Stress of MAX Phases

Compound	Grain Size[a] (μm)	Load[b]	σ (MPa)	References
Ta_2AlC	15D; 3W	3-Flex	360 ± 20	Hu et al. (2008b)
Ta_2AlC	15D; 3W	Comp	800	Hu et al. (2008b)
Ta_2AlC	15D; 3W	Shear	110 ± 25	Hu et al. (2008b)

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[a] D = grain diameter and W = grain width; FG = fine grained.

[b] Flex = Bending test (generally 3- or 4-point bending); Comp = Compression test.

[c] Load parallel to hot pressing direction.

[d] Load normal to hot pressing direction.

TABLE 8.6 Room Temperature Fracture Toughness of MAX Phases

Sample	Test[a]	Grain Size[b] (μm)	Fracture Toughness, K_{Ic} (MPa · $m^{1/2}$)	References
		413 Phases		
Nb_4AlC_3	SENB[c]	50D; 17W	7.4	Hu et al. (2008c)
Nb_4AlC_3	SENB[c]	–	12 ± 2–18 ± 5	Hu et al. (2011a)
β-Ta_4AlC_3	SENB[c]	10D; 3W	7.7	Hu et al. (2007)
		312 Phases		
Ti_3SiC_2	SENB	–	6.0	El-Raghy et al. (1997)
Ti_3SiC_2	CT	CG	16 (R-curve)[e]	Gilbert et al. (2000)
(2 vol% SiC)		FG	9.5 (R-curve)[e]	
Ti_3SiC_2 (<3 vol% TiC)	SENB[d]	FG	4.5 ± 0.1	Li et al. (2001)
Ti_3SiC_2	SENB	10	6.2	Wang et al. (2002)
Ti_3SiC_2	SENB[d]	–	6.2 ± 3.0	Bao and Zhou (2005)
(7 wt% TiC)	CNB[d]	–	6.6 ± 0.1	
	SENB[c]	–	6.6 ± 0.1	
Ti_3SiC_2 (TiC)	SENB[c]	–	7.2	Li et al. (2002)
$Ti_3Si(Al)C_2$	SENB[d]	16D; 4W	6.2	Zhou et al. (2006)
$Ti_3Si(Al)C_2$	CNB[d]	15D; 4W	6.4	Wan et al. (2008)
		50D; 16W	6.8	
Ti_3AlC_2	SENB[c]	–	7.2	Wang and Zhou (2002a)
Ti_3AlC_2	CNB[d]	28D; 6W	7.8 ± 0.1	Wan et al. (2008)
		80D; 20W	9.5 ± 0.1	
Ti_3AlC_2 (TiC)	SENB[c]	–	4.6 ± 0.3	Peng (2007)
		211 Phases		
Ti_2AlC	SENB[c]	CG	6.5	Wang and Zhou (2002b)
V_2AlC	SENB[c]	(≈100D; 40W)	5.7	Hu et al. (2008a)
Cr_2AlC	SENB[c]	10	5.8	Zhou et al. (2009)
Cr_2AlC	SENB[c]	10–40	6.2 ± 0.3	Ying et al. (2011b)
Cr_2AlC	SENB[c]	(CG; 35 μm)	6.2	Li et al. (2002)
		(FG; 2 μm)	4.7	

(*Continued*)

TABLE 8.6 (*Continued*) Room Temperature Fracture Toughness of MAX Phases

Sample	Test[a]	Grain Size[b] (μm)	Fracture Toughness, K_{Ic} (MPa $m^{1/2}$)	References
Cr_2AlC	SENB[c]	30	6.2	Yu et al. (2010)
$Cr_2(Al_{0.96},Si_{0.13})C$	SENB[c]	50	6.6	Yu et al. (2010)
Nb_2AlC	SENB[c]	17	5.9	Zhang et al. (2009)
Ta_2AlC	SENB[c]	15D; 3W	7.7	Hu et al. (2008b)

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[a] SENB = single-edged notched beam; CNB = chevron notched beam; CT = compact tension.

[b] D = grain diameter and W = grain width; CG = coarse grained; FG = fine grained.

[c] Three-point bend bars.

[d] Four-point bend bars.

[e] Test using the crack resistance curve (R-curve).

TABLE 8.7 Electrical Resistivity, Residual-Resistivity Ratio, and Temperature Coefficient of Resistivity of MAX Phases

Phases	T (K)	ρ (μΩ m)	RRR	αT_{CR} $(K)^{-1}$	d_ρ/d_T[a] (μΩ m/K)	References
			413 Phases			
Ti_4AlN_3	300	2.64	1.1	0.00034	0.0009	Barsoum et al. (2000d)
	4	2.35				
α-Ta_4AlC_3	273	0.354	6.0	0.0035	0.0012	Hu et al. (2007)
	4	0.064				
Nb_4AlC_3	300	0.75	2.5	0.0025	0.00175	Hu et al. (2008c)
	4	0.30				
Nb_4AlC_3	273	0.44	–	0.0030	–	Hu et al. (2009)
			312 Phases			
Ti_3SiC_2	300	0.23	–	0.0033	0.00075	Barsoum et al. (2000e)
	4	–				
Ti_3SiC_2	300	0.23	7.7	0.0028	0.00071	Finkel et al. (2001)
	4	≈0.03				
Ti_3AlC_2	300	0.353	1.95	0.00345	0.00078	Scabarozi et al. (2008c)
	4	0.18				
	300	0.287	3.2	0.0035	0.00083	Wang and Zhou (2002a)
	4	0.09				
Ti_3GeC_2	300	0.28	5.6	0.0032	0.0009	Finkel et al. (2004)
	4	0.05				
$Ti_3(Si, Ge)C_2$	300	0.27	3.1	0.0028	0.00075	Finkel et al. (2004)
	4	0.084				
Ti_3AlCN	300	0.40	1.5	0.0014	0.00064	Scabarozi et al. (2008c)
	4	0.27				
			211 Phases			
Ti_2AlC	300	0.32	4.8	0.0033	0.0011	Scabarozi et al. (2008c)
	4	0.067				

(*Continued*)

TABLE 8.7 (*Continued*) Electrical Resistivity, Residual-Resistivity Ratio, and Temperature Coefficient of Resistivity of MAX Phases

Phases	*T* (K)	ρ (μΩ m)	RRR	αT_{CR} $(K)^{-1}$	d_ρ/d_T[a] (μΩ m/K)	References
Ti_2AlC	300	0.23	2.9	0.0029	0.00067	Wang and Zhou (2002a)
	4	0.08 (estimate)				
Ti_2AlC	300	0.39	2.2	0.0023	0.0009	Wang et al. (2007)
	4	0.18 (estimate)				
$Ti_2AlC_{0.5}N_{0.5}$	300	0.43	1.5	0.0027	0.0012	Scabarozi et al. (2008c)
	4	0.167				
Ti_2AlN-a	300	0.25	8.6	0.0039	0.0010	Scabarozi et al. (2008c)
	4	0.029				
Ti_2GeC	300	0.30	3.2	0.0028	0.00084	Scabarozi et al. (2008b)
	4	0.094				
Ti_2AlN-b	300	0.343	2.8	0.0026	0.0009	Scabarozi et al. (2008c)
	4	0.123				
TiNbAlC	300	0.78	1.3	0.0019	0.00078	Barsoum et al. (2002b)
	4	0.6				
Ti_2SC	300	0.52	2.3	0.0027	0.0014	Scabarozi et al. (2008a)
	4	0.23				
Ti_2InC	300	0.2	4	0.0030	0.0006	Barsoum et al. (2002a)
	4	0.05				
TiHfInC	300	0.27	3.4	0.0026	0.0007	Barsoum et al. (2002a)
	4	0.08				
Cr_2GeC	300	0.72	11.2	0.0027	0.0027	Barsoum et al. (2011)
	4	0.064				
Cr_2AlC	300	0.74	4.9	0.0036	0.0027	Hettinger et al. (2005)
	4	0.15				
Cr_2AlC	300	0.6	2.0	0.0024	0.0014	Ying et al. (2011a)
	4	0.3 (estimate)				
Cr_2AlC	300	0.625	–	–	–	Zhou et al. (2009)
Cr_2AlC	300	0.72	2.2	0.0028	0.0020	Tian et al. (2006)
	4	0.32				
V_2AlC	300	0.25	6.4	0.004	0.0010	Hettinger et al. (2005)
	4	0.04				
V_2AsC	300	1.3	16.5	0.004	0.0053	Lofland et al. (2006)
	4	0.08				
V_2GeC	300	0.36	22.5	0.004	0.0014	Scabarozi et al. (unpublished)
	4	0.016				
Hf_2InC	300	0.19	8.3	0.0033	0.00063	Barsoum et al. (2002a)
	4	0.023				
Hf_2InC	300	0.55	2.75	0.0023	0.0013	Lofland et al. (2006)
	4	0.2				
Ta_2AlC	273	0.23	8.8	0.0042	0.00097	Hu et al. (2008b)
	4	0.026				

(*Continued*)

TABLE 8.7 (*Continued*) Electrical Resistivity, Residual-Resistivity Ratio, and Temperature Coefficient of Resistivity of MAX Phases

Phases	*T* (K)	ρ (μΩ m)	RRR	αT_{CR} (K)$^{-1}$	d_ρ/d_T[a] (μΩ m/K)	References
Nb_2AlC	300	0.29	2.6	0.0024	0.0007	Hettinger et al. (2005)
	4	0.14				
Nb_2SnC	300	0.58	1.93	0.0018	0.001	Lofland et al. (2006)
	4	0.30				
Nb_2AsC	300	1.3	18.6	–	0.0052	Lofland et al. (2006)
	4	0.07				

Source: Barsoum, M. W. *MAX Phases: Properties of Machinable Ternary Carbides and Nitrides*. 2013. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

[a] $d_\rho/d_T = \rho_{ref} \times \alpha_{TCR}$.

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TABLE 8.8 Environmental Stability of MAX Phases

Compound	T_{max}[a] (°C)	Time[a] (h)	HF[b] (conc %)	Time[b] (h)	References
			413 Phase		
Ta_4AlC_3	–	–	50	72	Naguib et al. (2012)
			312 Phases		
Ti_3AlC_2	–	–	50	2	Naguib et al. (2012)
Ti_3AlCN	–	–	30	18	Naguib et al. (2012)
$(V_{0.5},Cr_{0.5})_3AlC_2$	–	–	50	69	Naguib et al. (2012)
Ti_3SiC_2	900	10	–	–	Barsoum et al. (1997b)
Ti_3SiC_2–30 vol% SiC	925	500	–	–	Barsoum et al. (2003)
Ti_3GeC_2	700	36	–	–	Gupta et al. (2006b)
			211 Phases		
Ti_2AlC	1400	25	–	–	Byeon et al. (2007)
Ti_2AlC	1300	100	–	–	Basu et al. (2012)
Ti_2AlC	1200	3000	–	–	Tallman et al. (2012)
Ti_2AlC	–	–	10	10	Naguib et al. (2012)
$(Ti_{0.5},Nb_{0.5})_2AlC$	–	–	50	28	Naguib et al. (2012)
V_2AlC	600	24	–	–	Gupta and Barsoum (2004)
Cr_2AlC	1300	24	–	–	Lin et al. (2007a)
Nb_2AlC	650	15	–	–	Salama et al. (2003)
TiNbAlC	900	65	–	–	Salama et al. (2003)
Ti_2SC	500	300	–	–	Amini et al. (2009)
Ta_2AlC	600	100	–	–	Gupta et al. (2006a)

[a] T_{max} is the temperature to which MAX phases can be heated in air and for which the kinetics is slower than parabolic.

[b] Conditions needed to exfoliate MAX powders by immersion.

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9

Amorphous Metals

Physical Properties

TABLE 9.1 Mechanical Properties[a] of Metallic Glasses

Material	E (GPa)	Strain Rate (s^{-1})	σ_y (MPa)	σ_f (MPa)	ε_y(%)	ε_p(%)	Ref.
$Co_{43}Fe_{20}Ta_{5.5}B_{31.5}$	268	5×10^{-4}		5185	2		(1)
$Cu_{60}Hf_{40}$	120	5×10^{-4}		2245		0.4	(2)
$Cu_{60}Hf_{25}Ti_{15}$	124	5×10^{-4}	2024	2088		1.6	(3)
$(Cu_{60}Hf_{25}Ti_{15})_{96}Nb_4$	130	5×10^{-4}		2405		2.8	(4)
$Cu_{47}Ti_{33}Zr_{11}Ni_6Sn_2Si_1$			1930	2250			(5)
$Cu_{50}Zr_{50}$	84	8×10^{-4}	1272	1794	1.7	6.2	(6)
$Cu_{50}Zr_{50}$	107	5×10^{-4}		1920		0.2	(2)
$Cu_{64}Zr_{36}$	92.3	8×10^{-4}		2000	2.2		(7)
$Cu_{47.5}Zr_{47.5}Al_5$	87	8×10^{-4}	1547	2265	2.0	16	(6)
$Fe_{65}Mo_{14}C_{15}B_6$	195	1×10^{-4}	3400	3800		0.6	(8)
$Fe_{59}Cr_6Mo_{14}C_{15}B_6$	204	1×10^{-4}	3800	4400		0.8	(8)
$(Fe_{0.9}Co_{0.1})_{64.5}Mo_{14}C_{15}B_6Er_{0.5}$	192	1×10^{-4}	3700	4100		0.55	(8)
$Fe_{71}Nb_6B_{23}$		1×10^{-4}		4850		1.6	(9)
$Fe_{72}Si_4B_{20}Nb_4$	200			4200	2.1	1.9	(10)
$Fe_{74}Mo_6P_{10}C_{7.5}B_{2.5}$		2.1×10^{-4}	3330	3400		2.2	(11)
$[(Fe_{0.6}Co_{0.4})_{0.75}B_{0.2}Si_{0.05}]_{96}Nb_4$	210	6×10^{-4}	4100	4250	2	2.25	(12)
$Fe_{49}Cr_{15}Mo_{14}C_{15}B_6Er_1$	220	4×10^{-4}	3750	4140		0.25	(13)
$Gd_{60}Co_{15}Al_{25}$	70	5×10^{-4}		1380		1.97	(14)
$Gd_{60}Ni_{15}Al_{25}$	64	5×10^{-4}		1280		2.01	(14)
$Mg_{75}Cu_{15}Gd_{10}$	50	5×10^{-4}		743	1.5	0	(15)
$Mg_{75}Cu_5Ni_{10}Gd_{10}$	54	5×10^{-4}		874	1.55	0.2	(15)
$Mg_{65}Cu_{7.5}Ni_{7.5}Zn_5Ag_5Y_{10}$	39	1×10^{-4}		490–650	1.7	0	(16)
$Ni_{61}Zr_{28}Nb_7A_{14}$		1×10^{-4}		2620			(17)
$Ni_{61}Zr_{22}Nb_7Al_4Ta_6$		1×10^{-4}		3080		5	(17)

(*Continued*)

TABLE 9.1 (*Continued*) Mechanical Properties[a] of Metallic Glasses

Material	*E* (GPa)	Strain Rate (s^{-1})	σ_y (MPa)	σ_f (MPa)	ε_y(%)	ε_p(%)	Ref.
$Pd_{77.5}Cu_6Si_{16.5}$		4×10^{-4}	1476	1600		11.4	(18)
$Pd_{79}Cu_6Si_{10}P_5$	82	4.2×10^{-4}	1475	1575		3.5	(19)
$Pd_{40}Ni_{40}P_{20}$	96	1×10^{-4}	1700				(20)
$Pt_{57.5}Cu_{14.7}Ni_{5.3}P_{22.5}$		1×10^{-4}	1400	1470	2	20	(21)
$Ti_{41.5}Zr_{2.5}Hf_5Cu_{42.5}Ni_{7.5}Si_1$	103	3×10^{-4}		2080			(22)
$Ti_{41.5}Zr_{2.5}Hf_5Cu_{42.5}Ni_{7.5}Si_1$	95	3×10^{-4}		2040		0	(22)
$Zr_{55}Cu_{30}Al_{10}Ni_5$			1410	1420			(23)
$Zr_{41.25}Ti_{13.75}Cu_{12.5}Ni_{10}Be_{22.5}$	96		1900	1900	2		(24)
$Zr_{57}Nb_5Al_{10}Cu_{15.4}Ni_{12.6}$	86.7		1800	1800	2		(25)

Source: Data from Suryanarayana, C. and Inoue, A. *Bulk Metallic Glasses*, CRC Press, Boca Raton, FL, 2010. With permission.

References: (1) Inoue et al. (2003), (2) Inoue and Zhang (2004), (3) Qin et al. (2006), (4) Qin et al. (2005), (5) Fu et al. (2005), (6) Das et al. (2005), (7) Xu et al. (2004), (8) Gu et al. (2007b), (9) Yao et al. (2008), (10) Amiya et al. (2004), (11) Liu et al. (2008), (12) Inoue et al. (2004a), (13) Gu et al. (2007a), (14) Chen, D. et al. (2007), (15) Yuan et al. (2005), (16) Xu et al. (2005), (17) Na et al. (2006), (18) Yao et al. (2007), (19) Liu, L. et al. (2005), (20) Wright et al. (2001), (21) Schroers and Johnson (2001), (22) Ma et al. (2004), (23) Xie et al. (2007), (24) Conner et al. (1998), (25) Choi-Yim, et al. (2002).

[a] *E*: Young's modulus, σ_y: yield strength, σ_f: fracture strength, ε_y: strain at yielding, ε_p: plastic strain. (All tests were conducted under compression.)

TABLE 9.2 Fatigue Limits and Fatigue Ratios of Bulk Metallic Glasses under Bending, Uniaxial, and Rotating Loads

Material	Fracture Strength[a] (MPa)	Geometry (mm)	Loading Mode[b]	Frequency (Hz)	R^c Ratio	Fatigue Limit (MPa)	Fatigue Ratio[d]	Ref.
			Bending Loads					
$Cu_{47.5}Zr_{47.5}Al_5$		3 × 3 × 25	4PB	10	0.1	224	0.12	(1)
$Cu_{47.5}Zr_{38}Hf_{9.5}Al_5$ (Composite)		3 × 3 × 25	4PB	10	0.1	378	0.23	(1)
$(Cu_{60}Zr_{30}Ti_{10})_{99}Sn_1$	1800	2.85 × 2.85 × 25	4PB	10	0.1	350	0.19	(2)
$(Cu_{60}Zr_{30}Ti_{10})_{99}Sn_1$			3PB	10	0.1	475	0.26	(2)
$Fe_{48}Cr_{15}Mo_{14}Er_2C_{15}B_6$	4000–4400	2.85 × 2.85 × 25	4PB	10	0.1	682	0.17	(3)
$Zr_{39.6}Ti_{33.9}Nb_{7.6}Cu_{6.4}Be_{12.5}$ (Composite)	1210	3 × 3 × 50	4PB	25	0.1	340	0.28	(4)
$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$	1900 (YS)[a]	3 × 3 × 50	4PB	25	0.1	76	0.04	(5,6)
$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$	1900 (UTS)[b]	3 × 3 × 40	4PB	5	0.1		0.05	(7)
$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$	1900 (UTS)	2 × 2 × 60	3PB	20	0.1	359	0.09	(8)
$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$	1900 (UTS)	2 × 2 × 60	3PB	20	0.1	768	0.2	(8)
$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$	1900 (YS)	7 × 38	C–T					(5)
$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (Liquid metal)	1900 (UTS)	2 × 2 × 60	3PB	20	0.1	359	0.09	(8)
$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (Howmet)	1900 (UTS)	2 × 2 × 60	3PB	20	0.1	768	0.2	(8)
$Zr_{44}Ti_{11}Ni_{10}Cu_{10}Be_{25}$	1900 (UTS)	2.3 × 2.0 × 85	4PB	5–20	0.3	195 (stress relief)	0.17	(9)
$Zr_{44}Ti_{11}Ni_{10}Cu_{10}Be_{25}$	1900 (UTS)	2.3 × 2.0 × 85	4PB	5–20	0.3	275 (10τ) Less free vol		(9)
$(Zr_{58}Ni_{13.6}Cu_{18}Al_{10.4})_{99}Nb_1$	1700 (UTS)	2 × 2 × 25	4PB	10	0.1	559	0.33	(10)
$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10.0}Ti_{5.0}$	1700 (UTS)	3.5 × 3.5 × 30	4PB	10	0.1	425	0.25	(11)
$Zr_{47}Ti_{12.9}Nb_{2.8}Cu_{11}Ni_{9.6}Be_{16.7}$ + 25 vol% $Zr_{71}Ti_{16.3}Nb_{10}Cu_{1.8}Ni_{0.9}$	1480	2.1–2.9 × 30	C–T	25	0.1	148	0.1	(12)
$Zr_{55}Cu_{30}Ni_5Al_{10}$	1560 (UTS)	2 × 20 × 50	Plate bend	40	0.1	410	0.26	(13)
$Zr_{39.6}Ti_{33.9}Nb_{7.6}Cu_{6.4}Be_{12.5}$ (Composite)	1210	3 × 3 × 50	4PB	25	0.1	340	0.28	(4)

(Continued)

TABLE 9.2 (*Continued*) Fatigue Limits and Fatigue Ratios of Bulk Metallic Glasses under Bending, Uniaxial, and Rotating Loads

Material	Fracture Strength[a] (MPa)	Geometry (mm)	Loading Mode[b]	Frequency (Hz)	R^c Ratio	Fatigue Limit (MPa)	Fatigue Ratio[d]	Ref.
			Uniaxial Loading					
$Cu_{60}Hf_{25}Ti_{15}$	2130			5–10	0.1	860	0.4	(14)
$Cu_{60}Zr_{30}Ti_{10}$	2000			5–10	0.1	980	0.49	(14)
$Ti_{41.5}Zr_{2.5}Hf_5Cu_{42.5}Ni_{7.5}Si_1$ (NC Comp)	2040			5–10	0.1	1610	0.79	(14)
$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$	1850 (UTS)		T–T	10	0.1	703 (batch 59)	0.38	(15)
$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$	1850 (UTS)		T–T	10	0.1	615 (batch 94)	0.33	(15)
$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$+ $Zr_{47}Ti_{12.9}Nb_{2.8}Cu11Ni_{9.6}Be_{16.7}$ (Composite)								(16)
$Zr_{44}Ti_{11}Ni_{10}Cu_{10}Be_{25}$	1900 (UTS)	2.3 × 25.4	C–T		0.1			(9)
$Zr_{50}Cu_{40}Al_{10}$	1820 (UTS)		T–T	10	0.1	752	0.41	(17)
$Zr_{50}Cu_{40}Al_{10}$						752	0.41	(18)
$Zr_{50}Cu_{30}Ni_{10}Al_{10}$						865	0.46	(18)
$Zr_{50}Cu_{30}Ni_{10}Al_{10}$	1900 (UTS)		T–T	10	0.1	865	0.46	(17)
$Zr_{50}Cu_{37}Al_{10}Pd_3$	1900 (YS)	5.33 × 10.66	C–C	10	0.1			(19)
								(19)
$Zr_{50}Cu_{37}Al_{10}Pd_3$			T–T					
$Zr_{50}Cu_{37}Al_{10}Pd_3$	1900 (UTS)		T–T	10	0.1	983	0.52	(17)
$Zr_{55}Cu_{30}Ni_5Al_{10}$ (A)		5.4 × 3.8 × 20	SENB	57	0.33			(20)
$Zr_{55}Cu_{30}Ni_5Al_{10}$ (B)			SENB	25	0.33			(20)
$Zr_{55}Cu_{30}Ni_5Al_{10}$ (C)		$B = 3.2; W = 15$	C–T					(20)

(*Continued*)

TABLE 9.2 (*Continued*) Fatigue Limits and Fatigue Ratios of Bulk Metallic Glasses under Bending, Uniaxial, and Rotating Loads

Material	Fracture Strength[a] (MPa)	Geometry (mm)	Loading Mode[b]	Frequency (Hz)	R^c Ratio	Fatigue Limit (MPa)	Fatigue Ratio[d]	Ref.
$Zr_{59}Cu_{20}Al_{10}Ni_8Ti_3$	1580	6 × 3 × 1.5	T–T	1	0.1	No fatigue limit	1	(21)
$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10.0}Ti_{5.0}$	1700 (UTS)		Uniaxial	10	0.1	907 (in air)	0.53	(22)
$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10.0}Ti_{5.0}$			Uniaxial	10	0.1	907 (in air)	0.53	(23)
			Rotating Beam					
$Pd_{40}Cu_{30}Ni_{10}P_{20}$	1700	Ø4	R	60	–1	340	0.2	(24)
$Zr_{50}Cu_{40}Al_{10}$	1820 (UTS)	Ø4	R	50	–1	250		(25)
$Zr_{50}Cu_{30}Ni_{10}Al_{10}$	1900 (UTS)	Ø4	R	50	–1	500		(25)
$Zr_{50}Cu_{40}Al_{10}$		Ø4	R	50	–1	250		(26)
$Zr_{50}Cu_{39}Al_{10}Pd_1$	1910	Ø4	R	50	–1	650		(26)
$Zr_{50}Cu_{38}Al_{10}Pd_2$	1910	Ø4	R	50	–1	700		(26)
$Zr_{50}Cu_{37}Al_{10}Pd_3$	1900	Ø4	R	50	–1	1050		(26)
$Zr_{50}Cu_{35}Al_{10}Pd_5$	1930	Ø4	R	50	–1	800		(26)
$Zr_{50}Cu_{33}Al_{10}Pd_7$	1950	Ø4	R	50	–1	550		(26)

Source: Data from Suryanarayana, C. and Inoue, A. *Bulk Metallic Glasses*, CRC Press, Boca Raton, FL, 2010. With permission.

References: (1) Qiao et al. (2007a), (2) Freels et al. (2007), (3) Qiao et al. (2007c), (4) Launey et al. (2009), (5) Gilbert et al. (1998), (6) Gilbert et al. (1999), (7) Menzel and Dauskardt (2006), (8) Launey et al. (2006), (9) Launey et al. (2008), (10) Qiao et al. (2006), (11) Morrison et al. (2007), (12) Flores et al. (2003), (13) Nakai and Hosomi (2007), (14) Fujita et al. (2008), (15) Wang et al. (2005), (16) Wang et al. (2006), (17) Wang et al. (2007), (18) Wang et al. (2004), (19) Qiao et al. (2007b), (20) Keryvin et al. (2007), (21) Zhang et al. (2003), (22) Peter et al. (2002), (23) Peter et al. (2003), (24) Yokoyama et al. (1999), (25) Yokoyama et al. (2004), (26) Yokoyama et al. (2006).

[a] YS: yield strength and UTS: ultimate tensile strength.

[b] 4PB: four-point bend test, 3PB: three-point bend test, C–T: compact–tension specimen, SENB: single edge-notched beam, R: rotating beam, T–T: tensile–tensile, C–C: compressive–compressive.

[c] R ratio = $\sigma_{min}/\sigma_{max}$.

[d] Fatigue ratio = fatigue limit/fracture strength.

TABLE 9.3 Effect of Strain Rate on the Fracture Strength of Metallic Glass Alloys

Material	Specimen Shape	Loading Mode[a]	Strain Rate Range (s^{-1})	Effect on Fracture Strength	Ref.
$Ce_{60}Al_{15}Cu_{10}Ni_{15}$	2 mm dia rods	N	0.03–1 mN	Increases	(1)
Dy_3Al_2	20 µm thick ribbons	T	10^{-4} to 10^{-1}	Decreases	(2)
$Nd_{60}Fe_{20}Co_{10}Al_{10}$	5 mm dia rods	C	6×10^{-4} to 1×10^3	Increases	(3)
$Pd_{40}Ni_{40}P_{20}$	5 mm dia rods	C	3.3×10^{-5} to 2×10^3	Decreases	(4)
$Pd_{80}Si_{20}$	Ribbons	T	10^{-4} to 10^{-2}	No change	(5)
$Ti_{40}Zr_{25}Ni_8Cu_9Be_{18}$	1 and 3 mm dia rods	C	10^{-4} to 10^3	Increases	(6)
$Ti_{45}Zr_{16}Ni_9Cu_{10}Be_{20}$	1 mm dia rods	C	10^{-4} to 10^{-1}	Increases	(7)
$Zr_{41.25}Ti_{13.75}Cu_{12.5}Ni_{10}Be_{22.5}$ (Vit 1)	2.5 mm dia rods		10^2 to 10^4	No change	(8)
$Zr_{41.25}Ti_{13.75}Cu_{12.5}Ni_{10}Be_{22.5}$ (Vit 1)	3.8–6.25 mm dia rods	C	10^{-3} to 10^3	No change	(9)
$Zr_{57}Ti_5Cu_{20}Ni_8Al_{10}$	3 mm dia rods	C	1×10^{-4} to 3×10^3	Decreases	(10)
$Zr_{60}Ti_{14.7}Nb_{5.3}Cu_{5.6}Ni_{4.4}Be_{10}$	3 mm dia rods	C	2×10^{-4} to 3.7×10^2	Increases	(11)
$Zr_{65}Al_{10}Ni_{10}Cu_{15}$	20 µm thick ribbons	C	5×10^{-4} to 10^0	Increases	(12)
$Zr_{65}Al_{10}Ni_{10}Cu_{15}$	20 µm thick ribbons	T	1.67×10^{-4} to 5×10^{-1}	Increases	(13)

Source: Data from Suryanarayana, C. and Inoue, A. *Bulk Metallic Glasses*, CRC Press, Boca Raton, FL, 2010. With permission.

References: (1) Wei et al. (2007), (2) Sergueeva et al. (2004), (3) Liu, L.F. et al. (2005), (4) Mukai et al. (2002), (5) Maddin and Masumoto (1972), (6) Ma et al. (2009), (7) Zhang, J. et al. (2007), (8) Bruck et al. (1996), (9) Ghatu et al. (2002), (10) Hufnagel et al. (2002), (11) Qiao et al. (2009), (12) Kawamura et al. (1996), (13) Kawamura et al. (1997).

[a] N: nanoindentation, T: tension, C: compression.

TABLE 9.4 Mechanical Properties[a] of Bulk Metallic Glasses and their Composites

Alloy	Reinforcement	Reinforcement Size (µm)	V_r^b (%)	σ_f (MPa)	ε_p (%)	Ref.
$Cu_{60}Hf_{25}Ti_{15}$	Fully glassy	–	–	2088	1.6	(1)
$(Cu_{60}Hf_{25}Ti_{15})_{90}Nb_{10}$	Nb-rich SS dendrites	5–10	8	2232	14.1	(1)
$Cu_{50}Hf_{35}Ti_{10}Ag_5$	Fully glassy	–	–	2180	2.1[c]	(2)
$(Cu_{50}Hf_{35}Ti_{10}Ag_5)_{97}Ta_3$	Dendrites	30–40	4	2510	9.75[c]	(2)
$(Cu_{50}Hf_{35}Ti_{10}Ag_5)_{92}Ta_8$	Dendrites	18–23	17	2770	19.2[c]	(2)
$Cu_{60}Zr_{30}Ti_{10}$	Fully glassy	–	–	2080	3.3[c]	(3)
$(Cu_{60}Zr_{30}Ti_{10})_{95}Ta_5$	Ta(Ti, Zr) solid solution	3–20	9.2	2320	14.5[c]	(3)
$[(Fe_{0.5}Co_{0.5})_{0.75}B_{0.2}Si_{0.05}]_{96}Nb_4$	Fully glassy	–	–	3700	0	(4)
$\{[(Fe_{0.5}Co_{0.5})_{0.75}B_{0.2}Si_{0.05}]_{96}Nb_4\}_{99.75}Cu_{0.25}$	α-(Fe, Co) + $(Fe, Co)_{23}B_6$	3	13.6	4050	0.6	(4)
$La_{62}Al_{14}(Cu,Ni)_{24}$	–	–	–	561	0	(5)
$La_{72}Al_{14}(Cu,Ni)_{14}$	α-La dendrites	4–12	41	529	0.9	(5)
$La_{74}Al_{14}(Cu,Ni)_{12}$	α-La dendrites	4–12	50	521	4.1	(5)
$La_{85}Al_{14}(Cu,Ni)_1$	α-La dendrites	4–12	53	434	6	(5)
$Mg_{65}Cu_{20}Ag_5Gd_{10}$	Fully glassy	–	–	830	0	(6)
$Mg_{65}Cu_{20}Ag_5Gd_{10}$ + Nb	Nb	20–50	8	–	12.1	(6)
$Ni_{60.25}Nb_{39.75}$	Glass + nanocrystals	10–15	–	–	5.3	(7)
$Ti_{50}Cu_{25}Ni_{15}Sn_5Ta_5$	Nanocrystals	–	–	–	–	(8)
$Ti_{45}Zr_5Cu_{44}Ni_5Ta_1$	β-Ti phase + Ti_2Ni	–	–	–	3	(8)
$Zr_{50}Cu_{40}Al_{10}$	Fully glassy	–	–	1890	0.7	(9)

(*Continued*)

TABLE 9.4 (*Continued*) Mechanical Properties[a] of Bulk Metallic Glasses and their Composites

Alloy	Reinforcement	Reinforcement Size (μm)	V_r[b] (%)	σ_f (MPa)	ε_p (%)	Ref.
$(Zr_{50}Cu_{40}Al_{10})_{91}Ta_9$	Ta	–	–	2180	15.9	(9)
$Zr_{48}Cu_{36}Al_8Ag_8$	–	–	–	1885	–	(10)
$Zr_{48}Cu_{36}Al_8Ag_8$	Ta	40	10	2600	31[c]	(10)
$Zr_{57}Nb_5Al_{10}Cu_{15.4}Ni_{12.6}$	Mo wires	250	80	–	20	(11)
$Zr_{57}Nb_5Al_{10}Cu_{15.4}Ni_{12.6}$	Ta wires	250	80	–	27	(11)
$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$	–	–	–	–	3	(12)
$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$	Graphite	25–44	10	–	15	(12)
$Zr_{41.25}Ti_{13.75}Cu_{12.5}Ni_{10}Be_{22.5}$	–	–	–	–	<0.5%	(13)
$Zr_{41.25}Ti_{13.75}Cu_{12.5}Ni_{10}Be_{22.5}$	W	–	20	–	16%	(13)
$Zr_{56.2}Ti_{13.8}Nb_5Cu_{6.9}Ni_{5.6}Be_{12.5}$	β-Zr(Ti, Nb) dendrites	–	–	–	8.26[c]	(14)
$Zr_{56.2}Ti_{13.8}Nb_5Cu_{6.9}Ni_{5.6}Be_{12.5}$	β-Zr(Ti, Nb) dendrites	20–50 μm length × 1–3 μm diameter	–	1757	8.82	(15)
$Zr_{56.2}Ti_{13.8}Nb_5Cu_{6.9}Ni_{5.6}Be_{12.5}$	β-Zr(Ti, Nb) spherical	18 μm	–	1800	12	(15)
$Zr_{38}Ti_{17}Cu_{10.5}Co_{12}Be_{22.5}$	Fully glassy	–	–	1942	2.4	(16)
$Zr_{38}Ti_{17}Cu_{10.5}Co_{12}Be_{22.5}$	W	As-cast	80	1852	82	(16)
$Zr_{38}Ti_{17}Cu_{10.5}Co_{12}Be_{22.5}$	W	As-extruded	80	2112	53	(16)
$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$	Fully glassy	–	–	–	3	(17)
$Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$	Graphite	25–44	10	–	15	(17)
$Zr_{36.6}Ti_{31.4}Nb_7Cu_{5.9}Be_{19.1}$	–	–	42	–	7.6	(18)
$Zr_{38.3}Ti_{32.9}Nb_{7.3}Cu_{6.2}Be_{15.3}$	–	–	51	–	8.9	(18)
$Zr_{39.6}Ti_{33.9}Nb_{7.6}Cu_{6.4}Be_{12.5}$	–	–	67	–	11.5	(18)

Source: Data from Suryanarayana, C. and Inoue, A. *Bulk Metallic Glasses*, CRC Press, Boca Raton, FL, 2010. With permission.

References: (1) Qin et al. (2006), (2) Bian et al. (2005), (3) Kim et al. (2003), (4) Shen et al. (2006), (5) Lee et al. (2004), (6) Pan et al. (2006), (7) Chen, L.Y. et al. (2007), (8) Yamamoto et al. (2007), (9) Okazaki et al. (2006), (10) Zhang, Q.S. et al. (2007), (11) Choi-Yim et al. (2008), (12) Siegrist and Loffler (2007), (13) Conner et al. (1998), (14) Szuecs et al. (2001), (15) Sun et al. (2007), (16) Xue et al. (2007), (17) Sulitanu et al. (2005), (18) Hoffmann et al. (2008).

[a] σ_f: fracture strength; ε_p: plastic strain.

[b] V_r: volume fraction of the reinforcement.

[c] Total strain to fracture.

TABLE 9.5 Electrical Resistivity[a] of Bulk Metallic Glasses[b]

Alloy	ρ_{300} (μΩ m)	$[d\rho_{300}/dT]/\rho$ (×10⁻⁵)	$[d\rho_{sls}/dT]/\rho$ (×10⁻⁵)	TCR[c] (×10⁻⁵ K⁻¹)	Ref.
$Au_{81}Ge_{11}Si_8$				–20	(1)
$Pd_{82}Si_{18}$				15 (unrelaxed glass)	(1)
				40 (relaxed glass)	(1)
$Pd_{81}Au_4Si_{15}$	0.9			15	(1)
$Pd_{76}Cu_6Si_{18}$	0.81				(2)
$Pd_{40}Cu_3Ni_{37}P_{20}$	2.33			–11	(2)
$Pd_{40}Cu_{30}Ni_{10}P_{20}$	1.37	7.3			(3)
$Pd_{40}Ni_{40}P_{20}$	–	–8.61	–41.7		(4)
$Pd_{43}Ni_{37}P_{20}$	1.29	12.8	24.2		(3)
$Zr_{60}Ti_2Cu_{20}Ni_8Al_{10}$	1.41	3.9	23.3		(3)
	1.4 (gl)		–7 (gl)		(5)

(*Continued*)

TABLE 9.5 (*Continued*) Electrical Resistivity[a] of Bulk Metallic Glasses[b]

Alloy	ρ_{300} (μΩ m)	$[d\rho_{300}/dT]/\rho$ ($\times10^{-5}$)	$[d\rho_{sls}/dT]/\rho$ ($\times10^{-5}$)	TCR[c] ($\times10^{-5}$ K^{-1})	Ref.
	–		−13 (sls)		(5)
	0.73 (c)		+85 (c)		(5)
$Zr_{55}Al_{10}Cu_{35}$	2.56			−6.8	(6)
$Zr_{55}Al_{10}Cu_{30}Ni_{5}$	2.60			−10.9	(6)
$Zr_{55}Al_{10}Cu_{25}Ni_{10}$	2.53			−15.9	(6)
$Zr_{52}Ti_{5}Cu_{18}Ni_{15}Al_{10}$	1.6 (gl)		−9 (gl)		(5)
	–		−20 (sls)		(5)
	1.1 (c)		+10 (c)		(5)

Source: Data from Suryanarayana, C. and Inoue, A. *Bulk Metallic Glasses*, CRC Press, Boca Raton, FL, 2010.
References: (1) Chen (1980), (2) Haruyama et al. (1999), (3) Haruyama et al. (2002), (4) Haruyama et al. (2000), (5) Mattern et al. (2004), (6) Okai et al. (2004)
[a] ρ_{300}: electrical resistivity at 300 K.
[b] gl: glassy state, sls: supercooled liquid state, c: crystalline state.
[c] Thermal coefficient of resistivity.

TABLE 9.6 Magnetic Properties[a] of Bulk Metallic Glasses

Alloy	Form	Thickness/ Size (mm)	I_s (T)	H_c (A/m)	μ_e	λ_s (10^{-6})	T_c (K)	Ref.
$Co_{43}Fe_{20}Ta_{5.5}B_{31.5}$	Ribbon	0.02	0.51	0.9	40,000	–	–	(1)
$Co_{43}Fe_{20}Ta_{5.5}B_{31.5}$	Rod	2	0.49	–	–	–	–	(1)
$Co_{43}Fe_{20}Ta_{5.5}B_{31.5}$	Rod	3	0.49	0.25	550,000	–	–	(2)
$(Co_{0.705}Fe_{0.045}Si_{0.1}B_{0.15})_{96}Nb_{4}$	Rod	1	0.59	<3	–	–	–	(3)
$[(Co_{0.6}Fe_{0.4})_{0.75}B_{0.2}Si_{0.05}]_{96}Nb_{4}$	Ribbon	0.02	–	–	–	–	–	(3)
$Fe_{30}Co_{30}Ni_{15}Si_{8}B_{17}$	Rod	1.2	0.92	3	–	–	–	(4)
$Fe_{37.5}Ni_{22.5}Cr_{5}Co_{10}B_{15}Si_{10}$	Ribbon	20–25	0.89	3720	–	7.6		(5)
$Fe_{40}Co_{40}Cu_{0.5}Al_{2}Zr_{9}Si_{4}B_{4.5}$	Ribbon	–	1.18	3	–	–	736	(6)
$Fe_{52}Co_{9.5}Nd_{3}Dy_{0.5}B_{35}$	Ribbon	–	1.26	1	–	15.7	–	(7)
$Fe_{56}Co_{7}Ni_{7}Zr_{10}B_{20}$	Ribbon	–	0.92	–	51,000	–	567	(8)
$Fe_{56}Co_{7}Ni_{7}Zr_{10}B_{20}$	Ribbon	0.015	0.92	5.2	–	–	–	(9)
$Fe_{62}Nb_{8}B_{30}$	Ribbon	0.035	0.75	–	–	9.8	516	(10)
$Fe_{62}Co_{9.5}Gd_{3.5}Si_{10}B_{15}$	Ribbon	–	0.98	5	–	–	596	(6)
$Fe_{62}Co_{9.5}Nd_{3}Dy_{0.5}B_{25}$	Ribbon	–	1.37	4	–	17.9	–	(7)
$(Fe_{0.75}B_{0.15}Si_{0.1})_{96}Nb_{4}$	Rod	1.5	1.2	3.7	9.6	–	–	(11)
$[(Fe_{0.8}Co_{0.1}Ni_{0.1})_{0.75}B_{0.2}Si_{0.05}]_{96}Nb_{4}$	Rod	2.5	1.1	3	16,000	–	–	(11)
$[(Fe_{0.6}Co_{0.1}Ni_{0.3})_{0.75}B_{0.2}Si_{0.05}]_{96}Nb_{4}$	Rod	3	0.8	2.5	19,000	–	–	(11)
$[(Fe_{0.6}Co_{0.2}Ni_{0.2})_{0.75}B_{0.2}Si_{0.05}]_{96}Nb_{4}$	Rod	4	0.86	2.5	19,000	–	–	(11)
$[(Fe_{0.6}Co_{0.3}Ni_{0.1})_{0.75}B_{0.2}Si_{0.05}]_{96}Nb_{4}$	Rod	4	0.9	2	21,000	–	–	(11)
$[(Fe_{0.8}Co_{0.1}Ni_{0.1})_{0.75}B_{0.2}Si_{0.05}]_{96}Nb_{4}$	Rod	2.5	1.1	3	18,000	–	–	(12)
$Fe_{76}Al_{4}P_{12}B_{4}Si_{4}$	Ribbon	<0.025	1.38	3	–	–	623	(13)
$Fe_{76}Si_{9}B_{10}P_{5}$	Rod	2.5	1.51	1	–	–	–	(4)

(*Continued*)

TABLE 9.6 (*Continued*) Magnetic Properties[a] of Bulk Metallic Glasses

Alloy	Form	Thickness/ Size (mm)	I_s (T)	H_c (A/m)	μ_e	λ_s (10^{-6})	T_c (K)	Ref.
$Fe_{76}Mo_2Ga_2P_{10}C_4B_4Si_2$	Rod	2	1.32	3	–	–	–	(4)
$Fe_{76}P_5(Si_{0.3}B_{0.5}C_{0.2})_{19}$	Rod	3	1.44	1	17,000	–	680	(14)
$(Fe_{0.85}Co_{0.15})_{77}Ga_2P_{10}C_5B_{3.5}Si_{2.5}$	Rod	3	1.4	5	–	–	694	(15)
$Fe_{78}Ga_2P_{12}C_4B_4$	Ribbon	0.02	1.34	2	–	–	–	(16)
$Fe_{78}Ga_2P_{9.5}C_4B_4Si_{2.5}$	Rod	2	1.4	3	–	–	625	(17)

Source: Data from Suryanarayana, C. and Inoue, A. *Bulk Metallic Glasses*, CRC Press, Boca Raton, FL, 2010. With permission.

References: (1) Shen et al. (2001b), (2) Inoue et al. (2004b), (3) Inoue and Shen (2002), (4) Makino et al. (2007), (5) Sulitanu et al. (2005), (6) Mitra et al. (2003), (7) Zhang et al. (2002), (8) Inoue et al. (1997b), (9) Inoue et al. (1997a), (10) Gercsi et al. (2004), (11) Shen et al. (2007), (12) Inoue and Shen (2004), (13) Pawlik et al. (2004), (14) Chang et al. (2009), (15) Amiya et al. (2007), (16) Shen et al. (2001a), (17) Shen and Inoue (2002).

[a] I_s: saturation magnetization, H_c: low coercivity, μ_e: permeability, λ_s: magnetostriction, T_c: Curie temperature.

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