

Contents

Introduction.....	xxxvii
1 Properties of Materials.....	1
1.1 Physical Properties	1
1.1.1 Mass Density	1
1.1.2 Theoretical Density or X-ray Density of Solids	2
1.1.3 Apparent, Bulk, and Tap Densities	2
1.1.4 Specific Weight	3
1.1.5 Specific Gravity	3
1.1.6 Buoyancy and Archimedes' Principle.....	3
1.1.7 Pycnometers for Solids	4
1.1.8 Density of Mixtures	5
1.2 Mechanical Properties.....	6
1.2.1 Stress and Pressure.....	7
1.2.2 Strain.....	7
1.2.3 Elastic Moduli and Hooke's Law.....	7
1.2.4 The Stress–Strain Curve.....	8
1.2.5 Strain Hardening Exponent.....	11
1.2.6 Hardness.....	11
1.2.7 Resilience and Modulus of Resilience	15
1.2.8 Toughness	15
1.2.9 Maximum Allowable Stress	15
1.2.10 Fracture Toughness.....	16
1.2.11 Brittleness Indices	17
1.2.12 Creep.....	17
1.2.13 Ductile-Brittle Transition	18
1.2.14 Fatigue	18
1.2.15 Tribological and Lubricating Properties of Solids	19
1.2.15.1 Static Friction Coefficient	19
1.2.15.2 Sliding Friction Coefficient.....	20

1.2.16	Ashby's Mechanical Performance Indices.....	21
1.2.17	Order of Magnitude of Mechanical Properties of Solid Materials	21
1.3	Acoustical Properties.....	23
1.3.1	Velocity of Sound in Materials	23
1.3.2	Sound Intensity	23
1.3.3	Attenuation of Sound at a Given Distance from a Source	24
1.3.4	Damping Capacity of Solids and Loss Factor.....	24
1.4	Thermal Properties	25
1.4.1	Molar and Specific Heat Capacities.....	25
1.4.2	Coefficients of Thermal Expansion.....	26
1.4.3	Volume Expansion on Melting.....	27
1.4.4	Thermal Shock Resistance	27
1.4.5	Heat Transfer Processes.....	28
1.4.6	Thermal Conductivity	28
1.4.7	Thermal Diffusivity.....	29
1.4.8	Spectral Emissivity.....	30
1.4.9	Temperature and Latent Enthalpies of Fusion, Vaporization, and Sublimation.....	30
1.4.10	Order of Magnitude of Thermal Properties of Materials	32
1.5	Optical Properties	32
1.5.1	Index of Refraction	32
1.5.2	Total Reflection and Critical Angle.....	34
1.5.3	Specific and Molar Refraction	35
1.5.4	Refractivity	35
1.5.5	Dispersion.....	35
1.5.6	Coefficient of Dispersion.....	36
1.5.7	Abbe Number	36
1.5.8	Temperature Dependence of the Refractive Index.....	36
1.5.9	Anisotropic Materials.....	36
1.5.10	Birefringence	37
1.5.11	Albedo and Reflective Index.....	37
1.5.12	Electromagnetic Radiation Spectrum	38
1.5.13	Order of Magnitude of Optical Properties of Transparent Materials	38
1.5.14	Macroscopic Absorption of Light.....	39
1.5.14.1	Damping Constant.....	39
1.5.14.2	First Law of Absorption (Bouger's Law).....	39
1.5.14.3	Second Law of Absorption (Beer-Lambert Law).....	40
1.5.14.4	Absorbance or Optical Density	40
1.5.15	Microscopic Absorption and Emission Processes.....	41
1.5.16	Einstein Coefficients.....	42
1.5.16.1	Einstein Coefficient of Absorption.....	42
1.5.16.2	Einstein Coefficient of Spontaneous Emission	43
1.5.16.3	Einstein Coefficient of Stimulated Emission.....	44
1.5.16.4	Relation Between Einstein Coefficients	44
1.5.16.5	Relations Between Einstein and Extinction Coefficients	45
1.5.17	Luminescence.....	45
1.5.17.1	Excitation.....	46
1.5.17.2	Internal Conversion.....	46
1.5.17.3	Fluorescence.....	46
1.5.17.4	Intercombination.....	46
1.5.17.5	Delayed Fluorescence.....	47
1.5.17.6	Phosphorescence	47

1.6	Other Properties.....	47
1.6.1	Biocompatibility	47
1.6.2	Electronegativity.....	48
1.6.3	Chemical Abstract Registry Number	50
1.7	Fundamental Constants	50
1.8	Conversion Factors.....	52
1.9	Further Reading.....	54
1.9.1	Mathematics and Statistics	54
1.9.2	Units and Conversion Tables	55
1.9.3	Physics	55
1.9.4	Physical Chemistry	55
1.9.5	Engineering Fundamentals.....	56
1.9.6	General Handbooks.....	56
1.9.7	Mechanical Properties.....	56
1.9.8	Electrical Properties	56
1.9.9	Thermal Properties.....	56
1.9.10	Metallurgy	57
1.9.11	Materials Science	57
2	Ferrous Metals and Their Alloys.....	59
2.1	Iron and Steels.....	59
2.1.1	Description and General Properties	59
2.1.2	Phase Transitions and Allotropism of Iron	64
2.1.3	Metallographic Etchants for Iron and Steels.....	66
2.1.4	History	66
2.1.5	Natural Occurrence, Minerals, and Ores.....	66
2.1.6	Mining and Mineral Dressing.....	70
2.1.7	Iron- and Steelmaking.....	71
2.1.8	Pure Iron Grades.....	73
2.1.9	The Iron-Carbon (Fe-C) and Iron-Cementite (Fe-Fe ₃ C) Systems.....	73
2.1.10	Cast Irons	78
2.1.10.1	Gray Cast Iron or Graphitic Iron	79
2.1.10.2	White Cast Iron.....	79
2.1.10.3	Malleable Cast Irons.....	79
2.1.10.4	Ductile (Nodular) Cast Irons.....	79
2.1.10.5	High-Silicon Cast Irons.....	80
2.1.11	Carbon Steels (C-Mn Steels).....	84
2.1.11.1	Plain Carbon Steels.....	85
2.1.11.2	Low-Alloy Steels	89
2.1.11.3	Cast Steels.....	95
2.1.12	Stainless Steels	95
2.1.12.1	Description and General Properties	95
2.1.12.2	Classification of Stainless Steels.....	96
2.1.12.3	Martensitic Stainless Steels.....	97
2.1.12.4	Ferritic Stainless Steels.....	97
2.1.12.5	Austenitic Stainless Steels.....	101
2.1.12.6	Duplex Stainless Steels	102
2.1.12.7	Precipitation-Hardening Stainless Steels	103
2.1.12.8	Cast Heat-Resistant Stainless Steels.....	103
2.1.12.9	Processing and Melting Process.....	103

	2.1.12.10	Simplified Selection of Stainless Steels	108
	2.1.12.11	Stainless Steel Application Guidelines.....	109
2.1.13		High-Strength Low-Alloy Steels (HSLA)	112
2.1.14		Ultrahigh-Strength Steels.....	115
2.1.15		Tool and Machining Steels.....	115
2.1.16		Maraging Steels	120
2.1.17		Iron-Based Superalloys	121
2.1.18		Iron Powders	122
	2.1.18.1	Water-Atomized Iron Powders	122
	2.1.18.2	Gas-Atomized Iron Powders	123
	2.1.18.3	Sponge-Reduced Iron.....	123
2.1.19		Further Reading	123
2.2		Nickel and Nickel Alloys	124
	2.2.1	Description and General Properties.....	124
	2.2.2	History	124
	2.2.3	Natural Occurrence, Minerals and Ores	125
	2.2.4	Processing and Industrial Preparation	126
	2.2.5	Nickel Alloys.....	127
	2.2.6	Nickel Alloys and Superalloys	128
	2.2.7	Nickel-Titanium Shape Memory Alloys	139
		2.2.7.1 History	139
		2.2.7.2 Fundamental	139
		2.2.7.3 Shape Memory Effect.....	140
		2.2.7.4 Superelasticity.....	140
		2.2.7.5 Fabrication	140
	2.2.8	Major Nickel Producers	141
2.3		Cobalt and Cobalt Alloys.....	141
	2.3.1	Description and General Properties.....	141
	2.3.2	History	142
	2.3.3	Natural Occurrence, Minerals and Ores	143
	2.3.4	Processing and Industrial Preparation	144
		2.3.4.1 Cobalt as a Byproduct of Nickel Processing.....	144
		2.3.4.2 Electrowinning of Cobalt	144
	2.3.5	Properties of Cobalt Alloys and Superalloys	145
	2.3.6	Corrosion Resistance of Stellites	148
	2.3.7	Industrial Applications and Uses	148
	2.3.8	Major Cobalt Producers	149
2.4		Manganese and Manganese-Based Alloys	149
	2.4.1	Description and General Properties.....	149
	2.4.2	History	151
	2.4.3	Natural Occurrence, Minerals, and Ores	152
	2.4.4	Processing and Industrial Preparation	153
		2.4.4.1 Mining and Beneficiation of Manganese Ores	153
		2.4.4.2 Preparation of Pure Manganese Metal	153
		2.4.4.3 Ferromanganese and Silicomanganese.....	155
	2.4.5	Industrial Applications and Uses	156
		2.4.5.1 Metallurgical Uses	156
		2.4.5.2 Nonmetallurgical Uses	156
	2.4.6	Major Manganese Producers	157

3	Common Nonferrous Metals.....	159
3.1	Introduction	159
3.2	Aluminum and Aluminum Alloys.....	159
3.2.1	Description and General Properties	159
3.2.2	History	164
3.2.3	Natural Occurrence, Minerals, and Ores.....	165
3.2.4	Processing and Industrial Preparation.....	166
3.2.4.1	The Bayer Process.....	166
3.2.4.2	The Hall–Heroult Process for Electrowinning Aluminum	168
3.2.4.3	Secondary Aluminum Production and Recycling of Aluminum Drosses	169
3.2.5	Properties of Aluminum Alloys	170
3.2.5.1	Aluminum Alloy Standard Designations	171
3.2.5.2	Wrought Aluminum Alloys.....	172
3.2.5.3	Cast Aluminum Alloys.....	172
3.2.6	Industrial Applications and Uses.....	176
3.2.7	Major Aluminum Producers and Dross Recyclers.....	177
3.2.8	Further Reading.....	178
3.3	Copper and Copper Alloys.....	179
3.3.1	Description and General Properties	179
3.3.2	Natural Occurrence, Minerals, and Ores.....	179
3.3.3	Processing and Industrial Preparation.....	180
3.3.4	Properties of Copper Alloys.....	181
3.3.4.1	UNS Copper-Alloy Designation	181
3.3.4.2	Wrought Copper Alloys.....	183
3.3.4.3	Cast Copper Alloys.....	183
3.3.5	Major Copper Producers.....	187
3.3.6	Further Reading.....	187
3.4	Zinc and Zinc Alloys.....	187
3.4.1	Description and General Properties	187
3.4.2	History	188
3.4.3	Natural Occurrence, Minerals, and Ores.....	188
3.4.4	Processing and Industrial Preparation.....	189
3.4.4.1	Beneficiation of Zinc Ore.....	189
3.4.4.2	The Roasting Process	190
3.4.4.3	Mercury Removal	191
3.4.4.4	Hydrometallurgical Process	191
3.4.4.5	Pyrometallurgical Process	192
3.4.4.6	Treatment of Ferrite Residue	193
3.4.5	Industrial Applications and Uses.....	195
3.4.6	Properties of Zinc Alloys.....	196
3.5	Lead and Lead Alloys.....	196
3.5.1	Description and General Properties	196
3.5.2	History	199
3.5.3	Natural Occurrence, Minerals, and Ores.....	199
3.5.4	Beneficiation and Mineral Dressing	199
3.5.5	Processing and Industrial Preparation.....	199
3.5.6	Industrial Applications and Uses.....	201
3.5.7	Properties of Lead Alloys.....	201
3.5.8	Further Reading.....	201

3.6	Tin and Tin Alloys	204
3.6.1	Description and General Properties.....	204
3.6.2	History	205
3.6.3	Natural Occurrence, Minerals, and Ores	205
3.6.4	Processing and Industrial Preparation	206
3.6.4.1	Mining and Beneficiation.....	206
3.6.4.2	Processing and Smelting	207
3.6.5	Industrial Applications and Uses	208
3.6.6	Properties of Tin Alloys.....	208
3.7	Low-Melting-Point or Fusible Alloys	209
3.7.1	Further Reading	211
4	Less Common Nonferrous Metals	213
4.1	Alkali Metals.....	213
4.1.1	Lithium	217
4.1.1.1	Description and General Properties.....	217
4.1.1.2	History	219
4.1.1.3	Natural Occurrence, Minerals, and Ores	220
4.1.1.4	Processing and Industrial Preparation	223
4.1.1.5	Industrial Applications and Uses	228
4.1.1.6	Lithium Mineral and Chemical Prices	230
4.1.1.7	Lithium Mineral, Carbonate, and Metal Producers.....	230
4.1.1.8	Further Reading	231
4.1.2	Sodium.....	232
4.1.2.1	Description and General Properties.....	232
4.1.2.2	History	233
4.1.2.3	Natural Occurrence, Minerals, and Ores	233
4.1.2.4	Processing and Industrial Preparation	234
4.1.2.5	Industrial Applications and Uses	235
4.1.2.6	Transport, Storage, and Safety	236
4.1.2.7	Major Producers of Sodium Metal	236
4.1.2.8	Further Reading	236
4.1.3	Potassium	237
4.1.3.1	Description and General Properties.....	237
4.1.3.2	History	238
4.1.3.3	Natural Occurrence, Minerals, and Ores	238
4.1.3.4	Processing and Industrial Preparation	238
4.1.3.5	Industrial Applications and Uses.....	239
4.1.3.6	Further Reading	239
4.1.4	Rubidium.....	239
4.1.4.1	Description and General Properties.....	239
4.1.4.2	History	240
4.1.4.3	Natural Occurrence, Minerals, and Ores	240
4.1.4.4	Processing and Industrial Preparation	240
4.1.4.5	Industrial Applications and Uses.....	240
4.1.4.6	Major Rubidium Producers	241
4.1.4.7	Further Reading	241
4.1.5	Cesium	241
4.1.5.1	Description and General Properties.....	241
4.1.5.2	History	241
4.1.5.3	Natural Occurrence, Minerals, and Ores	242

	4.1.5.4	Processing and Industrial Preparation.....	242
	4.1.5.5	Industrial Applications and Uses.....	242
	4.1.5.6	Cesium Metal Producers.....	243
	4.1.5.7	Further Reading.....	243
	4.1.6	Francium.....	243
4.2		Alkaline-Earth Metals.....	243
	4.2.1	Beryllium.....	244
	4.2.1.1	Description and General Properties.....	244
	4.2.1.2	History.....	244
	4.2.1.3	Natural Occurrence, Minerals, and Ores.....	248
	4.2.1.4	Mining and Mineral Dressing.....	248
	4.2.1.5	Processing and Industrial Preparation.....	248
	4.2.1.6	Industrial Applications and Uses.....	249
	4.2.1.7	Major Beryllium Metal Producers.....	250
	4.2.1.8	Further Reading.....	250
4.2.2		Magnesium and Magnesium Alloys.....	250
	4.2.2.1	Description and General Properties.....	250
	4.2.2.2	History.....	251
	4.2.2.3	Natural Occurrence, Minerals, and Ores.....	251
	4.2.2.4	Processing and Industrial Preparation.....	252
	4.2.2.5	Properties of Magnesium Alloys.....	255
	4.2.2.6	Industrial Applications and Uses.....	255
	4.2.2.7	Recycling of Magnesium Scrap and Drosses.....	255
	4.2.2.8	Major Magnesium Metal Producers.....	259
	4.2.2.9	Further Reading.....	260
4.2.3		Calcium.....	260
	4.2.3.1	Description and General Properties.....	260
	4.2.3.2	History.....	260
	4.2.3.3	Natural Occurrence, Minerals, and Ores.....	260
	4.2.3.4	Processing and Industrial Preparation.....	261
	4.2.3.5	Industrial Applications and Uses.....	261
	4.2.3.6	Calcium Metal Producers.....	262
	4.2.3.7	Further Reading.....	262
4.2.4		Strontium.....	262
	4.2.4.1	Description and General Properties.....	262
	4.2.4.2	History.....	263
	4.2.4.2	Natural Occurrence, Minerals, and Ores.....	263
	4.2.4.3	Processing and Industrial Preparation.....	263
	4.2.4.4	Industrial Applications and Uses.....	263
4.2.5		Barium.....	263
	4.2.5.1	Description and General Properties.....	263
	4.2.5.2	History.....	264
	4.2.5.2	Natural Occurrence, Minerals, and Ores.....	264
	4.2.5.3	Processing and Industrial Preparation.....	264
	4.2.5.4	Industrial Applications and Uses.....	264
4.2.6		Radium.....	264
	4.2.6.1	Description and General Properties.....	264
	4.2.6.2	History.....	265
	4.2.6.3	Natural Occurrence.....	265
	4.2.6.4	Processing and Industrial Preparation.....	265
	4.2.6.5	Industrial Applications and Uses.....	265

4.3	Refractory Metals	266
4.3.1	General Overview	266
4.3.1.1	Common Properties	266
4.3.1.2	Corrosion Resistance	271
4.3.1.3	Cleaning, Descaling, Pickling, and Etching	271
4.3.1.4	Machining of Pure Reactive and Refractory Metals	273
4.3.1.5	Pyrophoricity of Refractory Metals	273
4.3.2	Titanium and Titanium Alloys	274
4.3.2.1	Description and General Properties	274
4.3.2.2	History	276
4.3.2.3	Natural Occurrence, Minerals, and Ores	276
4.3.2.4	Mining and Mineral Dressing	280
4.3.2.5	Titanium Slag and Slagging	281
4.3.2.6	Synthetic Rutiles	283
4.3.2.7	Titanium Dioxide (Titania)	286
4.3.2.8	Titanium Sponge	288
4.3.2.9	Ferrotitanium	296
4.3.2.10	Titanium Metal Ingot	297
4.3.2.11	Titanium Metal Powder	298
4.3.2.12	Commercially Pure Titanium	301
4.3.2.13	Titanium Alloys	302
4.3.2.14	Corrosion Resistance	313
4.3.2.15	Titanium Metalworking	319
4.3.2.16	Titanium Machining	320
4.3.2.17	Titanium Joining	320
4.3.2.18	Titanium Etching, Descaling, and Pickling	320
4.3.2.19	Titanium Anodizing	321
4.3.2.20	Industrial Applications and Uses	322
4.3.2.21	Major Producers of Titanium Metal Sponge and Ingot	324
4.3.2.22	World and International Titanium Conferences	325
4.3.2.23	Further Reading	325
4.3.3	Zirconium and Zirconium Alloys	326
4.3.3.1	Description and General Properties	326
4.3.3.2	History	327
4.3.3.3	Natural Occurrence, Minerals, and Ores	328
4.3.3.4	Mining and Mineral Dressing	328
4.3.3.5	Processing and Industrial Preparation	329
4.3.3.6	Zirconium Alloys	331
4.3.3.7	Corrosion Resistance	333
4.3.3.8	Zirconium Machining	333
4.3.3.9	Industrial Uses and Applications	334
4.3.3.10	Zirconium Metal Producers	334
4.3.3.11	Further Reading	334
4.3.4	Hafnium and Hafnium Alloys	336
4.3.4.1	Description and General Properties	336
4.3.4.2	History	336
4.3.4.3	Natural Occurrence, Minerals, and Ores	337
4.3.4.4	Processing and Industrial Preparation	337
4.3.4.5	Industrial Applications and Uses	337
4.3.4.6	Major Hafnium Metal Producers	337
4.3.4.7	Further Reading	338

4.3.5	Vanadium and Vanadium Alloys.....	338
4.3.5.1	Description and General Properties	338
4.3.5.2	History	339
4.3.5.3	Natural Occurrence, Minerals, and Ores.....	339
4.3.5.4	Processing and Industrial Preparation.....	340
4.3.5.5	Industrial Applications and Uses.....	342
4.3.5.6	Major Vanadium Producers	342
4.3.5.7	Further Reading.....	342
4.3.6	Niobium and Niobium Alloys	343
4.3.6.1	Description and General Properties	343
4.3.6.2	History	344
4.3.6.3	Natural Occurrence, Minerals, and Ores.....	345
4.3.6.4	Processing and Industrial Preparation.....	346
4.3.6.5	Properties of Niobium Alloys.....	347
4.3.6.6	Niobium Metalworking.....	347
4.3.6.7	Niobium Machining	347
4.3.6.8	Niobium Joining and Welding	349
4.3.6.9	Niobium Cleaning, Pickling, and Etching.....	349
4.3.6.10	Industrial Applications and Uses.....	350
4.3.6.11	Major Producers of Niobium Metal.....	350
4.3.6.12	Further Reading.....	350
4.3.7	Tantalum and Tantalum Alloys	353
4.3.7.1	Description and General Properties	353
4.3.7.2	History	354
4.3.7.3	Natural Occurrence, Minerals, and Ores.....	355
4.3.7.4	Processing and Industrial Preparation.....	356
4.3.7.5	Properties of Tantalum Alloys	357
4.3.7.6	Tantalum Metalworking	357
4.3.7.7	Tantalum Machining.....	359
4.3.7.8	Tantalum Joining.....	359
4.3.7.9	Tantalum Cleaning and Degreasing	360
4.3.7.10	Tantalum Cladding and Coating Techniques	361
4.3.7.11	Industrial Applications and Uses.....	365
4.3.7.12	Major Tantalum Metal Producers.....	366
4.3.7.13	Further Reading.....	367
4.3.8	Chromium and Chromium Alloys	367
4.3.8.1	Description and General Properties	367
4.3.8.2	History.....	368
4.3.8.3	Natural Occurrence, Minerals, and Ores.....	368
4.3.8.4	Processing and Industrial Preparation.....	369
4.3.8.5	Industrial Applications and Uses.....	372
4.3.8.6	Major Chromite and Ferrochrome Producers.....	372
4.3.8.7	Further Reading.....	372
4.3.9	Molybdenum and Molybdenum Alloys.....	373
4.3.9.1	Description and General Properties	373
4.3.9.2	History	373
4.3.9.3	Natural Occurrence, Minerals, and Ores.....	374
4.3.9.4	Processing and Industrial Preparation.....	374
4.3.9.5	Properties of Molybdenum Alloys	375
4.3.9.6	Molybdenum Metalworking.....	377
4.3.9.7	Molybdenum Joining	377
4.3.9.8	Molybdenum Machining	378

	4.3.9.9	Molybdenum Cleaning, Etching, and Pickling	380
	4.3.9.10	Industrial Applications and Uses	380
	4.3.9.11	World Molybdenum Metal Producers	384
	4.3.9.12	Further Reading	384
4.3.10		Tungsten and Tungsten Alloys	385
	4.3.10.1	Description and General Properties.....	385
	4.3.10.2	History	386
	4.3.10.3	Natural Occurrence, Minerals, and Ores	386
	4.3.10.4	Processing and Industrial Preparation	387
	4.3.10.5	Properties of Tungsten Alloys	387
	4.3.10.6	Industrial Applications and Uses	387
	4.3.10.7	Major Tungsten Metal and Hardmetal Producers.....	389
	4.3.10.8	Further Reading	391
4.3.11		Rhenium and Rhenium Alloys	391
	4.3.11.1	Description and General Properties.....	391
	4.3.11.2	History	392
	4.3.11.3	Natural Occurrence, Minerals, and Ores	392
	4.3.11.4	Processing and Industrial Preparation	393
	4.3.11.5	Industrial Applications and Uses	393
4.4		Noble and Precious Metals.....	393
4.4.1		Silver and Silver Alloys	396
	4.4.1.1	Description and General Properties.....	396
	4.4.1.2	History	397
	4.4.1.3	Natural Occurrence, Minerals, and Ores	397
	4.4.1.4	Processing and Industrial Preparation	397
	4.4.1.5	Silver Alloys.....	398
	4.4.1.6	Industrial Applications and Uses	398
	4.4.1.7	Further Reading	400
4.4.2		Gold and Gold Alloys.....	400
	4.4.2.1	Description and General Properties.....	400
	4.4.2.2	History	401
	4.4.2.3	Natural Occurrence, Minerals, and Ores	402
	4.4.2.4	Mineral Dressing, and Mining.....	402
	4.4.2.5	Processing and Industrial Preparation	403
	4.4.2.6	Gold Alloys	404
	4.4.2.7	Industrial Applications and Uses	406
	4.4.2.8	Major Gold Producers and Suppliers.....	406
4.5		Platinum-Group Metals.....	407
4.5.1		General Overview	407
4.5.2		Natural Occurrence, Chief Minerals, and Ores	408
4.5.3		Common Physical and Chemical Properties.....	409
4.5.4		The Six Platinum Group Metals	409
	4.5.4.1	Ruthenium.....	409
	4.5.4.2	Rhodium	413
	4.5.4.3	Palladium.....	413
	4.5.4.4	Osmium	414
	4.5.4.5	Iridium	414
	4.5.4.6	Platinum	415
4.5.5		PGM Alloys	416

4.5.6	PGMs Corrosion Resistance	417
4.5.6.1	Industrial Applications and Uses.....	420
4.5.6.2	Major Producers and Suppliers of PGMs.....	421
4.5.7	Further Reading.....	422
4.6	Rare-Earth Metals	422
4.6.1	Description and General Properties	422
4.6.2	History	423
4.6.3	Natural Occurrence, Minerals, and Ores.....	425
4.6.4	Processing and Industrial Preparation.....	427
4.6.5	Industrial Applications and Uses.....	429
4.6.6	Major Producers and Suppliers of Rare Earths	431
4.6.7	Further Reading.....	432
4.6.8	Scandium (Sc)	433
4.6.8.1	Description and General Properties	433
4.6.8.2	History.....	433
4.6.8.3	Natural Occurrence, Minerals, and Ores.....	433
4.6.8.4	Processing and Industrial Preparation.....	434
4.6.8.5	Industrial Applications and Uses.....	434
4.6.8.6	Scandium Metal, Alloys, and Chemicals	435
4.7	Uranides.....	436
4.7.1	Uranium	438
4.7.1.1	Description and General Properties	438
4.7.1.2	History	439
4.7.1.3	Natural Occurrence, Minerals, and Ores.....	440
4.7.1.4	Mineral Dressing and Mining	441
4.7.1.5	Processing and Industrial Preparation.....	442
4.7.1.6	Industrial Applications and Uses.....	446
4.7.1.7	Further Reading.....	447
4.7.2	Thorium.....	447
4.7.2.1	Description and General Properties	447
4.7.2.2	History.....	447
4.7.2.3	Natural Occurrence, Minerals, and Ores.....	448
4.7.2.4	Processing and Industrial Preparation.....	449
4.7.2.5	Industrial Applications and Uses.....	451
4.7.2.6	Further Reading.....	452
4.7.3	Plutonium.....	452
4.7.3.1	Description and General Properties	452
4.7.3.2	History.....	453
4.7.3.3	Natural Occurrence, Minerals, and Ores.....	454
4.7.3.4	Processing and Industrial Preparation.....	454
5	Semiconductors.....	455
5.1	Band Theory of Bonding in Crystalline Solids.....	455
5.2	Electrical Classification of Solids	456
5.3	Semiconductor Classes.....	457
5.3.1	Intrinsic or Elemental Semiconductors.....	457
5.3.2	Doped Extrinsic Semiconductors.....	458
5.3.3	Compound Semiconductors.....	459
5.3.4	Grimm-Sommerfeld Rule.....	459
5.4	Concentrations of Charge Carriers	460

5.5	Transport Properties	461
5.5.1	Electromigration	461
5.5.2	Diffusion	462
5.5.3	Hall Effect	462
5.6	Physical Properties of Semiconductors	463
5.7	Industrial Applications and Uses	463
5.8	Common Semiconductors.....	463
5.8.1	Silicon.....	463
5.8.2	Germanium.....	469
5.8.3	Boron.....	470
5.8.4	Other Semiconductors.....	471
5.9	Semiconductor Wafer Processing	471
5.9.1	Monocrystal Growth.....	472
5.9.2	Wafer Production	473
5.10	The P-N Junction	475
5.11	Further Reading	475
6	Superconductors	477
6.1	Description and General Properties	477
6.2	Superconductor Types.....	478
6.2.1	Type I Superconductors	478
6.2.2	Type II Superconductors.....	480
6.2.3	High-critical-temperature Superconductors	481
6.2.4	Organic Superconductors	482
6.3	Basic Theory	482
6.4	Meissner–Ochsenfeld Effect.....	483
6.5	History.....	483
6.6	Industrial Applications and Uses	485
6.7	Further Reading	485
7	Magnetic Materials.....	487
7.1	Magnetic Physical Quantities.....	487
7.1.1	Magnetic Field Strength and Magnetomotive Force	487
7.1.2	Magnetic Flux Density and Magnetic Induction.....	488
7.1.3	Magnetic Flux.....	489
7.1.4	Magnetic Dipole Moment	490
7.1.5	Magnetizability, Magnetization, and Magnetic Susceptibility	491
7.1.6	Magnetic Force Exerted on a Material	492
7.1.7	Magnetic Force Exerted by Magnets	493
7.1.8	Magnetic Energy Density Stored	493
7.1.9	Magnetoresistance	494
7.1.10	Magnetostriction.....	494
7.1.11	Magnetocaloric Effect.....	495
7.1.12	SI and CGS Units Used in Electromagnetism.....	498
7.2	Classification of Magnetic Materials	498
7.2.1	Diamagnetic Materials	499
7.2.2	Paramagnetic Materials.....	500
7.2.3	Ferromagnetic Materials	501
7.2.4	Antiferromagnetic Materials	503
7.2.5	Ferrimagnetic Materials	504

7.3	Ferromagnetic Materials	504
7.3.1	B-H Magnetization Curve and Hysteresis Loop	504
7.3.2	Eddy-Current Losses	506
7.3.3	Induction Heating	507
7.3.4	Soft Ferromagnetic Materials	507
7.3.5	Hard Magnetic Materials	510
7.3.6	Magnetic Shielding and Materials Selection	512
7.4	Industrial Applications of Magnetic Materials	516
7.5	Further Reading	516
8	Insulators and Dielectrics.....	519
8.1	Physical Quantities of Dielectrics.....	519
8.1.1	Permittivity of Vacuum.....	519
8.1.2	Permittivity of a Medium.....	519
8.1.3	Relative Permittivity and Dielectric Constant	520
8.1.4	Capacitance	520
8.1.5	Temperature Coefficient of Capacitance.....	520
8.1.6	Charging and Discharging a Capacitor	521
8.1.7	Capacitance of a Parallel-Electrode Capacitor.....	521
8.1.8	Capacitance of Other Capacitor Geometries.....	521
8.1.9	Electrostatic Energy Stored in a Capacitor.....	522
8.1.10	Electric Field Strength	522
8.1.11	Electric Flux Density	522
8.1.12	Microscopic Electric Dipole Moment	522
8.1.13	Polarizability	523
8.1.14	Macroscopic Electric Dipole Moment	523
8.1.15	Polarization	523
8.1.16	Electric Susceptibility	524
8.1.17	Dielectric Breakdown Voltage.....	524
8.1.18	Dielectric Absorption	524
8.1.19	Dielectric Losses	525
8.1.20	Loss Tangent or Dissipation Factor	525
8.1.21	Dielectric Heating.....	526
8.2	Physical Properties of Insulators.....	526
8.2.1	Insulation Resistance	526
8.2.2	Volume Electrical Resistivity.....	526
8.2.3	Temperature Coefficient of Electrical Resistivity	527
8.2.4	Surface Electrical Resistivity.....	528
8.2.5	Leakage Current.....	528
8.2.6	SI and CGS Units Used in Electricity	529
8.3	Dielectric Behavior	530
8.3.1	Electronic Polarization.....	530
8.3.2	Ionic Polarization	531
8.3.3	Dipole Orientation.....	531
8.3.4	Space Charge Polarization	531
8.3.5	Effect of Frequency on Polarization	531
8.3.6	Frequency Dependence of the Dielectric Losses.....	532
8.4	Dielectric Breakdown Mechanisms.....	532
8.4.1	Electronic Breakdown or Corona Mechanism.....	533
8.4.2	Thermal Discharge or Thermal Mechanism	533
8.4.3	Internal Discharge or Intrinsic Mechanism	533

8.5	Electrostriction.....	533
8.6	Piezoelectricity	534
8.7	Ferroelectrics	534
8.8	Aging of Ferroelectrics	538
8.9	Classification of Industrial Dielectrics.....	538
8.9.1	Class I Dielectrics or Linear Dielectrics	538
8.9.2	Class II Dielectrics or Ferroelectrics	539
8.10	Selected Properties of Insulators and Dielectric Materials	539
8.11	Further Reading	542
9	Miscellaneous Electrical Materials	543
9.1	Thermocouple Materials	543
9.1.1	The Seebeck Effect	543
9.1.2	Thermocouple	544
9.1.3	Properties of Common Thermocouple Materials.....	545
9.2	Resistors and Thermistors	548
9.2.1	Electrical Resistivity.....	548
9.2.2	Temperature Coefficient of Electrical Resistivity	548
9.3	Electron-emitting Materials	552
9.4	Photocathode Materials.....	553
9.5	Secondary Emission.....	554
9.6	Electrolytes	555
9.7	Electrode Materials	556
9.7.1	Electrode Materials for Batteries and Fuel Cells	556
9.7.2	Intercalation Compounds.....	559
9.7.3	Electrode Materials for Electrolytic Cells	561
9.7.3.1	Industrial Cathode Materials.....	563
9.7.3.1.1	Low-Carbon Steel Cathodes.....	563
9.7.3.1.2	Aluminum Cathodes.....	563
9.7.3.1.3	Titanium Cathodes	564
9.7.3.1.4	Zirconium Cathodes	565
9.7.3.1.5	Nickel Cathodes	565
9.7.3.1.6	Mercury Cathode	565
9.7.3.2	Industrial Anode Materials.....	565
9.7.3.2.1	Precious- and Noble-Metal Anodes	568
9.7.3.2.2	Lead and Lead-Alloy Anodes.....	569
9.7.3.2.3	Carbon Anodes.....	572
9.7.3.2.4	Lead Dioxide (PbO ₂)	573
9.7.3.2.5	Manganese Dioxide (MnO ₂).....	575
9.7.3.2.6	Spinel (AB ₂ O ₄)- and Perovskite (ABO ₃)-Type Oxides	575
9.7.3.2.7	Ebonex®(Ti ₄ O ₇ and Ti ₂ O ₉)	576
9.7.3.2.8	Noble-Metal-Coated Titanium Anodes (NMCT).....	578
9.7.3.2.9	Platinized Titanium and Niobium Anodes (70/30 Pt/Ir).....	579
9.7.3.2.10	Dimensionally Stable Anodes (DSA®) for Chlorine Evolution	580
9.7.3.2.11	Dimensionally Stable Anodes (DSA®) for Oxygen	581
9.7.3.2.12	Synthetic Diamond Electrodes	585

9.7.4	Electrodes for Corrosion Protection and Control	586
9.7.4.1	Cathodes for Anodic Protection	586
9.7.4.2	Anodes for Cathodic Protection.....	587
9.7.5	Electrode Suppliers and Manufacturers	589
9.8	Electrochemical Galvanic Series.....	590
10	Ceramics, Refractories, and Glasses.....	593
10.1	Introduction and Definitions	593
10.2	Raw Materials for Ceramics, Refractories and Glasses	594
10.2.1	Silica.....	594
10.2.1.1	Quartz, Quartzite, and Silica Sand	595
10.2.1.2	Diatomite.....	595
10.2.1.3	Fumed Silica.....	595
10.2.1.4	Silica Gels and Sol-Gel Silica.....	595
10.2.1.5	Precipitated Silica	595
10.2.1.6	Microsilica.....	596
10.2.1.7	Vitreous or Amorphous Silica.....	596
10.2.2	Aluminosilicates	596
10.2.2.1	Fireclay	597
10.2.2.2	China Clay	598
10.2.2.3	Ball Clay.....	598
10.2.2.4	Other Refractory Clays.....	599
10.2.2.5	Andalusite, Kyanite, and Sillimanite	599
10.2.2.6	Mullite.....	600
10.2.3	Bauxite and Aluminas	600
10.2.3.1	Bauxite.....	600
10.2.3.2	Alumina Hydrates	603
10.2.3.3	Transition Aluminas (TrA)	606
10.2.3.4	Calcined Alumina	606
10.2.3.5	Tabular Alumina	607
10.2.3.6	White Fused Alumina	608
10.2.3.7	Brown Fused Alumina	608
10.2.3.8	Electrofused Alumina-Zirconia.....	609
10.2.3.9	High-Purity Alumina	609
10.2.4	Limestone and Lime	610
10.2.5	Dolomite and Doloma.....	610
10.2.5.1	Dolomite.....	610
10.2.5.2	Calcined and Dead Burned Dolomite (Doloma)	611
10.2.6	Magnesite and Magnesia.....	612
10.2.6.1	Magnesite	612
10.2.6.2	Caustic Seawater and Calcined Magnesia	612
10.2.6.3	Dead Burned Magnesia	613
10.2.6.4	Electrofused Magnesia	614
10.2.6.5	Seawater Magnesia Clinker.....	614
10.2.7	Titania.....	614
10.2.7.1	Rutile.....	614
10.2.7.2	Anatase	616
10.2.7.3	Brookite.....	616
10.2.7.4	Anosovite.....	616
10.2.7.5	Titanium Sesquioxide	617
10.2.7.6	Titanium Monoxide or Hongquite	617

	10.2.7.7	Titanium Hemioxide	618
	10.2.7.8	Andersson–Magnéli Phases	618
10.2.8		Zircon and Zirconia	618
	10.2.8.1	Zircon	618
	10.2.8.2	Zirconia	618
10.2.9		Carbon and Graphite	623
	10.2.9.1	Description and General Properties	623
	10.2.9.2	Natural Occurrence and Mining	623
	10.2.9.3	Industrial Preparation and Processing	625
	10.2.9.4	Industrial Applications and Uses	625
10.2.10		Silicon Carbide	625
	10.2.10.1	Description and General Properties	625
	10.2.10.2	Industrial Preparation	626
	10.2.10.3	Grades of Silicon Carbide	628
10.2.11		Properties of Raw Materials Used in Ceramics, Refractories, and Glasses	628
10.3		Traditional Ceramics	629
10.4		Refractories	630
	10.4.1	Classification of Refractories	630
	10.4.2	Properties of Refractories	631
	10.4.3	Major Refractory Manufacturers	634
10.5		Advanced Ceramics	635
	10.5.1	Silicon Nitride	635
	10.5.1.1	Description and General Properties	635
	10.5.1.2	Industrial Preparation and Grades	635
	10.5.2	Silicon Aluminum Oxynitride (SiAlON)	636
	10.5.3	Boron Carbide	637
	10.5.3.1	Description and General Properties	637
	10.5.3.2	Industrial Preparation	637
	10.5.3.3	Industrial Applications and Uses	637
	10.5.4	Boron Nitride	637
	10.5.4.1	Description and General Properties	637
	10.5.4.2	Industrial Preparation	638
	10.5.4.3	Industrial Applications and Uses	638
	10.5.5	Titanium Diboride	638
	10.5.5.1	Description and General Properties	638
	10.5.5.2	Industrial Preparation and Processing	639
	10.5.5.3	Industrial Applications and Uses	639
	10.5.6	Tungsten Carbides and Hardmetal	639
	10.5.6.1	Description and General Properties	639
	10.5.6.2	Industrial Preparation	640
	10.5.6.3	Industrial Applications and Uses	640
	10.5.7	Practical Data for Ceramists and Refractory Engineers	641
	10.5.7.1	Temperature of Color	641
	10.5.7.2	Pyrometric Cone Equivalents	641
10.6		Standards for Testing Refractories	643
10.7		Properties of Pure Ceramics (Borides, Carbides, Nitrides, Silicides, and Oxides)	647
10.8		Further Reading	670
	10.8.1	Traditional and Advanced Ceramics	670
	10.8.2	Refractories	670

10.9	Glasses.....	671
10.9.1	Definitions.....	671
10.9.2	Physical Properties of Glasses	671
10.9.3	Glassmaking Processes.....	671
10.9.4	Further Reading.....	676
10.10	Proppants	677
10.10.1	Fracturing Techniques in Oil-Well Production.....	677
10.10.1.1	Hydraulic Fracturing.....	677
10.10.1.2	Pressure Acidizing.....	678
10.10.2	Proppant and Frac Fluid Selection Criteria	678
10.10.2.1	Proppant Materials.....	678
10.10.2.2	Frac Fluids.....	679
10.10.2.3	Properties and Characterization of Proppants.....	679
10.10.2.4	Classification of Proppant Materials	679
10.10.2.5	Production of Synthetic Proppants	682
10.10.2.6	Properties of Commercial Proppants	683
10.10.2.7	Proppant Market	687
10.10.2.8	Proppant Producers	687
10.10.3	Further Reading.....	689
11	Polymers and Elastomers	691
11.1	Fundamentals and Definitions	691
11.1.1	Definitions.....	691
11.1.2	Additives and Fillers.....	692
11.1.3	Polymerization and Polycondensation.....	693
11.2	Properties and Characteristics of Polymers	694
11.2.1	Molar Mass and Relative Molar Mass	694
11.2.2	Average Degree of Polymerization	695
11.2.3	Number-, Mass- and Z-Average Molar Masses	695
11.2.4	Glass Transition Temperature.....	697
11.2.5	Structure of Polymers.....	697
11.3	Classification of Plastics and Elastomers	697
11.4	Thermoplastics.....	697
11.4.1	Naturally Occurring Resins	697
11.4.1.1	Rosin	697
11.4.1.2	Shellac.....	699
11.4.2	Cellulosics.....	699
11.4.2.1	Cellulose Nitrate	699
11.4.2.2	Cellulose Acetate (CA)	700
11.4.2.3	Cellulose Propionate (CP)	700
11.4.2.4	Cellulose Xanthate.....	700
11.4.2.5	Alkylcelluloses	701
11.4.3	Casein Plastics.....	701
11.4.4	Coumarone-Indene Plastics	702
11.4.5	Polyolefins or Ethenic Polymers	702
11.4.5.1	Polyethylene (PE)	702
11.4.5.2	Polypropylene (PP)	703
11.4.5.3	Polybutylene (PB).....	704
11.4.6	Polymethylpentene (PMP).....	704

11.4.7	Polyvinyl Plastics	704
11.4.7.1	Polyvinyl Chlorides (PVCs)	704
11.4.7.2	Chlorinated Polyvinylchloride (CPVC)	705
11.4.7.3	Polyvinyl Fluoride (PVF)	705
11.4.7.4	Polyvinyl Acetate (PVA)	705
11.4.8	Polyvinylidene Plastics	705
11.4.8.1	Polyvinylidene Chloride (PVDC)	705
11.4.8.2	Polyvinylidene Fluoride (PVDF)	706
11.4.9	Styrenics.....	706
11.4.9.1	Polystyrene (PS).....	706
11.4.9.2	Acrylonitrile Butadiene Styrene (ABS)	706
11.4.10	Fluorinated Polyolefins (Fluorocarbons)	707
11.4.10.1	Polytetrafluoroethylene (PTFE)	707
11.4.10.2	Fluorinated Ethylene Propylene (FEP).....	708
11.4.10.3	Perfluorinated Alkoxy (PFA).....	708
11.4.10.4	Polychlorotrifluoroethylene (PCTFE)	708
11.4.10.5	Ethylene-Chlorotrifluoroethylene Copolymer (ECTFE)....	709
11.4.10.6	Ethylene-Tetrafluoroethylene Copolymer (ETFE)	709
11.4.11	Acrylics and Polymethyl Methacrylate (PMMA)	709
11.4.12	Polyamides (PA)	710
11.4.13	Polyaramides (PAR)	710
11.4.14	Polyimides (PI).....	710
11.4.15	Polyacetals (Pac)	711
11.4.16	Polycarbonates (PC)	711
11.4.17	Polysulfone (PSU)	711
11.4.18	Polyphenylene Oxide (PPO)	712
11.4.19	Polyphenylene Sulfide (PPS).....	712
11.4.20	Polybutylene Terephthalate (PBT).....	712
11.4.21	Polyethylene Terephthalate (PET)	712
11.4.22	Polydiallyl Phthalate (PDP)	713
11.5	Thermosets	713
11.5.1	Aminoplastics.....	713
11.5.2	Phenolics.....	714
11.5.3	Acrylonitrile-Butadiene-Styrene (ABS).....	714
11.5.4	Polyurethanes (PUR)	715
11.5.5	Furan Plastics	715
11.5.6	Epoxy Resins (EP).....	715
11.6	Rubbers and Elastomers.....	715
11.6.1	Natural Rubber (NR).....	716
11.6.2	Trans-Polyisoprene Rubber (PIR)	716
11.6.3	Polybutadiene Rubber (BR).....	716
11.6.4	Styrene Butadiene Rubber (SBR)	717
11.6.5	Nitrile Rubber (NR).....	717
11.6.6	Butyl Rubber (IIR)	717
11.6.7	Chloroprene Rubber (CPR)	717
11.6.8	Chlorosulfonated Polyethylene (CSM)	718
11.6.9	Polysulfide Rubber (PSR).....	718
11.6.10	Ethylene Propylene Rubbers.....	718
11.6.11	Silicone Rubber	719
11.6.12	Fluoroelastomers	719
11.7	Physical Properties of Polymers	720
11.8	Gas Permeability of Polymers.....	734

11.9	Chemical Resistance of Polymers.....	734
11.10	IUPAC Acronyms of Polymers and Elastomers.....	745
11.11	Economic Data on Polymers and Related Chemical Intermediates	746
11.11.1	Average Prices of Polymers	746
11.11.2	Production Capacities, Prices and Major Producers of Polymers and Chemical Intermediates.....	747
11.12	Further Reading	750
12	Minerals, Ores and Gemstones	751
12.1	Definitions	751
12.2	Mineralogical, Physical and Chemical Properties	756
12.2.1	Mineral Names.....	756
12.2.2	Chemical Formula and Theoretical Chemical Composition	757
12.2.3	Crystallographic Properties	757
12.2.4	Habit or Crystal Form	758
12.2.5	Color	759
12.2.6	Diaphaneity or Transmission of Light.....	760
12.2.7	Luster	760
12.2.8	Cleavage and Parting	760
12.2.9	Fracture	761
12.2.10	Streak	761
12.2.11	Tenacity	761
12.2.12	Density and Specific Gravity	762
12.2.13	Mohs Hardness	762
12.2.14	Optical Properties.....	765
12.2.15	Static Electricity and Magnetism.....	766
12.2.16	Luminescence.....	766
12.2.17	Piezoelectricity and Pyroelectricity	766
12.2.18	Play of Colors and Chatoyancy	767
12.2.19	Radioactivity	767
12.2.20	Miscellaneous Properties	767
12.2.21	Chemical Reactivity.....	767
12.2.22	Pyrognostic Tests or Fire Assays.....	768
12.2.22.1	The Flame Test.....	768
12.2.22.2	The Fusibility Test.....	770
12.2.22.3	The Reduction on Charcoal.....	771
12.2.22.4	Tests with Cobalt Nitrate and Sulfur Iodide	771
12.2.22.5	The Closed Tube Test.....	772
12.2.22.6	The Open Tube Test	774
12.2.22.7	The Bead Tests	775
12.2.23	Heavy-Media or Sink-float Separations in Mineralogy	776
12.2.23.1	Selection of Dense Media.....	777
12.2.23.2	Common Heavy Liquids Used in Mineralogy	777
12.3	Strunz Classification of Minerals	777
12.4	Dana's Classification of Minerals.....	779
12.5	Gemstones	781
12.5.1	Diamond.....	783
12.5.1.1	Introduction.....	783
12.5.1.2	Diamond Types.....	784
12.5.1.3	Diamond Physical and Chemical Properties	784
12.5.1.4	Diamond: Origins and Occurrence.....	786

12.5.1.5	Industrial Applications	787
12.5.1.6	Diamond Prices.....	788
12.5.1.7	Treatments	788
12.5.1.8	Diamond Shaping and Valuation.....	788
12.5.2	Beryl Gem Varieties	789
12.5.2.1	Emerald.....	790
12.5.2.2	Aquamarine.....	791
12.5.2.3	Morganite	792
12.5.2.4	Heliodor.....	792
12.5.2.5	Goshenite.....	792
12.5.3	Corundum Gem Varieties	792
12.5.3.1	Ruby	794
12.5.3.2	Sapphire.....	794
12.5.4	Synthetic Gemstones	795
12.5.4.1	Synthesis from Melts	795
12.5.4.2	Synthesis from Solutions	796
12.5.4.3	Diamond Synthesis.....	797
12.6	IMA Acronyms of Rock-forming Minerals	798
12.7	Mineral and Gemstone Properties Table	800
12.8	Mineral Synonyms	868
12.9	Further Reading	878
12.9.1	Crystallography.....	878
12.9.2	Optical Mineralogy	879
12.9.3	Mineralogy.....	880
12.9.4	Industrial Minerals	881
12.9.5	Ores	881
12.9.6	Gemstones	882
12.9.7	Heavy Liquids and Mineral Dressing.....	883
13	Rocks and Meteorites	885
13.1	Introduction	885
13.2	Structure of the Earth's Interior	886
13.3	Different Type of Rocks.....	889
13.4	Igneous Rocks	890
13.4.1	Classification of Igneous Rocks.....	891
13.4.1.1	Crystals Morphology and Dimensions	892
13.4.1.2	Mineralogy.....	892
13.4.1.3	Coloration.....	894
13.4.2	Texture of Igneous Rocks.....	895
13.4.3	Chemistry of Igneous Rocks	896
13.4.4	General Classification of Igneous Rocks	899
13.4.5	Vesicular and Pyroclastic Igneous Rocks	904
13.5	Sedimentary Rocks	904
13.5.1	Sediments	906
13.5.2	Residual Sedimentary Rocks.....	906
13.5.3	Detritic or Clastic Sedimentary Rocks	907
13.5.4	Chemical Sedimentary Rocks	908
13.5.5	Biogenic Sedimentary Rocks	909
13.5.6	Chemical Composition.....	910

13.6	Metamorphic Rocks	910
13.6.1	Classification of Metamorphic Rocks	911
13.6.2	Metamorphic Grade	911
13.6.3	Metamorphic Facies	912
13.7	Ice	912
13.8	Meteorites	914
13.8.1	Definitions	914
13.8.2	Modern Classification of Meteorites	914
13.8.3	Tektites, Impactites, and Fulgurites	920
13.9	Properties of Common Rocks	921
13.10	Further Reading	925
14	Soils and Fertilizers	927
14.1	Introduction	927
14.2	History	928
14.3	Pedogenesis	929
14.3.1	Weathering and Alteration of Minerals and Clays Formation	929
14.3.2	Incorporation of Organic Matter	929
14.3.3	Mass Transfer between Horizons	930
14.3.3.1	Descending Processes	930
14.3.3.2	Ascending Processes	931
14.4	Soil Morphology	931
14.4.1	Major Horizons	931
14.4.2	Transitional Horizons	931
14.4.3	Subdivisions of Master Horizons	932
14.5	Soil Properties	936
14.5.1	Horizon Boundaries	936
14.5.2	Coloration of Soils	936
14.5.2	Soil Texture	938
14.5.4	Soil Structure	941
14.5.5	Consistency	944
14.5.6	Roots	945
14.5.7	Acidity (pH) and Effervescence	945
14.6	Soil Taxonomy	945
14.6.1	USDA Classification of Soils	945
14.6.2	FAO Classification of Soils	948
14.6.3	French Classification of Soils	954
14.6.4	ASTM Civil Engineering Classification of Soils	956
14.7	Soil Identification	957
14.8	ISO and ASTM Standards	958
14.9	Physical Properties of Common Soils	961
14.10	Fertilizers	961
14.10.1	Nitrogen Fertilizers	962
14.10.2	Phosphorus Fertilizers	963
14.10.3	Potassium Fertilizers	964
14.10.4	Role of Micronutrients in Soils	965
14.11	Further Reading	966
15	Cements, Concrete, Building Stones and Construction Materials	967
15.1	Introduction	967
15.1.1	Nonhydraulic Cements	968

15.2	Portland Cement	968
15.2.1	History	969
15.2.2	Raw Materials for Portland Cement.....	969
15.2.3	Processing of Portland Cement	970
15.2.4	Portland Cement Chemistry	971
15.2.5	Portland Cement Nomenclature	973
15.3	Aggregates.....	974
15.3.1	Coarse Aggregates.....	975
15.3.2	Fine Aggregates.....	976
15.4	Mineral Admixtures.....	976
15.5	Mortars and Concrete.....	976
15.5.1	Definitions	976
15.5.2	Degradation Processes	977
15.6	Ceramics for Construction.....	978
15.7	Building Stones.....	979
15.7.1	Limestones and Dolomites.....	979
15.7.2	Sandstones	979
15.7.3	Basalt	979
15.7.4	Granite	979
15.8	Further Reading	981
16	Timbers and Woods.....	983
16.1	General Description	983
16.2	Properties of Woods	985
16.2.1	Moisture Content	985
16.2.2	Specific Gravity and Density.....	986
16.2.3	Drying and Shrinkage.....	987
16.2.4	Mechanical Properties	987
16.2.5	Thermal Properties	988
16.2.6	Electrical Properties.....	989
16.2.7	Heating Values and Flammability.....	989
16.2.8	Durability and Decay Resistance.....	990
16.3	Properties of Hardwoods and Softwoods	990
16.4	Applications.....	997
16.5	Wood Performance in Various Corrosives.....	997
16.6	Further Reading	998
17	Fuels, Propellants and Explosives.....	999
17.1	Introduction and Classification.....	999
17.2	Combustion Characteristics.....	999
17.2.1	Enthalpy of Combustion	999
17.2.1.1	Stoichiometric Combustion Ratios.....	1001
17.2.1.2	Low (Net) and High (Gross) Heating Values	1001
17.2.1.3	Air Excess	1002
17.2.1.4	Dulong's Equations and Other Practical Equations	1002
17.2.1.5	Adiabatic Flame Temperature.....	1003
17.2.1.6	Wobbe Index for Gaseous Fuels.....	1003
17.3	Solid Fuels: Coals and Cokes.....	1004
17.4	Liquid Fuels	1008
17.5	Gaseous Fuels	1009

17.6	Prices of Common Fuels	1011
17.7	Propellants.....	1011
17.7.1	Liquid Propellants	1011
17.7.1.1	Petroleum-based Propellants	1012
17.7.1.2	Cryogenic Propellants.....	1012
17.7.1.3	Hypergolic Propellants	1012
17.7.2	Solid Propellants.....	1014
17.8	Explosives	1015
17.9	Further Reading	1018
17.9.1	Fuels and Combustion	1018
17.9.2	Propellants and Explosives	1018
18	Composite Materials.....	1019
18.1	Definitions	1019
18.2	Properties of Composites.....	1021
18.2.1	Density.....	1021
18.2.2	Tensile Strength and Elastic Moduli	1022
18.2.3	Specific Heat Capacity.....	1023
18.2.4	Thermal Conductivity	1023
18.2.5	Thermal Expansion Coefficient.....	1024
18.3	Fabrication Processes for Monofilaments.....	1024
18.4	Reinforcement Materials.....	1025
18.4.1	Glass Fibers	1025
18.4.2	Boron Fibers.....	1025
18.4.3	Carbon Fibers.....	1026
18.4.4	Polyethylene Fibers	1027
18.4.5	Polyaramide Fibers.....	1027
18.4.6	Ceramic Oxide Fibers.....	1028
18.4.7	Silicon Carbide Fibers	1028
18.5	Polymer Matrix Composites (PMCs).....	1029
18.6	Metal Matrix Composites (MMCs)	1031
18.7	Ceramic Matrix Composites (CMCs).....	1033
18.8	Carbon–Carbon Composites (CCs)	1034
18.9	Further Reading	1035
19	Gases	1037
19.1	Properties of Gases	1037
19.1.1	Pressure	1037
19.1.2	The Boyle–Mariotte Law	1039
19.1.3	Charles and Gay-Lussac’s Law	1040
19.1.4	The Avogadro–Ampere Law.....	1040
19.1.5	Normal and Standard Conditions.....	1040
19.1.6	Equation of State of Ideal Gases	1041
19.1.7	Dalton’s Law of Partial Pressure	1041
19.1.8	Equations of State of Real Gases	1042
19.1.8.1	Van der Waals Equation of State	1042
19.1.8.2	Virial Equation of State.....	1043
19.1.9	Density and Specific Gravity of Gases	1044
19.1.10	Barometric Equation	1045
19.1.11	Isobaric Coefficient of Cubic Expansion.....	1046

19.1.12	Compressibility Factor	1046
19.1.13	Isotherms of Real Gases and Critical Constants	1046
19.1.14	Critical Parameters	1047
19.1.15	The Principle of Corresponding States	1048
19.1.16	Microscopic Properties of Gas Molecules.....	1048
19.1.17	Molar and Specific Heat Capacities.....	1049
19.1.18	Dynamic and Kinematic Viscosities	1049
19.1.19	Solubility of Gases in Liquids	1050
19.1.20	Gas Permeability of Polymers.....	1051
19.1.21	Dielectric Properties of Gases, Permittivity and Breakdown Voltage .	1052
19.1.22	Psychrometry and Hygrometry.....	1054
19.1.23	Vapor Pressure.....	1054
19.1.23.1	Absolute Humidity or Humidity Ratio.....	1054
19.1.23.2	Mass Fraction of Water Vapor or Specific Humidity.....	1056
19.1.23.3	Relative Humidity.....	1056
19.1.23.4	Humid Heat.....	1056
19.1.23.5	Humid or Specific Volume	1056
19.1.23.6	Dry-Bulb Temperature.....	1057
19.1.23.7	Wet-Bulb Temperature	1057
19.1.23.8	Wet-Bulb Depression	1057
19.1.23.9	Dew Point Temperature	1057
19.1.23.10	Specific Enthalpy	1057
19.1.23.11	Latent Heat of Fusion.....	1057
19.1.23.12	Latent Heat of Vaporization	1058
19.1.23.13	Refractivity of Moist Air.....	1058
19.1.23.14	Psychrometric Charts.....	1058
19.1.23.15	Psychrometric Equations.....	1058
19.1.24	Flammability of Gases and Vapors	1062
19.1.24.1	Flammability Limits	1062
19.1.24.2	Explosive Limits.....	1062
19.1.24.3	Autoignition Temperature.....	1063
19.1.24.4	Ignition Energy	1063
19.1.24.5	Maximum Explosion Pressure.....	1063
19.1.24.6	Maximum Rate of Pressure Rise	1063
19.1.24.7	High and Low Heating Values.....	1063
19.1.25	Toxicity of Gases and Threshold Limit Averages	1064
19.2	Physico-Chemical Properties of Major Gases.....	1064
19.3	Monographies on Major Industrial Gases	1074
19.3.1	Air.....	1074
19.3.2	Nitrogen	1075
19.3.3	Oxygen	1076
19.3.4	Hydrogen	1078
19.3.5	Methane	1086
19.3.6	Carbon Monoxide	1087
19.3.7	Carbon Dioxide	1089
19.3.8	Helium and Noble Gases.....	1090
19.3.8.1	Neon.....	1091
19.3.8.2	Argon	1092
19.3.8.3	Krypton.....	1092
19.3.8.4	Xenon.....	1092
19.3.8.5	Radon.....	1092
19.4	Halocarbons.....	1093

19.5	Hydrates of Gases and Clathrates.....	1094
19.6	Materials for Drying and Purifying Gases.....	1095
	19.6.1 Drying Agents and Dessiccants.....	1095
	19.6.2 Molecular Sieves.....	1095
	19.6.3 Getters and Scavengers.....	1099
19.7	Producers and Manufacturers of Major Industrial Gases.....	1100
19.8	Further Reading.....	1101
20	Liquids.....	1103
20.1	Properties of Liquids.....	1103
	20.1.1 Density and Specific Gravity.....	1103
	20.1.2 Hydrometer Scales.....	1104
	20.1.3 Dynamic and Kinematic Viscosities.....	1104
	20.1.3.1 Shear Stress.....	1105
	20.1.3.2 Shear Rate.....	1105
	20.1.3.3 Absolute or Dynamic Viscosity.....	1105
	20.1.3.4 Kinematic Viscosity.....	1105
	20.1.3.5 Temperature Dependence of the Dynamic Viscosity.....	1106
	20.1.4 Classification of Fluids.....	1106
	20.1.5 The Hagen–Poiseuille Equation and Pressure Losses.....	1106
	20.1.5.1 Pressure Drop.....	1106
	20.1.5.2 Friction Losses.....	1106
	20.1.6 Sedimentation and Free settling.....	1109
	20.1.7 Vapor Pressure.....	1110
	20.1.8 Surface Tension, Wetting and Capillarity.....	1110
	20.1.8.1 Surface Tension.....	1110
	20.1.8.2 Temperature Dependence and Order of Magnitude of Surface Tension.....	1112
	20.1.8.3 Parachor and Walden’s Rule.....	1113
	20.1.8.4 Wetting.....	1113
	20.1.8.5 Contact Angle.....	1113
	20.1.8.6 Young’s Equation.....	1113
	20.1.8.7 Work of Cohesion, Work of Adhesion and Spreading Coefficient.....	1114
	20.1.8.8 Two Liquids and a Solid.....	1115
	20.1.8.9 Antonoff’s Rule.....	1116
	20.1.8.10 Capillarity and the Young–Laplace Equation.....	1116
	20.1.8.11 Jurin’s Law.....	1116
	20.1.8.12 Measurements of Surface Tension.....	1117
	20.1.9 Colligative Properties of Nonvolatile Solutes.....	1118
	20.1.9.1 Raoult’s Law for Boiling Point Elevation.....	1118
	20.1.9.2 Raoult’s Law and Freezing Point Depression.....	1119
	20.1.9.3 Van’t Hoff Law for Osmotic Pressure.....	1120
	20.1.10 Flammability of Liquids.....	1121
20.2	Properties of Most Common Liquids.....	1121
20.3	Monographs on Liquids.....	1121
	20.3.1 Properties of Water and Heavy Water.....	1121
	20.3.2 Properties of Liquid Acids and Bases.....	1168
	20.3.3 Properties of Heavy Liquids (Heavy Media).....	1171
	20.3.3.1 Dense Halogenated Organic Solvents.....	1171
	20.3.3.2 Dense Aqueous Solutions of Inorganic Salts.....	1172

	20.3.3.3	Low Temperature of Molten Inorganic Salts	1174
	20.3.3.4	Dense Emulsions and Suspensions	1174
	20.3.3.5	Paramagnetic Liquid Oxygen	1175
20.4		Properties of Liquid Metals	1175
20.5		Properties of Molten Salts	1177
20.6		Properties of Heat Transfer Fluids	1178
20.7		Colloidal and Dispersed Systems.....	1180
20.8		Further Reading	1180
A		Background Data for the Chemical Elements.....	1181
A.1		Periodic Chart of the Elements.....	1181
A.2		Historical Names of the Chemical Elements	1181
A.3		UNS Standard Alphabetical Designation.....	1181
A.4		Names of Transfermium Elements 101–110.....	1184
A.5		Selected Physical Properties of the Elements	1185
A.6		Geochemical Classification of the Elements.....	1185
B		NIST Thermochemical Data for Pure Substances.....	1195
C		Natural Radioactivity and Radionuclides	1201
C.1		Introduction	1201
C.2		Mononuclidic Elements.....	1202
C.3		Nuclear Decay Series.....	1202
C.4		Non-Series Primordial Radionuclides	1205
C.5		Cosmogenic Radionuclides.....	1206
C.6		NORM and TENORM	1206
C.7		Activity Calculations.....	1207
	C.7.1	Activity of a Material Containing One Natural Radionuclide	1207
	C.7.2	Activity of a Material Containing Natural U and Th.....	1207
D		Crystallography and Crystallochemistry.....	1209
D.1		Direct Space Lattice Parameters	1209
D.2		Symmetry Elements	1210
D.3		The Seven Crystal Systems	1211
D.4		Conversion of a Rhombohedral to a Hexagonal Lattice	1211
D.5		The 14 Bravais Space Lattices	1211
D.6		Characteristics of Close-Packed Arrangements.....	1211
D.7		The 32 Classes of Symmetry.....	1212
D.8		Strukturbericht Structures	1215
D.9		The 230 Space Groups.....	1221
D.10		Crystallographic Calculations.....	1228
	D.10.1	Theoretical Crystal Density.....	1228
	D.10.2	Lattice Point and Vector Position	1228
	D.10.3	Scalar Product	1228
	D.10.4	Vector or Cross Product.....	1228
	D.10.5	Mixed Product and Cell Multiplicity.....	1229
	D.10.6	Unit Cell Volume	1230
	D.10.7	Plane Angle between Lattice Planes	1230
D.11		Interplanar Spacing	1231
D.12		Reciprocal Lattice Unit Cell	1232

E	Transparent Materials for Optical Windows	1233
F	Corrosion Resistance of Materials Towards Various Corrosive Media	1237
G	Economic Data for Metals, Industrial Minerals and Electricity	1245
	G.1 Prices of Pure Elements.....	1245
	G.2 World Annual Production of Commodities.....	1248
	G.3 Economic Data for Industrial Minerals.....	1249
	G.4 Prices of Electricity in Various Countries	1254
H	Geological Time Scale	1255
I	Materials Societies	1257
	Bibliography	1269
	1 General Desk References.....	1269
	1.1 Scientific and Technical Writing.....	1269
	1.2 Chemicals	1270
	1.3 Plant Cost Estimation and Process Economics	1270
	1.4 Thermodynamic Tables	1271
	1.5 Phase Diagrams.....	1271
	2 Dictionaries and Encyclopedias	1272
	3 Comprehensive Series in Material Sciences	1272
	Index	1277