

Contents

1	Primary Inorganic Materials	1
1.1	Water	1
1.1.1	Economic Importance	1
1.1.2	Production of Potable Water	2
1.1.2.1	Break-Point Chlorination and Ozonization	3
1.1.2.2	Flocculation and Sedimentation	4
1.1.2.3	Filtration	5
1.1.2.4	Removal of Dissolved Inorganic Impurities	5
1.1.2.5	Removal of Dissolved Organic Impurities	6
1.1.2.6	Safety Chlorination	7
1.1.2.7	Removal of Nitrates	7
1.1.2.8	Removal of Traces of Chlorohydrocarbons from Groundwater	8
1.1.2.9	Production of Soft or Deionized Water	8
1.1.3	Production of Freshwater from Seawater and Brackish Water	10
1.1.3.1	Production by Multistage Flash Evaporation	10
1.1.3.2	Production using Reverse Osmosis	12
	References for Chapter 1.1: Water	13
1.2	Hydrogen	14
1.2.1	Economic Importance	14
1.2.2	Hydrogen Manufacture	15
1.2.2.1	Petrochemical Processes and Coal Gasification	15
1.2.2.2	Water Electrolysis	16
1.2.2.3	Other Manufacturing Processes for Hydrogen	17
1.2.2.4	Production of Hydrogen as a Byproduct	18
1.2.3	Hydrogen Applications	19
	References for Chapter 1.2: Hydrogen	20
1.3	Hydrogen Peroxide and Inorganic Peroxo Compounds	21
1.3.1	Economic Importance	21
1.3.1.1	Hydrogen Peroxide	21
1.3.1.2	Sodium Perborate and Sodium Carbonate Perhydrate	22
1.3.1.3	Alkali Peroxodisulfates and Sodium Peroxide	22
1.3.2	Production	23
1.3.2.1	Hydrogen Peroxide	23
1.3.2.2	Sodium Perborate	26

1.3.2.3	Sodium Carbonate Perhydrate (Sodium Percarbonate)	27
1.3.2.4	Alkali Peroxodisulfates	27
1.3.2.5	Sodium Peroxide	28
1.3.3	Applications	29
1.3.3.1	Hydrogen Peroxide, Sodium Perborate and Sodium Carbonate Perhydrate	29
1.3.3.2	Alkali Peroxodisulfates and Sodium Peroxide	30
	References for Chapter 1.3: Hydrogen Peroxide and Inorganic Peroxo Compounds	30
1.4	Nitrogen and Nitrogen Compounds	30
1.4.1	Ammonia	30
1.4.1.1	Economic Importance	31
1.4.1.2	Synthetic Ammonia Manufacture	31
1.4.1.2.1	General Information	31
1.4.1.2.2	Synthesis Gas Production	33
1.4.1.2.3	Ammonia Synthesis Catalysts	39
1.4.1.2.4	Reaction of Synthesis Gas to Ammonia	41
1.4.1.2.5	Integrated Ammonia Synthesis Plants	43
1.4.1.3	Ammonia Applications	44
	References for Chapter 1.4.1: Ammonia	45
1.4.2	Hydrazine	45
1.4.2.1	Economic Importance	45
1.4.2.2	Manufacture of Hydrazine	45
1.4.2.2.1	Raschig Process	46
1.4.2.2.2	Urea Process	48
1.4.2.2.3	Bayer Process	48
1.4.2.2.4	H ₂ O ₂ Process	50
1.4.2.3	Applications for Hydrazine	51
	References for Chapter 1.4.2: Hydrazine	52
1.4.3	Hydroxylamine	52
1.4.3.1	Economic Importance and Applications	52
1.4.3.2	Manufacture	53
1.4.3.2.1	Raschig Process	53
1.4.3.2.2	Nitrogen(II) Oxide Reduction Process	53
1.4.3.2.3	Nitrate Reduction Process (DSM/HPO-Stamicarbon)	54
	References for Chapter 1.4.3: Hydroxylamine	55
1.4.4	Nitric Acid	55
1.4.4.1	Economic Importance	55
1.4.4.2	Manufacture	56
1.4.4.2.1	Fundamentals of Nitric Acid Manufacture	56
1.4.4.2.2	Plant Types	59
1.4.4.2.3	Process Description	60
1.4.4.2.4	Manufacture of Highly Concentrated Nitric Acid.	62

1.4.4.2.5	Tail Gases from Nitric Acid Manufacture	65
1.4.4.3	Nitric Acid Applications	67
	References for Chapter 1.4.4: Nitric Acid	68
1.5	Phosphorus and Its Compounds	68
1.5.1	Phosphorus and Inorganic Phosphorus Compounds	68
1.5.1.1	Raw Materials	68
1.5.1.2	Products	70
1.5.1.2.1	Phosphoric Acid	70
1.5.1.2.2	Phosphoric Acid Salts	79
1.5.1.2.3	Phosphorus	85
1.5.1.2.4	Products Manufactured from Phosphorus	90
	References for Chapter 1.5.1: Phosphorus and Inorganic Phosphorus Compounds	95
1.5.2	Organic Phosphorus Compounds	96
1.5.2.1	Economic Importance	96
1.5.2.2	Manufacture of Organic Phosphorus Compounds	96
1.5.2.2.1	Phosphoric Acid Triesters	96
1.5.2.2.2	Phosphorus(V) Ester Acids	98
1.5.2.2.3	Thiophosphoric Acid Derivatives	99
1.5.2.2.4	Phosphorous Acid Esters	99
1.5.2.2.5	Phosphonic Acids	100
1.5.2.3	Applications of Organic Phosphorus Compounds	102
1.5.2.3.1	Phosphoric Acid Triesters	102
1.5.2.3.2	Phosphorus(V) Ester Acids	103
1.5.2.3.3	Thiophosphoric Acid Derivatives	103
1.5.2.3.4	Phosphorous Acid Esters	104
1.5.2.3.5	Phosphonic Acids	105
	References for Chapter 1.5.2: Organic Phosphorus Compounds.	105
1.6	Sulfur and Sulfur Compounds	105
1.6.1	Sulfur	105
1.6.1.1	Occurrence	105
1.6.1.2	Economic Importance	106
1.6.1.3	Production	106
1.6.1.3.1	From Elemental Sulfur Deposits	106
1.6.1.3.2	From Hydrogen Sulfide and Sulfur Dioxide	107
1.6.1.3.3	From Pyrites	108
1.6.1.4	Applications	108
1.6.2	Sulfuric Acid	108
1.6.2.1	Economic Importance	108
1.6.2.2	Starting Materials for Sulfuric Acid Manufacture	109
1.6.2.2.1	Sulfuric Acid from Sulfur Dioxide	109

1.6.2.2.2	Sulfuric Acid from Waste Sulfuric Acid and Metal Sulfates	115
1.6.2.3	Applications of Sulfuric Acid	120
1.6.3	100% Sulfur Dioxide	120
1.6.4	100% Sulfur Trioxide	122
1.6.5	Disulfur Dichloride	123
1.6.6	Sulfur Dichloride	123
1.6.7	Thionyl Chloride	123
1.6.8	Sulfuryl Chloride	124
1.6.9	Chlorosulfonic Acid	125
1.6.10	Fluorosulfonic Acid	125
1.6.11	Sulfurous Acid Salts	125
1.6.12	Sodium Thiosulfate, Ammonium Thiosulfate	126
1.6.13	Sodium Dithionite and Sodium Hydroxymethanesulfinate	127
1.6.14	Hydrogen Sulfide	129
1.6.15	Sodium Sulfide	130
1.6.16	Sodium Hydrogen Sulfide	130
1.6.17	Carbon Disulfide	131
	References for Chapter 1.6: Sulfur and Sulfur Compounds	132
1.7	Halogens and Halogen Compounds	133
1.7.1	Fluorine and Fluorine Compounds	133
1.7.1.1	Economic Importance and Applications	133
1.7.1.2	Raw Materials	133
1.7.1.2.1	Fluorspar	134
1.7.1.2.2	Fluorapatite	135
1.7.1.3	Fluorine and Inorganic Fluorides	135
1.7.1.3.1	Fluorine	135
1.7.1.3.2	Hydrogen Fluoride	137
1.7.1.3.3	Aluminum Fluoride	140
1.7.1.3.4	Sodium Aluminum Hexafluoride, Cryolite	142
1.7.1.3.5	Alkali Fluorides	143
1.7.1.3.6	Hexafluorosilicates	144
1.7.1.3.7	Uranium Hexafluoride	144
1.7.1.3.8	Boron Trifluoride and Tetrafluoroboric Acid	145
1.7.1.3.9	Sulfur Hexafluoride	145
1.7.1.4	Organofluoro Compounds by Electrochemical Fluorination	146
	References for Chapter 1.7.1: Fluorine and Fluorine Compounds.	148

1.7.2	Chloralkali Electrolysis, Chlorine and Sodium Hydroxide	149
1.7.2.1	Economic Importance	149
1.7.2.2	Starting Materials	150
1.7.2.3	Manufacturing Processes	152
1.7.2.3.1	Mercury Process	152
1.7.2.3.2	Diaphragm Process	155
1.7.2.3.3	Membrane Process	157
1.7.2.3.4	Evaluation of the Mercury, Diaphragm and Membrane Processes . . .	161
1.7.2.4	Applications for Chlorine and Sodium Hydroxide	162
1.7.2.4.1	Chlorine	162
1.7.2.4.2	Sodium Hydroxide	162
	References for Chapter 1.7.2: Chloralkali Electrolysis, Chlorine, Sodium Hydroxide	163
1.7.3	Hydrochloric Acid — Hydrogen Chloride	164
1.7.3.1	Manufacture of Hydrogen Chloride	164
1.7.3.2	Economic Importance of Hydrogen Chloride and Hydrochloric Acid . .	165
1.7.3.3	Electrolysis of Aqueous Hydrochloric Acid Solutions.	166
1.7.3.4	Nonelectrolytic Processes for the Manufacture of Chlorine from Hydrogen Chloride	167
	References for Chapter 1.7.3: Hydrochloric Acid — Hydrogen Chloride	168
1.7.4	Chlorine-Oxygen Compounds	168
1.7.4.1	Economic Importance	168
1.7.4.2	Manufacture of Chlorine-Oxygen Compounds	169
1.7.4.2.1	Hypochlorite	169
1.7.4.2.2	Chlorites.	172
1.7.4.2.3	Chlorates	173
1.7.4.2.4	Perchlorates and Perchloric Acid.	175
1.7.4.2.5	Chlorine Dioxide	175
1.7.4.3	Applications of Chlorine-Oxygen Compounds	177
	References for Chapter 1.7.4: Chlorine-Oxygen Compounds	178
1.7.5	Bromine and Bromine Compounds	178
1.7.5.1	Natural Deposits and Economic Importance	178
1.7.5.2	Manufacture of Bromine and Bromine Compounds	179
1.7.5.2.1	Bromine	179
1.7.5.2.2	Hydrogen Bromide	181
1.7.5.2.3	Alkali Bromides, Calcium Bromide, Zinc Bromide	181
1.7.5.2.4	Alkali Bromates	182
1.7.5.3	Applications for Bromine and Bromine Compounds	182
	References for Chapter 1.7.5: Bromine and Bromine Compounds. . .	184
1.7.6	Iodine and Iodine Compounds.	184
1.7.6.1	Economic Importance	184
1.7.6.2	Manufacture of Iodine and Iodine Compounds	185
1.7.6.2.1	Iodine	185
1.7.6.2.2	Hydrogen Iodide	186

1.7.6.2.3	Alkali Iodides	187
1.7.6.2.4	Alkali Iodates	187
1.7.6.3	Applications for Iodine and Iodine Compounds	187
	References for Chapter 1.7.6: Iodine and Iodine Compounds	188
2	Mineral Fertilizers	189
2.1	Phosphorus-Containing Fertilizers	189
2.1.1	Economic Importance	189
2.1.1.1	General Information	189
2.1.1.2	Importance of Superphosphate	190
2.1.1.3	Importance of Triple Superphosphate	190
2.1.1.4	Importance of Ammonium Phosphates	191
2.1.1.5	Importance of Nitrophosphates	191
2.1.1.6	Importance and Manufacture of Thermal (Sinter, Melt) and Basic Slag (Thomas) Phosphates	191
2.1.2	Manufacture of Phosphorus-Containing Fertilizers	192
2.1.2.1	Superphosphate	192
2.1.2.2	Triple Superphosphate	194
2.1.2.3	Ammonium Phosphates	194
2.1.2.4	Nitrophosphates	197
2.2	Nitrogen-Containing Fertilizers	199
2.2.1	Economic Importance	199
2.2.1.1	Importance of Ammonium Sulfate	200
2.2.1.2	Importance of Ammonium Nitrate	200
2.2.1.3	Importance of Urea	201
2.2.2	Manufacture of Nitrogen-Containing Fertilizers	201
2.2.2.1	Ammonium Sulfate	201
2.2.2.2	Ammonium Nitrate	203
2.2.2.3	Urea	204
2.3	Potassium-Containing Fertilizers	208
2.3.1	Occurrence of Potassium Salts	208
2.3.2	Economic Importance of Potassium-Containing Fertilizers	209
2.3.3	Production of Potassium-Containing Fertilizers	210
2.3.3.1	Potassium Chloride	210
2.3.3.2	Potassium Sulfate	212
2.3.3.3	Potassium Nitrate	213
	References for Chapter 2: Mineral Fertilizers	213

3	Metals and their Compounds	215
3.1	Alkali and Alkaline Earth Metals and their Compounds	215
3.1.1	Alkali Metals and their Compounds	215
3.1.1.1	General Information	215
3.1.1.2	Lithium and its Compounds	215
3.1.1.2.1	Natural Deposits and Commercial Importance	215
3.1.1.2.2	Metallic Lithium	216
3.1.1.2.3	Lithium Compounds	217
3.1.1.3	Sodium and its Compounds	218
3.1.1.3.1	General Information	218
3.1.1.3.2	Metallic Sodium	218
3.1.1.3.3	Sodium Carbonate	219
3.1.1.3.4	Sodium Hydrogen Carbonate	222
3.1.1.3.5	Sodium Sulfate	223
3.1.1.3.6	Sodium Hydrogen Sulfate	225
3.1.1.3.7	Sodium Borates	226
3.1.1.4	Potassium and its Compounds	228
3.1.1.4.1	General Information	228
3.1.1.4.2	Metallic Potassium	228
3.1.1.4.3	Potassium Hydroxide	229
3.1.1.4.4	Potassium Carbonate	229
	References for Chapter 3.1.1: Alkali Metals and their Compounds . . .	230
3.1.2	Alkaline Earth Metals and their Compounds	231
3.1.2.1	General Information	231
3.1.2.2	Beryllium and its Compounds	232
3.1.2.3	Magnesium and its Compounds	233
3.1.2.3.1	Natural Deposits	233
3.1.2.3.2	Metallic Magnesium	233
3.1.2.3.3	Magnesium Carbonate	235
3.1.2.3.4	Magnesium Oxide	236
3.1.2.3.5	Magnesium Chloride	237
3.1.2.3.6	Magnesium Sulfate	238
3.1.2.4	Calcium and its Compounds	239
3.1.2.4.1	Natural Deposits	239
3.1.2.4.2	Metallic Calcium	239
3.1.2.4.3	Calcium Carbonate	240
3.1.2.4.4	Calcium Oxide and Calcium Hydroxide	240
3.1.2.4.5	Calcium Chloride	241
3.1.2.4.6	Calcium Carbide	242
3.1.2.5	Strontium and its Compounds	243
3.1.2.6	Barium and its Compounds	244
3.1.2.6.1	Natural Deposits and Economic Importance	244
3.1.2.6.2	Barium Carbonate	244

3.1.2.6.3	Barium Sulfide	245
3.1.2.6.4	Barium Sulfate	245
	References for Chapter 3.1.2: Alkaline Earth Metals and their Compounds	246
3.2	Aluminum and its Compounds	247
3.2.1	General Information	247
3.2.2	Occurrence	247
3.2.3	Aluminum Metal	248
3.2.3.1	Economic Importance	248
3.2.3.2	Manufacture	248
3.2.3.3	Aluminum Applications	249
3.2.4	Aluminum Oxide and Aluminum Hydroxide	250
3.2.4.1	Economic Importance	250
3.2.4.2	Manufacture	251
3.2.4.3	Applications	252
3.2.5	Aluminum Sulfate	253
3.2.6	Aluminum Chloride	253
3.2.7	Sodium Aluminate	254
	References for Chapter 3.2: Aluminum and its Compounds	254
3.3	Chromium Compounds and Chromium	255
3.3.1	Chromium Compounds	255
3.3.1.1	Economic Importance	255
3.3.1.2	Raw Material: Chromite	257
3.3.1.3	Manufacture of Chromium Compounds	258
3.3.1.3.1	Chromite Roasting to Alkali Chromates	258
3.3.1.3.2	Alkali Dichromates	261
3.3.1.3.3	Chromium(VI) Oxide ("Chromic Acid")	263
3.3.1.3.4	Chromium(III) Oxide	263
3.3.1.3.5	Basic Chromium(III) Salts (Chrome-Tanning Agents)	264
3.3.1.4	Applications for Chromium Compounds	265
3.3.2	Chromium Metal	266
3.3.2.1	Economic Importance	266
3.3.2.2	Manufacture of Chromium Metal	266
3.3.2.2.1	Chemical Reduction	266
3.3.2.2.2	Electrochemical Reduction of Chrome Alum	267
3.3.2.2.3	Electrochemical Reduction of Chromium(VI) Oxide	268
	References for Chapter 3.3: Chromium Compounds and Chromium	268
3.4	Silicon and its Inorganic Compounds	269
3.4.1	Elemental Silicon	269
3.4.1.1	General Information and Economic Importance	269
3.4.1.2	Manufacture	270

3.4.1.2.1	Metallurgical Grade Silicon and Ferrosilicon	270
3.4.1.2.2	Electronic Grade (EG) Silicon	271
3.4.1.3	Silicon Applications	273
3.4.2	Inorganic Silicon Compounds :	274
	References for Chapter 3.4: Silicon and its Inorganic Compounds	276
3.5 ⁱ	Manganese Compounds and Manganese	277
3.5.1	Manganese Compounds	277
3.5.1.1	Economic Importance	277
3.5.1.2	Raw Materials	277
3.5.1.3	Manufacture of Manganese Compounds	279
3.5.1.3.1	Manganese(II) Compounds	279
3.5.1.3.2	Manganese(II,III) Oxide (Mn_3O_4) and Manganese(III) Oxide (Mn_2O_3)	281
3.5.1.3.3	Manganese(IV) Oxide	281
3.5.1.3.4	Potassium Permanganate	284
3.5.1.4	Applications for Manganese Compounds	286
3.5.2	Manganese — Electrochemical Manufacture, Importance and Applications	287
	References for Chapter 3.5: Manganese Compounds and Manganese	288
4	Silicones	289
4.1	Structure and Properties	289
4.2	Economic Importance	290
4.3	Silicone Manufacture	291
4.3.1	Synthesis of the Starting Materials	291
4.3.1.1	(Chloro)methylsilanes	291
4.3.1.2	(Chloro)phenyl- and (Chloro)methylphenylsilanes	292
4.3.1.3	Other Industrially Important Silanes	293
4.3.2	Linear Poly(organosiloxanes)	294
4.3.2.1	Synthesis of Oligomeric Precursors	294
4.3.2.2	Synthesis of High Molecular Weight Linear Poly(dimethylsiloxanes)	295
4.3.3	Manufacture of Branched Poly(organosiloxanes)	297
4.4	Industrial Silicone Products	298
4.4.1	Silicone Oils	298
4.4.2	Products Manufactured from Silicone Oils	299
4.4.3	Silicone Rubbers	299
4.4.3.1	Room Temperature Vulcanizable Single Component Silicone Rubbers	299
4.4.3.2	Room Temperature Vulcanizable Two Component Silicone Rubbers	301
4.4.3.3	Hot Vulcanizable Peroxide Crosslinked Silicone Rubbers	302

4.4.3.4	Hot Vulcanizable Addition Crosslinkable Silicone Rubbers	302
4.4.3.5	Hot Vulcanizable Liquid Rubbers	303
4.4.3.6	Silicone Rubber Properties	303
4.4.4	Silicone Resins	304
4.4.5	Silicone Copolymers, Block Copolymers and Graft Copolymers	305
	References for Chapter 4: Silicones	306
5	Inorganic Solids	307
5.1	Silicate Products	307
5.1.1	Glass	307
5.1.1.1	Economic Importance	307
5.1.1.2	General Information	307
5.1.1.3	Glass Compositions	308
5.1.1.4	Glass Manufacture	310
5.1.1.4.1	Glass Raw Materials	310
5.1.1.4.2	Melting Process	311
5.1.1.4.3	Melting Furnaces	312
5.1.1.5	Molding	314
5.1.1.6	Glass Properties and Applications	316
5.1.1.7	Sol-Gel Process	317
	References for Section 5.1.1: Glass	318
5.1.2	Alkali Silicates	319
5.1.2.1	General Information and Economic Importance	319
5.1.2.2	Manufacture of Alkali Silicates	319
5.1.2.3	Applications	321
	References for Section 5.1.2: Alkali Silicates	321
5.1.3	Zeolites	321
5.1.3.1	Economic Importance	321
5.1.3.2	Zeolite Types	322
5.1.3.3	Natural Zeolites	325
5.1.3.4	Manufacture of Synthetic Zeolites	325
5.1.3.4.1	From Natural Raw Materials	325
5.1.3.4.2	From Synthetic Raw Materials	325
5.1.3.4.3	By Cation Exchange of Synthetic Zeolites	327
5.1.3.5	Pelletization of Zeolites	327
5.1.3.6	Dehydration of Zeolites	327
5.1.3.7	Applications for Zeolites	328
5.1.3.7.1	As Ion Exchangers	328
5.1.3.7.2	As an Adsorption Agent	328
5.1.3.7.3	For Separation Processes	329
5.1.3.7.4	As Catalysts	329
5.1.3.7.5	Miscellaneous Applications	330
	References for Section 5.1.3: Zeolites	330

5.2	Inorganic Fibers	330
5.2.1	General Information	330
5.2.2	Naturally Occurring Inorganic Fibers — Asbestos Fibers.	333
5.2.2.1	Deposits, Extraction and Economic Importance	333
5.2.2.2	Properties of Asbestos Fibers	335
5.2.2.3	Applications of Asbestos Fibers	337
	References for Section 5.2.2: Asbestos Fibers.	342
5.2.3	Synthetic Inorganic Fibers	342
5.2.3.1	Textile Glass Fibers	342
5.2.3.1.1	General Information	342
5.2.3.1.2	Economic Importance	342
5.2.3.1.3	Classification of Textile Glass Fibers	343
5.2.3.1.4	Manufacture	343
5.2.3.1.5	Applications	347
5.2.3.2	Optical Fibers	348
5.2.3.3	Mineral Fiber Insulating Materials.	349
5.2.3.3.1	General Information and Economic Importance	349
5.2.3.3.2	Manufacture	350
5.2.3.3.3	Applications	354
	References for Sections 5.2.3.1 to 5.2.3.3: Mineral Fiber Insulation Ma- terials	355
5.2.3.4	Carbon Fibers	356
5.2.3.4.1	Properties	356
5.2.3.4.2	Manufacture and Applications	358
5.2.3.4.3	Economic Importance	362
5.2.3.5	Aluminum Oxide Fibers	362
5.2.3.6	Boron Fibers	364
5.2.3.7	SiC-Fibers and SiC-Coated Carbon Fibers	365
5.2.3.8	Metal Fibers	367
5.2.3.8.1	Manufacture	367
5.2.3.8.2	Properties, Applications and Economic Importance	368
5.2.3.9	Whiskers and Miscellaneous Synthetic Short Fibers	369
	References for Sections 5.2.3.4 to 5.2.3.9: Other Inorganic Fibers.	370
5.3	Construction Materials	371
5.3.1	General Information	371
5.3.2	Lime	372
5.3.2.1	Economic Importance	372
5.3.2.2	Raw Materials	372
5.3.2.3	Quicklime	373
5.3.2.4	Slaked Lime	374
5.3.2.4.1	Wet Slaking of Quicklime	375
5.3.2.4.2	Dry Slaking of Quicklime	375

5.3.2.4.3	Lime Hydrate from Calcium Carbide	376
5.3.2.5	Steam-Hardened Construction Materials	376
5.3.2.6	Applications for Lime	377
5.3.3	Cement	378
5.3.3.1	Economic Importance	378
5.3.3.2	Cement Compositions	378
5.3.3.3	Portland Cement	378
5.3.3.3.1	Raw Materials	378
5.3.3.3.2	Composition of Portland Cement Clinkers	379
5.3.3.3.3	Manufacture of Portland Cement	379
5.3.3.3.4	Applications for Portland Cement	383
5.3.3.4	Slag Cement	383
5.3.3.5	Pozzolan Cements	384
5.3.3.6	Alumina Cement	384
5.3.3.7	Asbestos Cement	385
5.3.3.8	Miscellaneous Cement Types	385
5.3.3.9	Processes in the Solidification of Cement	386
5.3.4	Gypsum	389
5.3.4.1	Economic Importance	389
5.3.4.2	Modifications of Calcium Sulfate	389
5.3.4.3	Natural Gypsum	392
5.3.4.4	Natural Anhydrite	393
5.3.4.5	Synthetic Anhydrite from Hydrofluoric Acid Manufacture	393
5.3.4.6	Synthetic Gypsum	394
5.3.4.6.1	From the Manufacture and Purification of Organic Acids	394
5.3.4.6.2	Synthetic Gypsum from Flue Gas Desulfurization	394
5.3.4.6.3	Synthetic Gypsum from Phosphoric Acid Production	395
5.3.4.7	Processes in the Setting of Plaster	397
5.3.5	Coarse Ceramic Products for the Construction Industry	398
5.3.6	Expanded Products	399
5.3.6.1	General Information	399
5.3.6.2	Expanded Products from Clays and Shales	399
5.3.6.2.1	Raw Materials	399
5.3.6.2.2	Gas-Forming Reactions in the Manufacture of Expanded Products	401
5.3.6.2.3	Manufacture of Expanded Products	402
5.3.6.3	Expanded Products from Glasses (Foam Glass)	404
5.3.6.4	Applications for Expanded Products	404
	References for Chapter 5.3: Construction Materials	405
5.4	Enamels	406
5.4.1	General Information	406
5.4.2	Classification of Enamels	406
5.4.3	Frit Manufacture And Enameling Procedure	409
5.4.3.1	Survey	409

5.4.3.2	Manufacture of Enamel Frits	410
5.4.3.2.1	Raw Materials	410
5.4.3.2.2	Smelting of Frits	410
5.4.3.3	Conversion of the Frits into Coatable Forms.	411
5.4.3.4	Enamel Application on Sheet Steel.	412
5.4.3.4.1	Wet Application Processes	412
5.4.3.4.2	Dry Application Processes	412
5.4.3.5	Firing of Enamels	413
5.4.4	Applications for Enamel	413
	References for Chapter 5.4: Enamels.	414
5.5	Ceramics	414
5.5.1	General Information	414
5.5.2	Classification of Ceramic Products	415
5.5.3	General Process Steps in the Manufacture of Ceramics	417
5.5.4	Silicate Ceramic Materials	417
5.5.4.1	Composition and Raw Materials of Clay Ceramic Products	417
5.5.4.2	Extraction and Treatment of Raw Kaolin	419
5.5.4.3	Manufacture of Clay Ceramic Batches	420
5.5.4.4	Forming Processes	421
5.5.4.4.1	Casting Processes	422
5.5.4.4.2	Plastic Forming	423
5.5.4.4.3	Forming by Powder Pressing	423
5.5.4.5	Drying Processes	425
5.5.4.6	Firing of Ceramics	425
5.5.4.6.1	Physical-Chemical Processes	425
5.5.4.6.2	Firing Conditions	426
5.5.4.6.3	Glazes	427
5.5.4.7	Properties and Applications of Clay Ceramic Products	428
5.5.4.7.1	Fine Earthenware	428
5.5.4.7.2	Stoneware	429
5.5.4.7.3	Porcelain	429
5.5.4.7.4	Rapidly Fired Porcelain	430
5.5.4.8	Economic Importance of Clay Ceramic Products.	431
5.5.5	Refractory Ceramics	431
5.5.5.1	Definition and Classification	431
5.5.5.2	Silica Products	434
5.5.5.3	Fireclay Products	434
5.5.5.4	Alumina-Rich Products	435
5.5.5.5	Basic Products	436
5.5.5.6	Speciality Refractory Products	437
5.5.5.7	Refractory Silicon Carbide Products	437
5.5.5.8	Economic Importance	438

5.5.6	Oxide Ceramic Products	439
5.5.6.1	General Information	439
5.5.6.2	Aluminum Oxide	440
5.5.6.3	Zirconium(IV) Oxide	442
5.5.6.4	Beryllium Oxide	443
5.5.6.5	Uranium Oxide and Thorium Oxide	443
5.5.6.6	Other Oxidic Ceramics	444
5.5.6.7	Electro- and Magneto-Ceramics	445
5.5.6.7.1	Titanates	445
5.5.6.7.2	Ferrites	446
5.5.7	Nonoxide Ceramics	449
5.5.7.1	Economic Importance	450
5.5.7.2	Manufacturing Processes for Silicon Carbide	450
5.5.7.3	Fine Ceramic Silicon Carbide Products	451
5.5.7.4	Fine Silicon Nitride Ceramic Products	452
5.5.7.5	Manufacture and Properties of Boron Carbide	453
5.5.7.6	Manufacture and Properties of Boron Nitride	454
5.5.7.7	Aluminum Nitride	455
	References for Chapter 5.5: Ceramics	455
5.6	Metallic Hard Materials	457
5.6.1	General Information	457
5.6.2	General Manufacturing Processes and Properties of Metal Carbides	458
5.6.3	Carbides of the Subgroup of the IVth Group	460
5.6.3.1	Titanium Carbide	460
5.6.3.2	Zirconium Carbide and Hafnium Carbide	460
5.6.4	Carbides of the Subgroup of the Vth Group	461
5.6.4.1	Vanadium Carbide	461
5.6.4.2	Niobium Carbide and Tantalum Carbide	461
5.6.5	Carbides of the Subgroup of the VIth Group	461
5.6.5.1	Chromium Carbide	461
5.6.5.2	Molybdenum Carbide	462
5.6.5.3	Tungsten Carbide	462
5.6.5.4	Cemented Carbides Based on Tungsten Carbide	463
5.6.6	Thorium Carbide and Uranium Carbide	464
5.6.7	Metal Nitrides	464
5.6.8	Metal Borides	466
5.6.9	Metal Silicides	467
	References for Chapter 5.6: Metallic Hard Materials	468
5.7	Carbon Modifications	468
5.7.1	Introduction	468

5.7.2	Diamond	468
5.7.2.1	Economic Importance	469
5.7.2.2	Mining of Natural Diamonds	470
5.7.2.3	Manufacture of Synthetic Diamonds	470
5.7.2.4	Properties and Applications	472
5.7.3	Natural Graphite	472
5.7.3.1	Economic Importance	472
5.7.3.2	Deposits and Mining	473
5.7.3.3	Properties and Applications	474
5.7.4	Mass-Produced Synthetic Carbon and Synthetic Graphite	476
5.7.4.1	Economic Importance	476
5.7.4.2	General Information about Manufacture	476
5.7.4.3	Manufacture of Synthetic Carbon	477
5.7.4.3.1	Raw Materials	477
5.7.4.3.2	Processing	478
5.7.4.3.3	Densification and Molding	479
5.7.4.3.4	Carbonization	479
5.7.4.4	Graphitization of Synthetic Carbon	480
5.7.4.4.1	General Information	480
5.7.4.4.2	Acheson Process	480
5.7.4.4.3	Castner Process	481
5.7.4.4.4	Other Graphitization Processes	481
5.7.4.4.5	Purification Graphitization	482
5.7.4.5	Impregnation and Processing of Carbon and Graphite Articles	482
5.7.4.6	Properties and Applications	483
5.7.5	Special Types of Carbon and Graphite	484
5.7.5.1	Pyrolytic Carbon and Pyrolytic Graphite	484
5.7.5.2	Glassy Carbon and Foamed Carbon	486
5.7.5.3	Graphite Foils and Membranes	487
5.7.6	Carbon Black	488
5.7.6.1	Economic Importance	488
5.7.6.2	Manufacture	489
5.7.6.2.1	General Information	489
5.7.6.2.2	Pyrolysis Processes in the Presence of Oxygen	490
5.7.6.2.3	Pyrolysis Processes in the Absence of Oxygen	493
5.7.6.2.4	Posttreatment	494
5.7.6.3	Properties and Applications	495
5.7.7	Activated Carbon	498
5.7.7.1	Economic Importance	498
5.7.7.2	Manufacture	498
5.7.7.2.1	General Information	498
5.7.7.2.2	Chemical Activation Processes	499
5.7.7.2.3	Gas Activation Processes	500

5.7.7.3	Reactivation and Regeneration of Used Activated Carbons.	502
5.7.7.4	Applications for Activated Carbon.	503
	References for Chapter 5.7: Carbon Modifications	504
5.8	Fillers	505
5.8.1	General Information	505
5.8.2	Economic Importance	506
5.8.3	Natural Fillers	507
5.8.3.1	Silicon-Based Fillers	507
5.8.3.2	Other Natural Fillers	508
5.8.3.3	Beneficiation of Natural Fillers	508
5.8.4	Synthetic Fillers	509
5.8.4.1	Silicas and Silicates	509
5.8.4.1.1	Pyrogenic Silicas	509
5.8.4.1.2	Wet Chemically Manufactured Silicas and Silicates	510
5.8.4.1.3	Posttreatment of Silicas	511
5.8.4.1.4	Glass	512
5.8.4.1.5	Cristobalite	512
5.8.4.2	Aluminum Hydroxide	512
5.8.4.3	Carbonates	513
5.8.4.4	Sulfates	514
5.8.4.5	Other Synthetic Fillers	515
5.8.5	Properties and Applications	515
	References for Chapter 5.8: Fillers	518
5.9	Inorganic Pigments	518
5.9.1	General Information and Economic Importance	518
5.9.2	White Pigments	522
5.9.2.1	General Information	522
5.9.2.2	Titanium Dioxide Pigments	523
5.9.2.2.1	Economic Importance	523
5.9.2.2.2	Raw Materials for TiO ₂ Pigments	523
5.9.2.2.3	Manufacturing Processes for TiO ₂ Pigments	525
5.9.2.2.4	Applications for TiO ₂ Pigments	529
5.9.2.3	Lithopone and Zinc Sulfide Pigments	530
5.9.2.4	Zinc Oxide White Pigments	531
5.9.2.4.1	Manufacture	531
5.9.2.4.2	Applications	532
5.9.3	Colored Pigments	532
5.9.3.1	Iron Oxide Pigments	532
5.9.3.1.1	Natural Iron Oxide Pigments	533
5.9.3.1.2	Synthetic Iron Oxide Pigments	534

5.9.3.2	Chromium(III) Oxide Pigments	539
5.9.3.2.1	Manufacture	539
5.9.3.2.2	Properties and Applications of Chromium(III) Oxide	541
5.9.3.3	Chromate and Molybdate Pigments	541
5.9.3.4	Mixed Metal Oxide Pigments, Stains and Oxides	543
5.9.3.5	Cadmium Pigments	546
5.9.3.6	Ferrocyanate Pigments	547
5.9.3.7	Ultramarine Pigments	548
5.9.4	Corrosion Protection Pigments	549
5.9.5	Lustrous Pigments	551
5.9.5.1	Metallic Pigments	552
5.9.5.2	Nacreous Pigments	552
5.9.5.3	Interference Pigments	552
5.9.6	Luminescent Pigments	553
5.9.7	Magnetic Pigments	555
5.9.7.1	General Information and Properties	555
5.9.7.2	Manufacture of Magnetic Pigments	556
	References for Chapter 5.9: Inorganic Pigments	558
6	Nuclear Fuel Cycle	559
6.1	Economic Importance of Nuclear Energy	559
6.2	General Information about the Nuclear Fuel Cycle	562
6.3	Availability of Uranium and Thorium	563
6.4	Nuclear Reactor Types	565
6.4.1	General Information	565
6.4.2	Light Water Reactors	566
6.4.2.1	Boiling Water Reactors	567
6.4.2.2	Pressurized Water Reactors	567
6.4.3	Graphite-Moderated Reactors	567
6.4.3.1	Gas-Cooled Reactors	568
6.4.3.2	Light Water-Cooled Reactors	569
6.4.4	Heavy Water Reactors	569
6.4.5	Fast Breeder Reactors	570
6.5	Nuclear Fuel Production	571
6.5.1	Production of Uranium Concentrates	571
6.5.1.1	Uranium from Uranium Ores	571
6.5.1.1.1	Leaching Processes	572
6.5.1.1.2	Separation of Uranium from the Leaching Solutions	573

6.5.1.1.3	Manufacture of Marketable Uranium Compounds ("Yellow Cake") . . .	574
6.5.1.2	Uranium from Phosphates	575
6.5.1.3	Uranium from Seawater	576
6.5.2	Conversion of Uranium Concentrates to Uranium Hexafluoride . . .	576
6.5.2.1	General Information	576
6.5.2.2	Wet Process for UF ₆ Manufacture	577
6.5.2.3	Dry Process for UF ₆ Manufacture	578
6.5.3	²³⁵ U-Enrichment	579
6.5.4	Reconversion of UF ₆ into Nuclear Fuel	580
6.5.4.1	Conversion into Uranium(IV) Oxide	580
6.5.4.1.1	Wet Processes	581
6.5.4.1.2	Dry Process	582
6.5.4.1.3	Manufacture of UO ₂ Pellets	582
6.5.4.2	Other Uranium Nuclear Fuels	582
6.5.5	Fuel Element Manufacture.	584
6.6	Disposal of Waste from Nuclear Power Stations	584
6.6.1	General Information	584
6.6.2	Stages in Nuclear Waste Disposal	585
6.6.2.1	Interim Storage of Irradiated Fuel Elements	585
6.6.2.2	Reprocessing of Spent Fuel Elements	586
6.6.2.3	Further Processing of Uranium and Plutonium Solutions.	590
6.6.2.4	Conditioning of Radioactive Waste	590
6.6.2.5	Permanent Storage of Radioactive Waste.	593
6.6.3	Direct Permanent Storage of Irradiated Fuel Elements	594
	References for Chapter 6: Nuclear Fuel Cycle	594
	Company Abbreviations Index	597
	Subject Index	603