

# 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 Ozonation 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 Activated Charcoal Treatment 7
  - 1.1.2.6 Safety Chlorination 8
  - 1.1.2.7 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 11

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 Electrolysis of Water 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 18

References for Chapter 1.2: Hydrogen 19

### 1.3 Hydrogen Peroxide and Inorganic Peroxo Compounds 20

- 1.3.1 Economic Importance 20
  - 1.3.1.1 Hydrogen Peroxide 20
  - 1.3.1.2 Sodium Perborate and Sodium Carbonate Perhydrate 20
  - 1.3.1.3 Alkali Peroxodisulfates and Sodium Peroxide 21
- 1.3.2 Production 21
  - 1.3.2.1 Hydrogen Peroxide 21
  - 1.3.2.2 Sodium Perborate 24
  - 1.3.2.3 Sodium Carbonate Perhydrate 25
  - 1.3.2.4 Alkali Peroxodisulfate 26
  - 1.3.2.5 Sodium Peroxide 26



1.3.3 Applications 27  
 1.3.3.1 Hydrogen Peroxide, Sodium Perborate and Sodium Carbonate Perhydrate 27  
 1.3.3.2 Alkali Peroxodisulfates and Sodium Peroxide 28  
 References for Chapter 1.3: Hydrogen Peroxide and Inorganic Peroxo Compounds 28

**1.4 Nitrogen and Nitrogen Compounds 29**

1.4.1 Ammonia 29  
 1.4.1.1 Economic Importance 29  
 1.4.1.2 Synthetic Ammonia Manufacture 29  
 1.4.1.2.1 General Information 29  
 1.4.1.2.2 Ammonia Synthesis Catalysts 30  
 1.4.1.2.3 Synthesis Gas Production 32  
 1.4.1.2.4 Conversion of Synthesis Gas to Ammonia 39  
 1.4.1.2.5 Integrated Ammonia Synthesis Plants 41  
 1.4.1.3 Ammonia Applications 43  
 References for Chapter 1.4: Nitrogen and Nitrogen Compounds 43

1.4.2 Hydrazine 43  
 1.4.2.1 Economic Importance 43  
 1.4.2.2 Manufacture of Hydrazine 44  
 1.4.2.2.1 Raschig Process 44  
 1.4.2.2.2 Urea Process 45  
 1.4.2.2.3 Bayer Process 46  
 1.4.2.2.4 H<sub>2</sub>O<sub>2</sub> Process 47  
 1.4.2.3 Applications of Hydrazine 48  
 References for Chapter 1.4.2: Hydrazine 49

1.4.3 Hydroxylamine 50  
 1.4.3.1 Economic Importance and Applications 50  
 1.4.3.2 Manufacture 50  
 1.4.3.2.1 Raschig Process 51  
 1.4.3.2.2 Nitrogen(II) Oxide Reduction Process 51  
 1.4.3.2.3 Nitrate Reduction Process (DSM/HPO-Stamicarbon) 52  
 References for Chapter 1.4.3: Hydroxylamine 53

1.4.4 Nitric Acid 53  
 1.4.4.1 Economic Importance 53  
 1.4.4.2 Manufacture 53  
 1.4.4.2.1 Fundamentals of Nitric Acid Manufacture 53  
 1.4.4.2.2 Plant Types 57  
 1.4.4.2.3 Process Description 58  
 1.4.4.2.4 Manufacture of Highly Concentrated Nitric Acid 59  
 1.4.4.2.5 Tail Gases from Nitric Acid Manufacture 62  
 1.4.4.3 Nitric Acid Applications 64  
 References for Chapter 1.4.4: Nitric Acid 65

**1.5 Phosphorus and its Compounds 65**

1.5.1 Phosphorus and Inorganic Phosphorus Compounds 65  
 1.5.1.1 Raw Materials 65



1.5.1.2	Products	67
1.5.1.2.1	Phosphoric Acid	67
1.5.1.2.2	Phosphoric Acid Salts	75
1.5.1.2.3	Phosphorus	80
1.5.1.2.4	Products Manufactures from Phosphorus	85
References for Chapter 1.5.1: Phosphorus and Inorganic Phosphorus Compounds		90
1.5.2	Organophosphorus Compounds	91
1.5.2.1	Neutral Phosphoric Acid Esters	91
1.5.2.2	Phosphoric Ester Acids	94
1.5.2.3	Dithiophosphoric Ester Acids	94
1.5.2.4	Neutral Esters of Thio- and Dithio-Phosphoric Acids	95
1.5.2.5	Neutral Di- and Triesters of Phosphorous Acid	97
1.5.2.6	Phosphonic Acids	99
References for Chapter 1.5.2: Organophosphorus Compounds		101
<b>1.6</b>	<b>Sulfur and Sulfur Compounds</b>	<b>101</b>
1.6.1	Sulfur	101
1.6.1.1	Occurrence	101
1.6.1.2	Economic Importance	102
1.6.1.2.1	Sulfur from Elemental Sulfur Deposits	102
1.6.1.2.2	Sulfur from Hydrogen Sulfide and Sulfur Dioxide	102
1.6.1.2.3	Sulfur from Pyrites	103
1.6.1.3	Economic Importance	104
1.6.1.4	Applications	104
1.6.2	Sulfuric Acid	104
1.6.2.1	Economic Importance	104
1.6.2.2	Starting Materials for Sulfuric Acid Manufacture	105
1.6.2.2.1	Sulfuric Acid from Sulfur Dioxide	105
1.6.2.2.2	Sulfuric Acid from Waste Sulfuric Acid and Metal Sulfates	113
1.6.2.3	Applications of Sulfuric Acid	115
1.6.3	100% Sulfur Dioxide	116
1.6.4	100% Sulfur Trioxide	117
1.6.5	Disulfur Dichloride	118
1.6.6	Sulfur Dichloride	118
1.6.7	Thionyl chloride	119
1.6.8	Sulfuryl Chloride	119
1.6.9	Chlorosulfonic Acid	120
1.6.10	Fluorosulfonic Acid	120
1.6.11	Sulfurous Acid Salts	120
1.6.12	Sodium Thiosulfate, Ammonium Thiosulfate	121
1.6.13	Sodium Dithionite and Sodium Hydroxymethanesulfinate	122
1.6.14	Hydrogen Sulfide	124
1.6.15	Sodium Sulfide	124
1.6.16	Sodium Hydrogen Sulfide	125
1.6.17	Carbon Disulfide	126
References for Chapter 1.6: Sulfur and Sulfur Compounds		126



- 1.7 Halogens and Halogen Compounds 127**
- 1.7.1 Fluorine and Fluorine Compounds 127
    - 1.7.1.1 Fluorspar 127
      - 1.7.1.1.1 Fluorspar Extraction 128
      - 1.7.1.1.2 Qualities and Utilization of Fluorspar 128
      - 1.7.1.1.3 Fluorapatite 130
    - 1.7.1.2 Fluorine and Inorganic Fluorides 130
      - 1.7.1.2.1 Fluorine 130
      - 1.7.1.2.2 Hydrogen Fluoride 132
      - 1.7.1.2.3 Aluminum Fluoride 138
      - 1.7.1.2.4 Sodium Aluminum Hexafluoride (Cryolite) 140
      - 1.7.1.2.5 Alkali Fluorides 141
      - 1.7.1.2.6 Hexafluorosilicates 142
      - 1.7.1.2.7 Uranium Hexafluoride 142
      - 1.7.1.2.8 Boron Trifluoride and Tetrafluoroboric Acid 142
      - 1.7.1.2.9 Sulfur Hexafluoride 143
    - 1.7.1.3 Organofluoro Compounds by Electrochemical Fluorination 144
  - References for Chapter 1.7.1: Halogens and Halogen Compounds 145
  - 1.7.2 Chloralkali Electrolysis, Chlorine and Sodium Hydroxide 146
    - 1.7.2.1 Economic Importance 146
    - 1.7.2.2 Starting Materials 148
    - 1.7.2.3 Manufacturing Processes 151
      - 1.7.2.3.1 Mercury Process 152
      - 1.7.2.3.2 Diaphragm Process 154
      - 1.7.2.3.3 Membrane Process 157
      - 1.7.2.3.4 Evaluation of Mercury, Diaphragm and Membrane Processes 158
    - 1.7.2.4 Applications of Chlorine and Sodium Hydroxide 159
      - 1.7.2.4.1 Chlorine 159
      - 1.7.2.4.2 Sodium Hydroxide 160
  - References for Chapter 1.7.2: Chloralkali-Electrolysis 161
  - 1.7.3 Hydrochloric Acid – Hydrogen Chloride 162
    - 1.7.3.1 Manufacture of Hydrogen Chloride 162
    - 1.7.3.2 Economic Importance of Hydrogen Chloride and Hydrochloric Acid 163
    - 1.7.3.3 Electrolysis of Hydrochloric Acid 163
    - 1.7.3.4 Non-Electrolytic Processes for the Manufacture of Chlorine from Hydrogen Chloride 164
  - References for Chapter 1.7.3: Hydrochloric Acid – Hydrogen Chloride 165
  - 1.7.4 Chlorine-Oxygen Compounds 166
    - 1.7.4.1 Economic Importance 166
    - 1.7.4.2 Manufacture of Chlorine-Oxygen Compounds 167
      - 1.7.4.2.1 Hypochlorite 167
      - 1.7.4.2.2 Chlorites 170
      - 1.7.4.2.3 Chlorates 170
      - 1.7.4.2.4 Perchlorates and Perchloric Acid 172
      - 1.7.4.2.5 Chlorine Dioxide 173
    - 1.7.4.3 Applications of Chlorine-Oxygen Compounds 174



- References for Chapter 1.7.4: Chlorine-Oxygen Compounds 175
- 1.7.5 Bromine and Bromine Compounds 175
- 1.7.5.1 Natural Deposits and Economic Importance 175
- 1.7.5.2 Manufacture of Bromine and Bromine Compounds 176
- 1.7.5.2.1 Bromine 176
- 1.7.5.2.2 Hydrogen Bromide 178
- 1.7.5.2.3 Alkali Bromides, Calcium Bromide, Zinc Bromide 179
- 1.7.5.2.4 Alkali Bromates 179
- 1.7.5.3 Applications for Bromine and Bromine Compounds 179
- References for Chapter 1.7.5: Bromine and Bromine Compounds 181
- 1.7.6 Iodine and Iodine Compounds 181
- 1.7.6.1 Economic Importance 181
- 1.7.6.2 Manufacture of Iodine and Iodine Compounds 182
- 1.7.6.2.1 Iodine 182
- 1.7.6.2.2 Hydrogen Iodide 183
- 1.7.6.2.3 Alkali Iodides 183
- 1.7.6.2.4 Alkali Iodates 184
- 1.7.6.3 Applications of Iodine and Iodine Compounds 184
- References for Chapter 1.7.6: Iodine and Iodine Compounds 185

## 2 Mineral Fertilizers 187

- 2.1 Phosphorus-Containing Fertilizers 187**
- 2.1.1 Economic Importance 187
- 2.1.1.1 General Information 187
- 2.1.1.2 Importance of Superphosphate 188
- 2.1.1.3 Importance of Triple Superphosphate 188
- 2.1.1.4 Importance of Ammonium Phosphates 189
- 2.1.1.5 Importance of Nitrophosphates 189
- 2.1.1.6 Importance and Manufacture of Thermal (Sinter, Melt) and Basic Slag (Thomas) Phosphates 189
- 2.1.2 Manufacture of Phosphorus-Containing Fertilizers 190
- 2.1.2.1 Superphosphate 190
- 2.1.2.2 Triple Superphosphate 191
- 2.1.2.3 Ammonium Phosphates 192
- 2.1.2.4 Nitrophosphates 195
- 2.2 Nitrogen-Containing Fertilizers 196**
- 2.2.1 Economic Importance 196
- 2.2.1.1 General Information 196
- 2.2.1.2 Importance of Ammonium Sulfate 197
- 2.2.1.3 Importance of Ammonium Nitrate 197
- 2.2.1.4 Importance of Urea 198
- 2.2.2 Manufacture of Nitrogen-Containing Fertilizers 199
- 2.2.2.1 Ammonium Sulfate 199



- 2.2.2.2 Ammonium Nitrate 200
- 2.2.2.3 Urea 201

**2.3 Potassium-Containing Fertilizers 205**

- 2.3.1 Occurrence of Potassium Salts 205
- 2.3.2 Economic Importance of Potassium-Containing Fertilizers 206
- 2.3.3 Manufacture of Potassium-Containing Fertilizers 208
  - 2.3.3.1 Potassium Chloride 208
  - 2.3.3.2 Potassium Sulfate 210
  - 2.3.3.3 Potassium Nitrate 210

References for Chapter 2: Mineral Fertilizers 211

**3 Metals and their Compounds 213**

**3.1 Alkali and Alkaline Earth Metals and their Compounds 213**

- 3.1.1 Alkali Metals and their Compounds 213
  - 3.1.1.1 General Information 213
  - 3.1.1.2 Lithium and its Compounds 213
    - 3.1.1.2.1 Natural Deposits and Economic Importance 213
    - 3.1.1.2.2 Metallic Lithium 214
    - 3.1.1.2.3 Lithium Compounds 214
  - 3.1.1.3 Sodium and its Compounds 216
    - 3.1.1.3.1 General Information 216
    - 3.1.1.3.2 Metallic Sodium 217
    - 3.1.1.3.3 Sodium Carbonate 218
    - 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 225
  - 3.1.1.4 Potassium and its Compounds 227
    - 3.1.1.4.1 General Information 227
    - 3.1.1.4.2 Metallic Potassium 227
    - 3.1.1.4.3 Potassium Hydroxide 227
    - 3.1.1.4.4 Potassium Carbonate 228

References for Chapter 3.1.1: Alkali Metals and their Compounds 229

- 3.1.2 Alkaline Earth Metals and their Compounds 230
  - 3.1.2.1 General Information 230
  - 3.1.2.2 Beryllium and its Compounds 231
  - 3.1.2.3 Magnesium and its Compounds 231
    - 3.1.2.3.1 Natural Deposits 231
    - 3.1.2.3.2 Metallic Magnesium 232
    - 3.1.2.3.3 Magnesium Carbonate 234
    - 3.1.2.3.4 Magnesium Oxide 235
    - 3.1.2.3.5 Magnesium Chloride 236
    - 3.1.2.3.6 Magnesium Sulfate 237



3.1.2.4	Calcium and its Compounds	237
3.1.2.4.1	Natural Deposits	237
3.1.2.4.2	Metallic Calcium	238
3.1.2.4.3	Calcium Carbonate	238
3.1.2.4.4	Calcium Oxide and Calcium Hydroxide	239
3.1.2.4.5	Calcium Chloride	240
3.1.2.4.6	Calcium Carbide	240
3.1.2.5	Strontium and its Compounds	242
3.1.2.6	Barium and its Compounds	242
3.1.2.6.1	Natural Deposits and Economic Importance	242
3.1.2.6.2	Barium Carbonate	243
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		245

<b>3.2</b>	<b>Aluminum and its Compounds</b>	<b>246</b>
3.2.1	General Information	246
3.2.2	Natural Deposits	247
3.2.3	Metallic Aluminum	248
3.2.3.1	Economic Importance	248
3.2.3.2	Manufacture	248
3.2.3.3	Applications	249
3.2.4	Aluminum Oxide and Aluminum Hydroxide	250
3.2.4.1	Economic Importance	250
3.2.4.2	Manufacture	250
3.2.4.3	Applications	251
3.2.5	Aluminum Sulfate	252
3.2.5.1	Economic Importance	252
3.2.5.2	Manufacture	252
3.2.5.3	Applications	253
3.2.6	Aluminum Chloride	253
3.2.6.1	Economic Importance	253
3.2.6.2	Manufacture	253
3.2.6.3	Applications	254
3.2.7	Sodium Aluminate	254

References for Chapter 3.2: Aluminum and its Compounds 255

<b>3.3</b>	<b>Chromium Compounds and Chromium</b>	<b>255</b>
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 Digestion to Alkali Chromates	258
3.3.1.3.2	Alkali Dichromates	260
3.3.1.3.3	Chromium(VI) Oxide (“Chromic Acid”)	262
3.3.1.3.4	Chromium(III) Oxide	264



- 3.3.1.3.5 Basic Chromium(III) Salts (Chrome Tanning Agents) 265
- 3.3.1.4 Applications for Chromium Compounds 266
- 3.3.2 Metallic Chromium 266
- 3.3.2.1 Economic Importance 266
- 3.3.2.2 Manufacture of Chromium Metal 267
- 3.3.2.2.1 Chemical Reduction 267
- 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 Ferrosilicon and Metallurgical Grade Silicon 270
- 3.4.1.2.2 Electronic Grade Silicon (Semiconductor Silicon) 272
- 3.4.1.3 Silicon Applications 278
- 3.4.2 Inorganic Silicon Compounds 279
- References for Chapter 3.4: Silicon and its Inorganic Compounds 281

### **3.5 Manganese Compounds and Manganese 282**

- 3.5.1 Manganese Compounds 282
- 3.5.1.1 Economic Importance 282
- 3.5.1.2 Raw Materials 283
- 3.5.1.3 Manufacture of Manganese Compounds 284
- 3.5.1.3.1 Manganese(II) Compounds 284
- 3.5.1.3.2 Manganese(II,III) Oxide ( $Mn_3O_4$ ) and Manganese(III) Oxide ( $Mn_2O_3$ ) 286
- 3.5.1.3.3 Manganese(IV) Oxide 286
- 3.5.1.3.4 Potassium Permanganate 289
- 3.5.1.4 Applications of Manganese Compounds 292
- 3.5.2 Manganese - Electrochemical Manufacture, Importance and Applications 292
- References for Chapter 3.5: Manganese Compounds and Manganese 293

## **4 Organo-Silicon Compounds 295**

### **4.1 Industrially Important Organo-Silicon Compounds, Nomenclature 295**

### **4.2 Industrially Important Silanes 296**

- 4.2.1 Organohalosilanes 296
- 4.2.2 Industrial Important Silicon-functional Organo-Silanes 298
- 4.2.2.1 Organoalkoxysilanes 299
- 4.2.2.2 Acyloxysilanes 300
- 4.2.2.3 Oximino- and Aminoxy-Silanes 300
- 4.2.2.4 Amidosilanes, Silazanes 301
- 4.2.2.5 Organohydrogensilanes 301



- 4.2.3 Organofunctional Silanes 302
- 4.2.3.1 Alkenylsilanes 302
- 4.2.3.2 Halo-organosilanes 303
- 4.2.3.3 Organoaminosilanes 303
- 4.2.3.4 Organomercaptosilanes, Organosulfidosilanes 304
- 4.2.3.5 Other Organofunctional Silanes 304
- References for Chapter 4.1 and 4.2: Organo-Silicon Compounds 305

### 4.3 Silicones 305

- 4.3.1 Structure and Properties, Nomenclature 305
- 4.3.2 Economic Importance 306
- 4.3.3 Linear and Cyclic Polyorganosiloxanes 307
  - 4.3.3.1 Manufacture 307
  - 4.3.3.2 Hydrolysis 307
  - 4.3.3.3 Methanolysis 309
  - 4.3.3.4 Cyclization 310
  - 4.3.3.5 Polymerization 310
  - 4.3.3.6 Polycondensation 312
  - 4.3.3.7 Industrial Realization of Polymerization 313
- 4.3.4 Manufacture of Branched Polysiloxanes 314

### 4.4 Industrial Silicone Products 307

- 4.4.1 Silicone Oils 307
- 4.4.2 Products Manufactured from Silicone Oils 316
- 4.4.3 Silicone Rubbers 317
  - 4.4.3.1 Room Temperature Vulcanizable Single Component Silicone Rubbers 317
  - 4.4.3.2 Two Component Room Temperature Vulcanizable Silicone Rubbers 319
  - 4.4.3.3 Hot Vulcanizable Peroxide Crosslinkable Silicone Rubbers 320
  - 4.4.3.4 Hot Vulcanizable Addition Crosslinkable Silicone Rubbers 320
  - 4.4.3.5 Properties of Silicone Rubber 322
- 4.4.4 Silicone Resins 322
- 4.4.5 Silicone Copolymers, Block Copolymers and Graft Copolymers 323

References for Chapters 4.3 and 4.4: Silicones 324

## 5 Inorganic Solids 325

### 5.1 Silicate Products 325

- 5.1.1 Glass 325
  - 5.1.1.1 Economic Importance 325
  - 5.1.1.2 Structure 325
  - 5.1.1.3 Glass Composition 326
  - 5.1.1.4 Glass Manufacture 329
    - 5.1.1.4.1 Glass Raw Materials 329
    - 5.1.1.4.2 Melting Process 331
    - 5.1.1.4.3 Melting Furnaces 332



5.1.1.5	Forming	334
5.1.1.6	Glass Properties and Applications	336
References for Chapter 5.1.1: Glass 337		
5.1.2	Alkali Silicates	338
5.1.2.1	General and Economic Importance	338
5.1.2.2	Manufacture of Alkali Silicates	338
5.1.2.3	Applications	340
References for Chapter 5.1.2: Alkali Silicates 340		
5.1.3	Zeolites	340
5.1.3.1	Economic Importance	340
5.1.3.2	Zeolite Types	341
5.1.3.3	Natural Zeolites	344
5.1.3.4	Manufacture of Synthetic Zeolites	344
5.1.3.4.1	From Natural Raw Materials	344
5.1.3.4.2	From Synthetic Raw Materials	344
5.1.3.4.3	Modification of Synthetic Zeolites by Ion Exchange	346
5.1.3.5	Forming of Zeolites	346
5.1.3.6	Dehydration of Zeolites	347
5.1.3.7	Applications for Zeolites	347
5.1.3.7.1	As Ion Exchangers	347
5.1.3.7.2	As an Adsorption Agent	347
5.1.3.7.3	For Separation Processes	348
5.1.3.7.4	As Catalysts	349
5.1.3.7.5	Miscellaneous Applications	349
References for Chapter 5.1.3: Zeolites 350		
<b>5.2</b>	<b>Inorganic Fibers</b>	<b>351</b>
5.2.1	Introduction	351
5.2.1.1	Definitions, Manufacture and Processing	351
5.2.1.2	Economic Importance	352
5.2.1.3	Properties	352
5.2.1.4	Classification and Applications	354
5.2.1.5	Physiological Aspects	354
5.2.2	Asbestos Fibers	356
5.2.2.1	General and Economic Importance	356
5.2.2.2	Occurrence and Extraction	359
5.2.2.3	Applications of Asbestos Fibers	361
5.2.3	Textile Glass Fibers	364
5.2.3.1	General and Economic Importance	364
5.2.3.2	Manufacture	366
5.2.3.3	Applications	369
5.2.4	Optical Fibers	370
5.2.5	Mineral Fiber Insulating Materials	372
5.2.5.1	General Information and Economic Importance	372
5.2.5.2	Manufacture	373
5.2.5.3	Applications	377



5.2.6 Carbon Fibers 377

5.2.6.1 General Information and Economic Importance 377

5.2.6.2 Manufacture and Applications 380

5.2.7 Metal Fibers 384

5.2.7.1 Steel and Tungsten Fibers 384

5.2.7.2 Boron Fibers 386

5.2.8 Ceramic Reinforcing Fibers 388

5.2.8.1 General information and Economic Importance 388

5.2.8.2 Oxide Fibers 389

5.2.8.3 Non-oxide Fibers 391

5.2.8.4 Whiskers 394

References for Section 5.2: Inorganic Fibers 395

**5.3 Construction Materials 396**

5.3.1 General Introduction 396

5.3.2 Lime 397

5.3.2.1 Economic Importance 397

5.3.2.2 Raw Materials 398

5.3.2.3 Quicklime 398

5.3.2.4 Slaked Lime 400

5.3.2.4.1 Wet Slaking of Quicklime 400

5.3.2.4.2 Dry Slaking of Quicklime 401

5.3.2.4.3 Lime Hydrate from Calcium Carbide 401

5.3.2.5 Steam-Hardened Construction Materials 402

5.3.2.6 Applications of Lime 402

5.3.3 Cement 403

5.3.3.1 Economic Importance 403

5.3.3.2 Composition of Cements 404

5.3.3.3 Portland Cement 405

5.3.3.3.1 Raw Materials 405

5.3.3.3.2 Composition of Portland Cement Clinkers 405

5.3.3.3.3 Manufacture of Portland Cement 405

5.3.3.3.4 Applications of Portland Cement 409

5.3.3.4 Slag Cement 409

5.3.3.5 Pozzolan Cements 410

5.3.3.6 Alumina Cement 411

5.3.3.7 Asbestos Cement 411

5.3.3.8 Miscellaneous Cement Types 411

5.3.3.9 Processes in the Solidification of Cement 412

5.3.4 Gypsum 415

5.3.4.1 Economic Importance 415

5.3.4.2 Modifications of Calcium Sulfate 416

5.3.4.3 Natural Gypsum 418

5.3.4.4 Natural Anhydrite 420

5.3.4.5 Fluoroanhydrite 420

5.3.4.6 Byproduct Gypsum 420



- 5.3.4.6.1 Byproduct Gypsum from the Manufacture and Purification of Organic Acids 420
- 5.3.4.6.2 Byproduct Gypsum from Flue Gas Desulfurization 421
- 5.3.4.6.3 Phosphogypsum 421
- 5.3.4.7 Processes in the Setting of Plaster 423
- 5.3.5 Coarse Ceramic Products for the Construction Industry 424
- 5.3.6 Expanded Products 425
  - 5.3.6.1 General Information 425
  - 5.3.6.2 Expanded Products from Clays and Shales 425
    - 5.3.6.2.1 Raw Materials 425
    - 5.3.6.2.2 Gas-forming Reactions in the Manufacture of Expanded Products 428
    - 5.3.6.2.3 Manufacture of Expanded Products 429
  - 5.3.6.3 Expanded Products from Glasses (Foam Glass) 430
  - 5.3.6.4 Applications of Expanded Products 430
- References for Chapter 5.3: Construction Materials 431

## **5.4 Enamel 430**

- 5.4.1 General Information 432
- 5.4.2 Classification of Enamels 433
- 5.4.3 Enamel Frit Manufacture 437
  - 5.4.3.1 Raw Materials 437
  - 5.4.3.2 Smelting of Frits 437
- 5.4.4 Enameling 438
  - 5.4.4.1 Production of Coatable Systems 438
  - 5.4.4.2 Coating Processes 439
    - 5.4.4.2.1 Wet Application Processes 439
    - 5.4.4.2.2 Dry Application Processes 440
  - 5.4.4.3 Stoving of Enamels 441
  - 5.4.4.5 Applications of Enamel 442
- References for Chapter 5.4: Enamel 442

## **5.5 Ceramics 443**

- 5.5.1 General Information 443
- 5.5.2 Classification of Ceramic Products 443
- 5.5.3 General Process Steps in the Manufacture of Ceramics 444
- 5.5.4 Clay Ceramic Products 445
  - 5.5.4.1 Composition and Raw Materials 445
  - 5.5.4.2 Extraction and Treatment of Raw Kaolin 447
  - 5.5.4.3 Manufacture of Clay Ceramic Batches 447
    - 5.5.4.4 Forming Processes 448
      - 5.5.4.4.1 Casting Processes 449
      - 5.5.4.4.2 Plastic Forming 450
      - 5.5.4.4.3 Forming by Powder Pressing 451
      - 5.5.4.4.5 Drying Processes 452
      - 5.5.4.4.6 Firing of Ceramics 452
      - 5.5.4.6.1 Physical-Chemical Processes 452



5.5.4.6.2	Firing Conditions	454
5.5.4.6.3	Glazes	455
5.5.4.7	Properties and Applications of Clay Ceramic Products	455
5.5.4.7.1	Fine Earthenware	455
5.5.4.7.2	Stoneware	456
5.5.4.7.3	Porcelain	456
5.5.4.7.4	Rapidly Fired Porcelain	457
5.5.4.8	Economic Importance of Clay Ceramic Products	458
5.5.5	Specialty Ceramic Products	458
5.5.5.1	Oxide Ceramics	458
5.5.5.1.1	General Information	458
5.5.5.1.2	Aluminum Oxide	460
5.5.5.1.3	Zirconium Oxide	461
5.5.5.1.4	Beryllium Oxide	462
5.5.5.1.5	Uranium Oxide and Thorium Oxide	462
5.5.5.1.6	Other Oxide Ceramics	463
5.5.5.2	Electro- and Magneto-Ceramics	464
5.5.5.2.1	Titanates	464
5.5.5.2.2	Ferrites	465
5.5.5.3	Refractory Ceramics	468
5.5.5.3.1	Definition and Classification	468
5.5.5.3.2	Alumina-Rich Products	470
5.5.5.3.3	Fireclay Products	470
5.5.5.3.4	Silicate Products	471
5.5.5.3.5	Basic Products	472
5.5.5.3.6	Specialty Refractory Products	473
5.5.5.3.7	Economic Importance	473
5.5.5.4	Nonoxide Ceramics	474
5.5.5.4.1	Economic Importance	475
5.5.5.4.2	Manufacturing Processes for Silicon Carbide	475
5.5.5.4.3	Refractory Silicon Carbide Products	477
5.5.5.4.4	Fine Ceramic Silicon Carbide Products	477
5.5.5.4.5	Fine Silicon Nitride Ceramic Products	478
5.5.5.4.6	Manufacture and Properties of Boron Carbide	480
5.5.5.4.7	Manufacture and Properties of Boron Nitride	481
5.5.5.4.8	Manufacture and Properties of Aluminum Nitride	482
References for Chapter 5.5: Ceramics		482
<b>5.6</b>	<b>Metallic Hard Materials</b>	<b>484</b>
5.6.1	General Information	484
5.6.2	General Manufacturing Processes and Properties of Metal Carbides	485
5.6.3	Carbides of the Subgroup of the IVth Group	487
5.6.3.1	Titanium Carbide	487
5.6.3.2	Zirconium Carbide and Hafnium Carbide	488
5.6.4	Carbides of the Subgroup of the Vth Group	488
5.6.4.1	Vanadium Carbide	488



- 5.6.4.2 Niobium Carbide and Tantalum Carbide 488
- 5.6.5 Carbides of the Subgroup of the VIth Group 489
  - 5.6.5.1 Chromium Carbide 489
  - 5.6.5.2 Molybdenum Carbide 489
  - 5.6.5.3 Tungsten Carbide 489
  - 5.6.5.4 Cemented Carbides Based on Tungsten Carbide 490
- 5.6.6 Thorium Carbide and Uranium Carbide 491
- 5.6.7 Metal Nitrides 492
- 5.6.8 Metal Borides 493
- 5.6.9 Metal Silicides 494
- References for Chapter 5.6: Metallic Hard Materials 495

## **5.7 Carbon Modifications 496**

- 5.7.1 Introduction 496
- 5.7.2 Diamond 496
  - 5.7.2.1 Economic Importance 496
  - 5.7.2.2 Mining of Natural Diamonds 497
  - 5.7.2.3 Manufacture of Synthetic Diamonds 498
  - 5.7.2.4 Properties and Applications 500
- 5.7.3 Natural Graphite 500
  - 5.7.3.1 Economic Importance 500
  - 5.7.3.2 Natural Deposits and Mining 502
  - 5.7.3.3 Properties and Applications 503
- 5.7.4 Large Scale Production of Synthetic Carbon and Synthetic Graphite 505
  - 5.7.4.1 Economic Importance 505
  - 5.7.4.2 General Information about Manufacture 505
    - 5.7.4.3 Manufacture of Synthetic Carbon 506
      - 5.7.4.3.1 Raw Materials 506
      - 5.7.4.3.2 Processing 507
      - 5.7.4.3.3 Densification and Forming 507
      - 5.7.4.3.4 Carbonization 508
    - 5.7.4.4 Graphitization of Synthetic Carbon 509
      - 5.7.4.4.1 General Information 509
      - 5.7.4.4.2 Acheson Process 509
      - 5.7.4.4.3 Castner Process 510
      - 5.7.4.4.4 Other Graphitization Processes 510
      - 5.7.4.4.5 Purification Graphitization 511
    - 5.7.4.5 Impregnation and Processing of Carbon and Graphite Articles 511
    - 5.7.4.6 Properties and Applications 512
  - 5.7.5 Special Types of Carbon and Graphite 513
    - 5.7.5.1 Pyrolytic Carbon and Pyrolytic Graphite 513
    - 5.7.5.2 Glassy Carbon and Foamed Carbon 515
    - 5.7.5.3 Graphite Foils and Membranes 516
  - 5.7.6 Carbon Black 517
    - 5.7.6.1 Economic Importance 518
    - 5.7.6.2 Manufacture 518



5.7.6.2.1	General Information	518
5.7.6.2.2	Pyrolysis Processes in the Presence of Oxygen	519
5.7.6.2.3	Pyrolysis Processes in the Absence of Oxygen	522
5.7.6.2.4	Posttreatment	523
5.7.6.3	Properties and Applications	524
5.7.7	Activated Carbon	527
5.7.7.1	Economic Importance	527
5.7.7.2	Manufacture	528
5.7.7.2.1	General Information	8
5.7.7.2.2	Activated Carbon by "Chemical Activation"	529
5.7.7.2.3	Activated Carbon by "Gas Activation"	530
5.7.7.3	Reactivation and Regeneration of Used Activated Carbon	532
5.7.7.4	Applications of Activated Carbon	532
References for Chapter 5.7: Carbon Modifications		534

## 5.8 Fillers 535

5.8.1	General Information	535
5.8.2	Economic Importance	536
5.8.3	Natural Fillers	536
5.8.3.1	Silicon-Based Fillers	536
5.8.3.2	Other Natural Fibers	538
5.8.3.3	Beneficiation of Natural Fillers	538
5.8.4	Synthetic Fillers	539
5.8.4.1	Silicas and Silicates	539
5.8.4.1.1	Pyrogenic Silicas	539
5.8.4.1.2	Wet Chemically Manufactured Silicas and Silicates	540
5.8.4.1.3	Posttreatment of Silicas	541
5.8.4.1.4	Glasses	542
5.8.4.1.5	Cristobalite	542
5.8.4.2	Aluminum Hydroxide	542
5.8.4.3	Carbonates	543
5.8.4.4	Sulfates	544
5.8.4.5	Other Synthetic Fillers	545
5.8.5	Properties and Applications	545
References for Chapter 5.8: Fillers		546

## 5.9 Inorganic Pigments 548

5.9.1	General Information and Economic Importance	548
5.9.2	White Pigments	552
5.9.2.1	General Information	552
5.9.2.2	Titanium Dioxide Pigments	553
5.9.2.2.1	Economic Importance	553
5.9.2.2.2	Raw Materials for TiO <sub>2</sub> Pigments	553
5.9.2.2.3	Manufacturing Processes for TiO <sub>2</sub> Pigments	555
5.9.2.2.4	Applications for TiO <sub>2</sub> Pigments	558
5.9.2.3	Lithopone and Zinc Sulfide Pigments	559



- 5.9.2.4 Zinc Oxide White Pigments 560
    - 5.9.2.4.1 Manufacture 560
    - 5.9.2.4.2 Applications 561
  - 5.9.3 Colored Pigments 561
    - 5.9.3.1 Iron Oxide Pigments 561
      - 5.9.3.1.1 Natural Iron Oxide Pigments 561
      - 5.9.3.1.2 Synthetic Iron Oxide Pigments 563
    - 5.9.3.2 Chromium(III) Oxide Pigments 567
      - 5.9.3.2.1 Manufacture 567
      - 5.9.3.2.2 Properties and Applications of Chromium(III) Oxide 569
    - 5.9.3.3 Chromate and Molybdate Pigments 570
    - 5.9.3.4 Mixed-Metal Oxide Pigments and Ceramic Colorants 571
    - 5.9.3.5 Cadmium Pigments 573
    - 5.9.3.6 Cyanide Iron Blue Pigments 575
    - 5.9.3.7 Ultramarine Pigments 577
  - 5.9.4 Corrosion Protection Pigments 578
  - 5.9.5 Luster Pigments 580
    - 5.9.5.1 Metal Effect Pigments 580
    - 5.9.5.2 Nacreous Pigments 581
    - 5.9.5.3 Interference Pigments 581
  - 5.9.6 Luminescent Pigments 581
  - 5.9.7 Magnetic Pigments 582
    - 5.9.7.1 General Information and Properties 582
    - 5.9.7.2 Manufacture of Magnetic Pigments 584
- References for Chapter 5.9: Inorganic Pigments 586

## **6 Nuclear Fuel Cycle 587**

- 6.1 Economic Importance of Nuclear Energy 587
- 6.2 General Information about the Nuclear Fuel Cycle 591
- 6.3 Availability of Uranium 592
- 6.4 Nuclear Reactor Types 594
  - 6.4.1 General Information 594
  - 6.4.2 Light-water Reactors 594
    - 6.4.2.1 Boiling Water Reactors 594
    - 6.4.2.2 Pressurized Water Reactors 595
  - 6.4.3 Graphite-Moderated Reactors 595
    - 6.4.3.1 Gas-Cooled 595
    - 6.4.3.2 Light-Water Cooled 597
  - 6.4.4 Heavy-Water Reactors 597
  - 6.4.5 Fast Breeder Reactors 598



- 6.5 Nuclear Fuel Production 599**
  - 6.5.1 Production of Uranium Concentrates (“Yellow Cake”) 600
    - 6.5.1.1 Uranium from Uranium Ores 600
      - 6.5.1.1.1 Leaching Processes 600
      - 6.5.1.1.2 Separation of Uranium from the Leaching Solutions 602
      - 6.5.1.1.3 Manufacture of Marketable Uranium Compounds (“Yellow Cake”) 603
    - 6.5.1.2 Uranium from Phosphate Ores and Wet Phosphoric Acid 605
    - 6.5.1.3 Uranium from Seawater 606
  - 6.5.2 Conversion of Uranium Concentrates to Uranium Hexafluoride 607
    - 6.5.2.1 General Information 607
    - 6.5.2.2 Wet Process for Uranium(VI) Fluoride Manufacture 607
    - 6.5.2.3 Dry Process for Uranium(VI) Fluoride Manufacture 609
  - 6.5.3  $^{235}\text{U}$ -Enrichment 609
  - 6.5.4 Reconversion of Uranium(VI) Fluoride into Nuclear Fuel 610
    - 6.5.4.1 Into Uranium(IV) Oxide 610
      - 6.5.4.1.1 General Information 610
      - 6.5.4.1.2 Uranium(IV) Oxide by Wet Processes 611
      - 6.5.4.1.3 Uranium(IV) Oxide by the Dry (IDR) Process 612
      - 6.5.4.1.4 Manufacture of Uranium(IV) Oxide Pellets 612
    - 6.5.4.2 Other Uranium Nuclear Fuels 613
  - 6.5.5 Fuel Element Manufacture 614
- 6.6 Disposal of Waste from Nuclear Power Stations 615**
  - 6.6.1 General Information 615
  - 6.6.2 Stages in Nuclear Waste Disposal 617
    - 6.6.2.1 Interim Storage of Spent Fuel Elements 617
    - 6.6.2.2 Reprocessing of Spent Fuel Elements 617
    - 6.6.2.3 Further Processing of Uranium and Plutonium Solutions 620
    - 6.6.2.4 Treatment of Radioactive Waste 621
    - 6.6.2.5 Permanent Storage of Radioactive Waste 623
- References for Chapter 6: Nuclear Fuel Cycle 624

Company Abbreviations Index 627

Subject Index 631