

INDUSTRIAL INORGANIC CHEMICALS: Production and Uses



Edited by R. Thompson

Industrial Inorganic Chemicals: Production and Uses

Edited by
R. Thompson, CBE, FEd
Consultant



THE ROYAL
SOCIETY OF
CHEMISTRY

ISBN 0-85404-514-7

A catalogue record of this book is available from the British Library.

© The Royal Society of Chemistry 1995

All Rights Reserved

No part of this book may be reproduced or transmitted in any form or by any means – graphic, electronic, including photocopying, recording, taping, or information storage and retrieval systems – without written permission from The Royal Society of Chemistry

Published by The Royal Society of Chemistry,
Thomas Graham House, The Science Park, Cambridge CB4 4WF, UK

Typeset by Vision Typesetting, Manchester, UK
Printed by Redwood Books Ltd., Trowbridge, Wiltshire, UK

Industrial Inorganic Chemicals: Production and Uses

Preface

In 1977 'The Modern Inorganic Chemicals Industry' appeared as The Royal Society of Chemistry Special Publication No. 31, being the Proceedings of a two-day conference which formed part of that year's Annual Congress at University College, London. At the time there was no comprehensive collected textbook on the contemporary inorganic chemicals industry, and the conference content was specifically designed such that the delivered papers be publishable in book form to fill a recognized gap. As convener and editor I was also concerned that the treatment should be *authoritative*, so consequently recognized authors were invited to contribute.

SP31 was an almost instant success, becoming a standard text in university and polytechnic chemistry and chemical engineering courses. The first print quickly sold out and the Proceedings were later to be printed twice more.

Nearly two decades have passed since SP31 was begun. The inorganic chemicals industry, like others, has moved on; albeit perhaps more slowly in production methods as is the way with capital-intensive commodity industries. It was decided that the time had come to prepare what is in effect a second edition, again with the main criterion that each chapter be an authoritative contribution from an industry expert. Several of the authors are in fact the same as in the earlier work, while others had contributed to the almost equally popular companion volume SP40, 'Speciality Inorganic Chemicals'. That recorded papers from a Salford University symposium run by the Inorganic Chemicals Group of the Society's Industrial Division in 1980. Yesterday's specialities can become today's commodities, and the importance of alumina and silica (debatably then in the commodities league) in their various forms is, for example, sufficient to merit inclusion here alongside other high-tonnage chemicals. Three chapters not included this time relate to water, the chlor-alkali industry, and soluble silicates, for accounts of which the reader is referred to SP31.

Chapters which have been extended over the earlier volumes are on aluminium, fluorine, and phosphorus chemicals, where the production and uses of derived products (many of which are themselves sold in large tonnages) are described in some detail.

Inorganic chemicals manufacture is highly integrated: a product from one part of the industry is often a feed-stock of another. This is no better illustrated than by

sulfuric acid (Chapter 4) which finds major outlets *inter alia* in the production of boron, phosphorus, and titanium products described later in the book. The whole interplay across the industry is reviewed in Chapter 1, a further purpose of which is to place the various production and consumption rates in relative as well as absolute perspective.

The chemicals industry is often perceived (with some past justification) as being dirty and environmentally unacceptable. Air was polluted, rivers contaminated, and tracts of land laid waste, as well as the health and well-being both of employees and people living near to the plants being affected. The last two decades have seen considerable changes both in practical action being taken and the tightening of legislation requiring it. An overview given in Chapter 2 deals with these aspects, relating them also to metals smelting and the physical treatment and use of production by-products.

One of the features which heightened the demand for SP31 was the inclusion of an educational chapter that addressed some of the shortcomings of contemporary chemistry courses, at least insofar as degree courses in 'pure' chemistry were concerned. Graduate chemical engineers are often more fitted to enter manufacturing industry than their chemistry counterparts. It was therefore decided that we should again include a primer plus bibliography on at least the elements of chemical engineering. While this book is not designed primarily for student use, Chapter 3 could usefully be read first by those unfamiliar with the design and manufacturing procedures of the chemicals industry.

Finally, I must pay tribute to the individual authors, all busy people, who have contributed to this book; not least to those who finished their chapters on time and had to await completion by others. All were written within a span of about two years and thus none, bearing in mind any proof-stage alterations, will become outdated for some years to come.

Ray Thompson CBE, FEng

Contributors

S.P.S. Andrew, FRS, FEng, *Formerly ICI Plc., Agriculture Division*

A.K. Barbour, OBE, *Consultant, Environmental Science and Regulation*

B. Bertsch-Frank, *Degussa AG, Postfach 1345, D-6450, Hanau 1, Germany*

A. Dorfer, *Degussa AG, Postfach 1345, D-6450, Hanau 1, Germany*

T.A. Egerton, *Tioxide Group Services Ltd., West Site, Haverton Hill Road, Billingham, Cleveland TS23 1PS, UK*

K.A. Evans, *Alcan Chemicals Ltd., Chalfont Park, Gerrards Cross, Buckinghamshire SL9 0QB, UK*

D.C. Freshwater, FEng, *Louisiana State University, Baton Rouge*

K. Gilbert, *British Sulphur Corporation,*

G. Goor, *Degussa AG, Postfach 1345, D-6450, Hanau 1, Germany*

K.W.A. Guy, FEng, *Air Products Plc., Hersham Place, Molesey Road, Walton-on-Thames, Surrey KT12 4RZ, UK*

P. Kleinschmit, *Degussa AG, Postfach 1345, D-6450, Hanau 1, Germany*

J.C. McCoubrey, *Aston University, Aston Triangle, Birmingham B4 7ET, UK*

R.L. Powell, *Research and Technology Department, ICI Chemicals and Polymer Ltd., PO Box 8, The Heath, Runcorn, Cheshire WA7 4QD, UK*

T.A. Ryan, *Research and Technology Department, ICI Chemicals and Polymer Ltd., PO Box 8, The Heath, Runcorn, Cheshire WA7 4QD, UK*

H.U. Süss, *Degussa AG, Postfach 1345, D-6450, Hanau 1, Germany*

A. Tetlow, *Tioxide Group Services Ltd., West Site, Haverton Hill Road, Billingham, Cleveland TS23 1PS, UK*

R. Thompson, CBE, FEng, *Consultant, Formerly RTZ Borax*

A.A. Trickett, *Acid Technology, Chemetics International Company Ltd., 1818 Cornwall Avenue, Vancouver, British Columbia, Canada V6J 1C7*

R.D.A. Woode, *Brunner Mond and Company Limited, PO Box 4, Mond House, Northwich, Cheshire CW8 4DT, UK*

Contents

Chapter 1	Economic Importance of the Inorganic Chemical Sector	1
	<i>K. Gilbert</i>	
1	Introduction and Definitions	1
2	The Size of the Industry	2
3	The Main Sectors of the Inorganic Chemicals Industry	4
3.1	Alkalis and Chlorine	4
3.2	Chlorine and Caustic Soda	5
3.2.1	Soda Ash (Sodium Carbonate)	9
3.3	Mineral Acids	10
3.3.1	Sulfur and Sulfuric Acid	10
3.3.2	Hydrochloric Acid	11
3.3.3	Nitric Acid	13
3.4	Mineral Fertilizers	13
3.4.1	Nitrogen	14
3.4.2	Phosphorus	17
3.4.3	Potassium	18
3.5	Industrial and Food Phosphates	18
3.6	Aluminium Chemicals	19
3.7	Silicates and Zeolites	20
3.8	Hydrogen Peroxide and Persalts	21
3.9	Fluorine, Hydrofluoric Acid, and Fluorides	22
3.10	Bromine and Iodine	23
3.11	Titanium Dioxide	24
3.12	Borates	25
3.13	Industrial Gases	25
3.14	Miscellaneous	27
Chapter 2	Environmental Aspects of Inorganic Chemicals Production	33
	<i>A.K. Barbour</i>	
1	Introduction	33
2	Legislative/Regulatory Regimes	33

2.1 Plant and Process Safety	37
3 Standards Setting	38
4 Modern Process Technology and Environmental Protection	40
4.1 The Sulfur Dioxide Problem	40
4.1.1 In Copper Production	40
4.1.2 In Primary Zinc, Lead, (and Co-product Cadmium) Production	42
4.2 The Control of Fluoride Emissions in Primary Aluminium Smelting	43
4.3 Solid Waste Disposal	43
4.3.1 In Primary Zinc, Lead, (and By-product Cadmium) Production	44
4.3.2 In Primary Copper Production	46
4.3.3 In Primary Aluminium Production	46
5 Product Aspects and New Technology	46
5.1 Metal Arisings from the Manufacture and Use of Products	47
5.2 Factors Restraining Increases in the Recycling Level	48
5.2.1 Regulatory Definitions	48
5.2.2 Logistics and Technologies for Collection/ Separation	48
5.2.3 Process Technology	49
6 Some Areas Where New Technology is Desirable	49
6.1 Resources/Extraction/Concentration	49
6.2 Processing and Refining	50
6.3 Toxicology and Eco-toxicology	51
Chapter 3 Chemical Engineering for the Industrial Chemist	53
<i>D.C. Freshwater</i>	
1 Introduction	53
2 Chemical Process Design	55
3 Balances	57
4 Unit Operations	62
4.1 Fluid Flow	62
4.1.1 Pumps for Liquids	66
4.1.2 Pumps for Gases	66
4.2 Heat Transfer	67
4.3 Evaporation	69
4.4 Mass Transfer Operations: Absorption and Distillation	70
4.5 Extraction	77
4.6 Drying	79
4.7 Size Reduction	81
4.8 Sedimentation	82
4.9 Filtration	83
5 Control and Instrumentation	85

6	Safety and Loss Prevention	87
7	Bibliography	90
Chapter 4	Production of Sulfuric Acid and Other Sulfur Products	93
	<i>A.A. Trickett</i>	
1	Introduction	93
2	Sulfuric Acid Manufacture	94
2.1	Types of Sulfuric Acid Plants	94
2.2	Process Description	97
2.2.1	Sulfur-burning Acid Plant	97
2.2.2	Metallurgical Acid Plant	100
2.2.3	Sulfuric Acid Regeneration Plant	101
2.3	Recent Developments in Equipment Design	101
2.3.1	Gas Systems	101
2.3.2	Acid Systems	104
2.3.3	Gas Cleaning Systems	105
2.4	Catalysts Used in Acid Manufacture	106
2.5	Product Quality	106
2.6	Energy Recovery from the Sulfuric Acid Process	107
2.7	Emissions from Modern Acid Plants	108
2.8	Future Trends within the Industry	109
2.8.1	Energy Efficiency	109
2.8.2	Reduced Sulfur Dioxide Emissions	109
3	Sulfuric Acid Containment	109
3.1	Acid Storage	109
3.2	Transportation of Sulfuric Acid	111
4	Liquid Sulfur Dioxide	113
4.1	Introduction	113
4.2	Production of Liquid Sulfur Dioxide	113
4.3	Processes for the Production of Liquid Sulfur Dioxide	114
4.3.1	Compression Flowsheet	114
4.3.2	Refrigeration Flowsheet	116
4.3.3	Production of SO ₂ by Chemical Means	117
4.4	Uses of Liquid Sulfur Dioxide	117
5	Liquid Sulfur Trioxide	118
5.1	Introduction	118
5.2	Production of Liquid Sulfur Trioxide	118
5.2.1	Process Description	118
5.2.2	Storage Tanks for SO ₃	120
5.3	Uses of Sulfur Trioxide	120
Chapter 5	Sodium Carbonate	123
	<i>R.D.A. Woode</i>	
1	Introduction	123
2	Uses	124

2.1	Glass Manufacture	124
2.2	Sodium Silicates	126
2.3	Phosphates/Polyphosphates	126
2.4	Detergents	126
2.5	Chromium Chemicals	126
2.6	Pulp and Paper	126
2.7	Water Treatment and Brine Purification	126
2.8	Flue Gas Desulfurization	127
2.9	Miscellaneous Uses	127
2.10	Caustic Soda	127
3	The Manufacture of 'Synthetic' Soda Ash	127
3.1	The Leblanc Process	127
3.2	The Modern Ammonia Soda Process	128
3.2.1	Chemistry	128
3.2.2	The Overall Operating Process	129
3.2.3	Lime Burning Stage	130
3.2.4	Lime Slaking Stage	131
3.2.5	Filtration, Distillation, and Ammonia Absorption	132
3.2.6	Brine Preparation	133
3.2.7	The Solvay Tower	134
3.2.8	Calcination to Produce Light Ash	134
3.2.9	Heavy Ash Production	136
3.2.10	Steam and Power Generation	138
4	Ammonia Soda Co-products	139
4.1	Refined Sodium Bicarbonate – NaHCO_3	139
4.2	Sodium Sesquicarbonate – $\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$	140
4.3	Washing Soda – $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$	140
4.4	Ammonium Chloride – NH_4Cl	141
4.5	Calcium Chloride – CaCl_2	141
4.6	Precipitated Calcium Carbonate – CaCO_3	141
5	Variations and Developments in Synthetic Ash Production	141
5.1	The Combined Process	141
5.2	General Developments	142
5.3	Other 'Synthetic' Processes	142
6	'Natural Ash' Processes	143
6.1	'Dry' Lake Processes	143
6.2	'Wet' Lake Processes	144
6.3	Deep Mined Processes	145
7	Environmental Aspects	146
8	Siting	148

Chapter 6 Ammonia, Nitric Acid, Ammonium Nitrate, and Urea

S.P.S. Andrew

1	Introduction	149
2	Nitrogen Fertilizers in Agriculture	149

3	Ammonia Production	151
3.1	Feedstocks	151
3.2	Ammonia Production Using Methane	152
3.2.1	The Ideal Process	152
3.2.2	The Commercial Process	155
4	Nitric Acid Production	165
5	Ammonium Nitrate Production	169
6	Urea Production	170
7	Slow-release Nitrogen Fertilizers	173
Chapter 7	Hydrogen Peroxide and Inorganic Peroxy Compounds	175
	<i>B. Bertsch-Frank, A. Dorfer, G. Goor, and U. Süss</i>	
1	Hydrogen Peroxide	175
1.1	Introduction	175
1.2	Manufacture of Hydrogen Peroxide	176
1.2.1	AO-process	176
1.2.2	Other Processes	181
1.3	Properties of Hydrogen Peroxide	182
1.3.1	Physical Properties	182
1.3.2	Chemical Properties	182
1.4	Uses of Hydrogen Peroxide	183
1.4.1	Bleaching	184
1.4.2	Environmental Uses	186
1.4.3	Chemical Uses	187
2	Inorganic Peroxy Compounds	188
2.1	Sodium Perborate and Sodium Percarbonate	188
2.1.1	Introduction	188
2.1.2	Manufacture of Sodium Perborate	189
2.1.3	Manufacture of Sodium Percarbonate	190
2.1.4	Properties	192
2.1.5	Uses	192
2.2	Peroxysulfate Compounds	194
2.2.1	Introduction	194
2.2.2	Peroxydisulfate	195
2.2.3	Peroxymonosulfate	196
2.3	Other Peroxo Compounds	197
Chapter 8	Hydrofluoric Acid, Inorganic Fluorides, and Fluorine	199
	<i>R.L. Powell and T.A. Ryan</i>	
1	Introduction	199
2	Inorganic Fluorine Chemicals: A Brief History	199
3	Occurrence of Fluorine	200
4	Fluorspar	201
4.1	Structure of the Fluorspar Industry	201
4.2	Fluorspar Applications	202

5	Hydrofluoric Acid	203
5.1	The Production of Hydrogen Fluoride	203
5.2	Hydrogen Fluoride Producers	205
5.3	Safety	205
5.4	The Properties of Hydrogen Fluoride	205
5.5	Uses of Hydrogen Fluoride	206
5.5.1	Fluorocarbon Manufacture	206
5.5.2	Anhydrous Hydrofluoric Acid as an Electrolyte	208
5.5.3	Aromatic Fluorocarbons	209
5.5.4	Other Uses	209
6	Inorganic Fluorides	210
6.1	Group 1 Fluorides	211
6.1.1	Lithium Fluoride	211
6.1.2	Sodium Fluoride	211
6.1.3	Potassium Fluoride	212
6.1.4	Rubidium and Caesium Fluorides	212
6.2	Group 2 Fluorides	213
6.2.1	Beryllium Fluoride	213
6.2.2	Magnesium Fluoride	213
6.2.3	Strontium and Barium Fluoride	213
6.3	Group 3 and Lanthanide Fluorides	213
6.4	Group 4 Fluorides	214
6.5	Group 5 Fluorides	214
6.6	Group 6 Fluorides	215
6.6.1	Chromium Fluorides	215
6.6.2	Molybdenum Fluorides	215
6.6.3	Tungsten Fluorides	215
6.7	Group 7 Fluorides	215
6.8	Group 8 Fluorides	216
6.9	Fluorides of Copper and Silver	216
6.10	Fluorides of Zinc, Cadmium, and Mercury	217
6.11	Boron and Aluminium Fluorides	217
6.11.1	Boron Fluorides	217
6.11.2	Fluoroboric Acid and Derivatives	218
6.11.3	Aluminium Fluorides	219
6.12	Fluorides of Carbon, Silicon, Germanium, Tin, and Lead	221
6.12.1	Carbon Fluorides	221
6.12.2	Silicon Fluorides	221
6.12.3	Tin Fluorides	222
6.12.4	Lead Fluorides	222
6.13	Fluorides of Nitrogen, Phosphorus, Arsenic, Antimony, and Bismuth	223
6.13.1	Nitrogen Fluorides	223
6.13.2	Phosphorus Fluorides	224
6.13.3	Arsenic Fluorides	225

6.13.4 Antimony Fluorides	225
6.14 Sulfur Fluorides	226
6.15 Halogen Fluorides	227
6.16 Noble Gas Fluorides	227
6.17 Actinide Fluorides	227
7 Fluorine	228
7.1 Fluorine Production	228
7.2 Uses of Elemental Fluorine	229
8 The Future for Inorganic Fluorides	230
9 Bibliography	232
Chapter 9 Industrial Gases	233
<i>K.W.A. Guy</i>	
1 Introduction	233
2 Distribution of Industrial Gases	233
2.1 On-site or Tonnage Supply	234
2.2 Merchant Supply	234
2.3 The Cylinder Supply	234
3 Atmospheric Gases	234
3.1 Air	235
3.2 Separation	235
3.2.1 Cryogenic Plants	235
3.2.2 Non-cryogenic Plants	241
3.3 Oxygen	244
3.3.1 Production	244
3.3.2 Uses	245
3.3.3 Nitrogen	246
3.3.4 Liquid Nitrogen	248
3.3.5 Argon	249
3.4 Neon, Krypton, and Xenon	250
3.5 Helium	250
4 Hydrogen and Carbon Monoxide	251
4.1 Production	251
4.2 Steam Methane Reforming (SMR)	252
4.3 Hydrogen	254
4.3.1 Production	254
4.3.2 Uses	255
4.4 Carbon Monoxide	255
4.4.1 Production	255
4.4.2 Uses	255
4.5 A Large Industrial Gas Facility	256
Chapter 10 Production and Uses of Inorganic Boron Compounds	257
<i>R. Thompson</i>	
1 Occurrence and Mining	258
2 Production of Borax from Solid Ores	259

3	Production of Borax from Lake Brines	260
4	Manufacture of Boric Acid	261
5	Anhydrous Bulk Products	262
6	Other Inorganic Borates	263
6.1	Other Sodium Borates	263
6.2	Potassium Borates	263
6.3	Ammonium Borates	264
6.4	Calcium Borates	264
6.5	Barium Borate	264
6.6	Zinc Borate	264
6.7	Boron Phosphate	265
7	Major Applications of B_2O_3 Containing Materials	265
7.1	Glass and the Vitreous Industries	265
7.2	Metallurgical Fluxes	266
7.3	Bleaching and Detergency	266
7.4	Biological Applications	267
7.5	Uses of Boric Acid	267
7.6	Nuclear Applications	268
7.7	Miscellaneous Applications of Borax and Boric Acid	268
8	Other Boron Compounds Used Industrially	269
8.1	Boron Trifluoride	269
8.2	Fluoroboric Acid and Metal Fluoroborates	269
8.3	Other Boron Halides	270
8.4	Sodium Borohydride	271
8.5	Boranes	271
8.6	Boron	272
8.7	Boron Carbide	272
8.8	Metal Borides	273
8.9	Boron Alloys	274
8.10	Boron Nitride	274
8.11	Boric Acid Esters	275
Chapter 11	Production and Use of Aluminium Compounds	277
	<i>K.A. Evans</i>	
1	Introduction	277
2	Occurrence of Aluminium Compounds	277
3	Aluminium Hydroxide	278
3.1	Nomenclature of Aluminium Hydroxides	279
3.2	Properties of Aluminium Hydroxides	279
3.3	Production of Aluminium Hydroxides	280
3.4	Uses of Aluminium Hydroxides	282
3.4.1	Fire Retardancy	283
3.4.2	Toothpaste	286
3.4.3	Paper	287
3.4.4	Paint	288
3.4.5	Pharmaceuticals	288

4	Aluminium Oxide	288
4.1	Nomenclature and Properties of Aluminium Oxide	288
4.2	Industrial Grades of Aluminium Oxide	289
4.2.1	Smelter Grade Alumina	290
4.2.2	Calcined Alumina	291
4.2.3	Low Soda Aluminas	291
4.2.4	Tabular Alumina	294
4.2.5	High Purity Aluminas	294
4.3	Uses of Aluminium Oxide	294
4.3.1	Alumina in Technical Ceramics	294
4.3.2	Glass-ceramics	302
4.3.3	Refractories	303
4.3.4	Polishing and Grinding	306
4.4	Activated Alumina	307
4.4.1	Production of Activated Alumina	308
4.4.2	Uses of Activated Alumina	309
4.5	Fused Alumina	310
5	Anhydrous Aluminium Chloride	310
5.1	Properties of Anhydrous Aluminium Chloride	310
5.2	Production of Anhydrous Aluminium Chloride	311
5.2.1	Applications of Anhydrous Aluminium Chloride	312
6	Hydrated Aluminium Chloride	312
6.1	Production of Hydrated Aluminium Chloride	312
6.2	Uses of Hydrated Aluminium Chloride	313
6.3	Basic Aluminium Chlorides	313
7	Polymeric Aluminium Compounds	313
7.1	PAC	313
7.2	PASS [®]	314
8	Sodium Aluminate	315
8.1	Production of Sodium Aluminate	315
8.2	Applications of Sodium Aluminate	315
9	Aluminium Nitrate	316
10	Aluminium Phosphates	316
11	Aluminium Carboxylates	317
12	Aluminium Sulfate	319
12.1	Production of Aluminium Sulfate	319
12.2	Applications of Aluminium Sulfate	320
13	Zeolites	320
14	Aluminium Fluoride	321
15	Fluoroaluminates	321
16	Aluminium Bromide	322
17	Aluminium Iodide	322
18	Aluminium Alkoxides	323
19	Organoaluminium Compounds	323
20	Aluminium Nitride	324
20.1	Production of Aluminium Nitride	324

20.2 Use of Aluminium Nitride	325
Chapter 12 Silicas and Zeolites	327
<i>P. Kleinschmit</i>	
1 Introduction and General Survey	327
1.1 Silicas	327
1.2 Zeolites	330
2 Silicas Produced by Thermal Processes	330
2.1 Fumed (Pyrogenic) Silicas	330
2.1.1 Properties and Applications	331
2.1.2 Manufacturing Process	334
2.1.3 Modification with Organosilanes	336
2.1.4 Other Fumed Oxides	337
2.2 Electric Arc and Plasma Silicas	337
3 Silicas by Wet Processes	338
3.1 Silica Gels	339
3.1.1 Properties and Applications	339
3.1.2 Manufacturing Process	339
3.2 Precipitated Silicas	340
3.2.1 Properties and Applications	340
3.2.2 Manufacturing Process	341
3.2.3 Recent Developments	342
4 Zeolites	344
4.1 Properties and Applications	344
4.2 Manufacturing Processes	347
4.2.1 Zeolite A	347
4.2.2 Preparation of Other Zeolites	348
Chapter 13 Titanium Dioxide Products	351
<i>T.A. Egerton and A. Tellow</i>	
1 Introduction	351
2 Commercial Development	352
3 The Product Attributes of Titanium Dioxide	353
4 Raw Material Sources	355
5 Manufacturing Processes	359
5.1 The Sulfate Process	360
5.2 The Chloride Process	363
5.3 Wet Treatment (Coating)	366
6 Environmental Issues	368
7 Novel TiO ₂ Applications	369
7.1 Ultrafine Titanium Dioxide	369
7.2 Ceramic Applications of Titanium Dioxide	370
7.3 Catalytic Applications of Titanium Dioxide	371
8 Challenges for the Future	371