This Fifth Edition of the Handbook of Chlorination and Alternative Disinfectants is dedicated to George Clifford White for his lifetime commitment to the disinfection industry.
CONTENTS

Preface xxvii
Authors xxix
List of Contributors and Reviewers xxxi
List of Abbreviations xxxiii
Acknowledgments xxxix

1 Chlorine: History, Manufacture, Properties, Hazards, and Uses 1

Historical Background 1
Elemental Chlorine 1
Chlorine Gas 1
Chlorine Liquid 2
Manufacture of Chlorine 2
History 2
Electrolytic Processes 3
Electrolytic Cell Development 4
The Ideal Electrochemical Cell 4
Process Developments 5
Membrane Cell 5
Diaphragm Cells 8
Mercury Cells 11
Process Diagram for a Typical Chlor-Alkali Plant 15

Other Chlorine Manufacturing Processes 18
Salt Process 18
HCl Oxidation Processes 18
Electrolysis of Hydrochloric Acid Solutions 20

Impurities in the Manufacture of Chlorine 20
Historical Background 20
Consequences of Impurities 22
Nitrogen Trichloride in Liquid Chlorine 23
Silica Contamination 24
Physical and Chemical Properties of Chlorine  
  General  24
  Critical Properties  24
  Compressibility Coefficient  25
  Volume–Temperature Relationship  26
  Density of Chlorine Vapor  27
  Density of Liquid Chlorine  27
  Viscosity of Chlorine  27
  Latent Heat of Vaporization  27
  Vapor Pressure  27
  Specific Heat  27
  Solubility of Chlorine Gas in Water  27
  Solubility of Liquid Chlorine in Water  28
  Chemical Reactions  29

Hazards from Chlorine Vapor and Liquid  30
  Toxic Effects  30
  First Aid  31
  Physiological Response  32
  Intentional Release  32

Chlorine Leaks  33
  Definitions  33
  Fire and Building Codes  34
  Characteristics of a Major Liquid Chlorine Release  34

Calculating Chlorine Leak Rates  35
  Liquid Release  35
  Vapor Release  35
  Tanker Truck Leak during Unloading  36
  Guillotine Break in a Pipeline: Ton Container Supply  36
  A Major Leak from PVC Header Failure  38
  Ton Container Flexible Connection Failure  39
  Fusible Plug Failure from Corrosion  39

Summary  41

USEPA Risk Management Programs (RMPs)  41
  OSHA Process Safety Management (PSM) Regulations  45
  Worst-Case and Alternative Release Analyses  46

Chlorine Transport Accidents  47
  Railroad Transportation  47
  Highway Transportation  51

Notable Consumer Accidents  52
  General  52
  A Fatal 1-Ton Container Leak  53
  A Leak from Four 1-Ton Containers  54
A Leak from a Buried Chlorine Pipe 54
A 14,000-lb Liquid Leak 55
A Tank Car Leak at a Chlorine Packager 57
Brush Fire 59
Frequency and Magnitude of Chlorine Leaks 59

Production and Uses of Chlorine 62
Annual Production 62
End Uses of Chlorine 62
Help in Chlorine Emergencies 64

References 65

2 Chemistry of Aqueous Chlorine 68

Dissolution and Hydrolysis of Chlorine 68
Dissociation of Hypochlorous Acid 74
Effect of pH and Temperature 74
Ionic Strength Effects 77
Chlorine Speciation in Concentrated Solutions 81
Hypochlorite Solutions 82
Oxidation States of Chlorine 85
Free, Combined, and Available Chlorine 87
Chlorine and Nitrogenous Compounds 91
Nitrogenous Compounds in Water and Wastewater 92
Chlorination of Ammonia to Form Chloramines 94
The Breakpoint Reaction 103
The Organic Nitrogen Problem 116

The Chemistry of Chlorine in Seawater 122
Effect of Bromide 123
Ionic Strength Effects 126
Bromamine Formation and Decay 127

Oxidation–Reduction Reactions of Chlorine Compounds 129
Fundamental Considerations 129
Practical Considerations 133

ORP Measurements 135
Practical Applications of ORP Measurements 139

Reactions of Chlorine with Selected Constituents 141
Alkalinity 142
Arsenic 145
Carbon 145
Cyanide 146
Hydrogen Sulfide 146
Iron and Manganese 147
CONTENTS

Methane 148
Nitrite 148
Chlorine Demand 149
Germicidal Significance of Chlorine Residuals 151
   Mechanisms of Inactivation 152
   Hypochlorous Acid 153
   Hypochlorite Ion 154
   Chloramines 155
References 161

3 Determination of Chlorine Residuals in Water and Wastewater Treatment 174

   Historical Background 174
      The Early Years 174
      Following Discovery of the Breakpoint Phenomenon 175
      Recent Developments 179
   General Considerations 179
      Colorimetric and Titrimetric Methods 180
      Common Interferences 180
      Organic Nitrogen Interference 182
      Recommendations for Method Selection 184
      Detailed Descriptions of Individual Methods 187
   Amperometric Titration 187
      Principles of Titrator Operation 188
      The Single-Indicator-Electrode Titrator 188
      The Dual-Indicator-Electrode Titrator 191
      Operating Characteristics 193
      Chemistry of the Amperometric Method 194
      Preparation and Procedures for Titration 195
      Precision and Detection Limits 200
      Low-Level Amperometric Titrations 200
      Free Chlorine Residuals at Short Contact Times 201
      Determination of Residual Chlorine in Wastewater Effluents 202
   DPD Method 208
      DPD Colorimetric Method 210
      DPD–FAS Titrimetric Method 211
   FACTS (Syringaldazine) Method 214
   Iodometric Method I 215
      Procedure for Standardizing Chlorine Solutions 217
   Iodometric Method II (Wastewater) 217
   Iodometric Electrode Method 218
   Leuco Crystal Violet (LCV) Method 219
Methyl Orange (MO) Method  220  
Orthotolidine Method  221  
  Interfering Substances  221  
OTA Method  222  
Drop Dilution Method  222  
References  223

4 Chlorination of Potable Water  230

Microbes in Water Supplies  230  
  Surface Water and Springs  230  
  Groundwater  230  
Waterborne Diseases  231  
Chlorine as a Disinfectant  232  
  Use as a Biocide  232  
  Use to Inactivate Protozoa  235  
  Use as a Virucide  235  
  Consensus Indicator Organism  236  
Disinfection Requirements under (Provisions of the) Safe Drinking Water Act (SDWA)  236  
SWTR  236  
  Interim Enhanced Surface Water Treatment Rule (IESWTR)  238  
Stage 1 DBPR  239  
Long-Term 1 Enhanced Surface Water Treatment Rule  
  (LT1ESWTR)  239  
Long-Term 2 Enhanced Surface Water Treatment Rule  
  (LT2ESWTR)  239  
GWR  240  
Disinfection of Drinking Water with Chlorine  240  
  Historical Background  241  
  Points of Application  242  
  Types of Chemical  243  
  DBP  243  
  Trihalomethanes (THMs)  243  
  Haloacetic Acids (HAAs)  244  
  Total Organic Halides (TOX)  244  
  Bromate  245  
  Chlorine Demand  245  
  Chlorination–Dechlorination  247

Disinfection with Chloramines  248  
  Historical Background  248  
  The Ammonia–Chlorine Process  250  
  Basic Chemistry of Ammonia N Reactions with Chlorine  251
CONTENTS

Operation of the Chloramination Process 251
Issues of Concern 253

Distribution System 262
  Regulatory Compliance for Distribution Systems 264
  Regrowth 264
  Explanation of Terms Involving Regrowth 266
  Factors Influencing Microbial Growth 269
  Operation of the Distribution System 271
  Monitoring 272
  Control of Water Age 274
  Secondary Disinfectant Residuals 275
  Flushing 277
  Treatment Plant Performance Impacts on Distribution System Water
  Quality 278

Disinfection of New Infrastructure 278
  Typical Disinfection Chemicals 278
  Disinfectant Feed Systems 279
  Disinfection of Water Mains 280
  Procedures for Disinfecting Storage Tanks 281
  Procedure for Disinfecting Water Treatment Plants 281
  Disinfection of New Buildings 282
  Procedure for Disinfection of Wells 283
  Procedures for Maintaining Disinfection while Inspecting In-Service
  Water Storage Facilities 284

Other Uses of Chlorine in Water Treatment 285
  Tastes and Odors 285
  Tastes and Odors from Algae and Actinomycetes 286

Synthetic Sources of Tastes and Odors 288
  Taste and Odor of Chlorine 289
  Iron and Manganese 289
  Oxidation of Iron 291
  Oxidation of Manganese 292
  Coagulation Aid 293
  Filtration Aid 293
  Control of Mollusca in Seawater 295
  Zebra Mussels 296
  Quagga Mussels 297
  Aquifer Recharge 299
  Hydrogen Sulfide Control 299
  Color Removal 303
  Desalination 303
  Reflecting Pools 304
  Restoration of Wells 304
Chlorination in the United Kingdom 306
Chlorination in Germany 310
Treatment Strategies 310
  Disinfection of Coagulated Surface Water 310
  Disinfection of a Softened Surface Water 311
  Treatment and Disinfection of a Groundwater that Contains
    Iron and Manganese 311
Acknowledgments 311
References 312

5 Chlorination of Wastewater 326
Introduction 326
  History 326
    Chlorine Chemistry in Wastewater 327
Odor Control 329
  Prechlorination of Wastewater 330
    Scrubbing of Foul Air 333
Chlorine and Biological Treatment 338
  Trickling Filters 338
    BOD Reduction 339
    Control of Sludge Bulking 340
Other Uses of Chlorine in Wastewater Treatment 345
  Septicity Control 345
    Removal of Oils and Grease 348
    Removal of Ammonia 349
Industrial Waste Treatment Applications Using Chlorine 352
  Free and Combined Cyanides 352
    Phenols 359
    Textile Wastes 360
      Applications to Other Industrial Waste 361
References 361

6 Disinfection of Wastewater 363
Introduction 363
  History 363
    The Coliform Standard 364
Viruses 368
  Virus Inactivation 370
Methods of Wastewater Disinfection 376
Chemistry of Wastewater Disinfection by Chlorine 379
  Reactions with Wastewater Constituents 379
  Chlorine Dose and Effluent Quality 382
  Chlorination of Nitrified Effluents 384
Formation of DBPs 390
Other Disinfection Considerations 394
  Regrowth of Organisms 394
  Toxicity of Chlorine Residuals 395
  Need for Dechlorination 396
Wastewater Reuse 397
References 400

7 Chlorine Contact Basin Design 404

Introduction 404
Design Elements 405
  Chlorination and Dechlorination Doses 405
  Dispersion of Chlorine 405
  Mixing Technologies 406
  Chlorine Contact Chamber Sizing 411
Wastewater 413
Reuse Water 413
Potable Water 414
No-Tracer Test Design 416
Wet Weather Disinfection for Wastewater 416
Chlorine Contact Basin Construction 417
Disinfection By-products 417
Sampling and Reporting 417
References 417

8 Chlorine Feed Systems 418

Cylinders 420
Ton Containers 424
Tank Trucks/Tank Cars 427
Storage Tanks 430
Liquid Chlorine Feed 431
  Vaporizers 431
Appurtenances 436
  Pressure-Reducing Valve 436
  Gas Filter 437
  Gas Chlorine Feed 438
CONTENTS

Chlorine Feeders and Eductors 442
   Chlorine Diffusers 444
   Pipe and Valve Systems 445
   Chlorine Scrubbers 450
Reference 451

9 Hypochlorination—Sodium Hypochlorite 452

Background and History of Hypochlorites 452
Sodium Hypochlorite 454
   Concentration Properties, Feed Calculations, Codes, and Hazards 455
Degradation 463
   Estimating the Degradation Rate 465
   Concentration Effects 466
   Temperature Effects 468
   pH Effects 469
   UV Light Effects 470
   Impurities 471
   Suspended Solids 473
   Settled Particulates 473
   Other Impurities 474
Impact on Treatment Process 474
   Sodium Carbonate 474
   Sodium Bromate 475
   pH and Alkalinity Addition 475
   Scaling 475
   Chlorate/Perchlorates 476
   Recommendations 476
Tank Selection 477
   Lined Steel 479
   FRP 480
   HDPE 481
   Titanium 483
   Other Tank Materials 483
   Level Instrumentation 483
   Truck Unloading 484
   Top Access 485
   Underground Storage Tank (UST) 485
Transfer and Feed Equipment 486
   Transfer Pumps 486
   Diaphragm Metering Pumps 486
   Problems with Vapor Locking 490
Peristaltic Pumps 493
Liquid Dosing Systems 498
Sodium Hypochlorite Piping 499
  Thermoplastic Piping (PVC and CPVC) 501
  Lined Steel 503
  FRP Piping 504
  FRP-Armored Piping 504
  Titanium 504
  HDPE 505
  PVDF 505
  Polypropylene (PP) 506
  Hastelloy 506
  Gaskets, Seals, and O-Rings 506
Sodium Hypochlorite Valves 507
  Ball Valves 508
  Diaphragm Valves 510
Sodium Hypochlorite Facility Layouts 513
  Elevation Differences 513
  Tank and Pump Bases 515
  Access and Clearances 517
  Control Panels 518
Calcium Hypochlorite 518
  History 518
  Manufacturing Process 520
  Properties 521
  Disinfection 521
  Solubility 522
  Hazards and Stability 523
  Tablet and Briquette Systems 523
  Applicable Standards 524
Lithium Hypochlorite 525
References 526

10 On-Site Sodium Hypochlorite Generation System 528

  Historical Background 528
    The Beginning 528
    Early Experience in the United States 529
    Current Interest 529
  Raw Material Quality 530
    Salt and Brine Systems 530
    Impact of Salt Quality and Bromate Formation 530
    Seawater Systems 531
On-Site Generation of Sodium Hypochlorite 531
  Electrolytic Formation of Sodium Hypochlorite 531
  Process Overview 532
System Components 534
  Water Softener 534
  Brine Saturator Tank 537
  Soft-Water Heater 539
  Soft-Water Chiller 540
  Brine Metering 542
  Electrolytic Cell 542
  Brine Dilution 545
  Rectifier 546
  Hydrogen Formation, Separation, and Safety 546
  Hydrogen Dilution Blowers 553
  Sodium Hypochlorite Storage Tank 556
  Sodium Hypochlorite Feed Equipment 556
On-Site Sodium Hypochlorite Generation System Design 557
  Equipment Sizing 557
  System Redundancy 558
  Amount of Sodium Hypochlorite Storage 559
  System Layout 559
System Manufacturers 565
  ClorTec 565
  Klorigen 566
  MIOX 567
  OSEC 567
  Process Solutions, Inc. (PSI) 568
References 571

11 Dechlorination 572

Introduction 572
  History 572
  Significance of Chlorine Species 576
Sulfur Dioxide 577
  Chemical Properties 577
  Dechlorination Chemistry 579
  Contactor Design 580
  Chemical Dose Calculations 581
Sulfite Compounds 581
  Chemical Properties 581
  Dechlorination Chemistry 582
12 Process Controls for Chlorination and Dechlorination 594

Introduction 594
Background 596
Online Analytical Measurements 598
   Amperometry 598
   Voltametry 599
   Polarography 599
   Membrane Cell 600
   Potentiometry 600
   ORP 602
   Colorimetry 606

Online Analyzers for Chlorination 607
   Analytical Technology, Inc. 608
   Hach 611
   Capital Controls 614
   GLI International 619
   Orion Research, Inc. 620
   Wallace & Tiernan 621
   Stranco Products 622
   Field Comparison of Analyzers 629
   How to Select an Online Analyzer 631

Online Process Control Overview 633
Chlorination Process Control 637
   Manual Control 638
   Flow Pacing 641
   Feedback Control 644
   Compound Loop Control 647

Dechlorination 653
   Flow Pacing 654
   Feedback Control 654
   Compound Loop Control 654
   Zero Residual Control 655
Online Analyzers for Dechlorination 657
  Stranco HRR 657
  Wallace & Tiernan 658
  Capital Controls 662
Blending Chemistry with Process Control 663
Control System O&M 670
Record Keeping and Regulatory Issues 673
References 676

13 Operation and Maintenance 678

General 678
  Standard Operating Procedures (SOPs) 679
  Maintenance Plan 680
  Residual Analyzer Maintenance and Calibration of Residual Analyzer 681
Chlorine Gas Systems 682
  Operation 682
  Chlorine Gas System Maintenance 684
  Chlorine Detection Systems and Emergency Scrubber 686
Sodium Hypochlorite Systems 687
  Sodium Hypochlorite System Operation 687
  Sodium Hypochlorite System Maintenance 689
Dechlorination Gas Systems 690
  Sulfonator Operation 690
  Sulfonator Maintenance 691
Dechlorination Liquid Systems 692
  Operation of Liquid Dechlorination Systems 692
  Liquid Dechlorination Systems Maintenance 693
Operator Training and Safety 693
Storage Systems 693
  Small (100- and 150-lb) Gas Cylinders 693
  Ton Containers 694
  Rail Cars 695
  Liquid Chemical Storage 696
Regulatory Requirements 697
  Risk Management Plan 697
  SDWA and State Testing and Reporting Requirements 698
  Wastewater Chlorine Use Reporting Requirements for Wastewater Facilities 699
CONTENTS

14 Chlorine Dioxide

Introduction 700
  Historical Background 700
  European Practice 701
  Other Uses 702

Chemical and Biologic Properties 703
  Chemical Properties 703
  Chemistry in Potable Water Treatment 704
  Selectivity as an Oxidant 705
  Germicidal Efficiency 705
  Inactivation of Viruses and Bacteria 706
  Encysted Parasites 711

Equipment and Generation 712
  Purity 713
  Commercial Generation Methods and Chemistry 713
  Acid–Chlorite Solution 714
  Chlorine Solution–Chlorite Solution 717
  Three-Chemical Systems (D. A. Gates, pers. comm.) 718
  Chlorine Gas–Chlorite Solution 719
  Chlorine Gas–Solid Chlorite 720
  Electrochemical 720
  Chlorate-Based Systems 722
  Chemical Feed Design Considerations 722
  Batch Tank 723
  Storage 723
  Purity Specification 723
  Bench-Scale Generation of ClO₂ 724
  Potassium Persulfate–Chlorite Solution 724
  Sulfuric Acid–Chlorite Solution 725
  Sodium Hypochlorite–Hydrochloric Acid–Chlorite Solution 725
  Chlorine Gas–Solid Chlorite 726

Use in Drinking Water and Wastewater Disinfection 727
  Drinking Water Primary Disinfection Application Points 727
  Contactor Design Criteria 728
  Diffusers and Injectors 728
  Exposure to Sunlight 728
  DBPs 729
  Chlorite 729
  Chlorate 731
  THMs and HAAs 734
  Secondary Disinfection 734
  Objectionable Taste and Odor Formation 734
CONTENTS

Disinfection of Wastewater Effluent 735
Combined Sewer Overflow (CSO) 735

Other Disinfection Applications 736
Medical Devices 736
Food Processing 736
Other Pathogens 737

Other Uses for Chlorine Dioxide in Water Treatment 738
Taste and Odor Control 738
Iron and Manganese Oxidation 739
Algae Growth Control 740
Zebra Mussels 740
DBP Control 740

Analytic Methods for Chlorine Dioxide and its Oxyclo- 
By-Products 740
Iodometry 742
Amperometric Titration Methods 743
*Standard Methods* 4500-ClO₂-C, Amperometric Method I 743
*Standard Methods* 4500-ClO₂-E, Amperometric Method II 744
Amperometric Titration Equivalence Point 744
DPD Method 747
LGB 748
IC Methods 749
Other Analytic Methods 749
Spectrophotometry 749
Flow Injection Analysis (FIA) 750
Other Colorimetric Methods for Chlorine Dioxide 
Analysis 751

Health and Safety 752
Chlorine Dioxide 752
Sodium Chlorite 752
Chlorine 753
Toxicity 753
Workplace Monitoring 753

Regulatory Issues 754
Drinking Water Regulations for Disinfection 754
SWTR 754
LT2ESWTR 754
Chlorine Dioxide Residual Limits 754
Related Disinfection By-Products 755
Chlorite 755
Chlorate 755
ClO₂ Use to Meet Wastewater Treatment Plant Regulatory 
Requirements 755
Summary 755
Advantages of Chlorine Dioxide 756
Disadvantages of Chlorine Dioxide 756
Acknowledgments 756
References 757

15 Ozone 767

Introduction 767
History and Application 767
Chemical Properties 768
  Physical Properties 768
  Solubility of Ozone 768
  Ozone Reaction Pathways 769
  Ozone Demand 771
  Dissolved Ozone Decay 772
Inorganic Compound Treatment 773
  Iron and Manganese 773
  Sulfides 775
  Chlorine, Chlorine Dioxide, and Monochloramine 776
Organic Compounds 777
  Taste- and Odor-Causing Compounds 777
  Control of Chlorination By-Products 779
  TOC Oxidation 780
  Biological Filtration 780
  Removal of Particulates 781
  Color Removal 782
  Increase in UV Transmittance at 254 nm (UVT254) 782
  SOCs 783
  EDC and PPCP Treatment 784
  Cyanotoxins 785
  Treatment of Biological Solids in Wastewater 786
Disinfection 787
  Use in Drinking Water 787
  Use in Wastewater 790
Ozone DBPs 792
  Bromate Control 793
  Aldehydes, Carboxylic Acids, and Ketones 795
Use in Water and Wastewater Treatment 795
  Potable Water Installations 796
  Wastewater Installations 797
Equipment and Generation 798
  Theory of O₃ Generation 799
  Gas Source 800
  Generation 812
  Transfer 816
  Contactors 821
  Destruction Equipment 826
  Ancillary Equipment 829
  Cost Studies 831
Process Calculations 832
  Gas Flow 832
  Ozone Production 834
  Ozone Transfer Efficiency 834
  Applied Ozone Dose 835
  Transferred Ozone Dose 835
  Specific Energy 835
Quench Chemicals 836
Analytical Methods 836
  Ozone Concentration in Gas 837
  Measuring Dissolved Ozone Residual in Water 839
Health and Safety 842
Regulatory Issues 843
References 844

16 Bromine, Bromine Chloride, BCDMH, and Iodine 848

Bromine (Br₂) 848
  Physical and Chemical Properties 848
  Occurrence 849
  Bromine Production 849
  Chemistry of Bromine in Water and Wastewater Treatment 851
  Reactions with Chlorine 852
Use of Bromine in Water Treatment Processes 852
  Potable Water 852
  Wastewater 853
  Cooling Water 854
  Swimming Pools 854
  Br₂ Facility Design 854
Bromides: On-Site Generation of Br₂ 855
  System Description 855
  Current U.S. Practices 857
  Comparison with Other Methods 857
Bromine Chloride (BrCl) 858
  Physical and Chemical Properties 858
  Preparation of Bromine Chloride 859
  Chemistry of Bromine Chloride in Water 860
  Design of Bromine Chloride Facilities 861
  Comparison with Advantages of Other Methods 865

BCDMH 866
  Physical and Chemical Properties 866
  Application and Production 866
  Chemistry of BCDMH in Water and Wastewater 866
  Application of BCDMH in Wastewater 867
  Comparison with Chlorination 867
  Germicidal Efficiency (Br$_2$ and BrCl) 869
  Bromo-Organic Compounds 871
  Measurement of Bromine Residuals 872
  Amperometric Method 873
  DPD Differentiation Method 873
  Effect of Seawater Chlorination 874
  Toxicity of Bromine Residuals 874
  Health and Safety Aspects of Bromine Compounds 874
  Regulatory Issues 875

Iodine (I$_2$) 875
  Physical and Chemical Characteristics 875
  Occurrence and Production 876
  Production from Chile Saltpeter 876
  Production from Brine 877
  Applications 877
  Uses in Water Treatment 878
  Chemistry of Iodination 879
  Germicidal Efficiency 882
  Limitations of Iodination 883
  Comparison with Chlorination 884
  Iodination Facility 884
  Determination of Iodine Residuals 886
  Toxicity of Iodine Residuals 886
  Health and Safety Aspects of Iodine 886
  Regulatory Issues 887

Summary 887
  Bromine 887
  Bromine Chloride 888
  BCDMH 888
  Iodine 889

References 889
17 Ultraviolet Light

Introduction 893
   Wastewater Applications in Europe 893
   UV Applications in North America 894
   Drinking Water Applications in the United States 896

Chemical and Biological Properties 897
   UV Light 897
   Microbial Inactivation Mechanisms 898
   Microbial UV Sensitivity 899
   Microbial Repair 899
   UV Dose 902

Guidelines 904
   USEPA's Ultraviolet Disinfection Guidance Manual 904
   NWRI/AwwaRF's Ultraviolet Disinfection Guidelines for Drinking Water and Water Reuse 907
   USEPA's Design Manual for Municipal Wastewater Disinfection 908

UV Equipment 910
   UV Lamps 910
   UV Reactors 921
   Ballasts 924
   Lamp Sleeves 925
   UV Sensors 926
   Cleaning Systems 927
   Online UVT Monitors 928
   Temperature Sensors/Water Level Probes 928

Water Quality Issues 929
   UV Transmittance 929
   Particles/Suspended Solids 929
   Fouling 931

UV System Sizing Tools 932
   UV System Validation 932
   Nonbiological, Mathematical-Based Modeling 955
   Emerging Methods 959

Operation and Maintenance Activities 961
   Maintenance Activities 961
   Operational Issues 964

Troubleshooting Strategies 965
   Process Control Modifications 965
   Electrical System Modifications 965
   Mechanical System Modifications 966
Health and Safety for Water And Wastewater UV Systems 966
   General 966
   UV Light Exposure 967
   Perform a UV Safety Audit 968
   Acute Health Effects of UV Exposure 968
   Chronic Health Effects of UV Exposure 969
   Engineering Controls 969
   Administrative Controls 969
   Personal Protection 969
   References 970

18 Advanced Oxidation Processes 976
   Introduction 976
      Historical Perspective 976
      Types of AOPs 977
   Chemistry of AOPs 977
      Ozone Decomposition Initiated by Hydroxide 978
      O_3/H_2O_2 979
      O_3/UV 979
      H_2O_2/UV 979
      Fe(II)/H_2O_2 (Fenton Reaction) 980
      Fe(II)/H_2O_2/UV (Photo-Fenton Reaction) 980
      TiO_2/UV 981
      TiO_2/H_2O_2/UV 981
   Uses in Drinking Water and Wastewater Treatment 982
      Oxidation of VOCs 982
      Oxidation of Pesticides 985
      Oxidation of Taste and Odor Compounds 988
      Oxidation of Disinfection By-Product (DBP) Precursors 989
   Factors Affecting System Performance 990
      O_3/H_2O_2 990
      O_3/UV 991
      H_2O_2/UV 992
      Fenton and Photo-Fenton Reactions 992
      TiO_2/UV 993
   Regulations 994
   Equipment and Generation 995
   References 997

Appendix 1003

Index 1009
PREFACE

Over the years, the science and practice of disinfection has provided innumerable health benefits, although the general public is unaware of many of them. With the recognition of infectious organisms such as Cryptosporidium in our raw water supplies, along with the detrimental chronic health effects associated with disinfection by-products, it is critical to balance the extent of their inactivation with the concentrations of disinfection by-products. Many water and wastewater utilities are implementing the use of multiple disinfectants in order to optimize the results while minimizing unwanted side effects.

The four previous editions of this handbook have proven to be a valuable resource to countless utilities, regulators, engineers, and operators for information on disinfection of potable water, wastewater, industrial water, and swimming pools. George Clifford White’s efforts in compiling these editions are invaluable; and much of the information he has gathered is included in this current edition; some of it is retained solely to provide a historical perspective.

Since the publication of the fourth edition, the water industry has gained a substantial amount of experience with chlorine, hypochlorite, and alternative disinfectants through research, development, and regulation. Consequently, this handbook has been extensively revised and updated to reflect the most current understanding and practices. The reader will find substantial and important information not only on chlorination but also on alternative disinfectants such as ozone, chlorine dioxide, bromine-related products, and ultraviolet light. In addition, the global focus on reuse to address the issue of water scarcity has elevated the use of advanced oxidation practices, and that chapter has therefore been updated to reflect today’s environment.

Each chapter has been prepared by experts and reviewed by their peers in an effort to impart accurate, complete, and current knowledge on the subject being discussed. Black & Veatch considers it a privilege to present this updated resource on chlorination and alternative disinfectants for the water and wastewater industries.

It is our intention that this handbook continue to be the disinfection reference of choice for designers, operator, engineers, students, and regulators.

Cindy Wallis-Lage
Black & Veatch
Editor

xxvii