

Wastewater Treatment and Reuse

Theory and Design Examples

Volume 2

Post-Treatment, Reuse, and Disposal

Syed R. Qasim
Guang Zhu

Wastewater Treatment and Reuse

Theory and Design Examples

Volume 2: Post-Treatment, Reuse, and Disposal



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Wastewater Treatment and Reuse

Theory and Design Examples

Volume 2: Post-Treatment, Reuse, and Disposal

Syed R. Qasim

The University of Texas at Arlington

Guang Zhu

CP&Y, Inc.

In Cooperation with

CP&Y, Inc.

Consulting Engineers · Planners · Project Managers

Dallas, Texas



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2018 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper

International Standard Book Number-13: 978-1-138-30094-1 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Contents

Preface	xv
Acknowledgment	xxi
Authors	xxiii

VOLUME 1 Principles and Basic Treatment

1	Introduction to Wastewater Treatment: An Overview	1-1
1.1	Historical Development	1-1
1.2	Current Status	1-1
1.3	Future Directions	1-3
1.3.1	Health and Environmental Concerns	1-3
1.3.2	Improved Wastewater Characterization and Sidestreams	1-4
1.3.3	Rehabilitation of Aging Infrastructure	1-4
1.3.4	Energy Reduction and Recovery from Wastewater	1-5
1.3.5	Building, Retrofitting, and Upgrading POTWs	1-5
1.3.6	Process Selection, Performance, Reliability, and Resiliency	1-5
1.3.7	Reduction in Sludge Quantity, Nutrients Recovery, and Biosolids Reuse	1-6
1.3.8	Effluent Disposal and Reuse	1-6
1.3.9	Control of Combined Sewer Overflows and Stormwater Management	1-7
1.3.10	Decentralized and On-Site Treatment and Disposal	1-8
1.3.11	Technology Assessment and Implementation	1-8
1.4	Wastewater Treatment Plants	1-8
1.5	Scope of This Book	1-9
	Discussion Topics and Review Problems	1-9
	References	1-9
2	Stoichiometry and Reaction Kinetics	2-1
2.1	Chapter Objectives	2-1
2.2	Stoichiometry	2-1
2.2.1	Homogeneous Reactions	2-1
2.2.2	Heterogeneous Reactions	2-2
2.3	Reaction Rates and Order of Reaction	2-4
2.3.1	Reaction Rates	2-5
2.3.2	Saturation-Type or Enzymatic Reactions	2-8
2.4	Effect of Temperature on Reaction Rate	2-11

2.5	Reaction Order Data Analysis and Design	2-12
2.5.1	Zero-Order Reaction.....	2-12
2.5.2	First-Order Reaction.....	2-15
2.5.3	Second-Order Reaction	2-26
	Discussion Topics and Review Problems	2-33
	References	2-35
3	Mass Balance and Reactors.....	3-1
3.1	Chapter Objectives	3-1
3.2	Mass Balance Analysis.....	3-1
3.2.1	Procedure for Mass Balance Analysis.....	3-2
3.2.2	Combining Flow Streams of a Single Material.....	3-3
3.2.3	Combining a Conservative Substance and Flow	3-6
3.2.4	Mass or Concentration of Nonconservative Substances in Reactors	3-13
3.3	Flow Regime.....	3-16
3.4	Types of Reactors.....	3-16
3.4.1	Batch Reactor	3-16
3.4.2	Continuous-Flow Stirred-Tank Reactor	3-18
3.4.3	Plug Flow Reactor	3-34
3.4.4	Comparative Performance of a PFR and CFSTR	3-39
3.4.5	Performance of CFSTRs in Series (Cascade Arrangement)	3-44
3.4.6	Graphical Solution of Series CFSTRs	3-52
3.5	Plug Flow Reactors with Dispersion and Conversion.....	3-56
3.5.1	Flow Regime and Dispersion of Tracer	3-56
3.5.2	Performance Evaluation of Sedimentation Basin	3-56
3.5.3	Dispersion with Conversion	3-62
3.6	Equalization of Flow and Mass Loadings.....	3-69
3.6.1	Need and Types.....	3-69
3.6.2	Design Considerations.....	3-70
3.6.3	Design Volume of Equalization Basin	3-71
	Discussion Topics and Review Problems	3-83
	References	3-85
4	Sources and Flow Rates of Municipal Wastewater	4-1
4.1	Chapter Objectives	4-1
4.2	Relationship between Municipal Water Demand and Wastewater Flow	4-1
4.3	Components of Municipal Water Demand.....	4-3
4.3.1	Residential or Domestic Water Use.....	4-4
4.3.2	Commercial Water Use.....	4-4
4.3.3	Institutional and Public Water Use.....	4-4
4.3.4	Industrial Water Use.....	4-6
4.3.5	Water Unaccounted for or Lost	4-6
4.3.6	Factors Affecting Water Use.....	4-6
4.4	Wastewater Flow	4-12
4.5	Wastewater Flow Variation.....	4-13
4.5.1	Dry Weather Flow	4-13
4.5.2	Infiltration and Inflow	4-14
4.5.3	Common Terms Used to Express Flow Variations	4-15

Discussion Topics and Review Problems	4-25
References	4-27
5 Characteristics of Municipal Wastewater	5-1
5.1 Chapter Objectives	5-1
5.2 Physical Quality	5-1
5.2.1 Temperature	5-1
5.2.2 Color, Turbidity, and Odor	5-1
5.2.3 Settleable and Suspended (Non), Dissolved (Filterable), Volatile and Fixed Solids	5-3
5.3 Chemical Quality	5-7
5.4 Measurement of Organic Matter and Organic Strength	5-7
5.4.1 Biochemical Oxygen Demand	5-7
5.4.2 Nitrogenous Oxygen Demand	5-24
5.4.3 Chemical Oxygen Demand	5-30
5.4.4 Total Organic Carbon	5-33
5.4.5 Total Oxygen Demand and Theoretical Oxygen Demand	5-33
5.4.6 Relationship between BOD ₅ and Other Tests Used for Organic Content	5-33
5.4.7 Other Nonspecific and Specific Tests for Organic Contents	5-35
5.4.8 Nonbiodegradable and Toxic Compounds	5-36
5.5 Microbiological Quality	5-36
5.5.1 Basic Concepts	5-36
5.5.2 Indicator Organisms	5-38
5.5.3 Measurement Techniques	5-39
5.6 Priority Pollutants	5-50
5.7 Toxicity and Biomonitoring	5-50
5.7.1 Toxicity Test	5-51
5.7.2 Toxicity Test Evaluation	5-51
5.8 Unit Waste Loading and Population Equivalent	5-57
5.9 Mass Loadings and Sustained Mass Loadings	5-60
Discussion Topics and Review Problems	5-65
References	5-69
6 Wastewater Treatment Objectives, Design Considerations, and Treatment Processes	6-1
6.1 Chapter Objectives	6-1
6.2 Treatment Objectives and Regulations	6-1
6.2.1 Objectives	6-1
6.2.2 Regulations	6-1
6.3 Basic Design Considerations	6-3
6.3.1 Initial and Design Years and Design Population	6-4
6.3.2 Service Area and Treatment Plant Site Selection	6-13
6.3.3 Regulatory Requirements and Effluent Limitations	6-15
6.3.4 Characteristics of Wastewater and Degree of Treatment	6-16
6.3.5 Treatment Processes, Process Diagrams, and Equipment	6-17
6.3.6 Plant Layout	6-38
6.3.7 Plant Hydraulic Conditions	6-39

6.3.8	Plant Hydraulic Profile	6-50
6.3.9	Energy and Resource Requirements and Plant Economics.....	6-53
6.3.10	Environmental Impact Assessment	6-53
6.4	Wastewater Facility Planning, Design, and Management.....	6-57
6.4.1	Facility Planning	6-57
6.4.2	Design Plans, Specifications, Cost Estimates, and Support Documents	6-58
6.4.3	Construction and Construction Management	6-61
	Discussion Topics and Review Problems	6-61
	References	6-63
7	Screening.....	7-1
7.1	Chapter Objectives	7-1
7.2	Screening Devices	7-1
7.2.1	Coarse Screens.....	7-1
7.2.2	Design Considerations of Coarse Screens and Installations.....	7-2
7.2.3	Fine Screens	7-31
7.2.4	Design of Fine Screens.....	7-32
7.2.5	Special Screens.....	7-40
7.3	Quantity, Characteristics, and Disposal of Screenings	7-41
7.3.1	Quantity and Characteristics.....	7-41
7.3.2	Processing and Disposal of Screenings.....	7-41
	Discussion Topics and Review Problems	7-43
	References	7-45
8	Grit Removal.....	8-1
8.1	Chapter Objectives	8-1
8.2	Need and Location of Grit Removal Facility.....	8-1
8.3	Gravity Settling.....	8-2
8.3.1	Types of Gravity Settling.....	8-2
8.3.2	Discrete Settling (Type I)	8-2
8.4	Types of Grit Removal Facilities.....	8-19
8.4.1	Horizontal-Flow Grit Chamber	8-19
8.4.2	Design of Effluent Trough	8-36
8.4.3	Aerated Grit Chamber	8-43
8.4.4	Vortex-Type Grit Chambers.....	8-51
8.4.5	Sludge Degritting	8-55
8.4.6	Grit Collection and Removal	8-56
8.5	Grit Characteristics and Quality.....	8-56
8.6	Grit Processing, Reuse, and Disposal	8-57
	Discussion Topics and Review Problems	8-59
	References	8-60
9	Primary and Enhanced Sedimentation	9-1
9.1	Chapter Objectives	9-1
9.2	Flocculent Settling (Type II).....	9-1
9.3	Influent Quality of Primary Sedimentation Basin	9-8
9.4	Types of Primary Sedimentation Basins	9-11
9.4.1	Rectangular Basin.....	9-11

9.4.2	Circular Basins.....	9-14
9.4.3	Square Tanks	9-15
9.4.4	Stacked, Multilevel, or Multitray Tanks.....	9-16
9.4.5	Basic Design and Performance Criteria.....	9-17
9.5	Enhanced Primary Treatment.....	9-52
9.5.1	Preaeration.....	9-52
9.5.2	Chemical Coagulation and Precipitation.....	9-53
9.5.3	Effluent Neutralization.....	9-60
9.5.4	Sludge Production	9-60
9.5.5	Rapid Mixing	9-85
9.5.6	Slow Mixing or Flocculation.....	9-91
9.6	High-Rate Clarification.....	9-143
9.6.1	Solids Contact Clarifiers	9-143
9.6.2	Inclined Surface Clarifiers	9-144
9.6.3	Micro-Sand Ballasted Flocculation Process	9-147
9.6.4	Solids-Ballasted Flocculation Process	9-150
9.7	Fine Mesh Screens for Primary Treatment	9-161
	Discussion Topics and Review Problems	9-166
	References	9-169
10	Biological Waste Treatment.....	10-1
10.1	Chapter Objectives	10-1
10.2	Fundamentals of Biological Waste Treatment.....	10-1
10.2.1	Biological Growth and Substrate Utilization.....	10-1
10.2.2	Types of Biological Treatment Processes	10-9
10.3	Suspended Growth Aerobic Treatment Processes	10-19
10.3.1	Microbial Growth Kinetics in Batch Reactor.....	10-20
10.3.2	Microbial Growth Kinetics in Continuous Flow Reactor	10-30
10.3.3	Continuous Flow Completely Mixed Reactor.....	10-32
10.3.4	Determination of Biological Kinetic Coefficients in a Continuous Flow Completely Mixed Reactor.....	10-54
10.3.5	Continuous Plug-Flow Reactor	10-63
10.3.6	Operational Parameters of Activated Sludge Process	10-68
10.3.7	Activated Sludge Process Modifications.....	10-74
10.3.8	Oxygen Transfer	10-103
10.3.9	Aeration Device, Equipment, and Hardware Assembly.....	10-142
10.3.10	Aeration System Design	10-144
10.3.11	Aerated Lagoon.....	10-172
10.3.12	Stabilization Ponds	10-191
10.4	Fixed-Film or Attached Growth Aerobic Treatment Processes.....	10-209
10.4.1	Nonsubmerged Attached Growth Processes	10-209
10.4.2	Combined Attached and Suspended Growth Processes.....	10-247
10.4.3	Integrated Fixed-Film Media in Aeration Basin	10-254
10.4.4	Submerged Attached Growth Systems	10-260
10.5	Anaerobic Treatment Processes	10-265
10.5.1	Capabilities of Anaerobic Treatment Processes	10-265
10.5.2	Fundamentals of Anaerobic Process	10-265
10.5.3	Environmental Factors.....	10-266
10.5.4	Process Analysis	10-267

10.5.5	Anaerobic Suspended Growth Processes.....	10-279
10.5.6	Anaerobic Attached Growth Processes	10-290
10.6	Biological Nitrogen Removal	10-297
10.6.1	Nitrification.....	10-297
10.6.2	Denitrification	10-337
10.7	Enhanced Biological Phosphorus Removal	10-371
10.7.1	Process Fundamentals	10-371
10.7.2	Biochemical Reactions in Anaerobic Zone.....	10-372
10.7.3	Biochemical Reactions in Aerobic Zone	10-375
10.7.4	Overall Process Considerations	10-375
10.7.5	Biosolids from EBPR Process	10-376
10.8	Biological Nutrient Removal.....	10-384
10.8.1	General Description of BNR Processes	10-385
10.8.2	Performance of BNR Processes	10-385
10.8.3	General Design Considerations for BNR Facilities.....	10-385
10.8.4	Computer Application for BNR Facility Design	10-408
10.9	Secondary Clarification.....	10-412
10.9.1	Design Considerations for Secondary Clarifier.....	10-412
10.9.2	Zone or Hindered Settling (Type III)	10-412
10.9.3	Design of Secondary Clarifiers.....	10-427
	Discussion Topics and Review Problems	10-435
	References	10-445

VOLUME 2 Post-Treatment, Reuse, and Disposal

11	Disinfection	11-1
11.1	Chapter Objectives	11-1
11.2	Objectives and Requirements of Disinfection.....	11-1
11.2.1	Pathogens and Indicator Organisms	11-1
11.2.2	Microbial Reduction in Wastewater Treatment Processes	11-3
11.2.3	Regulatory Process and Requirements	11-7
11.3	Disinfection Techniques	11-7
11.3.1	Chemical Disinfection Processes.....	11-8
11.3.2	Physical Disinfection Processes	11-8
11.3.3	Suitability of Disinfection Processes	11-8
11.3.4	Chlorine and Ozone Doses for Required Disinfection	11-9
11.3.5	Disinfection By-products	11-9
11.4	Inactivation Mechanisms.....	11-9
11.5	Inactivation Kinetics.....	11-11
11.5.1	Natural Die-Off Kinetics.....	11-11
11.5.2	Inactivation Kinetics for Chemical Disinfection Processes.....	11-15
11.6	Chlorination.....	11-29
11.6.1	Physical Properties of Chlorine and Hypochlorite	11-30
11.6.2	Basic Chlorine Chemistry.....	11-36
11.6.3	Components of Chlorination System	11-55
11.6.4	Other Beneficial Applications of Chlorine	11-68
11.6.5	Disinfection with Chlorine Dioxide.....	11-73
11.7	Dechlorination	11-76
11.7.1	Dechlorination with Sulfur Dioxide (SO ₂)	11-76

11.7.2	Dechlorination with Sodium Bisulfite (NaHSO_3)	11-77
11.7.3	Dechlorination with Other Reducing Agents	11-78
11.7.4	Dechlorination with Activated Carbon	11-78
11.7.5	Dechlorination of Chlorine Dioxide	11-78
11.8	Disinfection with Ozone	11-81
11.8.1	Ozone Chemistry	11-81
11.8.2	Properties of Ozone	11-82
11.8.3	Ozone Dosage for Disinfection	11-82
11.8.4	Ozone Generation	11-83
11.8.5	Ozone Application	11-85
11.8.6	Kinetic Equations for Ozone Disinfection	11-87
11.9	Disinfection with UV Radiation	11-97
11.9.1	Mechanism of UV Disinfection	11-97
11.9.2	Source of UV Radiation	11-97
11.9.3	Types of UV Reactors and Lamp Arrangements	11-98
11.9.4	Microbial Repair after UV Disinfection	11-98
11.9.5	Inactivation Kinetics for UV Irradiation	11-100
11.9.6	UV Transmittance, Density, Intensity, and Dose	11-111
11.9.7	Major Components of Open-Channel UV Disinfection Systems	11-115
11.9.8	Hydraulics of UV Channel	11-116
11.10	Recent Developments in Disinfection Reactor Design	11-129
	Discussion Topics and Review Problems	11-130
	References	11-134
12	Effluent Reuse and Disposal	12-1
12.1	Chapter Objectives	12-1
12.2	Major Issues Related to Effluent Reuse	12-1
12.2.1	Quality Parameters of Reclaimed Water	12-1
12.2.2	Treatment Technology for Reclaimed Water	12-2
12.2.3	Regulations or Guidelines Regarding Reuse of Reclaimed Water	12-7
12.3	Health Risk Analysis	12-7
12.3.1	Quantitative Toxicology	12-7
12.3.2	Risk Assessment	12-12
12.3.3	Assessment of Noncarcinogenic Effects	12-13
12.3.4	Assessment of Carcinogenic Effects	12-16
12.4	Storage Facility for Reclaimed Water	12-24
12.4.1	Enclosed Storage Reservoirs	12-24
12.4.2	Open Storage Reservoirs	12-25
12.5	Reclaimed Water Reuse	12-27
12.5.1	Urban Water Reuse	12-27
12.5.2	Industrial Water Reuse	12-28
12.5.3	Agricultural Irrigation Reuse	12-35
12.5.4	Impoundments for Recreational and Aesthetic Reuse	12-40
12.5.5	Environmental Reuse for Habitat Restoration and Enhancement	12-40
12.5.6	Groundwater Recharge	12-41
12.5.7	Augmentation of Potable Water Supply	12-45
12.6	Effluent Discharge into Natural Waters	12-48
12.6.1	Requirements of Outfall	12-48
12.6.2	Water Quality Models of Surface Water	12-49
12.6.3	Design of Outfall Structures	12-65

Discussion Topics and Review Problems	12-73
References	12-77
13 Residuals Processing, Disposal, and Reuse	13-1
13.1 Chapter Objectives	13-1
13.2 Conventional and Emerging Technologies for Sludge Processing	13-1
13.3 Characteristics of Municipal Sludge	13-2
13.3.1 Sources and Solids Content	13-2
13.3.2 Sludge Quantity Variations and Solids and Volume Relationship	13-2
13.3.3 Sludge and Scum Pumping	13-4
13.3.4 Preliminary Sludge Preparation Operations	13-6
13.4 Conventional Sludge Processing Systems, Process Diagrams, and Regulatory Requirements	13-14
13.4.1 Sludge Processing Systems	13-14
13.4.2 Sidestreams	13-14
13.4.3 Process Diagrams	13-14
13.4.4 Regulatory Requirements for Biosolids Reuse and Disposal	13-14
13.5 Sludge Thickening	13-22
13.5.1 Gravity Thickening	13-22
13.5.2 Dissolved Air Flotation Thickening	13-33
13.5.3 Centrifugal Thickening	13-37
13.5.4 Gravity Belt Thickening	13-38
13.5.5 Rotary Drum Thickener	13-40
13.5.6 Membrane Thickener	13-40
13.6 Sludge Stabilization	13-41
13.6.1 Anaerobic Digestion	13-41
13.6.2 Aerobic Digestion	13-72
13.6.3 Chemical Stabilization	13-89
13.6.4 Heat Treatment or Thermal Stabilization	13-90
13.7 Sludge Conditioning	13-90
13.7.1 Chemical Conditioning	13-90
13.7.2 Physical Conditioning	13-97
13.8 Sludge Dewatering	13-97
13.8.1 Natural Dewatering Systems	13-98
13.8.2 Mechanical Dewatering Systems	13-109
13.9 Material Mass Balance Analysis	13-125
13.10 Emerging Technologies for Enhanced Sludge Stabilization and Resource Recovery	13-134
13.10.1 Pretreatment of Sludge	13-134
13.10.2 Enhanced Anaerobic Digestion Performance	13-136
13.10.3 Resource Recovery from Municipal Sludge	13-137
13.10.4 Nitrogen Removal by Partial Nitrification/Anammox (PN/A) Process	13-139
13.11 Sludge Disposal and Biosolids Reuse	13-147
13.11.1 Composting	13-148
13.11.2 Heat Drying	13-159
13.11.3 Thermal Oxidations	13-159
13.11.4 Recalcination	13-164
13.11.5 Land Application of Biosolids	13-164

13.11.6 Residuals Disposal by Landfilling	13-176
Discussion Topics and Review Problems	13-182
References	13-186
14 Plant Layout, Yard Piping, Plant Hydraulics, and Instrumentation and Controls	14-1
14.1 Chapter Objectives	14-1
14.2 Plant Layout	14-1
14.2.1 Factors Affecting Plant Layout and Site Development	14-1
14.2.2 Construction Requirements	14-2
14.2.3 Compact and Modular Site Development	14-3
14.2.4 Plant Utilities	14-4
14.2.5 Environmental Considerations and Security	14-4
14.2.6 Occupational Health and Safety	14-5
14.2.7 Future Expansion	14-5
14.3 Yard Piping	14-10
14.3.1 Organizing Yard Piping	14-10
14.3.2 Pipe Galleries	14-10
14.3.3 Considerations for Plant Upgrading	14-11
14.4 Plant Hydraulics	14-11
14.4.1 Hydraulic Profile	14-11
14.4.2 Head Losses through Treatment Units	14-12
14.4.3 Head Losses through Connecting Conduits	14-12
14.5 Instrumentation and Controls	14-21
14.5.1 Benefits of Instrumentation and Control Systems	14-21
14.5.2 Components of Control Systems	14-21
Discussion Topics and Review Problems	14-37
References	14-40
15 Advanced Wastewater Treatment and Upgrading Secondary Treatment Facility	15-1
15.1 Chapter Objectives	15-1
15.2 Application of Advanced Treatment Technologies and Upgrading of Secondary Effluent	15-1
15.3 Natural Treatment Systems	15-1
15.3.1 Terrestrial Treatment Systems	15-2
15.3.2 Aquatic Treatment Systems	15-14
15.4 Advanced Wastewater Treatment Processes	15-26
15.4.1 Biological Nutrient Removal (BNR) Processes	15-26
15.4.2 Chemical Coagulation and Phosphorus Precipitation	15-27
15.4.3 Lime Precipitation	15-28
15.4.4 Breakpoint Chlorination for Ammonia Removal	15-28
15.4.5 Air Stripping for Removal of Dissolved Gases and VOCs	15-29
15.4.6 Granular Filtration	15-40
15.4.7 Surface Filtration	15-74
15.4.8 Carbon Adsorption	15-78
15.4.9 Ion Exchange	15-100

15.4.10 Membrane Processes.....	15-120
15.4.11 Concentration and Disposal of Waste Brine	15-146
Discussion Topics and Review Problems	15-153
References	15-156
Appendix A: Abbreviations and Symbols, Basic Information about Elements, Useful Constants, Common Chemicals Used in Water and Wastewater Treatment, and the U.S. Standard Sieves and Size of Openings.....	A-1
Appendix B: Physical Constants and Properties of Water, Solubility of Dissolved Gases in Water, and Important Constants for Stability and Sodidity of Water.....	B-1
Appendix C: Minor Head Loss Coefficients for Pressure Conduits and Open Channels, Normal Commercial Pipe Sizes, and Design Information of Parshall Flume	C-1
Appendix D: Unit Conversions	D-1
Appendix E: Summary of Design Parameters for Wastewater Treatment Processes	E-1
Appendix F: List of Examples and Solutions.....	F-1
Index	I-1

Preface

Over the last decade there have been rapid developments and changes in the field of wastewater treatment. The emphasis has been on identification, detection, and removal of specific constituents; computer simulation and modeling; membrane processes; renovation and reuse of wastewater effluent; nutrients recovery, and reduction and utilization of biosolids; energy conservation; greater understanding of theory and principles of treatment processes; and application of these fundamentals into facility design. Environmental engineers have many responsibilities. One of the most demanding yet satisfying of these are the design of wastewater treatment and reuse facilities. There are several books that discuss the fundamentals, scientific principles, and concepts and methodologies of wastewater treatment. The actual design calculation steps in numerical examples with intense focus on practical application of theory and principles into process and facility design are not fully covered in these publications. The intent of the authors writing this book is threefold: *first*, to present briefly the theory involved in specific wastewater treatment processes; *second*, to define the important design parameters involved in the process, and provide typical design values of these parameters for ready reference; and *third*, to provide a design approach by providing numerical applications and step-by-step design calculation procedure in the solved examples. Over 700 illustrative example problems and solutions have been worked out to cover the complete spectrum of wastewater treatment and reuse from fundamentals through advanced technology applied to primary, secondary and advanced treatment, reuse of effluent, by-product recovery and reuse of biosolids. These examples and solutions enhance the readers' comprehension and deeper understanding of the basic concepts. They also serve as a good source of information for more experienced engineers, and also aid in the formal design training and instruction of engineering students. Equipment selection and design procedures are the key functions of engineers and should be emphasized in engineering curricula. Many practice problems with step-by-step solution provide skills to engineering students and professionals of diverse background for learning, and to master the problem-solving techniques needed for professional engineering (PE) exams. Also, these solved examples can be applied by the plant designers to design various components and select equipment for the treatment facilities. Thus, the book is a consolidated resource of valuable quick-and-easy access to a myriad of theory and practice information and solved examples on wastewater treatment processes and reuse.

This work is divided into two volumes. Principles and basic treatment processes are covered in Volume 1, which includes Chapters 1 through 10. Volume 2 contains Chapters 11 through 15 to cover post-treatment processes, reuse, and solids disposal.

Volume 1: Principles and Basic Treatment. Chapter 1 is an overview of wastewater treatment: past, present, and future directions. Chapters 2 and 3 cover the stoichiometry, reaction kinetics, mass balance, theory of reactors, and flow and mass equalization. Sources of municipal wastewater and flow rates and characteristics are provided in Chapters 4 and 5. Chapter 6 provides an in-depth coverage of wastewater treatment objectives, design considerations, and treatment processes and process diagrams. The preliminary treatment processes are covered in Chapters 7 and 8. These unit processes are screening and grit removal. Chapter 9 deals with primary treatment with plain and chemically

enhanced sedimentation. Chapter 10 provides an in-depth coverage of biological waste treatment and nutrients removal processes.

Volume 2: Post-Treatment, Reuse, and Disposal. Chapter 11 covers major processes for effluent disinfection, while Chapter 12 deals with effluent disposal and reuse. Chapter 13 is devoted to residuals management, recovery of resources, and biosolids reuse. The plant layout, yard piping, plant hydraulics, and instrumentation and controls are covered in Chapter 14. Upgrading of secondary treatment facility, land application, wetlands, filtration, carbon adsorption, BNR and MBR; and advanced wastewater treatment processes such as ion exchange, membrane processes, and distillation for demineralization are covered in Chapter 15.

This book will serve the needs of students, teachers, consulting engineers, equipment manufacturers, and technical personnel in city, state, and federal organizations who are involved with the review of designs, permitting, and enforcement. To maximize the usefulness of the book, the technical information is summarized in many tables that have been developed from a variety of sources. To further increase the utility of this book six appendices have been included. These appendices contain (a) abbreviations and symbols, basic information about elements, useful constants, common chemicals used in water and wastewater treatment, and U.S. standard sieves and size of openings; (b) physical constants and properties of water, solubility of dissolved gases in water, and important constants for solubility and sodicity of water; (c) minor head loss coefficients for pressure conduits and open channels, normal commercial pipe sizes, and design information of Parshall flumes; (d) unit conversions; (e) design parameters for wastewater treatment processes; and (f) list of examples presented and solved in this book. These appendices are included in both volumes. The numerical examples are integrated with the key words in the subject index. This gives additional benefit to the users of this book to identify and locate the solved examples that deal with the step-by-step calculations on the specific subject matter.

Enough material is presented in this textbook that cover supplemental material for a water treatment course, and a variety of wastewater treatment courses that can be developed and taught from this title. The supplemental material for a water treatment course include components of municipal water demand (Section 4.3), rapid mix, coagulation, flocculation, and sedimentation (Sections 9.6, 9.7, and 10.9), filtration (Section 15.4.6), carbon adsorption (Section 15.4.8), chlorine and ozone disinfection (Sections 11.6 and 11.8), demineralization by ion exchange and membrane processes (Sections 15.4.9 and 15.4.10), and residuals management (Sections 13.4.1 through 13.4.3, 13.5 through 13.8, and 13.11.6). At least *three* one-semester, and *one* two-semester sequential wastewater treatment courses at undergraduate or graduate levels can be developed and taught from this book. The specific topics to be covered will depend on time available, depth of coverage, and the course objectives. The suggested wastewater treatment and reuse courses are:

Course A: A one-semester introductory course on wastewater treatment and reuse

Course B: A sequential two-semester advance course on wastewater treatment and reuse

Course C: A one-semester course on physical and chemical unit operations and processes

Course D: A one-semester course on biological wastewater treatment

The suggested course outlines of these courses are provided in the tables below. The information in these tables is organized under three columns: topic, chapter, and sections. The examples are not included in these tables. It is expected that the instructor of the course will select the examples to achieve the depth of coverage required.

Course A: Suggested course contents of a one-semester introductory course on wastewater treatment and reuse

Topic	Chapter	Section
Overview of wastewater treatment	1	All
Stoichiometry and reaction kinetics	2	2.1 and 2.2

Continued

Topic	Chapter	Section
Mass balance, reactors, and equalization	3	3.1 to 3.3, and 3.4.1 to 3.4.3
Sources and flow rates of wastewater	4	All
Characteristics of municipal wastewater	5	5.1 to 5.6, 5.7.1, 7.8, and 5.9
Treatment and design objectives, and processes	6	All
Screening	7	All
Grit removal	8	8.1 to 8.3, 8.4.1 to 8.4.5, 8.5, and 8.6
Conventional and chemically enhanced primary sedimentation	9	9.1 to 9.6, 9.7.1, and 9.7.2
Biological waste treatment: basics, oxygen transfer, fixed film attached growth processes, anaerobic treatment, biological nitrogen removal, and final clarifier	10	10.1, 10.2, 10.3.1, 3.3.2, 10.3.4 to 10.3.8, 10.3.10, 10.3.11, 10.4 to 10.6, 10.7.1 to 10.7.3, 10.8, and 10.9
Effluent disinfection	11	11.1 to 11.7
Effluent reuse and disposal	12	12.1, 12.2, 12.5, and 12.6
Residuals processing, reuse, and disposal	13	13.1 to 13.8, and 13.11
Plant layout, piping, hydraulics, and instrumentation and control	14	All
Advanced wastewater treatment and upgrading secondary treatment facility	15	15.1 to 15.3, 15.4.5, 15.4.6, and 15.4.8 to 15.4.10

Course B: Suggested course contents of a sequential two-semester advanced course on wastewater treatment and reuse

Topic	Chapter	Section
First Semester		
Overview of wastewater treatment	1	All
Stoichiometry and reaction kinetics	2	All
Mass balance, reactors, and equalization	3	All
Sources and flow rates of wastewater	4	All
Characteristics of municipal wastewater	5	All
Treatment objectives, design considerations, and treatment processes	6	All
Screening	7	All
Grit removal	8	All
Primary and enhanced sedimentation	9	All
Biological waste treatment: fundamentals and types	10	10.1 and 10.2
Second Semester		
Biological waste treatment (cont'd): suspended, attached, aerobic, anaerobic kinetics, oxygen transfer, biological nutrient removal (BNR), computer application, and final clarifiers	10	10.3 to 10.10
Disinfection and kinetics	11	All
Effluent reuse and disposal	12	All

Continued

Topic	Chapter	Section
Residuals processing, reuse, and disposal	13	All
Plant layout, piping, hydraulics, and instrumentation and control	14	All
Advanced wastewater treatment facilities	15	All

Course C: Suggested course contents of a one-semester course on physical and chemical unit operations and processes

Topic	Chapter	Sections
Overview of wastewater treatment	1	All
Stoichiometry and reaction kinetics	2	All
Mass balance, reactors, and equalization	3	All
Sources and flow rates of wastewater	4	4.4 and 4.5
Characteristics of municipal wastewater	5	5.1 to 5.4
Wastewater treatment processes	6	6.3.5
Screening: coarse and fine screens	7	7.1, and 7.2.1 to 7.2.4
Discrete settling and grit removal	8	8.1, 8.3, 8.4.2, and 8.4.4
Flocculant settling, rapid mixing, flocculation, and sedimentation	9	9.1, 9.2, 9.5.5, 9.6.5, 9.6.6, and 9.7.2
Zone or hindered settling	10	10.9.2
Disinfection kinetics, chlorination, dechlorination, ozonation, and UV radiation	11	11.4, 11.5, 11.6.1, 11.6.2, 11.7.1, 11.8.6, and 11.9.4 to 11.9.6
Compression settling, dissolved air flotation, anaerobic digestion, conditioning, and dewatering	13	13.4.1, 13.4.2, 13.5.1 to 13.5.3, 13.6.1, 13.6.2, 13.7.1, 13.8.1, and 13.8.2
Air stripping, filtration, carbon adsorption, ion exchange, and membrane processes	15	15.4.5, 15.4.6, 15.4.8, 15.4.9, and 15.4.10

Course D: Suggested course contents of a one-semester course on biological wastewater treatment

Topic	Chapter	Section
Overview of wastewater treatment	1	All
Stoichiometry and reaction kinetics	2	All
Mass balance, reactors, and equalization	3	All
Sources and flow rates of wastewater	4	All
Characteristics of municipal wastewater	5	All
Wastewater treatment processes	6	6.3.5
Biological waste treatment, biological nutrient removal (BNR), and final clarifier	10	All
Pathogens reduction in treatment processes and natural die-off kinetics	11	11.2.1, and 11.5.1
Anaerobic and aerobic digestion of sludge, material mass balance, and composting	13	13.6.1, 13.6.2, 13.9, and 13.11.1
Aquatic treatment systems, and membrane processes	15	15.3.2, and 15.4.10

In the solutions of examples, full expressions are provided to demonstrate step-by-step calculations. Many process and hydraulic parameters are involved in these expressions. To be more efficient, these parameters are represented by symbols. Sometimes, in the same example, parameters are applied multiple times to different streams or reactors. Therefore, subscripted notations are also used to identify these parameters. Each symbol is fully defined when it appears for the first time in the solution of the example. After that this symbol is repeated in the entire solution. This approach is helpful in (1) saving space by replacing lengthy descriptions of a parameter, and (2) providing an identification of the numerical value used or obtained in the expression. Additionally, these symbols provide the designers a ready reference in their design calculations while using Mathcad or spreadsheet software.

The International System of Units (SI) is used in this book. This is consistent with the teaching practices in most universities in the United States and around the world. Most tables in the book have dual units and include conversion from SI to U.S. customary units in footnotes. Useful conversion data and major treatment process design parameters are provided in Appendices D and E.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Acknowledgment

A project of this magnitude requires the cooperation and collaboration of many people and organizations. We are indebted to many professionals, faculty members, students, and friends who have helped and provided constructive suggestions. We must acknowledge the support, encouragement, and stimulating discussion by Michael Morrison, W. Walter Chiang, and Pete K. Patel throughout this project. CP&Y, Inc., a multidisciplinary consulting engineering firm in Dallas, Texas provided the technical support. We gratefully appreciate the support and assistance provided by Michael F. Graves, Marisa T. Vergara, Gregory W. Johnson, Ellen C. Carpenter, Barbara E. Vincent, Megan E. Martin, Gil W. Barnett, and Dario B. Sanchez. Many students also assisted with typing, artwork, literature search, and proofreading. Among them are Bernard D'Souza, Rajeshwar Kamidi, Neelesh Sule, Richa Karanjekar, Gautam Eapi, and Olimatou Ceesay.

Kelcy Warren established Syed Qasim Endowed Professorship in Environmental Engineering in the Department of Civil Engineering at The University of Texas at Arlington. Funds from this endowment helped to support students. The support of the Department of Civil Engineering at The University of Texas at Arlington is greatly appreciated. In particular, we thank the support of Dr. Ali Abolmaali, and tireless support of Sara Ridenour in making departmental resources available.

Finally, we must acknowledge with deep appreciation the support, encouragement, and patience of our families.

Although the portions of this book have been reviewed by professionals and students, the real test will not come until this book is used in classes, and by professionals in design of wastewater treatment facilities. We shall appreciate it very much if all who use this book will let us know of any errors and changes they believe would improve its usefulness.

Syed R. Qasim and Guang Zhu
Arlington, Texas



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

Authors

Syed R. Qasim is a professor emeritus in the Department of Civil Engineering at the University of Texas at Arlington. Dr. Qasim earned PhD and MSCE from West Virginia University, and BSCE from India. He served on the faculty of Polytechnic University, Brooklyn, New York, and on the faculty of the University of Texas at Arlington, Texas, from 1973 till his retirement in 2007. Dr. Qasim has conducted full-time research with Battelle Memorial Institute, Columbus Laboratories, and has worked as a design engineer with a consulting engineering firm in Columbus, Ohio. He has over 47 years of experience as an educator, researcher, and practitioner in the related fields of environmental engineering. His principal research and teaching interests include water and wastewater treatment processes and plant design, industrial waste treatment, and solid and hazardous waste management. He served nationally and internationally as a consultant with governmental agencies and private concerns. Dr. Qasim has written 3 books, and he is the author or coauthor of over 150 technical papers, encyclopedia and book chapters, and research reports. His papers, seminars, and short courses have been presented nationally and internationally. He is a *life member* and *Fellow* of American Society of Civil Engineers, and a *life member* of Water Environment Federation; a member of Association of Environmental Engineering and Science Professors, American Water Works Association, and other professional and honor societies. He is a registered professional engineer in the state of Texas.

Guang Zhu is an associate and senior water and wastewater engineering director with CP&Y, Inc., a multidisciplinary consulting engineering firm headquartered in Dallas, Texas. Dr. Zhu has over 30 years of consulting experience in planning, process evaluation, pilot testing, design, and commissioning of numeral conventional and advanced water and wastewater treatment plants in the United States and China. He had 10 years of consulting experience with Beijing General Municipal Engineering Design and Research Institute, Beijing, China. Dr. Zhu has coauthored one textbook and many technical papers and has translated two water and wastewater books in Chinese. He has taught several design courses as an adjunct assistant professor at the University of Texas at Arlington. He is a registered professional engineer in the state of Texas.



Taylor & Francis

Taylor & Francis Group

<http://taylorandfrancis.com>

11

Disinfection

11.1 Chapter Objectives

Wastewater contains many types of human enteric organisms that are associated with various waterborne diseases. Disinfection is the primary mechanism for inactivation and destruction of disease-causing organisms present in the wastewater, and it is one of the common steps required in wastewater treatment and reuse. Presently, chlorination of both water supply and wastewater effluent is a widespread practice for the control of waterborne diseases. Alternate methods of disinfection are receiving a great deal of attention because chlorination may result in the formation of disinfection by-products (DBPs); many of which are known carcinogens. The material presented in this chapter covers the following important issues related to the disinfection process and facility design:

- Objectives and requirements of disinfection
- Disinfection techniques to meet the disinfection goals
- Basic design considerations for chlorination and dechlorination
- Application of alternate methods of disinfection such as ozone and ultraviolet (UV) radiation

11.2 Objectives and Requirements of Disinfection

A disinfection process should be properly selected as the final defense after the routine nondisinfection treatment processes. The main objectives of wastewater disinfection are to protect public health from waterborne diseases, reduce adverse side effects to the aquatic life, eliminate threats to the environment, and comply with the regulatory requirements.

11.2.1 Pathogens and Indicator Organisms

The pathogens are normally divided into four major microbial groups: (1) bacteria, (2) virus, (3) protozoa, and (4) helminthes. Common pathogens that may be present in domestic wastewater are summarized in [Table 11.1](#).¹⁻¹⁰ Because of the presence of a large number of organisms in wastewater samples, their number is usually expressed to the base 10 of the logarithmic scale (Equation 11.1).

$$\log \text{ concentration} = \log(N) \quad (11.1)$$

where N = number of organism present in a specified sample volume

It is important to specify the sample volume for the log scale. The volume of wastewater is typically 100 mL for bacteria and virus, and 100 L for protozoa and helminthes. A general discussion on the microbiological quality of wastewater, indicator organisms, and measurement techniques are presented in Chapter 5.

Traditional Indicator Organisms: The identification and measurement techniques for pathogens in wastewater are neither simple nor clear-cut. For this reason, a group of indicator organisms are used to

TABLE 11.1 Common Pathogens Carried in Raw Domestic Sewerage

Organism (Size Range)	Probable Concentration ^a , log(<i>N</i>)	Probable Median Infectious Dose ^b , log(<i>N</i> ₅₀)	Relative Infectivity	Associated Waterborne Disease
Bacteria (0.2–10 μm)				
<i>Escherichia coli</i> (enteropathogenic)	5–8	6–10	Low	Gastroenteritis
<i>Salmonella</i> spp. (nontyphoid)	2–4	4–7	Low	Salmonellosis
<i>Salmonella typhi</i>	0–4	5–7	Low	Typhoid fever
<i>Shigella</i> spp.	0–3	1–2	Moderate	Shigellosis (dysentery)
<i>Vibrio cholerae</i>	1–4	3–8	Low	Cholera
Viruses (0.02–0.3 μm)				
Astroviruses (7 types)	–	< 2	–	Gastroenteritis
Caliciviruses (Norwalk and Sapporo)	<6	1–2	High	Gastroenteritis
Coronavirus	–	–	–	Gastroenteritis
Enteric viruses (72 types)	6–7	0–3	High	Paralysis, gastroenteritis, fever, herpangina
Hepatitis A virus	–	0–2	High	Infectious hepatitis
Parvoviruses (3 types)	–	–	High	Gastroenteritis
Rotaviruses (4 types)	4–7	< 1	High	Gastroenteritis
Protozoa (4–60 μm)				
<i>Cryptosporidium parvum</i>	2–6	0–2	High	Cryptosporidiosis
<i>Entamoeba histolytica</i>	2–8	0–2	High	Amebiasis
<i>Giardia lamblia</i>	2–7	0–2	High	Giardiasis
Helminths (20–80 μm)				
<i>Ascaris lumbricoides</i> (roundworm)	2–6	0–1	High	Ascariasis
<i>Schistosoma mansoni</i>	1–2	0–1	High	Schistosomiasis
<i>Trichuris trichiura</i> (whipworm)	2–4	0–1	High	Trichuriasis

^a The number of organisms (*N*) is typically expressed as colony forming unit (CFU) or most probable number (MPN) for bacteria, ova for helminthes, cysts or oocysts for protozoa, and plaque-forming unit (PFU) or MPN for viruses.

^b The median infectious dose (*N*₅₀) indicates the number of organisms at which 50% of an exposed population exhibit a response.

Source: Adapted in part from References 1 through 10.

measure the potential for occurrence of pathogens in the water and wastewater. The traditional indicator organisms are the coliform bacteria of fecal origin. They have been used for a long time in establishing the bacterial surface water quality criteria. Federal water quality criteria for primary contact recreation waters were first established in 1968 based on fecal and total coliforms.¹¹ Under Section 304 (a) of the Clean Water Act of 1977, the criteria were revised by the U.S. Environmental Protection Agency in 1986 with the recommendations for establishing water quality standards based on *Escherichia coli* (*E. coli*) for fresh waters and *Enterococci* for fresh and marine waters. It was confirmed through time that *E. coli* and *Enterococci* were better indicator organisms than fecal and total coliforms for predicting the gastrointestinal illness-causing pathogens.¹² The characteristics of the traditional indicator organisms and the basic measurement techniques are covered in Sections 5.5.2 and 5.5.3.

Emerging Indicator Organisms: The recent practice of wastewater reclamation and reuse has indicated that use of only traditional indicator organisms may not be sufficient for predicting the safety of wastewater against most pathogens in the disinfected effluent.¹³ Alternative emerging indicator organisms have been identified and recommended for microbial quality assessment.^{2,5,14} The organisms most

TABLE 11.2 Indicator Organisms Used in Microbial Water Quality Criteria

Organism	Indication	Characteristics Shape and Size, μm	Probable Concentration in Raw Wastewater ^a , $\log(N)/V$
Traditional Bacterial Indicator Organisms			
Total coliforms	Bacteria	Rod 0.5–2	6–9
Fecal coliforms	Bacteria	Rod 0.5–2	5–8
<i>Escherichia coli</i> (<i>E. coli</i>)	Bacteria	Rod 1–2	5–8
<i>Enterococci</i>	Bacteria	Cocci 0.5–1	4–6
Emerging Indicator Organisms			
Viruses			
Enteric viruses	Viral pathogen	Icosahedral capsid 0.025–0.03	6–7
Coliphages	Viral indicator	Icosahedral protein shell 0.025–0.2	5–7
Bacteria			
<i>Clostridium perfringens</i>	Protozoa surrogate	Rod spore 0.6–1.3 by 2.4–19	3–5
Protozoa			
<i>Cryptosporidium parvum</i>	Protozoan pathogen	Ovoid oocyst 4–6	2–6
<i>Giardia lamblia</i>	Protozoan pathogen	Ovoid cyst 8–12	2–7

^a N = number of organisms, where CFU or MPN for bacteria and viruses, and cysts or oocysts for protozoan parasites. V indicates sample volume; 100 mL for bacteria and viruses, and 100 L for protozoa. For example, total coliform $\log N = 6$ means 10^6 organisms per 100 mL sample.

Source: Adapted in part from References 2, 5, 9, and 10.

commonly used in the recent microbial water quality criteria are summarized in Table 11.2. It is expected that the improved techniques for pathogens detection in reclaimed effluent for reuse may utilize multiple indicators rather than a single indicator.⁵

11.2.2 Microbial Reduction in Wastewater Treatment Processes

In wastewater treatment practice, the removal efficiency is usually expressed by percent removal of the most common contaminants. On account of high numbers, the efficiency as high as 99.99999% may be required for removal or inactivation of pathogens. It is, therefore, more convenient to express the log reduction or log inactivation for microbial removal or inactivation efficiency for wastewater treatment processes. The log reduction is expressed by Equation 11.2.

$$\log \text{ reduction} = \log \text{ inactivation} = \log \text{ removal} = -\log \text{ survival} \quad (11.2a)$$

$$\log \text{ reduction} = -\log(N/N_0) = -[\log(N) - \log(N_0)] \quad (11.2b)$$

$$\log \text{ reduction} = \log(N_0/N) = \log(N_0) - \log(N) \quad (11.2c)$$

where

N = number of organism present in the effluent from a treatment unit

N_0 = number of organism present initially in the influent

Wastewater treatment plants utilize many processes that can be selected for removal of different contaminants to meet the desired discharge permits or reuse criteria. Microbial reduction is achieved in most of these processes. The probable range of microbial log reductions through different wastewater treatment processes is developed and summarized in Table 11.3.^{2,5,10–41} These ranges can be used only as

TABLE 11.3 Probable Microbial Log Reductions of Common and Advanced Wastewater Treatment Processes

Treatment Process	Viruses		Bacteria			Protozoa		Helminth Ova, Cyst, Oocyst
	Enteric Viruses	Coliphages	Total Coliform	<i>E. coli</i> , Fecal Coliform, <i>Enterococci</i>	<i>Clostridium</i> <i>perfringens</i>	<i>Cryptosporidium</i> <i>parvum</i>	<i>Giardia</i> <i>lamblia</i>	
Conventional Treatment Systems								
Primary treatment								
Conventional	0-0.5	0-1	0-0.5	0-0.5	0-0.5	0-0.5	0.5-1	0-2
CEPT	1-2	1-2	1-2.5	1-2.5	1-2.5	1-1.5	1-2	1-3
Secondary treatment								
Activated sludge	0.5-2	0-3	1-3	1-3	0.5-2	0.5-1.5	0.5-1.5	1-2
BNR facility	1-2	1.5-3	1-3	2-3	2-3	0.5-1.5	1.5-2.5	1-2
Extended aeration	1-2	1-3	1-3	1-3	0.5-2	0.5-1.5	0.5-1.5	1-2
Trickling filter	0-1.5	0-2	0-2	0-2	0-1	0-0.5	0-0.5	0.5-1
BAF	0.5-1.5	0.5-2	0.5-2	0.5-2	0-1	0-0.5	0-0.5	0.5-1
RBC	0-1	0-1.5	0.5-1.5	0.5-1.5	0-1	0-0.5	0-0.5	0.5-1
Tertiary treatment								
Coagulation/floc.	0.5-2	1-3	0-1	0-1	0-1	1-2	1-3	1-2
Slow sand filter	1-3	1-3	0-3	0-3	0-2	0-2.5	0-3	1-2
Monomedium filter	0.5-1	0-3	0.5-2	0-1	0-0.5	0-0.5	0-2	2-3
Dual media filter	0.5-2	0.5-1.5	0-3	0-2	0.5-1.5	1-1.5	1-2.5	2-3
Traveling bridge filter	0.5-1.5	0.5-1	2-2.5	1.5-2	1-1.5	0.5-1	0.5-1.5	2-3
Cloth media filter	0-0.5	0-0.5	2-3	1.5-2.5	0.5-1	0-0.5	0.5-1	2-3
MF	0.5-2	1-2	1-4	1-4	1-4	2-4	2-4	2-4
UF	2-4	3-4	3-4	3-4	3-4	3->4	3->4	>4
Natural Treatment Systems								
Constructed wetlands	0.5-2	0.5-2	0.5-3	0.5-3	0.5-3	0.5-1	0.5-2	1-3
Stabilization pond	1-3	1-3	0.5-4	0.5-4	1-3	1-3	1-4	1-3
Storage pond/lagoon	1-4	1-4	1-5	1-5	1-5	1-3.5	3-4	1.5-3
Advanced Treatment Systems								
MBR	1.5-6	2.5-6	3.5-6	3.5-6	3.5-6	2.5->6	2.5->6	3->6
NF with MF or UF	4-7	4-7	4-7	4-7	4-7	>6	>6	>6
RO with MF or UF	>6	>6	>6	>6	>6	>7	>7	>7

Note: BAF = biological aerated filter; BNR = biological nutrient removal; CEPT = chemically enhanced primary treatment; MBR = membrane bioreactor; MF = microfiltration NF = nanofiltration; RBC = rotating biological contactor; UF = ultrafiltration.
Source: Adapted in part from References 2, 5, and 10 through 41.

a general guide. Actual reductions may be affected by the specific design and operating conditions at the plants. Normally, the primary treatment has limited microbial reductions. Secondary treatment achieves high reduction of pathogenic bacteria and enteric viruses. Removal increases with increasing mean cell residence time (MCRT) in biological treatment processes. Membrane processes are very efficient and reliable for control of pathogens. The performance of each and every pre-disinfection treatment process in a process train influences the overall removal of pathogens. As a result, the load on the disinfection process (which is the final step) can be greatly reduced by optimizing all components of the process train.

EXAMPLE 11.1: LOG CONCENTRATION OF ORGANISMS

A fecal coliforms count of 12,000 MPN/100 mL was found in the filtered effluent from a wastewater treatment plant. Calculate the log concentration of fecal coliforms in the filtered effluent.

Solution

Estimate from Equation 11.1, the log concentration of coliforms in filtered effluent

$$\log \text{ concentration} = \log(N) = \log(12,000) = 4.08 \log$$

EXAMPLE 11.2: LOG REMOVAL OF ORGANISMS

A tertiary filtration process was evaluated for removal of *Cryptosporidium parvum* oocysts from treated secondary effluent. The filter influent and effluent counts of oocysts were 100,000 and 300 per 100 L, respectively. Estimate the removal efficiency on (1) percentage basis and (2) log reduction basis.

Solution

1. Estimate the removal efficiency on percentage basis.

The number or concentration of *Cryptosporidium parvum* oocysts in the filter influent

$$N_0 = 100,000 \text{ oocysts}/100 \text{ L}$$

The number or concentration of *Cryptosporidium parvum* oocysts in the filtered effluent

$$N = 300 \text{ oocysts}/100 \text{ L}$$

Calculate the removal efficiency on percentage basis.

$$\text{Percent removal} = \frac{N_0 - N}{N_0} \times 100\% = \frac{100,000 \text{ oocysts}/100 \text{ L} - 300 \text{ oocysts}/100 \text{ L}}{100,000 \text{ oocysts}/100 \text{ L}} \times 100\% = 99.7\%$$

The removal efficiency of *Cryptosporidium parvum* oocysts by the filter is 99.7%.

2. Estimate the removal efficiency on log reduction basis.

The log removal efficiency can be estimated from the following two methods.

- a. Direct method.

The log removal (or reduction) is calculated directly from Equation 11.2b.

$$\log \text{ removal} = -\log(N/N_0) = -\log\left(\frac{300}{100,000}\right) = 2.52 \log$$

b. Indirect method.

Calculate log concentrations in the filter influent and effluent from Equation 11.1.

$$\log \text{ concentration per 100 L in the filter influent} = \log(N_0) = \log(100,000) = 5 \log$$

$$\log \text{ concentration per 100 L in the filter effluent} = \log(N) = \log(300) = 2.48 \log$$

Calculate the log removal from Equation 11.2c.

$$\log \text{ removal} = \log(N_0) - \log(N) = (5 - 2.48) \log = 2.52 \log$$

The log removal efficiency of *Cryptosporidium parvum* oocysts by the tertiary filter is 2.52 log.

EXAMPLE 11.3: LOG CONCENTRATION AND MPN OF ORGANISMS AFTER TREATMENT PROCESS

A process assessment study was conducted to determine the microbial concentration remaining in the effluent from a tertiary plant. The process train includes primary and secondary treatment processes followed by dual media filtration. The monitoring records indicate that the total coliform count in the raw wastewater is 4×10^7 MPN/100 mL. The log reductions of total coliforms (MPN) by each treatment process are given below:

Primary treatment	0.25
Secondary treatment	2.00
Dual media filtration	2.50

Estimate the number of total coliforms (MPN) in the effluents from the primary, secondary, and tertiary treatment system.

Solution

1. Calculate the log concentration of total coliforms in the raw wastewater from Equation 11.1.

$$\log(N_0) = \log(4 \times 10^7) = 7.60 \log$$

2. Estimate the log concentration remaining after primary, secondary, and tertiary treatment processes.

- a. Estimate the log concentration remaining in the primary effluent.

Rearrange Equation 11.2c and calculate the log concentration remaining after 0.25 log reduction during primary treatment.

$$\log(N_1) = \log(N_0) - \log \text{ reduction by primary treatment} = (7.60 - 0.25) \log = 7.35 \log$$

Rearrange Equation 11.1 and calculate the MPN (or concentration remaining) in the primary effluent.

$$N_1 = 10^{\log(N_1)} = 10^{7.35} = 22,400,000 \text{ or } 2.24 \times 10^7 \text{ MPN/100 mL}$$

- b. Estimate the log concentration remaining in the secondary and tertiary effluents.

Apply the procedure in Step 2.a to obtain the log concentration remaining and MPNs in the secondary and tertiary effluents, respectively.

$$\log(N_2) = \log(N_1) - \log \text{ reduction by secondary treatment} = (7.35 - 2.00) \log = 5.35 \log$$

$$N_2 = 10^{\log(N_2)} = 10^{5.35} = 224,000 \text{ or } 2.24 \times 10^5 \text{ MPN/100 mL}$$

$$\log(N_3) = \log(N_2) - \log \text{ reduction by tertiary treatment} = (5.35 - 2.50) \log = 2.85 \log$$

$$N_3 = 10^{\log(N_3)} = 10^{2.85} = 708 \text{ or } 7.08 \times 10^2 \text{ MPN/100 mL}$$

3. Summarize the estimation results for log concentration and MPN.

Location	log reduction	log concentration	Total coliforms concentration, MPN/100 mL
Raw wastewater influent	–	7.60	40,000,000 or 4×10^7
Primary effluent	0.25	7.35	22,400,000 or 2.24×10^7
Secondary effluent	2.00	5.35	224,000 or 2.24×10^5
Tertiary effluent from dual medial filtration	2.50	2.85	708 or 7.08×10^2

11.2.3 Regulatory Process and Requirements

Under the National Pollutant Discharge Elimination System (NPDES), a site-specific effluent discharge permit is required for all publically owned treatment works (POTWs). The discharge permit includes limitations on wastewater flow, and concentrations and mass loadings of specified pollutants. The U.S. Environmental Protection Agency has delegated the implementing authority of the NPDES to the individual states. The delegated states are responsible to establish the standards and compliance strategy for disinfection based on site-specific discharge limitations. Specific microbial criteria and monitoring requirements have also been established by the federal and many state governments for reuse of reclaimed effluent for many potential applications.

Discharge Limits: The individual states have variable and site-specific bacteria limitations based on coliforms for discharging effluent. The ranges can be from nondetectable to 5000 MPN/100 mL for fecal coliforms and from 2.2 to 10,000 MPN/100 mL for total coliforms. The most common standard is 200 and 1000 MPN/100 mL fecal coliforms for primary- and secondary-body contact recreation uses.

Criteria for Reuse of Reclaimed Effluent: The criteria for reuse of reclaimed effluent are much more stringent than those for effluent discharge. The guidance on desired microbial ranges as well as the minimum treatment requirements for reuse of reclaimed wastewater is covered in [Chapter 12](#).

Design and Monitoring Requirements: The disinfection is the last barrier at a plant against microbial safety. For this reason, the design and monitoring requirements for effluent disinfection in the regulations are based on certain parameters that are properly specified and monitored. The parameters for chemical disinfection are based on disinfection properties of the chemical, and include the residual, contact time, initial mixing energy input, and the hydraulic characteristics of the reactor. The most important parameter for the UV disinfection process is the target dose. Detailed information about these parameters for major disinfection processes are covered in several examples later in this chapter.

11.3 Disinfection Techniques

The disinfection method broadly falls into three major categories: (1) chemical, (2) physical, and (3) radiation. Disinfection by radiation using gamma rays has been studied for a long time but is not practical

for wastewater application. Chemical and physical processes have been successfully used for disinfection of wastewater effluent. Limited microbial removal is also achieved by natural die-off in a lagoon. These processes are described below.

11.3.1 Chemical Disinfection Processes

Chemical processes have been the traditional approach for disinfection of both drinking water and wastewater effluent. A chemical is fed into the effluent to maintain a desired residual for a desired contact time. Many chemicals are used for different disinfection applications. These chemicals include oxidants, alcohols, phenol and phenolic compounds, salts and heavy metals, quaternary ammonium compounds, soaps and detergents, and alkalis and acids.⁴² The chemicals for disinfection of wastewater effluent are normally limited to strong oxidants that include halogen-based disinfectants, ozone (O_3), hydrogen peroxide (H_2O_2), potassium permanganate ($KMnO_4$), and peracetic acid (PAA). Hydrogen peroxide and $KMnO_4$ have been effectively used for odor control and color removal. They are rarely used for disinfection alone. Peracetic acid ($C_2H_4O_3$) is a mixture of acetic acid (CH_3COOH) and H_2O_2 . It is a strong disinfectant with relatively high oxidation potential. One of the major advantages is that PAA does not react with TOC to form DBPs. The key concern of using PAA for wastewater disinfection is adding organics in the effluent.^{43–45} The halogen-based disinfectants and ozone are most commonly used for chemical disinfection of wastewater. Recently, new technologies have been explored to use *mixed oxidants* for more effective disinfection than a single conventional disinfectant.^{46,47}

Halogen-Based Disinfectants: The chlorine-based disinfectants include liquid/gas chlorine (Cl_2), sodium hypochlorite ($NaOCl$), calcium hypochlorite ($Ca(OCl)_2$), and chlorine dioxide (ClO_2). Chlorine dioxide is a stronger oxidant than chlorine and does not react with natural organic matters (NOMs) to produce trihalomethanes (THMs). However, application of chlorine dioxide is limited in wastewater disinfection because of its short residual life due to quick decomposition in sunlight and high costs associated with on-site generation. Other alternative halogen-based disinfectants include bromine, bromine chloride, and iodine. These chemicals are rarely used for general purpose of wastewater disinfection.^{42,48,49} Liquid or gas chlorine and sodium hypochlorite are the most widely used halogen-based disinfectants.

Ozone: Ozone is a highly effective disinfectant that has been used for odor and color control as well as disinfection of water supply. Disinfection of wastewater effluent by ozone over chlorine is growing in recent years because of concerns over chlorinated organics, toxicity of chlorine residual to aquatic life in the receiving waters, and added cost of dechlorination.^{42,48}

11.3.2 Physical Disinfection Processes

Common physical disinfection processes include heat (pasteurization), membrane, ultrasonic, and UV radiation. Heat or pasteurization is widely used in food processing, beverage and pharmaceutical industries, as well as medical practice. Heat is however cost prohibitive for wastewater disinfection. At a proper intensity, ultrasonic cavitation can effectively kill organisms by rupturing the cell wall. It is however limited to academic studies as well as small-scale applications. Membrane process for wastewater treatment is gaining popularity in recent years. It is effective for removal of larger organisms simply because of pore size. The application of membrane process is discussed in details in [Chapter 15](#). UV irradiation is an excellent disinfectant and is now an effective and practical technology for disinfection of wastewater effluent. UV irradiation is discussed in Section 11.9.

11.3.3 Suitability of Disinfection Processes

The most commonly used technique for wastewater application is chlorination with or without dechlorination. Dechlorination is needed to reduce the toxicity of chlorine residual on aquatic life in the receiving water. Common chemicals used for dechlorination are sulfur dioxide and sodium bisulfite. Activated

carbon adsorption may also be used as a physical dechlorination process. Ozone and UV irradiation are the effective emerging technologies that eliminate adverse effects of chlorine on the environment.⁴⁹ Suitability of chlorination with chlorine (Cl_2) or sodium hypochlorite (NaOCl), ozonation and UV irradiation are compared in Table 11.4.^{2,42,48-57} The characteristics of an ideal disinfectant are availability, noncorrosive and nonscaling, nontoxic to higher forms of life, high solubility, homogeneity, stability, low side reactions, deep penetration, and safety.

Disinfection effectiveness is usually the most important consideration to assess the suitability of disinfectants. Chlorine, ozone, and UV irradiation are very effective for inactivation of bacterial pathogens and indicator organisms. Ozone is the best for inactivation of viruses, and UV irradiation for control of protozoa. A high UV irradiation target dose may be required for inactivation of some viruses and bacteria spores, including *Clostridium perfringens*. Chlorination is ineffective for control of viruses and protozoa. UV irradiation is ineffective for control of helminthes. Limited removal of helminth ova can be achieved by chlorination or ozonation processes. Tertiary treatment need to be considered seriously if removal of helminthes is a major concern. Probable log reduction of various organisms by chlorination, ozone, and UV irradiation are compared in Table 11.5.^{5,10,13,44,58-63}

The predisinfection effluent quality is another major factor that may also affect the suitability of disinfection technologies, operation and maintenance (O&M), and costs. The predisinfection treatment and effluent quality criteria recommended for effective pathogens reduction by chlorination, ozone, and UV irradiation are summarized in Table 11.6.^{9,55-57,64}

11.3.4 Chlorine and Ozone Doses for Required Disinfection

The disinfection efficiency for chlorination depends upon dosage, type and number of organisms, contact time, chlorine residual, and nature of liquid disinfected. Organic matter, ammonia, and reducing agents react with chlorine thus reducing its effectiveness. Suspended solids protect entrapped organisms. The typical chlorine and ozone dosages for reduction of total coliform in wastewater effluents from different processes are compared in Table 11.7.^{2,42,48,52-54}

11.3.5 Disinfection By-products

The reaction of free chlorine with organic compounds in the effluent results in the production of many undesirable DBPs. These are halogenated organics or total organic halides (TOX). Among these are THMs, haloacetic acids (HAAs), haloaceticnitriles (HANs), chlorophenols, and chlorinated aldehydes, ketones, and others. Bromate concentration may also be elevated after ozonation if high bromide concentration is present in the predisinfection effluent. Many of these compounds are persistent in nature, and their reported toxicological effects in water supply are carcinogenic, mutagenic, genotoxic, hepatotoxic, neurotoxic, and like.⁶³

11.4 Inactivation Mechanisms

The inactivation mechanism for disinfection may be different depending upon the types of target organism as well as the chemical or physical agent selected. The impacts of these factors can be assessed by applicable microbial inactivation kinetics. For nondisinfection processes, microbial removal occurs simply through natural die-off. When disinfectants are used, different mechanisms may cause microbial inactivation. Some disinfectants have inhibition effect on special enzymes. Some may produce radicals that oxidize cellular material directly. Others may damage the cell wall, destroy proteins, or attack nucleic acid. The potential mechanisms that have been suggested for different disinfectants are summarized in Table 11.8.^{2,42,49,55-57}

TABLE 11.4 Suitability of Common Disinfection Technologies for Wastewater Effluent

Application and Consideration	Chlorination		Ozone	UV Irradiation
	Cl ₂	NaOCl		
Disinfection Effectiveness				
Oxidation potential at 25°C, volt	-1.36	1.49 (HOCl)	-2.07	—
Bacteria	Good	Good	Very good	Good
Viruses	Poor	Poor	Very good	Fair
Protozoa (cysts and oocysts)	Poor	Poor	Good	Very good
System Requirements				
Bulk supply	Common	Available	Not applicable	Not applicable
On-site generation	Not common	Common	Required	Required
Facility footprint	Large	Large	Medium to large	Small
Equipment reliability	Good	Good	Fair to good	Fair to good
Process Concerns				
Contact time	Long	Long	Moderate	Short
Stability of agent	Stable	Unstable	Unstable	Stable
Solubility	Moderate	High	High	Not applicable
Operational Concerns				
Process control	Well developed	Well developed	Developing	Developing
O&M intensity	Minimal	Minimal	High	Moderate
Energy consumption	Low	Low	High	Moderate
Capital	Low	Low to moderate	High	Moderate to high
O&M	Low	Low	High	Moderate
Impact of Predisinfection Effluent Quality				
BOD ₅ and NOM	Increase demand	Increase demand	Increase demand	Increase UV absorption
TSS	Moderate	Moderate	Moderate	High
Hardness and TDS	Not significant	Not significant	Not significant	Fouling deposits
Alkalinity	Minor, consumed	Minor, produced	Minor	Affects UV absorbance
Fe, Mn, and H ₂ S	Increase demand	Increase demand	Increase demand	Decrease UV absorption
Ammonia	Reacts	Reacts	Reacts at high pH	Minor
Nitrite	Increases demand	Increases demand	Minor	Minor
Other Beneficial Applications				
Odor and color control	Common	Applicable	Good	No
Sludge bulking control	Common	Applicable	Not applicable	Not applicable
Removal of organics	Moderate	Moderate	Good	No
Potential Adverse Effects				
Corrosive	Yes	Yes	No	No
Explosive/flammable	Yes	No	No	No
Formation of DBPs	High	High	Medium	Negligible
U.S. EPA, RMP	Covered chemical	Not covered	Not covered	Not covered
Safety concern	High	Low	Moderate	Low
Overdosing concerns	Yes	Yes	Minor	No
Toxicity to aquatic life	High	High	None	None
Bacteria regrowth	Low	Low	Moderate to high	Moderate to high

(Continued)

TABLE 11.4 (Continued) Suitability of Common Disinfection Technologies for Wastewater Effluent

Application and Consideration	Chlorination		Ozone	UV Irradiation
	Cl ₂	NaOCl		
Persistent by-products	Yes	Yes	None	None
Impact on TDS	Increase	Increase	No	No
Impact on pH	Reduce pH	Raise pH	None	None

Note: DBP = disinfection by-product; NOM = natural organic matter; O&M = operation and maintenance; RMP = Risk Management Program; TDS = total dissolved solids.

Source: Adapted from References 2, 42, and 48 through 57.

One of the most important concerns when using UV irradiation for wastewater disinfection is that certain indicator organisms and pathogens may have the capability of reversing the UV-induced DNA damages and regaining their infectivity during a critical period through the following two potential mechanisms:

- Photoreactivation using specific repairing enzymes after exposure to the visible light between 300 and 500 nm
- Photoreactivation or dark repair in the absence of light.

Due to lack of specific repairing enzymes in viral DNA, viruses may need to get the enzymes from the host cell to perform repair and therefore their repairing process is more complicated and slower than that of bacteria. Reactivation of pathogenic protozoa is unlikely after effective inactivation by UV irradiation. The amount of repairs required to regain their infectivity may not occur within the critical period.

11.5 Inactivation Kinetics

Microbial removal or inactivation kinetics is expressed by the rate of kill, that is, the change in the number of organisms with time. It is usually developed from a die-off coefficient or rate constant. For a nondisinfection treatment process, the microbial removal kinetics may be simply a function of time. When a disinfectant is involved, a residual or intensity is normally involved in the development of microbial inactivation kinetics. The residual-based kinetic is used to express microbial inactivation by chemical disinfection processes. UV irradiation is a physical disinfection process where the dosage is expressed by intensity-based kinetics.

11.5.1 Natural Die-Off Kinetics

Microbial inactivation can occur through natural die-off. The microbial die-off with time in natural water body can be expressed by Equation 11.3.^{42,49}

$$N = \frac{1}{1 + k_d t_d} N_0 \quad (11.3)$$

where

N = number of organisms present at time = t_d , number of organisms per unit sample volume

N_0 = number of organisms present initially at $t = 0$, number of organisms per unit sample volume

k_d = die-off coefficient or rate constant of a given type of organism, d^{-1}

t_d = average hydraulic retention time based on the flow through the water body, d

Equation 11.3 is also used to estimate the microbial reduction by enhanced die-off through a nondisinfection treatment processes such as natural treatment as well as primary or secondary treatment.⁴² Many

TABLE 11.5 Probable Microbial Log Reductions in Effluent by Common Disinfection Technologies

Disinfection Technology	Log Reduction									
	Viruses		Bacteria				Protozoa		Helminth	
	Enteric Viruses	Coliphages	Total Coliform	Fecal Coliform	<i>E. coli</i>	<i>Enterococci</i>	<i>Clostridium perfringens</i>	<i>Cryptosporidium parvum</i>	<i>Giardia lamblia</i>	Ova, Cyst, and Oocyst
Chlorination ^a	1-3	0-2.5	2-6	2-6	2-6	2-6	1-2	0-0.5	0.5-1.5	0-1
Ozone	3-6	2-6	2-6	2-6	2-6	2-6	0-0.5	1-2	2-4	0-2
UV irradiation	1->3	3-6	2->4	2->4	2->4	2->4	< 0.5	> 3	> 3	0

^a Includes use of either Cl₂ or NaOCl.

Source: Adapted in part from References 5, 10, 13, 44, and 58 through 63.

TABLE 11.6 Predisinfection Treatment and Effluent Quality Criteria Recommended for Common Wastewater Disinfection Technologies

Disinfection Technology	Predisinfection Treatment	Predisinfection Effluent Quality			
		BOD ₅ , mg/L	TSS, mg/L	Turbidity, NTU	Other Parameter
Chlorination ^a	No requirement but prefer at least primary treatment	<15–20	<15–20	<5–10	Ammonia concentration must be assessed. High chlorine dose is required if free chlorine residual is desired.
Ozone	Usually requires secondary treatment with nitrification	<15–20	<10–15	<5	An ammonia concentration <1 mg/L as NH ₃ -N may be required to reduce initial ozone demand if effluent has high pH.
UV irradiation	Require tertiary treatment with filtration or membrane	<15–20	<5–10	<5	Water quality parameters required to ensure effective UV irradiation and to reduce the fouling potential due to scaling: <ul style="list-style-type: none"> • UV transmittance >50–70% or UV absorbance <0.15–0.3 cm⁻¹ • Hardness <140 mg/L as CaCO₃, • Iron <0.1 mg/L as Fe, and • Hydrogen sulfide <0.2 mg/L as H₂S.

^a Includes use of either Cl₂ or NaOCl.

Source: Adapted from References 9, 55 through 57, and 64.

environmental factors have impact on the enhanced pathogen die-off process. These factors may include temperature, retention time, algal toxins, predation, adsorption, sedimentation, filtration, photolysis, and solar UV irradiation.^{17,18} The die-off rate constant may therefore vary significantly with actual conditions in a given treatment process. For instance, a rate constant of 0.5 and 0.03 d⁻¹ has been reported for coliforms in a lagoon system under summer and winter conditions, respectively.⁵⁴

TABLE 11.7 Typical Chlorine and Ozone Dosages Required to Achieve Total Coliform Reduction in Effluent from Various Treatment Processes^{a,b}

Effluent from Treatment Process	Total Coliform, MPN/100 mL	Chlorine (Ozone) Dosage, mg/L			
		Effluent Standard, MPN/100 mL			
		1000	200	23	≤2.2
Septic tank	10 ⁷ –10 ⁹	15–40 (15–40)	–	–	–
Raw wastewater	10 ⁷ –10 ⁹	15–30 (15–40)	–	–	–
Primary	10 ⁷ –10 ⁹	10–30 (10–40)	20–40	–	–
Trickling filter	10 ⁵ –10 ⁶	6–10 (4–10)	12–20	20–30	–
Activated sludge	10 ⁵ –10 ⁶	4–10 (4–10)	10–15 (4–8)	13–20 (16–30)	(30–40)
Filtered activated sludge	10 ⁴ –10 ⁶	4–8 (6–10)	5–15 (4–8)	10–20 (16–25)	13–25 (30–40)
Filtered nitrified	10 ⁴ –10 ⁶	4–10 (3–6)	6–12 (3–6)	8–14 (4–15)	8–16 (15–20)
Intermittent sand filter	10 ² –10 ⁴	1–5 (4–8)	2–8 (10–15)	5–10 (12–20)	8–15 (16–25)
Microfiltration	10–10 ³	1–3 (2–6)	2–4 (2–6)	3–6 (3–8)	4–10 (4–8)

^a The contact time for chlorination is 30 min and that for ozonation is 15 min.

^b Chlorine dosages are based on the disinfection requirements of using chloramine residual.

Source: Adapted in part from References 2, 42, 48, and 52 through 54.

TABLE 11.8 Mechanisms of Common Wastewater Disinfection Technologies

Organism	Chlorination	Ozonation	UV Irradiation
Bacteria	Inhibits specific enzymes	Totally or partially destroys the cell membrane and causes lysis of the cell; and attacks enzymes to interrupt their activities	Causes photochemical damage to the cellular nucleic acids (deoxyribonucleic acid (DNA) or ribonucleic acid (RNA)) from the dimerization of pyrimidine molecules and destroys their replication abilities; and causes permanent damages to proteins, enzymes, coenzymes, and hormones through photochemical reactions
Viruses	Causes damages to either nucleic acids, the viral coat protein or both	Breaks viral capsid, particularly its proteins to liberate the nucleic acid and inactivate the DNA	Similar to that for bacteria
Protozoa	Not very effective	Totally or partially destroys the cyst wall and makes it more permeable; penetrates into the cyst and damages the plasma membrane; and attacks the nucleus ribosomes and other ultrastructural components	Similar to that for bacteria

Source: Adapted in part from References 2, 42, 49, and 55 through 57.

EXAMPLE 11.4: NATURAL DIE-OFF COLIFORMS AND REMOVAL EFFICIENCY

Wastewater collected from a residential park is treated in a stabilization pond system. Based on the results of a field study, a natural die-off rate constant of 0.4 d^{-1} was obtained for coliforms in the lagoon system. The initial coliform count in the raw wastewater is 10^7 MPN/100 mL. Estimate the number of coliforms in the effluent from the lagoon system. Also calculate the coliform reduction efficiency of the pond system on both percentage and log bases. The basic information about the residential area and the stabilization pond system is summarized below:

Estimated population	600
Daily average wastewater generation rate	100 gallons per capita per day (gpcd)
Total surface area of the stabilization pond system	2 acres
Average water depth in the stabilization pond system	5 ft

Solution

1. Estimate daily average flow from the residential area.

$$\text{Daily average flow} = 100 \text{ gpcd} \times 600 \text{ persons} = 60,000 \text{ gpd} \text{ or } 0.06 \text{ MGD}$$

2. Calculate total volume of the stabilization pond system.

$$\text{Total surface area of the pond system} = 43,560 \text{ ft}^2/\text{acre} \times 2 \text{ acres} = 87,120 \text{ ft}^2$$

$$\begin{aligned} \text{Total volume of the pond system} &= \text{total surface area} \times \text{average water depth} = 87,120 \text{ ft}^2 \times 5 \text{ ft} \\ &= 435,600 \text{ ft}^3 \text{ or } 435,600 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 = 3,260,000 \text{ gal} \text{ or } 3.26 \text{ Mgal} \end{aligned}$$

3. Calculate average hydraulic retention time in the pond system.

$$t_d = \frac{3.26 \text{ Mgal}}{0.06 \text{ MGD}} = 54 \text{ d}$$

4. Estimate the number of coliforms in the effluent.

Apply Equation 11.3, the number of coliforms in the effluent,

$$N = \frac{1}{1 + kt_d} N_0 = \frac{1}{1 + 0.4 \text{ d}^{-1} \times 54 \text{ d}} \times 10^7 \text{ MPN/100 mL} = 4.4 \times 10^5 \text{ MPN/100 mL}$$

5. Calculate the coliform reduction efficiency of the pond system.

- a. Calculate the coliform percentage reduction efficiency.

$$\begin{aligned} \text{Percent reduction efficiency} &= \frac{N_0 - N}{N_0} \times 100\% \\ &= \frac{(10^7 - 4.4 \times 10^5) \text{ MPN/100 mL}}{10^7 \text{ MPN/100 mL}} \times 100\% = 96\% \end{aligned}$$

- b. Calculate the coliform log reduction efficiency from Equation 11.2b.

$$\log \text{ reduction} = -\log(N/N_0) = -\log\left(\frac{4.4 \times 10^5 \text{ MPN/100 mL}}{10^7 \text{ MPN/100 mL}}\right) = 1.4 \log$$

Therefore, it is estimated that the coliform count in the effluent from the pond system is about 4.4×10^5 MPN/100 mL, and the coliform reduction efficiency is ~96% or 1.4 log.

11.5.2 Inactivation Kinetics for Chemical Disinfection Processes

Many important kinetic models have been developed to express the inactivation of organisms by chemical disinfectants. These kinetic models have been developed from chlorination studies, although models have been used for other oxidants, including ozone. These models are broadly divided into (1) first-order reaction-based models, (2) empirical models, (3) rationale models, and (4) mathematical models. These models are briefly presented below. Additional information for inactivation models is also presented for disinfection by ozonation in Section 11.8.6. The microbial inactivation equations for UV radiation are presented in Section 11.9.4.

First-Order Reaction-Based Models: During the early studies, the microbial inactivation by chlorination was assumed to follow the chemical reaction kinetics or the first-order reaction. This assumption was well applied in the Chick's law (Equation 11.4a). This earlier approach was then modified to include the effects of the chlorine residual on the microbial inactivation. On this premise, the Chick-Watson model was developed (Equation 11.4b). This equation is also recognized as the "mixed second-order" model that utilized the basic concept of "Ct" (residual concentration \times contact time), also known as Ct or CT value. It was later confirmed that the actual microbial inactivation observed in disinfection practice deviated from the results obtained from the Chick-Watson model.^{49,65} Many factors may be responsible for these deviations. Major factors are listed below:

- Disinfectant residual is not constant.
- Continuous and plug-flow conditions are more realistic than the batch and complete-mix conditions.
- Change in pH may affect reaction rate.

- Disinfectant may also be consumed by many competitive reactions.
- Resistance to disinfectant may develop.
- Initial microbial density may have impact on disinfection efficiency.

Two simplest deviations from Chick-Watson model were identified and known as *shoulder* (or *lag*) and *tailing off*. These phenomena are illustrated in Figure 11.1. The lag or shoulder effect is due to reaction and loss of disinfectant with many constituents in the liquid. The tailing effect is due to occlusion, shielding, or shadowing of organisms by suspended solids. To express the nonheat-kill-related temperature dependence, the Arrhenius correction was later integrated into the Chick-Watson model (Equation 11.4c).

The Hom equation was developed to express these deviations and has been quite successful in describing the inactivation kinetics of a variety of pathogens, including viruses and protozoa.^{49,55,65,66} Significant *tailing off* effect has been observed in disinfection by ozone in a batch mode because of rapid decay of ozone after application. The Hom model with $m < 1$ (Equation 10.4d) is considered better than other models to describe ozone inactivation of parasite cysts and oocysts, including *Giardia* and *Cryptosporidium*.^{67,68} Haas equation (Equation 10.4e) further modified Hom model to include the effect of first-order decay of disinfectant with time on microbial inactivation.⁶⁹⁻⁷²

$$\text{Chick's model } N = N_0 e^{-kt} \quad \text{or} \quad \frac{N}{N_0} = e^{-kt} \quad \text{or} \quad \ln\left(\frac{N}{N_0}\right) = -kt \quad (11.4a)$$

$$\text{Chick-Watson } N = N_0 e^{-k' C^n t} \quad \text{or} \quad \frac{N}{N_0} = e^{-k' C^n t} \quad (11.4b)$$

Chick-Watson with temperature correction

$$N = N_0 \exp(-k'_{20} \beta^{(T-20)} C^n t) \quad (11.4c)$$

$$\text{Hom } N = N_0 \exp[-k'' C^n t^m] \quad \text{or} \quad \frac{N}{N_0} = \exp[-k'' C^n t^m] \quad (11.4d)$$

$$\text{Haas } N = N_0 \exp\left[-\left(\frac{m}{nk_c}\right)^m k'' C_0^n \times \left(1 - e^{-\frac{nk_c t}{m}}\right)^m\right] \quad (11.4e)$$

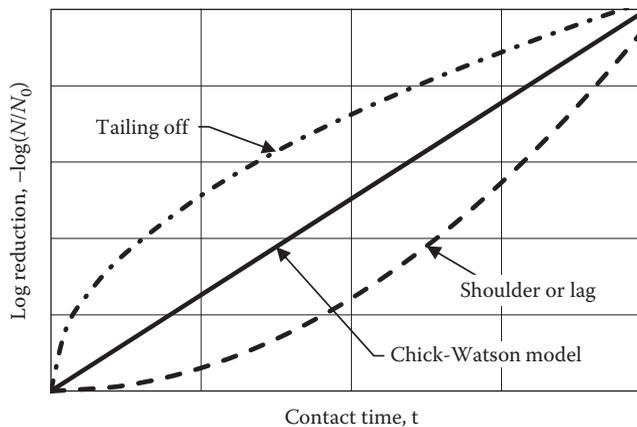


FIGURE 11.1 Chick-Watson model with typical deviations observed in chemical disinfection processes.

where

- k = inactivation rate constant of a given type of organism due to a disinfectant, min^{-1}
 k' = modified inactivation rate constant of a given type of organism due to a disinfectant, $(\text{L}/\text{mg})^n/\text{min}$
 C = disinfectant residual, mg/L
 n = coefficient obtained experimentally ($n > 0$, dimensionless). The significance of constant n in determining the activation efficiency is as follows. If $n = 1$, both C and t are equally important and the product Ct is actually more important than either C or t ; and if $n > 1$, C is the dominant factor. If $n < 1$, t is the dominant factor.
 t = contact time, min
 k'_{20} = modified inactivation rate constant of a given type of organism due to a disinfectant at 20°C , $(\text{L}/\text{mg})^n/\text{min}$
 β = empirical temperature-dependent constant found experimentally
 T = temperature in the contact basin, $^\circ\text{C}$
 k'' = modified inactivation rate constant of a given type of organism and disinfectant, $(\text{L}/\text{mg})^n/\text{min}^m$
 m = coefficient obtained experimentally, dimensionless. The significance of constant m on model behavior is as follows: (a) it is identical with the Chick-Watson model when $m = 1$, (b) it expresses the *shoulder* deviation when $m > 1$, and (c) it expresses the *tailing off* deviation when $m < 1$.
 C_0 = initial disinfectant concentration, mg/L
 k_c = first-order decay rate of disinfectant, min^{-1} . The disinfectant concentration with time is expressed by equation $C = C_0 e^{-k_c t}$ (Equation 2.15a).

Empirical Models: All first-order reaction-based models have been developed through academic development efforts. Experimental data for inactivation of different organisms by different disinfectants under predetermined experimental conditions have been used, including the “ Ct ” ranges. For a better expression of the actual microbial inactivation observed in wastewater disinfection practice, the original first-order model was heavily modified using actual experimental data. Developed on the basis of the “ Ct ” concept, three empirical models are given by Equation 11.5.^{42,48,49,73–75} It should be noted that the similar empirical constants used in these equations may not be related to each other.⁴⁹ These models have been considered helpful design tools to estimate microbial inactivation by chlorine for disinfection of wastewater.^{49,54,73} Among the empirical models, the Collins equation was developed from a study of disinfection of primary effluent. It can express a *tailing* phenomenon. The Selleck equation was developed for chlorine inactivation of coliform in wastewater.

$$\text{Collins} \quad N = N_0 \frac{1}{(1 + 0.23Ct)^3} \quad (11.5a)$$

$$\text{Collins-Selleck} \quad N = N_0 \quad \text{for } Ct \leq b \quad (11.5b)$$

$$N = N_0 \left(\frac{Ct}{b} \right)^{-n} \quad \text{for } Ct > b \quad (11.5c)$$

$$\text{Selleck} \quad -\log(N/N_0) = a \log \left(1 + \frac{Ct}{b} \right) \quad (11.5d)$$

where

a = empirical constant determined experimentally, dimensionless

b = empirical constant determined experimentally, mg-min/L. The constant b is a threshold constant. Microbial inactivation can occur only until $Ct > b$. A b value of 4 and 3 is reported for total and fecal coliforms, respectively.

n = coefficient obtained experimentally, dimensionless. An n value of approximately 3 is typically used. All other terms have been defined previously.

Rational Models: A rational approach has been used to develop specific kinetic models for disinfection by ozone. In these models, the effects of initial microbial density on disinfection are included.⁷⁶⁻⁷⁹ The Power, and Hom-Power equations are expressed by Equation 11.6.

$$\text{Power law} \quad \ln(N/N_0) = -\frac{1}{x-1} \ln[1 + N_0^{x-1}(x-1)k' C^n t] \quad (11.6a)$$

$$\text{Hom-Power law} \quad \ln(N/N_0) = -\frac{1}{x-1} \ln[1 + N_0^{x-1}(x-1)k' C^n t^m] \quad (11.6b)$$

where

x = coefficient obtained experimentally ($x \neq 1$), dimensionless. The significance of constant x is as follows: it expresses the tailing off phenomenon when $x > 1$, and it expresses the shoulder phenomenon when $x < 1$.

n = coefficient obtained exponentially, dimensionless

Mathematical Models: Many nonideal factors may have either favorable or adverse impacts on the inactivation of organisms by UV irradiation. Mathematical models are suitable to deal with these nonideal factors since matching the data set is the primary goal of this method even though it may not require the model to be mechanistically approved.⁸⁰ Two mathematical expressions have been successfully established to account for the “shoulder” behavior in chemical disinfection processes based on available laboratory experimental or actual plant operating data.⁸¹⁻⁸³ The series-event model (Equation 11.7a) considers that a finite number of lethal events are required to occur for inactivation. The multiple-target model (Equation 11.7b) assumes that the microbial inactivation can only happen when multiple “target sites” are attacked by the disinfectant. A numerical method is usually required to solve these mathematical expressions as well as the rational models.

$$\text{Series-event} \quad N = N_0 e^{-kCt} \left(\sum_{i=0}^{l-1} \frac{(kCt)^i}{i!} \right) \quad (11.7a)$$

$$\text{Multiple target} \quad N = N_0 \left(1 - (1 - e^{-kCt})^{n_c} \right) \quad (11.7b)$$

where

i = the event level

k = inactivation rate constant that is mathematically obtained for the model, L/min-mg

l = a threshold for effective inactivation for an organism

n_c = number of target sites that must be attacked by the disinfectant to inactivate the organisms

Inactivation Efficiency of Various Disinfectants: The inactivation efficiency of different disinfectants and target organisms can be compared on the basis of Ct value (product of disinfectant residual and contact time). Table 11.9 is developed from batch reactor data under controlled conditions to compare the effectiveness of various disinfectants on different organisms. For example, a 3-log inactivation of bacteria and viruses is achieved by free chlorine at Ct of 1.5–3 and 4–5 mg-min/L, respectively. This means that free chlorine is more effective for inactivation of bacteria than for viruses. Likewise, chlorine dioxide is a more effective disinfectant for protozoan cysts than chlorine.

TABLE 11.9 Ct Values Required for Inactivation of Organisms by Various Disinfectants

Organism	Disinfectant	Ct Value Required for Log Inactivation ^a , mg-min/L			
		1-log	2-log	3-log	4-log
Bacteria (total coliform)	Chlorine (free)	0.4–0.6	0.8–1.2	1.2–1.8	1.6–2.4
	Chloramine	50–70	95–150	140–220	200–300
	Chlorine dioxide	0.4–0.6	0.8–1.2	1.2–1.8	1.6–2.4
	Ozone	0.005–0.01	0.01–0.02	0.015–0.02	0.02–0.04
	UV irradiation ^b	10–35	15–40	20–70	30–110
Viruses	Chlorine (free)	–	1.5–1.8	2.2–2.6	3–3.5
	Chloramine	–	370–400	550–600	750–800
	Chlorine dioxide	–	5–5.5	9–10	12.5–13.5
	Ozone	–	0.25–0.3	0.35–0.45	0.5–0.6
	UV irradiation ^b	20–60	25–70	30–120	50–190
Protozoan (<i>Giardia lamblia</i> or <i>Giardia lamblia</i> cysts)	Chlorine (free)	20–30	45–55	70–80	–
	Chloramine	400–450	800–900	1100–1300	–
	Chlorine dioxide	5–5.5	9–11	15–16	–
	Ozone	0.25–0.3	0.45–0.5	0.75–0.8	–
	UV irradiation ^b	5–10	10–15	10–20	15–30
Protozoan (<i>Cryptosporidium parvum</i>)	Chlorine (free)	2000–2600	4000–5000	–	–
	Chloramine	4000–5000	8000–10,000	–	–
	Chlorine dioxide	120–150	235–260	350–400	–
	Ozone	4–4.5	8–8.5	12–13	–
	UV irradiation ^b	10–15	10–15	15–25	20–40

^a Applicable in filtered secondary effluent at pH 7 and temperature 20°C.

^b UV dose (D_{UV}) = average UV irradiation intensity (I_{avg}) × exposure time (t) (Equation 11.39).

Source: Adapted in part from References 52 through 55, and 72.

EXAMPLE 11.5: CONTACT TIME FOR MICROBIAL INACTIVATION IN CHICK'S LAW

Batch tests were conducted to determine the contact time of an effluent disinfection facility at an activated sludge plant. At a desired chlorine residual, 99% kill of coliform organisms was achieved in 13 min. Calculate the contact time required to achieve 99.9%.

Solution

- Determine the inactivation rate constant k .

At 99% coliform kill, the organisms ratio N/N_0 remaining = $1 - 0.99 = 0.01$ and $t = 13$ min.

Use Chick's law (Equation 11.4a) to calculate k .

$$\frac{N}{N_0} = 0.01 = e^{-kt} \quad \text{or} \quad \ln\left(\frac{N}{N_0}\right) = \ln(0.01) = -kt$$

$$-4.6 = -kt \quad \text{or} \quad k = \frac{4.6}{t} = \frac{4.6}{13 \text{ min}} = 0.35 \text{ min}^{-1}$$

2. Determine the contact time for 99.9% kill.

At 99.9% coliform kill, the organism ratio N/N_0 remaining = $1 - 0.999 = 0.001$.

$$t = \frac{\ln(0.001)}{-k} = \frac{-6.9}{-0.35 \text{ min}^{-1}} = 19.7 \text{ min} \approx 20 \text{ min}$$

EXAMPLE 11.6: CHLORINE RESIDUAL AND CONTACT TIME FOR MICROBIAL INACTIVATION IN CHICK-WATSON MODEL

The Chick-Watson model applies to the product of chlorine residual and contact time Ct . Prove by using numerical data that log inactivation has a linear relationship with Ct . Also prove that log reduction decreases linearly as C increases. Assume $n = 1$ and $k' = 10 \text{ L/mg-min}$.

Solution

1. Develop the linear relationship of log reduction $\log(N/N_0)$ with Ct using Equation 11.4b with $n = 1$.

$$\frac{N}{N_0} = e^{-k' Ct}$$

Take logarithm on both sides and rearrange the expression to have the following log reduction.

$$-\log\left(\frac{N}{N_0}\right) = k' Ct \times \log(e) = k' Ct \times 0.434 = (0.434 k') Ct \quad \text{or} \quad -\log\left(\frac{N}{N_0}\right) = S_1 Ct$$

A linear relationship between $-\log(N/N_0)$ and Ct is developed with a slope $S_1 = 0.434 k'$. At $k' = 10 \text{ L/mg-min}$ the slope $S_1 = 0.434 k' = 0.434 \times 10 \text{ L/mg-min} = 4.34 \text{ L/mg-min}$ is obtained for the relationship.

Calculate $-\log(N/N_0)$ at $Ct = 0, 0.125, 0.25, 0.5, \text{ and } 1 \text{ mg-min/L}$.

$Ct, \text{ mg-min/L}$	0	0.125	0.25	0.5	1
$-\log(N/N_0)$	0.00	0.54	1.09	2.17	4.34

Plot the liner relationship in Figure 11.2a.

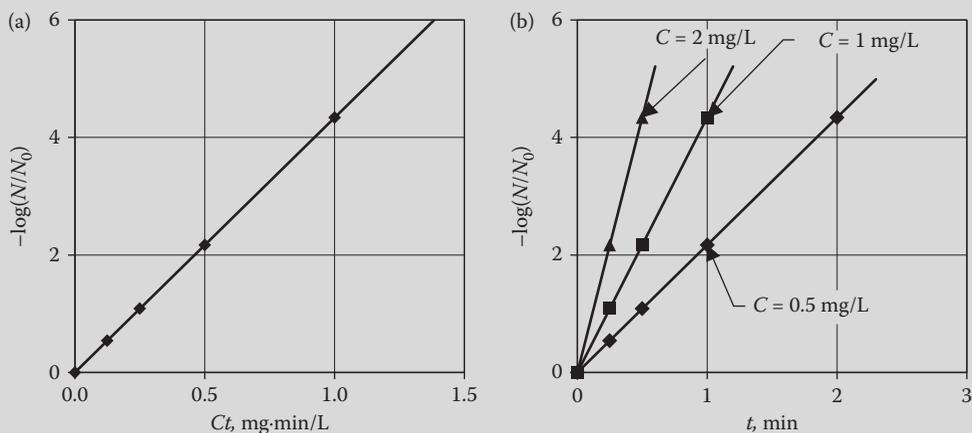


FIGURE 11.2 Log reduction expressions by Chick-Watson model using numerical data: (a) $-\log(N/N_0)$ versus Ct and (b) $-\log(N/N_0)$ versus t (Example 11.6).

2. Develop the linear expression of log reduction with t for disinfection concentration C of 0.5, 1.0, and 2.0.

Apply the Chick-Watson equation and rearrange the linear equation in Step 1.

$$-\log\left(\frac{N}{N_0}\right) = (0.434 k' C)t \quad \text{or} \quad -\log\left(\frac{N}{N_0}\right) = S_2 t$$

A linear relationship is obtained at each given C . The slope of the line is $S_2 = 0.434 k' C$ or $S_2 = 0.434 \times 10 \text{ L/mg}\cdot\text{min} \times C = 4.34 \text{ L/mg}\cdot\text{min} \times C$

Calculate S_2 for each assumed C and $-\log(N/N_0)$ values at different values of t .

Assume $C = 0.5 \text{ mg/L}$ at $t = 0, 0.25, 0.5, 1, \text{ and } 2 \text{ min}$.

$$S_2 = 4.34 \text{ L/mg}\cdot\text{min} \times C = 4.34 \text{ L/mg}\cdot\text{min} \times 0.5 \text{ mg/L} = 2.17 \text{ min}^{-1}$$

$t, \text{ min}$	0	0.25	0.5	1	2
$-\log(N/N_0)$	0.00	0.54	1.09	2.17	4.34

Assume $C = 1 \text{ mg/L}$ at $t = 0, 0.25, 0.5, \text{ and } 1 \text{ min}$.

$$S_2 = 4.34 \text{ L/mg}\cdot\text{min} \times C = 4.34 \text{ L/mg}\cdot\text{min} \times 1 \text{ mg/L} = 4.34 \text{ min}^{-1}$$

$t, \text{ min}$	0	0.25	0.5	1
$-\log(N/N_0)$	0.00	1.09	2.17	4.34

Assume $C = 2 \text{ mg/L}$ at $t = 0, 0.25, \text{ and } 0.5 \text{ min}$.

$$S_2 = 4.34 \text{ L/mg}\cdot\text{min} \times C = 4.34 \text{ L/mg}\cdot\text{min} \times 2 \text{ mg/L} = 8.68 \text{ min}^{-1}$$

$t, \text{ min}$	0	0.25	0.5
$-\log(N/N_0)$	0.00	2.17	4.34

Plot the liner relationships in [Figure 11.2b](#).

3. Discuss the results obtained from the linear plots using numerical data.
- The log reduction, expressed as $-\log(N/N_0)$ is a linear function of Ct with a slope $S_1 = 0.434 k'$ ([Figure 11.2a](#)).
 - At a given C , the log reduction increases with t at a constant rate of $S_2 = 0.434 k' C$. As C increases the value of S_2 also increases. This means that log reduction at a given t increases rapidly as C is increased ([Figure 11.2b](#)).
 - Both chlorine residual (C) and contact time (t) are equally important for an efficient disinfection. For a given log reduction, one-half of t is required when C is doubled.

EXAMPLE 11.7: CONTACT TIME AND CHLORINE RESIDUAL FOR A DESIRED INACTIVATION EFFICIENCY OBTAINED FROM THE CHICK-WATSON MODEL

The impact of contact time t and chlorine residual C on the inactivation efficiency is evaluated using experimental data from a bench-scale test. The experimental results indicate that the Chick-Watson model (Equation 11.4b) is good to express the *E. coli* inactivation kinetics. From the experimental results, the empirical constants were developed: $k' = 10.9 \text{ (L/mg)}^{1.2}/\text{min}$, and $n = 1.2$. In order to achieve an inactivation efficiency of 99.9% or 3-log reduction, estimate (1) the contact time required at a constant chlorine residual of 0.2 mg/L and (2) the chlorine residual at a constant contact time of 10 min.

Solution

1. Determine the required contact time.

Rearrange Equation 11.4b to obtain the following expression and calculate the contact time t required for a log inactivation efficiency $-\log(N/N_0) = 3$ at $C = 0.2$ mg/L.

$$t = \frac{1}{\log(e)k'C^n} [-\log(N/N_0)] = \frac{1}{0.434 \times 10.9 \text{ (L/mg)}^{1.2}/\text{min} \times (0.2 \text{ mg/L})^{1.2}} \times 3 = 4.4 \text{ min}$$

A contact time $t = 4.4$ min is required to achieve an inactivation efficiency of 99.9% or 3-log reduction at a chlorine residual $C = 0.2$ mg/L.

2. Determine the required chlorine residual.

Rearrange Equation 11.4b to obtain the following expression and calculate the chlorine residual C required for a log inactivation efficiency $-\log(N/N_0) = 3$ at $t = 10$ min.

$$C = \left(\frac{1}{\log(e)k't} [-\log(N/N_0)] \right)^{\frac{1}{n}} = \left(\frac{1}{0.434 \times 10.9 \text{ (L/mg)}^{1.2}/\text{min} \times 10 \text{ min}} \times 3 \right)^{\frac{1}{1.2}} = 0.1 \text{ mg/L}$$

A chlorine residual $C = 0.10$ mg/L is required to achieve an inactivation efficiency of 99.9% or 3-log reduction at a contact time $t = 10$ min.

EXAMPLE 11.8: TEMPERATURE-DEPENDENT CONSTANT FOR THE CHICK-WATSON MODEL

A virus disinfection study indicated that the contact time needs to be increased two fold when the temperature is lowered by 10°C to achieve the same inactivation level at a constant chlorine residual. Determine the applicable temperature-dependent constant for the Chick-Watson model based on the observations from the above study.

Solution

1. Develop the temperature-dependent β constant as an expression of contact time t and operating temperature T .

Using Equation 11.4c to express the survival number of virus N_1 at a chlorine residual C_1 , contact time t_1 , and temperature T_1 .

$$N_1 = N_0 \exp(-k'_{20}\beta^{(T_1-20)}C_1^n t_1)$$

Similarly, express the survival number of virus N_2 at C_2 , t_2 , and T_2 .

$$N_2 = N_0 \exp(-k'_{20}\beta^{(T_2-20)}C_2^n t_2)$$

At the same inactivation level, $N_1 = N_2$, the following expression is obtained.

$$N_0 \exp(-k'_{20}\beta^{(T_1-20)}C_1^n t_1) = N_0 \exp(-k'_{20}\beta^{(T_2-20)}C_2^n t_2)$$

$$\exp(-k'_{20}\beta^{(T_1-20)}C_1^n t_1) = \exp(-k'_{20}\beta^{(T_2-20)}C_2^n t_2)$$

Take natural logarithm on both sides of the equation.

$$-k'_{20}\beta^{(T_1-20)}C_1^n t_1 = -k'_{20}\beta^{(T_2-20)}C_2^n t_2 \quad \text{or} \quad \beta^{(T_1-20)}C_1^n t_1 = \beta^{(T_2-20)}C_2^n t_2$$

At the constant chlorine residual, $C_1 = C_2$, an expression of β as t and T is developed.

$$\beta^{(T_1-20)t_1} = \beta^{(T_2-20)t_2} \quad \text{or} \quad \beta^{(T_1-T_2)} = \frac{t_2}{t_1} \quad \text{or} \quad \beta = \left(\frac{t_2}{t_1}\right)^{\frac{1}{T_1-T_2}}$$

2. Estimate the temperature-dependent constant β .

Since the contact time is doubled when the temperature is lowered by 10°C , $\frac{t_2}{t_1} = 2$ and $T_1 - T_2 = 10^\circ\text{C}$. Calculate the temperature-dependent constant β .

$$\beta = (2)^{\frac{1}{10}} = 1.072$$

Therefore, the applicable temperature-dependent constant β is 1.072. This will give twice the contact time to achieve the same level of virus deactivation if the reaction temperature is lowered by 10°C at a constant chlorine residual concentration.

EXAMPLE 11.9: DETERMINATION OF EMPIRICAL CONSTANTS IN HOM EQUATION FROM EXPERIMENTAL DATA

A chlorination study was conducted to determine the inactivation of total coliforms. The batch data at different chlorine residuals and contact times are given below:

	Inactivation ($1 - N/N_0$) at the residual concentration (%)					
Time (t), min	1	2	4	8	16	32
$C_1 = 0.05$ mg/L	57	65	75	85	91	96
$C_2 = 0.1$ mg/L	68	80	87	92.5	97.5	99
$C_3 = 0.2$ mg/L	81	88.5	94	97.5	99.3	–
$C_4 = 0.4$ mg/L	90	95	97.9	99.5	–	–

Determine the empirical constants of k'' , n , and m in Hom equation (Equation 11.4a).

Solution

1. Develop the linear expression for determination of empirical constant m .

Take logarithm on both sides of Equation 11.4d.

$$-\log\left(\frac{N}{N_0}\right) = k'' C^n t^m \times \log(e) = k'' C^n t^m \times 0.434 = (0.434 k'' C^n) t^m$$

Assume $z = 0.434 k'' C^n$ at a given C to obtain the following expression.

$$-\log\left(\frac{N}{N_0}\right) = z t^m$$

Take logarithm on both sides to have the linear expression.

$$\log\left[-\log\left(\frac{N}{N_0}\right)\right] = m \log(t) + \log(z)$$

In this linear relationship, m is the slope and $\log(z)$ is the intercept on Y axis.

2. Prepare the values for linear plots from the experimental data.

At each chlorine residual, calculate $\log[-\log(N/N_0)]$ and $\log(t)$, and tabulate the calculation results below.

At $C_1 = 0.05$ mg/L	t , min	1	2	4	8	16	32
	$1 - N/N_0$	0.57	0.65	0.75	0.85	0.91	0.96
	N/N_0	0.43	0.35	0.25	0.15	0.09	0.04
	$\log(t)$	0	0.301	0.602	0.903	1.204	1.505
	$\log[-\log(N/N_0)]$	-0.436	-0.341	-0.220	-0.084	0.019	0.145
At $C_2 = 0.1$ mg/L	t , min	1	2	4	8	16	32
	$1 - N/N_0$	0.68	0.80	0.87	0.925	0.975	0.99
	N/N_0	0.32	0.20	0.13	0.075	0.025	0.01
	$\log(t)$	0	0.301	0.602	0.903	1.204	1.505
	$\log[-\log(N/N_0)]$	-0.306	-0.156	-0.053	0.051	0.205	0.301
At $C_3 = 0.2$ mg/L	t , min	1	2	4	8	16	
	$1 - N/N_0$	0.81	0.885	0.94	0.975	0.993	
	N/N_0	0.19	0.115	0.06	0.025	0.007	
	$\log(t)$	0	0.301	0.602	0.903	1.204	
	$\log[-\log(N/N_0)]$	-0.142	-0.027	0.087	0.205	0.333	
At $C_4 = 0.4$ mg/L	t , min	1	2	4	8		
	$1 - N/N_0$	0.9	0.95	0.98	0.995		
	N/N_0	0.1	0.05	0.02	0.005		
	$\log(t)$	0	0.301	0.602	0.903		
	$\log[-\log(N/N_0)]$	0	0.114	0.230	0.362		

3. Plot $\log[-\log(N/N_0)]$ versus $\log(t)$.

Plot $\log[-\log(N/N_0)]$ versus $\log(t)$ data for each chlorine residual in [Figure 11.3](#).

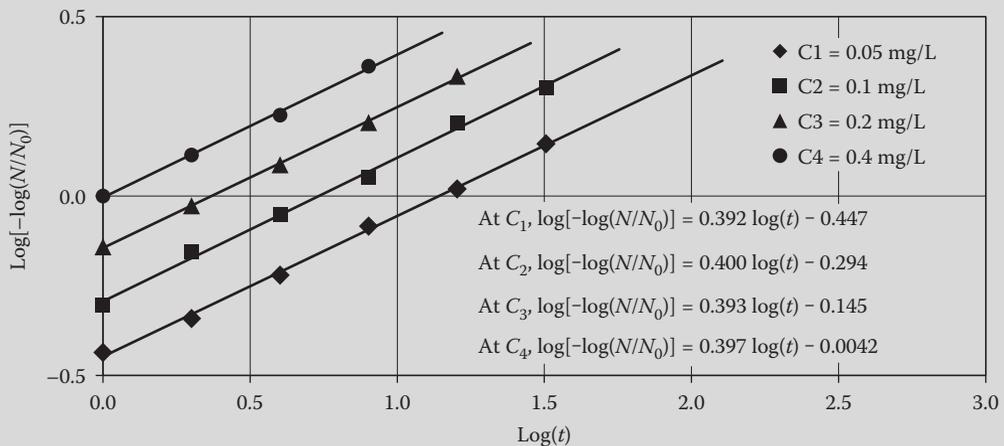


FIGURE 11.3 Plots of $\log[-\log(N/N_0)]$ versus $\log(t)$ at different chlorine residuals (Example 11.9).

From the plots, the following relationships are obtained.

C, mg/L	0.05	0.1	0.2	0.4
Slope, m	0.392	0.400	0.393	0.397
Intercept, $\log(z)$	-0.447	-0.294	-0.145	-0.0042

Calculate the average slope or constant m .

$$m = 0.396 \approx 0.40$$

4. Develop the linear expression for determination of empirical constants k'' and n .

Take logarithm on both sides of the assumption $z = 0.434 k'' C^n$ to obtain the following expression.

$$\log(z) = n \log(C) + \log(0.434 k'')$$

A plot of $\log(z)$ versus $\log(C)$ gives a linear relationship in which n is the slope and $\log(0.434 k'')$ is the intercept.

Tabulate $\log(z)$ and $\log(C)$ from the results obtained from Step 2.

C, mg/L	0.05	0.1	0.2	0.4
$\log(C)$	-1.30	-1	-0.699	-0.398
$\log(z)$	-0.447	-0.292	-0.145	-0.0042

5. Plot $\log(z)$ versus $\log(C)$.

The linear relationship between $\log(z)$ and $\log(C)$ is shown in [Figure 11.4](#).

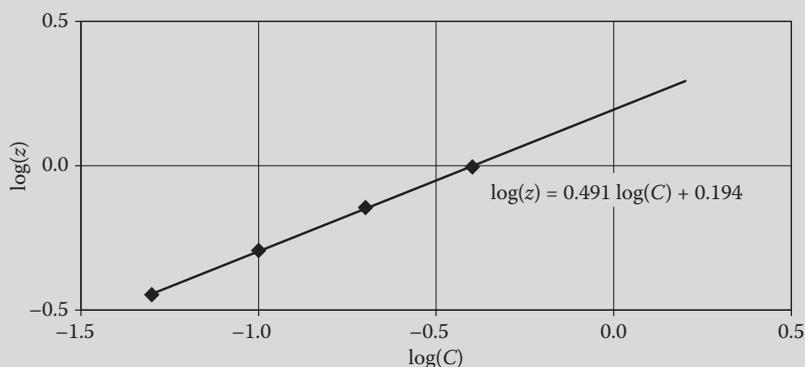


FIGURE 11.4 Plot of $\log(z)$ versus $\log(C)$ (Example 11.9).

From the plot, Slope, $n = 0.491 \approx 0.5$

$$\text{Intercept, } \log(0.434 k'') = 0.194$$

Solve, $0.434 k'' = 10^{0.194}$

$$k'' = \frac{10^{0.194}}{0.434} = \frac{1.56}{0.434} = 3.59 \approx 3.6 \text{ (L/mg)}^{0.5} / \text{min}^{0.4}$$

6. Summarize the developed kinetic coefficients.

The kinetic coefficients in Hom equation for inactivation of total coliforms with chlorine are: $m = 0.4$, $n = 0.5$, and $k'' = 3.6 \text{ (L/mg)}^{0.5} / \text{min}^{0.4}$. The Hom equation is therefore expressed as $N = N_0 e^{-3.6 C^{0.5} t^{0.4}}$.

EXAMPLE 11.10: MICROBIAL INACTIVATION FROM HAAS EQUATION

The Haas equation (Equation 11.4e) includes the effect of first-order decay of disinfectant. In a chlorination study of coliform kill, the following kinetic coefficients were obtained for a calibrated the Haas equation: $m = 0.4$, $n = 0.5$, $k' = 3.0$, $k_c = 0.8 \text{ min}^{-1}$. Determine the log inactivation of coliform. The chlorine dose is 0.5 mg/L and contact time is 3 min.

Solution

Rearrange Equation 11.4e and substitute the kinetic coefficients in the Haas equation to determine the N/N_0 at chlorine dose of 0.5 mg/L and contact time of 3 min.

$$\begin{aligned} \frac{N}{N_0} &= \exp \left[- \left(\frac{m}{nk_c} \right)^m k' C_0^n \times \left(1 - e^{-\frac{nk_c t}{m}} \right)^m \right] \\ &= \exp \left[- \left(\frac{0.4}{0.5 \times 0.8} \right)^{0.4} \times 3.0 \times 0.5^{0.5} \times \left(1 - e^{-\frac{0.5 \times 0.8 \times 3}{0.4}} \right)^{0.4} \right] \\ &= \exp \left[-(1)^{0.4} \times 3.0 \times 0.707 \times (1 - e^{-3})^{0.4} \right] = \exp \left[-2.12 \times (0.950)^{0.4} \right] = \exp(-2.12 \times 0.980) \\ &= e^{-2.08} = 0.125 \end{aligned}$$

Calculate the percent inactivation.

$$\text{Percent inactivation} = \left(1 - \frac{N}{N_0} \right) \times 100\% = (1 - 0.125) \times 100\% = 87.5\%$$

Calculate the log inactivation.

$$\text{log inactivation} = -\log \left(\frac{N}{N_0} \right) = -\log(0.125) = 0.9 \text{ log}$$

Therefore, the coliform inactivation at chlorine dose $C_0 = 0.5 \text{ mg/L}$ and contact time $t = 3 \text{ min}$ is 87.5% or 0.9 log.

EXAMPLE 11.11: CHLORINE RESIDUAL TO ACHIEVE A DESIRED COLIFORM COUNT FROM COLLINS EQUATION

Chlorination is evaluated for disinfection of treated effluent from a wastewater treatment plant. The filtered effluent had a coliform count of 10^4 MPN/100 mL . The discharge requirement for coliform count is $\leq 200 \text{ MPN/100 mL}$. Determine the chlorine residual required for disinfection of filtered effluent to meet the coliforms requirement at an average contact time of 20 min. Assume that the Collins equation applies.

Solution

Rearrange Equation 11.5a and estimate the chlorine residual (C) required to meet the coliforms requirement in the disinfected filtered effluent.

$$\begin{aligned} C &= \frac{1}{0.23t} \left[\left(\frac{N_0}{N} \right)^{\frac{1}{3}} - 1 \right] = \frac{1}{0.23 \text{ L/mg} \cdot \text{min} \times 20 \text{ min}} \left[\left(\frac{10^4 \text{ MPN/100 mL}}{200 \text{ MPN/100 mL}} \right)^{\frac{1}{3}} - 1 \right] \\ &= \frac{1}{4.6 \text{ L/mg}} \times (50^{\frac{1}{3}} - 1) = \frac{3.68 - 1}{4.6 \text{ L/mg}} \\ &= 0.58 \text{ mg/L as Cl}_2 \end{aligned}$$

EXAMPLE 11.12: DETERMINATION OF EMPIRICAL CONSTANTS IN COLLINS–SELLECK EQUATION FROM EXPERIMENTAL DATA

In an environmental laboratory class, a disinfection kinetic experiment was performed at a constant chlorine residual of 1 mg/L. The geometric mean density of fecal coliforms is 2×10^4 MPN/100 mL in the treated effluent sample. The experimental results are summarized below.

Time (t), min	5	10	20	30	40
Coliform count (N), MPN/100 mL	3200	390	50	14	5

Determine the empirical constants n and b , and validate the Collins–Selleck equation for disinfection of treated effluent using chlorine.

Solution

1. Develop the linear expression.

Assume that the Collins–Selleck equation (Equation 11.5c) is applicable ($Ct > b$). Take the logarithm on both sides of the equation and rearrange the expression.

$$-\log\left(\frac{N}{N_0}\right) = n \log(Ct) - n \log(b)$$

A plot of $-\log(N/N_0)$ versus $\log(Ct)$ gives a linear relationship in which n is the slope and $-n \log(b)$ is the intercept.

Tabulate calculation results at $C = 1$ mg/L and $N_0 = 2 \times 10^4$ MPN/100 mL.

t , min	5	10	20	30	40
Ct , mg-min/L	5	10	20	30	40
$\log(Ct)$	0.699	1.00	1.30	1.48	1.60
$N/100$ mL	3200	390	50	14	5
N/N_0	0.16	0.0195	0.0025	0.00070	0.00025
$-\log(N/N_0)$	0.796	1.71	2.60	3.15	3.60

2. Plot $-\log(N/N_0)$ versus $\log(Ct)$.

The linear relationship between $-\log(N/N_0)$ and $\log(Ct)$ is shown in [Figure 11.5](#).

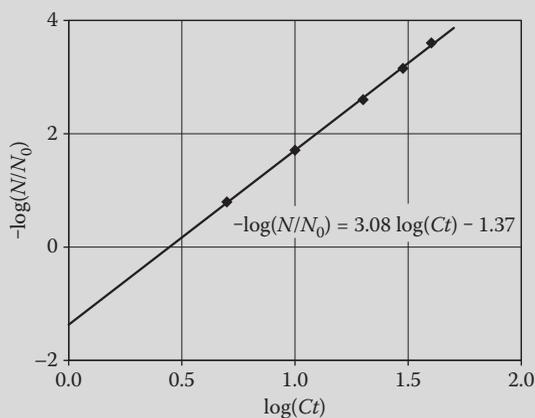


FIGURE 11.5 Plot of $-\log(N/N_0)$ versus $\log(Ct)$ using Collins–Selleck equation (Example 11.12).

3. Determine n and b from the plot.

From the plot, Slope, $n = 3.08$

Intercept, $-n \log(b) = -1.37$ or $n \log(b) = 1.37$

Solve, $b = 10^{\frac{1.37}{n}} = 10^{\frac{1.37}{3.08}} = 10^{0.445} = 2.79 \text{ mg}\cdot\text{min}/\text{L}$

4. Validate the equation.

Calculate the minimum value of Ct_{\min} at $C = 1 \text{ mg}/\text{L}$ and $t = 5 \text{ min}$ (the shortest contact time used during the experiment).

$$Ct_{\min} = 1 \text{ mg}/\text{L} \times 5 \text{ min} = 5 \text{ mg}\cdot\text{min}/\text{L} > b = 2.79 \text{ mg}\cdot\text{min}/\text{L}$$

Therefore, the experimental results indicate that the Collins-Selleck equation is applicable to express the kinetics of disinfection. The empirical form of Collins-Selleck equation for $Ct > 2.79 \text{ mg}\cdot\text{min}/\text{L}$ is given below:

$$N = N_0 \left(\frac{Ct}{2.79} \right)^{-3.08} \quad \text{or} \quad N = 23.6N_0(Ct)^{-3.08}$$

EXAMPLE 11.13: CONTACT TIME AND CHLORINE RESIDUAL ON MICROBIAL SURVIVAL FROM SELLECK EQUATION

The experimental results indicate that the Selleck equation applies to express the total coliform inactivation kinetics. The empirical constants are: $a = 2.1$ and $b = 0.1 \text{ mg}\cdot\text{min}/\text{L}$. Describe the effect of chlorine residual (C) and contact time (t) on the log reduction of total coliforms ($-\log(N/N_0)$).

Solution

1. Develop the log reduction of total coliforms ($-\log(N/N_0)$) as a function of Ct .

Apply Equation 11.5d $-\log(N/N_0) = a \log\left(1 + \frac{Ct}{b}\right)$ at $a = 2.1$ and $b = 0.1 \text{ mg}\cdot\text{min}/\text{L}$ to calculate $-\log(N/N_0)$ at several assumed Ct values.

$Ct, \text{ mg}\cdot\text{min}/\text{L}$	0	0.125	0.25	0.5	1	2
$-\log(N/N_0)$	0.00	0.74	1.14	1.63	2.19	2.78

Plot $-\log(N/N_0)$ versus Ct in [Figure 11.6](#).

2. Develop the log reduction of total coliforms ($-\log(N/N_0)$) as a function of t for a given chlorine concentration C .

At $C = 0.5 \text{ mg}/\text{L}$, $1 \text{ mg}/\text{L}$, and $2 \text{ mg}/\text{L}$, apply Equation 11.5d at $a = 2.1$ and $b = 0.1 \text{ mg}\cdot\text{min}/\text{L}$ to prepare a table of $-\log(N/N_0)$ at different contact times $t = 0, 0.25, 0.5, 1, 2$, and 4 min .

Contact time $t, \text{ min}$	0	0.25	0.5	1.0	2.0	4
$-\log(N/N_0)$ at $C = 0.5 \text{ mg}/\text{L}$	0	0.74	1.14	1.63	2.19	2.78
$-\log(N/N_0)$ at $C = 1 \text{ mg}/\text{L}$	0	1.14	1.63	2.19	2.78	-
$-\log(N/N_0)$ at $C = 2 \text{ mg}/\text{L}$	0	1.63	2.19	2.78	-	-

Plot $-\log(N/N_0)$ versus t at different C in [Figure 11.7](#).

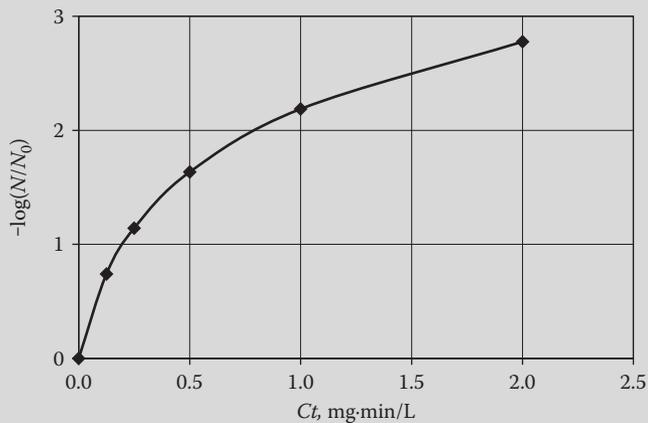


FIGURE 11.6 Plot of $-\log(N/N_0)$ versus Ct using Selleck equation (Example 11.13).

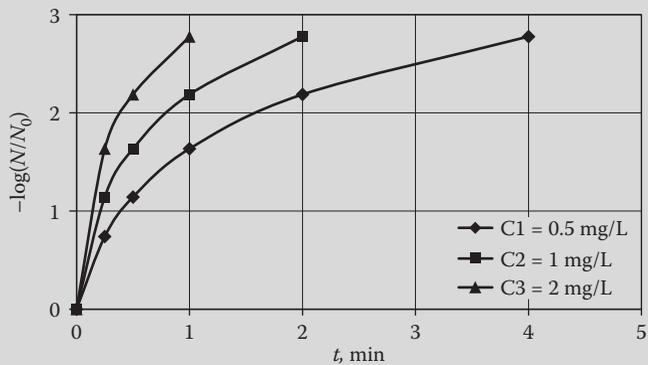


FIGURE 11.7 Plot of $-\log(N/N_0)$ versus t at different C values using Selleck equation (Example 11.13).

3. Describe the effect of Ct , C , and t on log reduction of organisms.
 - a. The log reduction, that is, $-\log(N/N_0)$ is a nonlinear function of Ct in a *tailing off* trend. The increasing rate of log reduction is reduced with an increase in Ct .
 - b. C and t are equally important for an efficient disinfection. For a given log reduction, C should be doubled if the contact time t is halved, and vice versa.
 - c. When C is a constant, the log reduction shows also a *tailing off* trend with t .
 - d. In general, the log reduction efficiency is improved when C is elevated at a given contact time t .

11.6 Chlorination

Chlorination is achieved by using liquid or gaseous chlorine (Cl_2), sodium hypochlorite (NaOCl), calcium hypochlorite ($\text{Ca}(\text{OCl})_2$), or chlorine dioxide (ClO_2). *Dechlorination* is used to trim chlorine residual to meet the residual limit in the effluent for final discharge. The most common chemicals for dechlorination are sulfur dioxide (SO_2) and sodium bisulfite (NaHSO_3). The physical, chemical, and disinfection properties of Cl_2 and NaOCl are presented below.

11.6.1 Physical Properties of Chlorine and Hypochlorite

Chlorine: Chlorine is an elemental compound that normally occurs as Cl₂. It can be present in either gaseous or liquid states. At standard conditions (0°C and 1 atm), chlorine is present as an elemental gas. Liquefied chlorine is available from commercial suppliers in pressure vessels. When its pressure is reduced enough, the liquid vaporizes rapidly to a gas that is ready for use. On-site generation systems are also available to produce chlorine gas (99%) directly from a sodium chloride solution using a membrane-based electrolytic process. Important physical properties of chlorine, chlorine dioxide, and sulfur dioxide are summarized in Table 11.10.^{42,48–55,84,85} Additional information about disinfection with chlorine dioxide and dechlorination with sulfur dioxide may be found in Sections 11.6.5 and 11.7, respectively.

Gaseous chlorine is almost 2.5 times heavier than air. It accumulates at the lowest point after being released to the atmosphere. Liquefied chlorine is about 1.5 times heavier than water. One liter (0.26 gal) of liquid chlorine weighs about 1.5 kg (3.2 lbs) and can produce ~460 L (16 ft³) of chlorine gas at 0°C and 1 atm. In the chlorination process, a chlorine solution is usually prepared from the chlorine gas and then fed at the application point. Chlorine is soluble in water with a maximum solubility of ~10,000 mg/L or 1% near 10°C (50°F) and 1 atm. Its solubility decreases rapidly with increase in temperature. To avoid excessive emission of gaseous chlorine from the solution, a maximum concentration limit of 3500 mg/L or 0.35% is practically used to prepare the chlorine solution through a vacuum injector. Normally, the chlorine concentration may range from 1000 to 2500 mg/L in the solution. Chlorine is a highly

TABLE 11.10 Physical Properties of Chlorine, Chlorine Dioxide, and Sulfur Dioxide

Property	Value for Chemical		
	Chlorine	Chlorine Dioxide	Sulfur Dioxide
General			
Molecular weight, g	70.9	67.5	64.1
Chemical form in use	Gas, liquid, or solution	Gas or solution	Gas, liquid, or solution
Odor	Distinct and irritating	Acrid	Pungent
Color of gas	Greenish-yellow	Yellow to reddish	Colorless
Vapor			
Specific gravity at 0°C (32°F), 1 atm and dry air = 1, dimensionless	2.49	1.86	2.26
Density at 0°C (32°F) and 1 atm, kg/m ³ (lb/ft ³)	3.21 (0.201)	2.40 (0.150)	2.93 (0.183)
Specific volume at 0°C (32°F) and 1 atm, m ³ /kg (ft ³ /lb)	0.311 (4.99)	0.417 (6.67)	0.342 (5.47)
Solubility at 20°C (68°F) and 1 atm, kg/m ³ (lb/gal)	7.3 (0.061)	70 (0.58)	100 (0.83)
Liquid			
Specific gravity at 0°C (32°F) and water = 1, dimensionless	1.47	–	1.44
Density at 20°C (68°F), kg/m ³ (lb/gal)	1410 (11.8)	–	1380 (11.5)
Specific volume at 20°C (68°F), L/kg (gal/lb)	0.71 (0.085)	–	0.72 (0.087)
Gas yield at 0°C (32°F) and 1 atm			
Yield per unit liquid volume, m ³ /L (ft ³ /gal)	0.46 (61)	–	0.49 (65)
Yield per unit liquid weight, m ³ /kg (ft ³ /lb)	0.31 (5.0)	–	0.34 (5.4)

Note: 1 atmosphere (atm) = 101.325 kPa = 760 mm Hg = 14.696 psi 1 kg/m³ = 0.06243 lb/ft³ = 0.008346 lb/gal.

Source: Adapted in part from References 42, 48 through 55, 84, and 85.

toxic substance that poses potential health risks to the plant personnel and off-site general publics. Therefore, a special risk management program (RMP) must be implemented under the federal regulations to ensure safe design and operation of chlorination process when the usage of liquid chlorine is exceeding a threshold quantity at the plant.

Sodium Hypochlorites: Sodium and calcium hypochlorites are hypochlorite salts. Their chemical formulas are NaOCl and Ca(OCl)₂. Calcium hypochlorite is available as powder, granules, and pellets. Calcium is the hardness causing component and tends to clog pipes and filters. It reacts with carbon dioxide and produces calcium carbonate precipitate. Also, it is not highly soluble in water. For all these reasons, its use is limited to on-site disinfection and disposal of effluent, in swimming pools, and as bleaching powder. On account of safety reasons, there has been a trend of replacing chlorine gas with sodium hypochlorite solution for disinfection at many larger plants in the populated urban areas.

Chlorine Content of Sodium Hypochlorite: Sodium hypochlorite is a strong oxidant and is obtained from commercial suppliers in solutions of many strengths. The chlorine content of the chemical is expressed as either actual or available chlorine.

The *weight percent actual chlorine* in a chlorine-containing disinfectant is obtained from Equation 11.8a. It is a simply measurement of chlorine content of the compound by weight.⁸⁵

$$(\text{Weight \% Cl})_{\text{chemical}} = \frac{w_{\text{Cl}}}{mw_{\text{chemical}}} \times 100\% \quad (11.8a)$$

where

$$\begin{aligned} (\text{Weight \% Cl})_{\text{chemical}} &= \text{weight percent actual chlorine (Cl) of the pure chemical, \% by wt} \\ w_{\text{Cl}} &= \text{weight of chlorine per mole chemical, g Cl/mole} \\ mw_{\text{chemical}} &= \text{molecular weight of the pure chemical, g/mole} \end{aligned}$$

Since the measurement of actual chlorine does not provide direct information about the effectiveness in the disinfection process, the strength of the compound is typically measured by the *available chlorine*. It is a measure of the equivalent *oxidizing* or *disinfection* power of the chemical in comparing with that of Cl₂. The half oxidation reaction for Cl₂ to chloride ion (Cl⁻) is shown in Equation 11.8b. In this reaction, the chlorine valance changes from 0 to -1 by accepting *one* electron (e⁻). Therefore, the each chlorine element (Cl) in Cl₂ has an oxidizing power of accepting *one* (1) electron.



The half oxidation reaction for NaOCl to chloride ion (Cl⁻) is shown in Equation 11.8c. In this reaction, the chlorine valance changes from +1 to -1. As a result, each chlorine element in NaOCl molecule has an oxidizing power of accepting *two* (2) electrons. Therefore, the oxidizing power of chlorine in NaOCl is double that of chlorine. The chlorine equivalent of NaOCl, $eq_{\text{Cl}} = 2 \text{ g Cl}_2/\text{g NaOCl}$. The *weight percent available chlorine* of the chemical is expressed by Equation 11.8d or 11.8e.⁸⁵

$$(\text{Weight \% Cl}_2)_{\text{chemical}} = eq_{\text{Cl}} \times (\text{Weight \% Cl})_{\text{chemical}} \quad (11.8d)$$

$$(\text{Weight \% Cl}_2)_{\text{chemical}} = \frac{eq_{\text{Cl}} w_{\text{Cl}}}{mw_{\text{chemical}}} \times 100\% \quad (11.8e)$$

where

$$\begin{aligned} (\text{Weight \% Cl}_2)_{\text{chemical}} &= \text{weight percent available chlorine (Cl}_2\text{) of the pure NaOCl, \% by wt} \\ eq_{\text{Cl}} &= \text{chlorine equivalent of the pure chemical, g Cl}_2\text{/g NaOCl} \end{aligned}$$

Therefore, the weight percent actual and available chlorine of pure NaOCl are:

$$\begin{aligned} (\text{Weight \% Cl})_{\text{NaOCl}} \text{ (from Equation 11.8a)} &= \frac{35.5 \text{ g Cl/mole NaOCl}}{74.4 \text{ g/mole NaOCl}} \times 100\% \\ &= 47.7\% \text{ or } 0.477 \text{ g Cl/g NaOCl} \end{aligned}$$

$$(\text{Weight \% Cl}_2)_{\text{NaOCl}} = 2 \times 47.7\% \text{ (from Equation 11.8d)} = 95.4\% \text{ or } 0.954 \text{ g Cl}_2/\text{g NaOCl}$$

$$\begin{aligned} (\text{Weight \% Cl}_2)_{\text{NaOCl}} \text{ (from Equation 11.8e)} &= \frac{2 \text{ g Cl}_2/\text{g Cl} \times 35.5 \text{ g Cl/mole NaOCl}}{74.4 \text{ g/mole NaOCl}} \times 100\% \\ &= 95.4\% \text{ or } 0.954 \text{ g Cl}_2/\text{g NaOCl} \end{aligned}$$

The molecular weight, chlorine equivalent, and weight percent actual and available chlorine in different chlorine-containing chemicals are given in Table 11.11.^{48,49,51–54,84,85}

Concentration of Sodium Hypochlorite: The concentration of sodium hypochlorite solution may be expressed as either available chlorine or sodium hypochlorite.

As a common practice, the available chlorine concentration in a chemical solution is typically expressed by (a) *weight percent*, (b) *trade percent*, or (c) *grams per liter (gpl) available chlorine*. The weight percent available chlorine is the grams of available chlorine per gram of the chemical solution. The trade percent available chlorine is the weight of available chlorine (g/L as available Cl₂) over the weight of water per same unit volume (1000 g/L as H₂O). The gpl available chlorine is expressed as the grams of available chlorine per liter of the chemical solution. The relationships between these available chlorine concentrations are given by Equation 11.9a when the specific gravity of a chemical solution is known.⁸⁶

$$(\text{Weight \% Cl}_2)_{\text{solution}} = \frac{(\text{Trade \% Cl}_2)_{\text{solution}}}{\text{sp. gr. solution}} = \frac{C_{\text{Cl}_2, \text{solution}}}{\rho_{\text{water}} \times \text{sp. gr. solution}} \times 100\% \quad (11.9a)$$

where

$$\begin{aligned} (\text{Weight \% Cl}_2)_{\text{solution}} &= \text{weight percent available chlorine of the chemical solution, \% by wt} \\ (\text{Trade \% Cl}_2)_{\text{solution}} &= \text{trade percent available chlorine of the chemical solution, \% by wt} \\ \text{sp. gr. solution} &= \text{specific gravity of the chemical solution at water} = 1, \text{ unitless} \\ C_{\text{Cl}_2, \text{solution}} &= \text{gpl available chlorine of the chemical solution, g/L (kg/m}^3\text{)} \\ \rho_{\text{water}} &= \text{density of water, g/L (kg/m}^3\text{)} \end{aligned}$$

Similar to the available chlorine, the strength of sodium hypochlorite solution may also be directly expressed by the concentration of NaOCl in the solution. The relationships between sodium hypochlorite

TABLE 11.11 Actual and Available Chlorine Contents of Chlorine-Containing Chemicals

Chlorine-Containing Chemical	Molecular Weight (mw), g/mole	Chlorine Equivalent (eq _{Cl}), g Cl ₂ /g Cl	Weight Percent Actual Chlorine ((Weight % Cl) _{chemical}), %	Weight Percent Available Chlorine ((Weight % Cl ₂) _{chemical}), %
Chlorine, Cl ₂	70.9	1	100	100
Sodium hypochlorite, NaOCl	74.4	2	47.7	95.3
Calcium hypochlorite, Ca(OCl) ₂	143	2	49.6	99.2
Hypochlorous acid, HOCl	52.5	2	67.5	135
Chlorine dioxide, ClO ₂	67.45	5	52.6	263
Monochloramine, NH ₂ Cl	51.5	2	68.9	138
Dichloramine, NHCl ₂	85.9	2	82.5	165

Source: Adapted in part from References 48, 49, 51–54, 84, and 85.

and available chlorine concentrations are expressed by Equations 11.9b and 11.9c.⁸⁶

$$(\text{Weight \% NaOCl})_{\text{solution}} = \frac{(\text{Weight \% Cl}_2)_{\text{solution}}}{(\text{Weight \% Cl}_2)_{\text{NaOCl}}} \times 100\% \quad (11.9b)$$

$$C_{\text{NaOCl},\text{solution}} = \frac{C_{\text{Cl}_2,\text{solution}}}{(\text{Weight \% Cl}_2)_{\text{NaOCl}}} \times 100\% \quad (11.9c)$$

$$C_{\text{NaOCl},\text{solution}} = \rho_{\text{water}} \times \text{sp. gr.}_{\text{solution}} \times (\text{Weight \% NaOCl})_{\text{solution}} \quad (11.9d)$$

where

$(\text{Weight \% NaOCl})_{\text{solution}}$ = weight percent NaOCl of the solution, % by wt

$(\text{Weight \% Cl}_2)_{\text{NaOCl}}$ = weight percent available chlorine (Cl_2) of the pure NaOCl, 95.3 % by wt

$C_{\text{NaOCl},\text{solution}}$ = gpl NaOCl concentration of the solution, g/L (kg/m^3)

Sodium hypochlorite solution is heavier than water and can be obtained from commercial supplies at a *trade percent* or *trade content* between 4% and 20% for available chlorine. At a trade percent of 12%, the specific gravity of the solution is about 1.17. The density of the solution is therefore $1170 \text{ kg}/\text{m}^3$ (9.8 lbs/gal) and the weight percent available chlorine is 10.3%. The trade percent is a very convenient practice to use in wastewater disinfection practice since 1 gal of 12% trade solution provides ~1 lb of available chlorine ($9.8 \text{ lbs}/\text{gal} \times 0.103 \text{ lb Cl}_2/\text{lb solution} = 1.01 \text{ lb Cl}_2/\text{gal} \approx 1 \text{ lb Cl}_2/\text{gal solution}$). See Example 11.15 for conversion calculations between different concentrations of a NaOCl solution.

Sodium hypochlorite is a strong oxidant, and is very reactive with many compounds and reducing substances. As an unstable weak base, an increase in acidity can cause a rapid breakdown of the hypochlorite in the presence of metallic ions. To improve its stability, excess caustic soda (NaOH) up to 10 g/L is normally added into a commercial sodium hypochlorite solution to raise the pH in the range of 11–13.5. Decomposition of sodium hypochlorite solution is accelerated significantly upon exposure to heat and UV from sunlight. These characteristics need to be considered thoroughly and properly during transportation, storage, and use of sodium hypochlorite solution. Important physical properties of NaOCl at typical trade percent available chlorine are summarized in Table 11.12.^{48,49,51–54,84,86}

TABLE 11.12 Physical Properties of Sodium Hypochlorite at Typical Trade Percent Available Chlorine

Parameter	Typical Value at Different Trade Percent Available Chlorine ($(\text{Trade \% Cl}_2)_{\text{solution}}$)			
	4%	8%	12%	16%
sp. gr. _{solution} at water = 1 at 20°C (68°F), unitless	1.06	1.12	1.17	1.21
Available chlorine concentration				
$(\text{Weight \% Cl}_2)_{\text{solution}}$, %	3.8	7.1	10.3	13.2
$C_{\text{Cl}_2,\text{solution}}$, g/L or kg/m^3 (lb/gal) as available Cl_2	40 (0.33)	80 (0.67)	120 (1.00)	160 (1.33)
NaOCl concentration				
$(\text{Weight \% NaOCl})_{\text{solution}}$, %	4.0	7.5	10.8	13.9
$C_{\text{NaOCl},\text{solution}}$, g/L or kg/m^3 (lb/gal) as NaOCl	42 (0.35)	84 (0.70)	126 (1.05)	168 (1.40)
Density, kg/m^3 (lb/gal) as solution	1058 (8.8)	1118 (9.3)	1168 (9.7)	1208 (10.1)
Specific volume				
L/kg (gal/lb) as available Cl_2	25 (3.0)	12.5 (1.5)	8.3 (1.0)	6.3 (0.75)
L/kg (gal/lb) as solution	0.95 (0.113)	0.89 (0.107)	0.86 (0.103)	0.83 (0.099)

Note: A water density of 998.2 g/L at 20°C is used (Table B.2 in Appendix B).

Source: Adapted in part from References 48, 49, 51–54, 84, and 86.

EXAMPLE 11.14: VOLUME OF LIQUID CHLORINE STORAGE FACILITY

A chlorine storage facility is designed for storage of 100,000 lbs (45,400 kg) of liquid chlorine. Estimate the bulk storage tank volume required at the facility.

Solution

1. Determine the volume requirement for the liquid chlorine.

The Chlorine Institute guidelines suggest that the chlorine tank volume shall be at least 192.2 gal for each ton of liquid chlorine stored.⁸⁷ Calculate the Cl_2 storage volume requirement (req_{Cl_2}) using a conservative value of 200 gal/ton.

$$req_{\text{Cl}_2} = \frac{1 \text{ ton} \times 2000 \text{ lb/ton}}{200 \text{ gal/ton}} = 10 \text{ lb/gal (1200 kg/m}^3\text{)}$$

Note: The guidelines of Chlorine Institute suggest that bulk tank should be able to hold the design quantity of liquid chlorine with only ~95% full at a temperature of 122°F (50°C). There should be no release of chlorine from a pressure relief device set at 255 psig.⁸⁷

2. Calculate the total liquid chlorine volume and select the tank volume.

Calculate the total volume required to store the design quantity $w_{\text{Cl}_2} = 100,000$ lbs.

$$V_{\text{Cl}_2} = \frac{w_{\text{Cl}_2}}{req_{\text{Cl}_2}} = \frac{100,000 \text{ lbs}}{10 \text{ lb/gal}} = 10,000 \text{ gal (38 m}^3\text{)}$$

Provide two bulk storage tanks, each tank of capacity $V_{\text{tank}} = 5000$ gal (approx. 19 m^3).

3. Determine the limit for bulk shipment.

The maximum storage capacity of each tank (w_{tank}).

$$w_{\text{tank}} = req_{\text{Cl}_2} V_{\text{tank}} = 10 \text{ lb/gal} \times 5000 \text{ gal} = 50,000 \text{ lbs or 25 tons (22,700 kg)}$$

Calculate the maximum shipment limit at a safety factor of 1.25.

$$w_{\text{shipment}} = \frac{w_{\text{tank}}}{\text{S.F.}} = \frac{25 \text{ tons}}{1.25} = 20 \text{ tons (18,100 kg)}$$

Note: A safety factor of 1.2 is provided in the guidelines of the Chlorine Institute, Inc.⁸⁷ For safe operation the tank truck should be less than 20 tons to receive and hold the entire shipment. This limit is within the typical range of 15–22 tons for the chlorine tank truck capacities in North America.⁸⁷ A larger storage tank volume may be required if the shipment size used by the local chemical suppliers exceeds this limit.

EXAMPLE 11.15: AVAILABLE CHLORINE IN SODIUM HYPOCHLORITE SOLUTION

Commercial sodium hypochlorite solution is used for effluent disinfection at a wastewater treatment facility. The solution has a trade percent available chlorine of 12%. At a solution temperature of 20°C, estimate (a) the weight percent available Cl_2 , (b) gpl available chlorine concentration, (c) weight percent NaOCl , (d) gpl NaOCl concentration, (e) density of the solution, and (f) specific volume of the solution.

Solution

1. Estimate the weight percent available chlorine, $(\text{Weight \% Cl}_2)_{\text{solution}}$ in the solution.

From Table 11.12, a typical specific gravity $sp. gr. solution = 1.17$ is obtained for the sodium hypochlorite solution at $(Trade \% Cl_2)_{solution} = 12\%$. Apply Equation 11.9a to calculate $(Weight \% Cl_2)_{solution}$.

$$(Weight \% Cl_2)_{solution} = \frac{(Trade \% Cl_2)_{solution}}{sp. gr. solution} = \frac{12\%}{1.17} = 10.3\%$$

2. Estimate the gpl available chlorine concentration $(C_{Cl_2, solution})$ in the solution.

The water density ρ_{water} at $20^\circ C = 998.2 \text{ g/L}$ (Table B.2 in Appendix B). Rearrange Equation 11.9a and calculate the gpl available chlorine concentration $C_{Cl_2, solution}$.

$$C_{Cl_2, solution} = \frac{(Trade \% Cl_2)_{solution}}{100\%} \times \rho_{water} = \frac{12\%}{100\%} \times 998.2 \text{ g/L} = 120 \text{ g/L} \quad \text{or} \quad 120 \text{ kg/m}^3$$

3. Estimate the weight percent NaOCl $(Weight \% NaOCl)_{solution}$ in the solution from Equation 11.9b.

$$(Weight \% NaOCl)_{solution} = \frac{(Weight \% Cl_2)_{solution}}{(Weight \% Cl_2)_{NaOCl}} \times 100\% = \frac{10.3\%}{95.3\%} \times 100\% = 10.8\%$$

4. Estimate the gpl NaOCl concentration $(C_{NaOCl, solution})$ in the solution from Equation 11.9c.

$$C_{NaOCl, solution} = \frac{C_{Cl_2, solution}}{(Weight \% Cl_2)_{NaOCl}} \times 100\% = \frac{120 \text{ g/L}}{95.3\%} \times 100\% = 126 \text{ g/L}$$

5. Estimate the density of the solution $(\rho_{solution})$.

The density of the solution can be calculated from $sp. gr. solution = 1.17$ and $\rho_{water} = 998.2 \text{ g/L}$.

$$\rho_{solution} = sp. gr. solution \times \rho_{water} = 1.17 \times 998.2 \text{ g/L} = 1168 \text{ g/L} \quad \text{or} \quad 1168 \text{ kg/m}^3$$

6. Estimate the specific volume of the solution $(sp. vol. solution)$.

The specific volume is the invert of the density of the solution.

$$sp. vol. solution = \frac{1}{\rho_{solution}} = \frac{1}{1168 \text{ g/L}} \times 10^3 \text{ g/kg} = 0.86 \text{ L/kg}$$

EXAMPLE 11.16: PERCENT LOSS OF AVAILABLE CHLORINE DUE TO DEGRADATION OF SODIUM HYPOCHLORITE SOLUTION

The available chlorine content of sodium hypochlorite solution is continuously monitored in a bulk storage tank. The results indicate that the available chlorine concentration is 107 g/L as Cl_2 in the solution after a storage period of 2 weeks. What is the percent loss of available chlorine due to decomposition if the initial trade percent available chlorine was 12%? Ignore the change in density with temperature.

Solution

1. Determine the initial weight percent available chlorine concentration of the NaOCl solution as g/L.

The initial gpl available chlorine concentration $C_{Cl_2, solution, initial} = 120 \text{ g/L}$ is obtained from Example 11.15, Step 2.

2. Estimate the percent loss of available chlorine at the end of storage period.