www.abpsoil.com

Second Edition

Waste Management

in the Chemical and Petroleum Industries

Alireza Bahadori







WILEY

Материал, защищенный авторским правом

www.abpsoil.com

Waste Management in the Chemical and Petroleum Industries

www.abpsoil.com

Waste Management in the Chemical and Petroleum Industries

Second Edition

Alireza Bahadori

Southern Cross University
Lismore
Australia

WILEY

www.abpsoil.com

This edition first published 2020
© 2020 John Wiley & Sons Ltd

Edition History
John Wiley & Sons Ltd (1e, 2014)

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at http://www.wiley.com/go/permissions.

The right of Alireza Bahadori to be identified as the author of this work asserted in accordance with law.

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Limit of Liability/Disclaimer of Warranty
In view of ongoing research, equipment modifications, changes in governmental regulations, and the constant flow of information relating to the use of experimental reagents, equipment, and devices, the reader is urged to review and evaluate the information provided in the package insert or instructions for each chemical, piece of equipment, reagent, or device for, among other things, any changes in the instructions or indication of usage and for added warnings and precautions. While the publisher and authors have used their best efforts in preparing this work, they make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives, written sales materials or promotional statements for this work. The fact that an organization, website, or product is referred to in this work as a citation and/or potential source of further information does not mean that the publisher and authors endorse the information or services the organization, website, or product may provide or recommendations it may make. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for your situation. You should consult with a specialist where appropriate. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

Library of Congress Cataloging-in-Publication Data

Names: Bahadori, Alireza, author.
Title: Waste management in the chemical and petroleum industries / Alireza Bahadori (Southern Cross University, Lismore, New South Wales, Australia).
Description: Second edition. | Hoboken, NJ : John Wiley & Sons, Inc., [2020] | Includes bibliographical references and index.
Identifiers: LCCN 2019024462 (print) | LCCN 2019024463 (ebook) | ISBN 9781119551720 (cloth) | ISBN 9781119551737 (adobe pdf) | ISBN 9781119551751 (epub)
Subjects: LCSH: Petroleum industry and trade – Waste disposal. | Chemical industry – Waste disposal. | Petroleum refineries – Waste disposal.
Classification: LCC TD899.P4 B34 2020 (print) | LCC TD899.P4 (ebook) | DDC 628.5/1 – dc23
LC record available at https://lccn.loc.gov/2019024462
LC ebook record available at https://lccn.loc.gov/2019024463

Cover Design: Wiley
Cover Images: © kessudap/Shutterstock,
© PICHITBO/Shutterstock, © pan demin/Shutterstock

Set in 10/12pt TimesLTStd by SPi Global, Chennai, India

10 9 8 7 6 5 4 3 2 1

Contents

Preface **xv**
About the Author **xix**

1 Wastewater Treatment **1**

1.1 Characteristics of Wastewater 2
1.1.1 Wastewater Classifications 5
1.1.2 Water Pollution Terminals 5
1.1.3 Suspended Solids 6
1.1.4 Heavy Metals 6
1.1.5 Dissolved Inorganic Solids 7
1.1.6 Toxic Organic Compounds 7
1.1.7 Surfactants 7
1.1.8 Priority Pollutants 9
1.1.9 Volatile Organic Compounds 9
1.2 Treatment Stages 9
1.2.1 Sources of Wastewater 11
1.2.2 Discharge Options and Quality Requirements 11
1.3 Effluent Water Pollution Control 13
1.3.1 Spill Prevention and Control 14
1.3.2 Groundwater Pollution Control 16
1.4 Treatment Processes 18
1.4.1 Wastewater Pollution Oil Terminals 20
1.4.2 Simple Gravity Separation 21
1.4.3 Residual Suspended Matter 21
1.4.4 Selection of Treatment Processes 22
1.5 Siting and Design 24
1.5.1 Aquatic Ecosystems 25
1.5.2 Terrestrial Ecosystems 25
1.5.3 Wetland Ecosystems 27
1.5.4 Land Use 28
1.5.5 Water Pollution Control 28

1.6 Sources of Effluent in the Petrochemical Industry 29
1.6.1 Water Pollution 29
1.6.2 Cooling Water 29
1.6.3 Washing Water and Process Water 29
1.6.4 Typical Pollutants in the Petrochemical Industry 29
1.6.5 Petrochemical Waste Treatment 30
1.6.6 Fertilizer 31
1.7 Effect of Pollution 33
1.7.1 Major Pollutants 33
1.8 Olefin Plants 34
1.8.1 Polymeric Plants 35
1.8.2 Polyvinyl Chloride Plants 36
1.8.3 Aromatic Plants 37
1.9 Environmental Protection for Industrial Waste 37
1.9.1 Important Factors in Process Selection 37
1.10 Chemical Oxygen Demand in Wastewater Systems 44
1.10.1 Determination of COD 44
1.10.2 Calculation of Theoretical Oxygen Demand 45

2 Physical Unit Operations 47

2.1 Flow Measurement 47
2.2 Screening 47
2.3 Comminution 50
2.4 Grit Removal 50
2.5 Gravity Separation 51
2.5.1 General 51
2.5.2 Application 52
2.5.3 Oil–Water Separators: General Design Considerations 53
2.5.4 Conventional, Rectangular Channel (API) Separators 53
2.5.5 Parallel-Plate Separators 65
2.5.6 Oil Traps 67
2.5.7 Oil Holding Basins 68
2.6 Flow Equalization 68
2.6.1 Application and Location 68
2.6.2 Volume Requirements 69
2.7 Mixing 70
2.7.1 Description and Type 70
2.7.2 Application 70
2.8 Sedimentation 71
2.8.1 Sedimentation Theory 71
2.8.2 Application and Type 73
2.8.3 Design Considerations 74
2.8.4 Number of Basins 75
2.8.5 Inlet Arrangements 75
2.8.6 Short-Circuiting 76

2.8.7 Outlet Arrangements 76
2.8.8 Detention Time 76
2.8.9 Surface Loading Rate 76
2.8.10 Factors Affecting Sedimentation 76
2.9 Dissolved Air Flotation 78
2.9.1 General 78
2.9.2 System Configuration 79
2.9.3 Variables Affecting DAF Efficiency 80
2.9.4 Treatability Testing 80
2.9.5 Design Considerations 81
2.9.6 Instruments and Control 86
2.9.7 Piping 86
2.9.8 Chemicals Facilities 87
2.9.9 Material 87
2.9.10 Estimation of Air Concentration in DAF Systems 87
2.10 Granular-Media Filters 93
2.10.1 General 93
2.10.2 Filter Types and Applications 94
2.10.3 System Design Parameters 96
2.10.4 Cycle Time 98
2.10.5 Vessels and Appurtenances 99
2.10.6 Instrumentation and Controls 100

3 Chemical Treatments 103

3.1 Introduction 103
3.1.1 Chemical Precipitation 103
3.1.2 Chemical Coagulation 103
3.1.3 Chemical Oxidation and Advanced Oxidation 104
3.1.4 Ion Exchange 104
3.1.5 Chemical Stabilization 106
3.2 Definition and Application 106
3.2.1 Activated Carbon Adsorption 106
3.3 Chemical Precipitation 109
3.4 Chemical Flocculation 109
3.4.1 Definition and Applications 110
3.4.2 Design Considerations 112
3.4.3 Clarifiers 112
3.4.4 Chemical Addition Systems 115
3.5 Disinfection 116
3.5.1 Chemical Agents 116
3.5.2 Mechanical Means of Disinfection 116
3.6 Chlorination 118
3.6.1 Chlorine Dosages 118
3.6.2 Design Considerations 119

3.7 Water Monitoring 120
3.7.1 Design Considerations for a Water Monitoring System 121
3.8 On-Site Portable Instruments for Water Pollution Control 121
3.8.1 Alternative Current Colorimeter 122
3.8.2 Online Fixed Measurement or Continuous Monitoring 122
3.8.3 Continuous Water Sampling and Clarification System 122
3.8.4 Laboratory Instruments 122
3.8.5 Soil Water Sampling 125
3.8.6 Groundwater Sampling 126
3.9 Physical Examination 126
3.9.1 Color 126
3.9.2 Conductivity 127
3.9.3 Turbidity 128
3.9.4 Determination of Metals 128
3.9.5 Polarography 128
3.9.6 Determination of Organic Constituents 129
3.9.7 Combustible Gas Indicator 130
3.9.8 Total Organic Carbon 130
3.9.9 Biochemical Oxygen Demand 131
3.9.10 Chemical Oxygen Demand 131
3.9.11 Examination of Water and Wastewater Radioactivity 131
3.10 Automated Laboratory Equipment for Monitoring Water and Wastewater 133
3.10.1 Loading Losses 133
3.10.2 Emissions to Water 134

4 Biological Treatments 137

4.1 Theory 137
4.1.1 Biological Activated Carbon Process 139
4.1.2 Biokinetic Theoretical Model 140
4.2 Biological Treatment Processes 142
4.2.1 Major Differences in Aerobic and Anaerobic Treatment 144
4.2.2 Aerobic Processes 146
4.2.3 Anaerobic Waste Treatment 149
4.2.4 Aerobic-Anaerobic (Facultative) Waste Treatment 149
4.3 Activated Sludge Units 150
4.3.1 Applications 151
4.3.2 Effects of Activated Sludge 151
4.3.3 Feed Composition 152
4.3.4 Process Design 157
4.3.5 Design Considerations 158
4.4 Trickling Filters 160
4.4.1 Trickling Filter Process Design 162
4.5 Rotating Biological Contactor System 163
4.6 Sewage Oxidation Ponds 164

5 Wastewater Treatment in the Unconventional Oil and Gas Industries 167

5.1 Background 167
5.1.1 Dissolved and Dispersed Hydrocarbon Components 169
5.1.2 Dissolved Minerals 169
5.1.3 Production Chemicals 169
5.1.4 Produced Solids 170
5.1.5 Dissolved Gases 170
5.2 Toxicity Limitations of Coal Bed Water 171
5.3 Shale Gas and CSG Produced Water: Treatment, and Disposal 174
5.3.1 Evaporation Ponds 174
5.3.2 Surface-Stream Disposal 174
5.3.3 Ion Exchange 176
5.3.4 Membrane Filtration Technology 176
5.3.5 Freeze-Thaw Evaporation 178
5.3.6 Adsorption 178
5.3.7 Chemical Oxidation 178
5.3.8 Filtration 179
5.3.9 Constructed Wetlands 179
5.3.10 Electrodialysis and Electrodialysis Reversal 179
5.3.11 Deep Well Injection at Dedicated Onshore Sites 180
5.3.12 Biological Aerated Filters 180
5.3.13 Macro-porous Polymer Extraction Technology 181
5.3.14 Thermal Technologies 181
5.4 Re-thinking Technologies for Safer Facing 185
5.5 Water Treatment for Oil Sands Mining 191
5.5.1 Recycling and Water Treatment Options 192
5.5.2 Oily Water Treatment in Oil Sands Mining 193

6 Wastewater Sewer Systems 199

6.1 Storm Water Sewer System 200
6.2 Oily Water Sewer System 200
6.3 Non-Oily Water Sewer System 201
6.4 Chemical Sewer System(s) 202
6.4.1 Disposal of Chemical Sewers 202
6.4.2 Neutralization Systems 202
6.4.3 Types of Chemical Waste 202
6.5 Sanitary Sewer System 203
6.6 Special Sewer Systems 203
6.7 Effluent Sources and Disposal 203
6.8 Particular Effluents in Refinery and Petrochemical Plants 205
6.8.1 Caustic Scrubs (Heavy Oils) 205
6.8.2 Desalter Wastewater 205
6.8.3 Foul or Sour Water 206
6.8.4 Spent Caustic Solutions 206
6.8.5 MTBE or Leaded Contaminated Streams 208

6.8.6 Benzene Contaminated Streams 208
6.8.7 Spent Sulfuric Acid Products 209
6.8.8 Nitrogen Base Components 210
6.8.9 Cyanides 210
6.8.10 Aluminum Chloride 210
6.8.11 Polyelectrolyte 210
6.8.12 Ferric Chloride 211
6.8.13 Phosphoric Acid 211
6.8.14 Hydrofluoric Acid 211
6.8.15 Other Spent Catalysts 211
6.8.16 Chemical Cleaning Waste 211
6.8.17 Sulfur Solidification and Crushing Facilities, and Loading Systems Drainage 211
6.8.18 Water Containing Solids, Emulsifying Agents, etc 212
6.8.19 Heavy Viscous Oils Drainage 212
6.8.20 Toxic Metal Contaminated Streams 212
6.8.21 Solvent Processes Drainage 212
6.8.22 Treating Processes Drainage 212
6.9 Petrochemical Plant Special Effluents 212
6.9.1 Summary of Disposal/Treatment Methods 213
6.10 NGL, LNG, and LPG Area Effluents 215
6.10.1 Liquefied Gas Spill 215
6.11 Gas Treatment Facilities Effluents 216
6.12 Effluents from Terminals, Depots, and Product Handling Areas 216
6.13 General Considerations and Conditions for Release of Waste 216
6.13.1 Characteristics and Composition of Waste 216
6.13.2 Characteristics of the Discharge Site and Receiving Environment 217
6.13.3 Availability of Waste Technologies 217
6.14 Effluent Wastewater Characteristics 218
6.14.1 Flow 218
6.14.2 Temperature 218
6.14.3 pH 218
6.14.4 Oxygen Demand 219
6.14.5 Phenol Content 219
6.14.6 Sulfide Content 219
6.14.7 Oil Content 220
6.14.8 Light Hydrocarbon Solubility in Water 220
6.14.9 Predicting the Mutual Solubility of Water–Hydrocarbon Systems 221
6.15 Wastewater Emissions 226
6.15.1 Point Source Discharge 226
6.15.2 Effluent Permissible Concentrations 228
6.16 Unsaturated Zone 232
6.17 Site Assessment 232
6.18 Gathering Release Information 233

7 Sewage Treatment **237**

7.1 Sewage Effluents 238
7.1.1 Receiving Water 238
7.1.2 Final Effluents of Domestic Wastewater Plants 239
7.2 Methods of Sewage Treatment: General 239
7.2.1 Conventional Methods 239
7.3 Choice of System: General 239
7.4 Design of Sewage Treatment Plants: General Guidance 240
7.5 Design of Small Sewage Treatment Plants 240
7.5.1 Collection of Information 240
7.6 Preliminary Treatment 242
7.7 Primary and Secondary Settlement Tanks 242
7.7.1 Capacities of Primary Settlement Tanks 243
7.8 Sludge Digesters 244
7.9 Drying Beds 244
7.9.1 Secondary Settlement Tanks 245
7.10 Biological Filters 246
7.10.1 Distribution 247
7.10.2 Volume of Filter 247
7.10.3 Mineral Filter Media 247
7.11 Activated Sludge Units 248
7.12 Tertiary Treatment (Polishing) Processes 249
7.13 Disposal of Final Effluent 249
7.14 Advanced Wastewater Treatment 250
7.14.1 Effects of Chemical Constituents in Wastewater 250
7.14.2 Advanced Wastewater Treatment Operations and Processes 250
7.15 Effluent Disposal and Reuse 250
7.15.1 Direct and Indirect Reuse of Wastewater 250

8 Solid Waste Treatment and Disposal **257**

8.1 Basic Considerations 257
8.1.1 Classification 257
8.1.2 Methodology 257
8.1.3 Sources 258
8.1.4 Characteristics 261
8.1.5 Quantities 261
8.2 Sludge Handling, Treatment, and Reuse 261
8.2.1 General 261
8.2.2 Sludge and Scum Pumping 264
8.2.3 Sludge Piping 268
8.2.4 Preliminary Operation Facilities 270
8.2.5 Thickening (Concentration) 272
8.3 Stabilization 274
8.3.1 Design Considerations 275
8.3.2 Lime Stabilization 275

8.3.3 Heat Treatment 275
8.3.4 Anaerobic Sludge Digestion 276
8.3.5 Composting 278
8.4 Conditioning 278
8.5 Disinfection 278
8.6 Dewatering 279
8.6.1 Sludge Dewatering Methods 279
8.6.2 Vacuum Filtration 279
8.6.3 Centrifugation 281
8.6.4 Belt Filter Press 282
8.6.5 Sludge Drying Beds 282
8.6.6 Lagoons 283
8.7 Heat Drying 283
8.8 Thermal Reduction 284
8.8.1 Thermal Reduction Process Applications 284
8.9 Land Application of Sludge 285
8.10 Chemical Fixation 286
8.11 Gathering Contaminant-Specific Information 286
8.12 Evaluating Contaminant Mobility 288
8.13 Technology Selection 288
8.13.1 Soil Venting 289
8.13.2 Biorestoration 289
8.13.3 Soil Flushing 289
8.13.4 Hydraulic Methods 290
8.13.5 Excavation 290
8.14 Saturated Zone 291
8.15 Site Assessment 291
8.15.1 Gathering Contaminant-Specific Information 291
8.15.2 Evaluating the Contaminant Phase in the Saturated Zone 292
8.16 Evaluating Contaminant Mobility 294
8.16.1 Mass of Dissolved and Sorbed Contaminants in Groundwater 294
8.16.2 Extent of Contaminant Plume 295
8.16.3 Mobility of Contamination in the Saturated Zone 296
8.17 Setting Remediation Goals 296
8.18 Technology Selection 296
8.19 Dissolved Contaminants 297
8.19.1 Trench Excavation 297
8.19.2 Pumping Well Installation 297
8.19.3 Recovery of Floating NAPL 298
8.19.4 Treatment of Contaminants Dissolved in Groundwater 298
8.20 Methodology for Pipeline Leak Consequence Evaluation 300
8.20.1 Evaluation of Leak 300
8.20.2 Potential Leak Rate and Leak Mass 302
8.20.3 Environmental Consequence Factor 304

8.21 Leak Detection Techniques 306
8.21.1 Balancing Mass Input Versus Output 307
8.21.2 Pressure and/or Flow Analysis 310
8.21.3 Monitoring of Characteristic Signals Generated by a Leak 310
8.21.4 Off-Line Leak Detection 311
8.22 Leakproof Control of Pipeline Gas Piping, Tanks, and Technological Installations Using Radioactive Tracers 312
8.22.1 Leak Detection in Liquid Pipelines 313
8.22.2 Leak Detection in Gas Pipelines 313
8.23 Final Sludge and Solids Conveyance, Storage, and Disposal 314
8.23.1 Conveyance Methods 315
8.23.2 Environmental Considerations in Sludge Transportation 315
8.23.3 Sludge Storage 315
8.23.4 Final Disposal 316
8.23.5 Incineration 317
8.23.6 Ash Handling and Disposal 318
8.24 Disposal of Solid Waste 318
8.24.1 Types of Waste 318
8.24.2 Siting of Hazardous Waste Facilities 319
8.24.3 Non-Hazardous Waste 320
8.24.4 Sources, Segregation, Quantities, and Characteristics of Solid Waste in Refineries 321
8.24.5 Source Reduction Methods 323
8.24.6 Resource Recovery and Waste Minimization 324
8.24.7 Hazardous Waste Reduction 328
8.24.8 Treatment Prior to Ultimate Disposal 330
8.24.9 Disposal of Waste Generated in Drilling Wells 336
8.24.10 General Sampling Considerations 337
8.24.11 Air Monitoring of Waste for Employee Protection 343
8.24.12 Procedures 344
8.24.13 Hazards 345
8.24.14 Quality Assurance Considerations 346
8.25 Emissions to Land 346
8.25.1 Groundwater Monitoring 346
8.25.2 Spills 347
8.26 Evaluation of Soil Infiltration Problems 348
8.26.1 Predictive Tool 348
8.26.2 Sample Calculations for Practice Engineers 351

Definitions and Terminology **353**
Bibliography **383**
Index **403**

Preface

Oil and gas are major sources of energy and revenue for many countries today – their production has been described as one of the most important industrial activities in the twenty-first century – and obviously waste treatment and disposal assume a greater degree of importance in the petroleum, chemical processing, and unconventional oil and gas industries than ever before.

Wastewater quality and the quantity produced determine the means of disposal and the costs of disposal. Suspended solids, total dissolved solids, and oxygen demand of produced waters have the most impact on wastewater treatment.

Wastewater is a complex mixture of organic and inorganic compounds, and the largest volume of by-product generated during chemical processing and both conventional and unconventional oil and gas recovery operations. The potential of oilfield produced water to be a source of fresh water for water-stressed oil-producing countries and the increasing environmental concerns in addition to stringent legislation on produced water discharge into the environment have made produced water management a significant part of the oil and gas business.

In marginally economic coal bed projects, the water disposal costs and the attendant environmental accounting are critical factors in the investment decision; water disposal costs economically make or break a marginal project.

Before investing in a coal bed methane (CBM) process, a multiplicity of questions have to be answered concerning the water to be produced – questions concerning quantity, flow rates, chemical content, disposal means, monitoring, and environmental regulations. Perhaps no other factor affects the economics and feasibility of CBM projects as much as water removal and disposal.

In heavy oil production, between 2 and 4.5 volume units of water are used to produce each volume unit of synthetic crude oil in an *ex situ* mining operation. Despite recycling, almost all of it ends up in tailings ponds. However, in steam assisted gravity drainage (SAGD) operations, 90–95% of the water is recycled and about 0.2 volume units of water is used per volume unit of bitumen produced.

A major hindrance to the monitoring of oil sands produced waters has been the lack of identification of the individual compounds present. By better understanding the nature of the highly complex mixture of compounds, including naphthenic acids, it may be possible to monitor rivers for leachate and also to remove toxic components. Such identification of

individual acids has for many years proved to be impossible but a recent breakthrough in analysis has begun to reveal what is in the oil sands produced waters.

The extraction and use of shale gas can affect the environment through leaking of extraction chemicals and waste into water supplies, leaking of greenhouse gasses during extraction, and pollution caused by the improper processing of natural gas.

A challenge to preventing pollution is that shale gas extractions vary widely in this regard, even between different wells in the same project; the processes that reduce pollution sufficiently in one extraction may not be enough in another.

Chemicals are added to the water to facilitate the underground fracturing process that releases natural gas. Fracturing fluid is primarily water and approximately 0.5% chemical additives (friction reducer, agents countering rust, agents killing microorganism). Since (depending on the size of the area) millions of liters of water are used, this means that hundreds of thousands of liters of chemicals are often injected into the soil.

Only about 50–70% of the resulting volume of contaminated water is recovered and stored in above-ground ponds to await removal by tanker. The remaining "produced water" is left in the earth, where it can lead to contamination of groundwater aquifers, though the industry deems this "highly unlikely." However, the wastewater from such operations often may lead to foul-smelling odors and heavy metals contaminating the local water supply above ground.

This book unravels essential requirements for the process design and engineering of the equipment and facilities pertaining to wastewater treatment units, solid waste disposal and wastewater sewer systems of oil and gas refineries, chemical plants, oil terminals, petrochemical plants, unconventional oil and gas industries (coal seam gas or CBM, shale gas and oil sand production), and other facilities as required. In this new edition, the latest developments with regard to minimization of soil and water pollution have been added to the book and some chapters have been significantly updated. Included in the scope are:

- liquid and solid disposal systems
- primary oil/solids removal facilities
- further oil and suspended solids removal (secondary oil/solids removal), such as dissolved air flotation units
- granular media filters and chemical flocculation units
- chemical addition systems
- biological treatment
- filtration and/or other final polishing
- sewage system handling domestic and medical sanitary appliances of buildings
- drainage system carrying surface and rainwater
- wastewater gathering systems
- clean water drainage, e.g. from buildings and paved areas
- evaporation ponds and disposal by natural percolation into the subsoil in permeable ground
- sanitary sewage treatment
- sludge handling and treatment.

It is obvious that the aim of any drainage/effluent disposal system should be to segregate uncontaminated water from contaminated water or effluents and to segregate different types of effluents in order to reduce the size, complexity, and costs of any treatment units which

may be required for handling the contaminated water and effluents before they are discharged from a unit.

All wastewater effluents from the industries which are discharged to public and/or natural water sources or directed to recycling purposes inside the industry and may contain a wide variety of matters in solution or suspension should be controlled according to the requirements imposed by the final destination. However, in any case elimination of the waste or the hazard potential of the waste shall be ultimate goal in the management of hazardous wastes.

Under no circumstances should the effluent water cause oil traces on the surface or embankments of the receiving water, or affect the natural self-purification capacity of the receiving water to such an extent that it would cause hindrance to others.

Under no conditions should polluted streams be combined with unpolluted streams if the resultant stream would then require purification. In general, the main sewer systems in the industry should be segregated according to the following categories:

- storm water sewer systems
- oily water sewer systems
- non oily water sewer systems
- chemical sewer systems
- sanitary sewer systems
- special sewer systems.

In all areas, including process, offsite, and utility units, provisions should be made to foresee any of the above-mentioned sewer systems as required.

The treatment of wastewater involves a sequence of treatment steps. Every wastewater treatment process involves the separation of solids from water in at least some part of the operation and removal of biochemical oxygen demand (BOD) to some extent.

The end of pipe treatment sequence can be divided into the following elements: primary or pretreatment, intermediate treatment, secondary treatment, and tertiary treatment plus ancillary, sludge dewatering, and disposal operations.

The key to optimize the treatment sequence for provision of maximum water treatment at minimum cost is to identify the rule of each unit operation and optimize that operation. Optimizing the performance of specific unit operations, such as the American Petroleum Institute (API) separator, dissolved air flotation, biological treatment, etc. can best be achieved if:

a) the properties of influent streams are considered
b) the chemical principles that are used in solids pretreatment are understood
c) the variety of chemicals available for solids treatment is recognized
d) the properties of effluent water are established based on the local environmental regulations and final disposal
e) the protocols for quantifying results are identified.

In general, most industries require water for processing or other purposes; much of this water after use is discharged either to public and/or natural water sources or directed to recycling purposes inside the industry.

Such discharge, which may contain a wide variety of matter in solution or suspension, should be controlled according to the requirements imposed by the final destination and/or environmental regulations.

Moreover, according to the type of plant and the method of plant operation, the sources of solids in a wastewater treatment plant can be realized. Solids may also be formed by interaction of waste streams in the sewer.

Wastewaters contain metal ions, such as iron, aluminum, copper, magnesium etc. from corrosion of the process equipment, chemicals used in treating cooling water, salts in the water intake, and chemicals used in processing.

Insoluble metal hydroxide floc may be formed when alkaline wastes are discharged and raise the pH of wastewater above neutral. The wastes containing considerable concentrations of phenols, sulfides, emulsifying agents and alkalines should be segregated. In general, discharging of any material to the oily sewer system or other drainage systems should be investigated for the final waste treatment and disposal targets.

In view of the above, this book will unravel the fundamental engineering for waste recovery, treatment, and disposal systems in the petroleum, chemical, and unconventional oil and gas processing industries. These new fundamental discoveries will enable the development of practical solutions to these pressing environmental issues.

Dr. Alireza Bahadori

About the Author



Dr. Alireza Bahadori, PhD, CEng, MIChemE, CPEng, MIEAust, RPEQ, NER is a research staff member in the School of Environment, Science and Engineering at Southern Cross University, Lismore, NSW, Australia, and managing director and CEO of Australian Oil and Gas Services, Pty. Ltd. He received his PhD from Curtin University, Western Australia and has held various positions in the process and petroleum industry for more than twenty years. He has been involved in many large scale oil and gas projects, and has written extensively on the field. He is a Chartered Engineer (CEng) and a Chartered Member of the Institution of Chemical Engineers, London, UK (MIChemE), a Chartered Professional Engineer (CPEng) and a Chartered Member of the Institution of Engineers Australia, a Registered Professional Engineer of Queensland (RPEQ), a Registered Chartered Engineer of the Engineering Council of the United Kingdom and is on the Engineers Australia's National Engineering Register (NER).

1

Wastewater Treatment

Oil and gas are major sources of energy and revenue for many countries today, and their production has been described as one of the most important industrial activities in the 21st century therefore obviously waste treatment and disposal assume a greater degree of importance in the petroleum, chemical processing and unconventional oil and gas industries.

Wastewater treatment refers to the treatment of sewage and water used by residences, business, and industry to a sufficient level that it can be safely returned to the environment. It is important to treat wastewater to remove bacteria, pathogens, organic matter, and chemical pollutants that can harm human health, deplete natural oxygen levels in receiving water, and pose risks to animals and wildlife.

Natural water and wastewater are characterized in terms of their physical, chemical, and biological composition. The principal physical properties and the chemical and biological constituents of wastewater and their sources make a lengthy list. Each designated water body should be controlled according to regulations which may be composed of both basic and more detailed numerical criteria, as briefly discussed below.

Basic freedom from pollution. As far as is practically possible, all bodies of water should attain the basic criteria of the Five Freedoms from Pollution:

1. Free from suspended solids or other substances that enter the water as a result of human activity and that will settle to form putrid or otherwise objectionable sludge deposits, or that will adversely affect aquatic life.
2. Free from floating debris, oil, scum, and other floating materials entering the water as a result of human activity in amounts sufficient to be unsightly or cause degradation.
3. Free from materials entering the water as a result of human activity producing color, odor, or other conditions in such a degree as to create a nuisance.
4. Free from substances entering the water as a result of human activity in concentrations that are toxic or harmful to human, animal or aquatic life and/or are rapidly lethal in the mixing zone.
5. Free from nutrients entering the water as a result of human activity in concentrations that create nuisance growths of aquatic weeds and algae.

Waste Management in the Chemical and Petroleum Industries, Second Edition. Alireza Bahadori.
© 2020 John Wiley & Sons Ltd. Published 2020 by John Wiley & Sons Ltd.

Table 1.1 *Wastewater pollutants and sources.*

Pollution	Sources
Heavy metals	Process wastewater, tankage wastewater discharges, cooling tower blowdown (if chromate-type cooling water treatment chemicals are used)
NH_3, H_2S, trace organics	Process wastewater (particularly from fluid catalytic cracking unit and coker)
Total suspended solids	Process wastewater, cooling tower blowdown, ballast water tank flow drainage and runoff
BOD5, COD, oil	Process wastewater, cooling tower blowdown (if hydrocarbons leak into cooling water system), ballast water, tank flow drainage and runoff
Phenolics	Process wastewater (particularly from fluid catalytic cracking unit)

The water contaminant parameters determined in refinery wastewater include biochemical oxygen demand (BOD), chemical oxygen demand (COD), oil, total suspended solids (TSS), ammonia (NH_3), phenolics, hydrogen sulfide (H_2S), trace organics, and some heavy metals.

Table 1.1 shows the major sources of each of these contaminants. Process wastewater contributes a portion of virtually all of these, while other sources have more specific contaminant discharges.

1.1 Characteristics of Wastewater

A number of chemical and physical characteristics are used to describe wastewater. The most common are the following:

- Total nitrogen (TN) and total phosphorus (TP) are the sums of all forms of nitrogen and phosphorus in the water, respectively.
- BOD is a measure of the amount of unstable organic matter in the water. It measures how much oxygen is required by the available microorganisms to break down the readily available organic matter into simpler forms, such as carbon dioxide, ammonia, and water.
- Fecal microbes (which includes viruses, bacteria, and protozoans) are found in wastewater and may cause disease.
- Suspended solids, biodegradable organics, nutrients, refractory organics, heavy metals, dissolved inorganic solids, and pathogens are the important contaminants which may be found in the oil, gas, and chemical processing industries' wastewater. Table 1.2 presents a list of important wastewater contaminants and the reasons for their importance.

Suspended solids can be removed by physical treatment to some extent. Removal of biodegradable organics, suspended solids, and pathogens is achieved through secondary treatment operation units.

Table 1.3 shows typical waste compounds classified as priority pollutants. The more stringent rules deal with the removal of nutrients and priority pollutants. When wastewater

Table 1.2 *Contaminant importance in wastewater treatment.*

Contaminant	Reason for importance
Physical suspended solids	Suspended solids are important for esthetical reasons and because they can lead to the development of sludge deposits and anaerobic conditions.
Chemical biodegradable organics	Composed principally of proteins, carbohydrates, and fats, biodegradable organics are measured most commonly in terms of BOD and COD. If discharged untreated to the environment, the biological stabilization of these materials can lead to the depletion of natural oxygen resources and the development of septic conditions.
Nutrients	Carbon, nitrogen, and phosphorus are essential nutrients for growth. When discharged to the aquatic environment, these nutrients can lead to the growth of undesirable aquatic life. When discharged in excessive amounts on land, they can also lead to the pollution of groundwater.
Refractory organics	These organics tend to resist conventional biological methods of wastewater treatment. Typical examples include surfactants, phenols, and agricultural pesticides.
Heavy metals	Due to their toxic nature, certain heavy metals can negatively impact upon biological waste treatment processes and stream life.
Dissolved inorganic solids	Inorganic constituents such as calcium, sodium, and sulfate are added to the original domestic water supply as a result of water use and may have to be removed if the wastewater is to be reused.
Biological pathogens	Communicable diseases can be transmitted by the pathogenic organisms in wastewater.

is to be reused, rules normally include requirements for the removal of refractory organics, heavy metals, and in some case dissolved inorganic solids.

Wastewater from the petroleum industry contains organic compounds, phenols, toxic metals, and other pollutants such as iron, dissolved and suspended solids, oil, cyanides, sulfides, and chlorine. In order to reduce these contaminants, an accurate analysis of processes is necessary.

Pollutants or contaminants which enter a body of water can be divided into:

- *degradable (non-conservative) pollutants*: impurities which eventually decompose into harmless substances or which may be removed by treatment methods, e.g. certain organic materials and chemicals, domestic sewage, heat, plant nutrients, most bacteria and viruses, and certain sediments
- *non-degradable (conservative) pollutants*: impurities which persist in the water environment and do not reduce in concentration unless diluted or removed through treatment, e.g. certain organic and inorganic chemicals, salts, and colloidal suspensions
- *hazardous waterborne pollutants*: complex forms of deleterious wastes, including toxic trace metals, and certain inorganic and organic compounds
- *radionuclide pollutants*: materials which have been subjected to a radioactive source.

Table 1.3 *Typical waste compounds classified as priority pollutants.*

Name (formula)	Concern
Non-metals	
Arsenic (As)	Carcinogen and mutagen Long term: sometimes causes fatigue and loss of energy; dermatitis
Selenium (Se)	Long term: red staining of fingers, teeth, and hair; general weakness; depression; irritation of nose and mouth
Metals	
Barium (Ba)	Flammable at room temperature in powder form Long term: increased blood pressure and nerve block
Cadmium (Cd)	Flammable in powder form; toxic by inhalation of dust or fumes; carcinogen; soluble compounds of cadmium are highly toxic Long term: concentrates in the liver, kidneys, pancreas, and thyroid; hypertension suspected effect
Chromium (Cr)	Hexavalent chromium compounds are carcinogenic and corrosive on tissue Long term: skin sensitization and kidney damage
Lead (Pb)	Toxic by ingestion or inhalation of dust or fumes Long term: brain and kidney damage; birth defects
Mercury (Hg)	Highly toxic by skin absorption and inhalation of fume or vapor Long term: toxic to central nervous system; may cause birth defects
Silver (Ag)	Toxic metal Long term: permanent gray discoloration of skin, eyes, and mucus membranes
Organic compounds	
Benzene (C_6H_6)	Carcinogen; highly toxic Flammable, dangerous fire risk
Ethylbenzene ($C_6H_5C_2H_5$)	Toxic by ingestion, inhalation, and skin absorption; irritant to skin and eyes Flammable, dangerous fire risk
Toluene ($C_6H_5CH_3$)	Flammable, dangerous fire risk Toxic by ingestion, inhalation, and skin absorption
Halogenated compounds	
Chlorobenzene (C_6H_5Cl)	Moderate fire risk Avoid inhalation and skin contact
Chloroethene (CH_2CHCl)	An extremely toxic and hazardous material by all avenues of exposure; carcinogen
Dichloromethane (CH_2Cl_2)	Toxic; carcinogen, narcotic
Tetrachloroethene (CCl_2CCl_2)	Irritant to eyes and skin
Pesticides, herbicides, insecticides (pesticides, herbicides, and insecticides are listed by trade name; the compounds listed are also halogenated organic compounds)	
Endrin ($C_{12}H_8OCl_6$)	Toxic by inhalation and skin absorption, carcinogen
Lindane ($C_6H_6Cl_6$)	Toxic by inhalation, ingestion, skin absorption
Methoxychlor [$Cl_3CCH(C_6H_4OCH_3)_2$]	Toxic
Toxaphene ($C_{10}H_{10}Cl_8$)	Toxic by ingestion, inhalation, skin absorption
Silvex [$Cl_3C_6H_2OCH(CH_3)COOH$]	Toxic; use has been restricted

1.1.1 Wastewater Classifications

1.1.1.1 Water Free of Oil and Organic Material

This category includes boiler blowdown, effluent from cooling water and boiler feed water make-up units, rain water from oil free areas, and cooling water which cannot have direct contact with oil.

1.1.1.2 Water Accidentally Contaminated with Oil

This category includes water streams that are normally free of oil, but may contain oil after an accident. These streams comprise rain water from tank farms, pipe alleys and oil-free processing areas, once-through cooling water, etc.

1.1.1.3 Water Continuously Contaminated with Oil but with Soluble Organic Material

This category comprises rain water from oil processing areas, tank drain water, deballasting water, cooling water blowdown, and flushing and cleaning water.

1.1.1.4 Process water

This water is in contact with process streams, originating from steam stripping, crude oil washing, some chemical oil treatment processes, etc. It contains variable amounts of oil and soluble material such as ammonium sulfide, phenols, thiophenols, organic acids, and inorganic salts such as sodium chloride.

1.1.1.5 Sanitary and Domestic Water

The end result of sanitation and domestic water used in the chemical and petroleum industries is classed as wastewater. Relevant to the above-mentioned facts these categories of water may need different treatments and for this reason, water streams are often kept segregated in a modern refinery to reduce the cost of water treatment facilities. However, in the chemical and petroleum industries different processes could cause pollution, which should be treated.

1.1.2 Water Pollution Terminals

Terminals are storage facilities where refined petroleum products are received from either refineries or import facilities. Fuel is distributed from terminals by truck or rail to retailers or bulk users.

Terminals are the points where wholesalers, distributors, retailers, and other end users access petroleum products. All terminals have loading gantries and storage, and can be supplied by pipeline, ship, and in some cases by road transport.

Import terminals, however, are only supplied by pipeline from refineries or ports. Community health and safety issues associated with the operation of terminal facilities may include potential public exposure to spills, fires, and explosions, although the probability of large magnitude events directly associated with storage operations in well designed and managed facilities is usually low. The likelihood of community exposure to chemical hazards may be greater during road, rail, or water transport activities associated with fuel delivery and distribution.

1.1.2.1 Wastewater Pollutant Sources in Oil Terminals

The onshore facilities for most crude terminals will consist of storage tanks and associated equipment for crude oil, ballast water, and sanitary water. Thus, the major environmental concern is contamination of wastewater with oil and the treatment of the ballast and sanitary water prior to discharge. The treating methods for oil-contaminated wastewater include various types of gravity separators. It is most beneficial to segregate the dirty and clean water and thereby minimize the volume of water requiring treatment.

1.1.2.2 Product Terminals

Product terminals typically are separate from a refinery but in some cases may be associated with a refinery. The products typically handled at a terminal include gasoline, diesel, fuel oil, liquefied petroleum gas (LPG), kerosene, aviation gasoline, and jet fuels.

The few environmental concerns encountered in a product terminal are similar to those in a refinery, and the pollution control methods for product terminals are similar to those in a refinery.

1.1.3 Suspended Solids

Typically, suspended solids carry a significant portion of organic material, thus significantly contributing to the organic load of the wastewater (solids can contribute up to 60% of the BOD of a wastewater). Hence, effective solids removal can significantly contribute to wastewater treatment. The widely accepted way of testing a wastewater for suspended solids is to filter the wastewater through a 0.45 μm porosity filter. Anything on the filter after drying at about 103 °C is considered a portion of the suspended solids. Table 1.4 provides another classification system for the solids found in wastewater.

1.1.4 Heavy Metals

Any cation having an atomic mass (weight) greater than 23 (atomic mass of sodium) is considered to be a heavy metal. Motivations for controlling heavy metal concentrations in gas streams are diverse. Some heavy metals are dangerous to health or to the environment (e.g. mercury, cadmium, lead, chromium), some may cause corrosion (e.g. zinc, lead), and some are harmful in other ways (e.g. arsenic may pollute catalysts). Unlike organic pollutants, heavy metals do not decay and thus pose a different kind of challenge for remediation.

Currently, plants or microorganisms are tentatively used to remove some heavy metals such as mercury. Plants which exhibit hyper accumulation can be used to remove

Table 1.4 *General classification of wastewater solids.*

Particle classification	Particle size (mm)
Dissolved	Less than 10^{-6}
Colloidal	10^{-6} to 10^{-3}
Suspended	Greater than 10^{-3}
Settleable	Greater than 10^{-1}
Supracolloidal	10^{-3} to 10^{-1}

heavy metals from soils by concentrating them in their bio matter. Some treatment of mining tailings has occurred where the vegetation is then incinerated to recover the heavy metals.

1.1.5 Dissolved Inorganic Solids

Total dissolved inorganic solids (TDIS) is a value calculated to assess the actual inorganic salts content of a water or process water.

The following procedure can be used to determine the inorganic dissolved solids in wastewater. A sample of wastewater is filtered through a 0.45 μm filter, the filtrate is collected, then first the water (at 103 °C) and then the organic fraction (at 550 °C) are vaporized from the filtrate. The amount of material left in the vessel after incineration at 550 °C is referred to as the fixed or inorganic dissolved solids level.

1.1.6 Toxic Organic Compounds

Wastewater systems are known to contain toxic metals, organic micro pollutants, and pathogens that may add constraints to their beneficial uses. Environmental risks related to toxic inorganics, dioxins, furans, and pathogens can be controlled by:

(i) selecting a wastewater system having low content of regulated contaminants that respect the local legislation for land application
(ii) application of decontamination process to remove toxic metals
(iii) the necessary step of sterilization for monoculture process that eliminates pathogens.

These toxic organic compounds eventually reach sewage treatment plants and can be concentrated in wastewater systems. Disposal of wastewater systems is one way that these pollutants can be introduced into environment, among others. The presence of toxic organic compounds may add constraints to the ultimate disposal of sludges and/or reduce the possibilities for their beneficial uses.

Tables 1.5 and 1.6 list some organic compounds that are considered toxic and/or carcinogenic.

1.1.7 Surfactants

Surfactants, or surface-active agents, are large organic molecules that are slightly soluble in water and cause foaming in wastewater treatment plants and in the surface water into which the waste effluent is discharged.

The surfactants present in detergent products remain chemically unchanged during the washing process and are discharged down the drain with the dirty washing water. In the vast majority of cases, the drain is connected to a sewer and ultimately to a wastewater treatment plant where the surfactants present in the sewage can be removed by biological and physical-chemical processes.

During aeration of wastewater, surfactants are collected on the surface of the air bubbles and thus create very stable foam. The determination of surfactants is accomplished by measuring the color change in a standard solution of methylene blue active substance (MBAS).

Table 1.5 *Occupational exposure to carcinogenic substances.*

Compound	Site	Comment
Organic substances for which there is wide agreement on carcinogenicity		
4-Aminodiphenyl	Bladder	Contaminant in diphenylamine
Benzidine	Bladder	Ingredient of aniline dyes, plastics, and rubber
Beta-naphthylamine (2-NA)	Bladder	Dye and pesticide ingredient; exposed workers have 30–60 times as much bladder cancer Synonym: 2-naphthylamine
Bis(chloromethyl) ether	Lung	Used in making exchange resins; exposed workers have seven times as much lung cancer
Vinyl chloride	Liver	Angiosarcoma cases among PVC workers
Additional organic substances on USDA-OSHA cancer-causing substances list		
Alpha-naphthylamine (1-NA)	Bladder	Human case implicated; used in making dyes, herbicides, (1-NA) food colors, color film; antioxidant
Ethyleneamine	Unknown	Carcinogenic in animals; used in paper and textile processing and making of herbicides, resins, and rocket and jet fuels
3,3-Dichlorobenzidine	Unknown	Carcinogenic in animal species; exposure accompanies benzidine and beta-naphthylamine
Methyl chloromethyl methyl ether	Unknown	Carcinogenic in animals Synonyms: CMME; BCME contaminants CMME; used in resin making, textiles, and drug production
4,4-Methylene bis (2-chloroaniline)	Unknown	Tumorigenic in rats and mice; skin absorption may be the hazard; curing agent for iso-cyanate polymers Synonym: MOCA

PVC, polyvinyl chloride.

Table 1.6 *Industrial substances suspected of carcinogenic potential for humans.*

Antimony trioxide production	Epichlorhydrin
Benzene (skin)	Hexamethyl phosphoramide (skin)
Benzo(a) pyrene	Hydrazine
Beryllium	4,4-Methylene bis (2-chloroaniline) (skin)
Cadmium oxide production	4,4-Methylene dianiline
Chloroform	Monomethyl hydrazine
Chromates of lead and zinc	Nitrosamines
3,3-Dichlorobenzidine	Propane sulfone
1,1-Dimethyl hydrazine	Beta-propiolactone
Dimethyl sulfate	Vinyl cyclohexene dioxide
Dimethylcarbamyl chloride	

1.1.8 Priority Pollutants

Priority pollutants (both inorganic and organic) are selected on the basis of their known or suspected carcinogenicity, mutagenicity, teratogenicity, or high acute toxicity. Many organic priority pollutants are also classified as volatile organic compounds (VOCs).

Representative examples of priority pollutants are shown in Table 1.3. Within a wastewater collection and treatment system, organic priority pollutants may be removed, transformed, generated, or simply transported through the system unchanged. Five primary mechanisms are involved: (i) volatilization (also gas stripping), (ii) degradation, (iii) adsorption to particles and sludge, (iv) transporting through the entire system, and (v) generation as result of chlorination or as by-products of the degradation of precursor compounds.

1.1.9 Volatile Organic Compounds

Wastewater is collected and treated in a variety of ways, some of which result in the emission of VOCs from the wastewater to the air. Water may come into direct contact with organic compounds during a variety of different chemical processing steps, thus generating wastewater streams that must be discharged for treatment or disposal. Direct contact wastewater includes:

- water used to wash impurities from organic compound products or reactants
- water used to cool or quench organic compound vapor streams
- condensed steam from jet eductor systems pulling vacuum-on vessels containing organic compounds
- water from raw material and product storage tanks
- water used as a carrier for catalysts and neutralizing agents (e.g. caustic solutions)
- water formed as a by-product during reaction steps.

Direct contact wastewater is also generated when water is used in equipment washes and spill clean-ups. This wastewater is normally more variable in flow rate and concentration than the streams listed above and may be collected in a way that is different from process wastewater. Wastewater streams generated by unintentional contact with organic compounds through equipment leaks are defined as “indirect contact” wastewater. Indirect contact wastewater may become contaminated as a result of leaks from heat exchangers, condensers, and pumps.

Organic compounds that have a boiling point $\leq 100\,^{\circ}C$ and/or a vapor pressure of >1 mmHg (or 133.3 Pa) at $25\,^{\circ}C$ are generally considered to be VOCs, e.g. vinyl chloride. The release of these compounds in sewers and at treatment plants, especially at the head works, is of particular concern with respect to the health of the collection system and treatment plant workers.

1.2 Treatment Stages

Generally, the terms “preliminary” and “primary” refer to physical unit operations, “secondary” refers to chemical and biological unit processes, and “advanced” or “tertiary” refers to combinations of all three.

Application and definition of the various stages of treatment and methods to perform specific functions are described in the following sections. Figure 1.1 shows a schematic of the wastewater treatment stages.

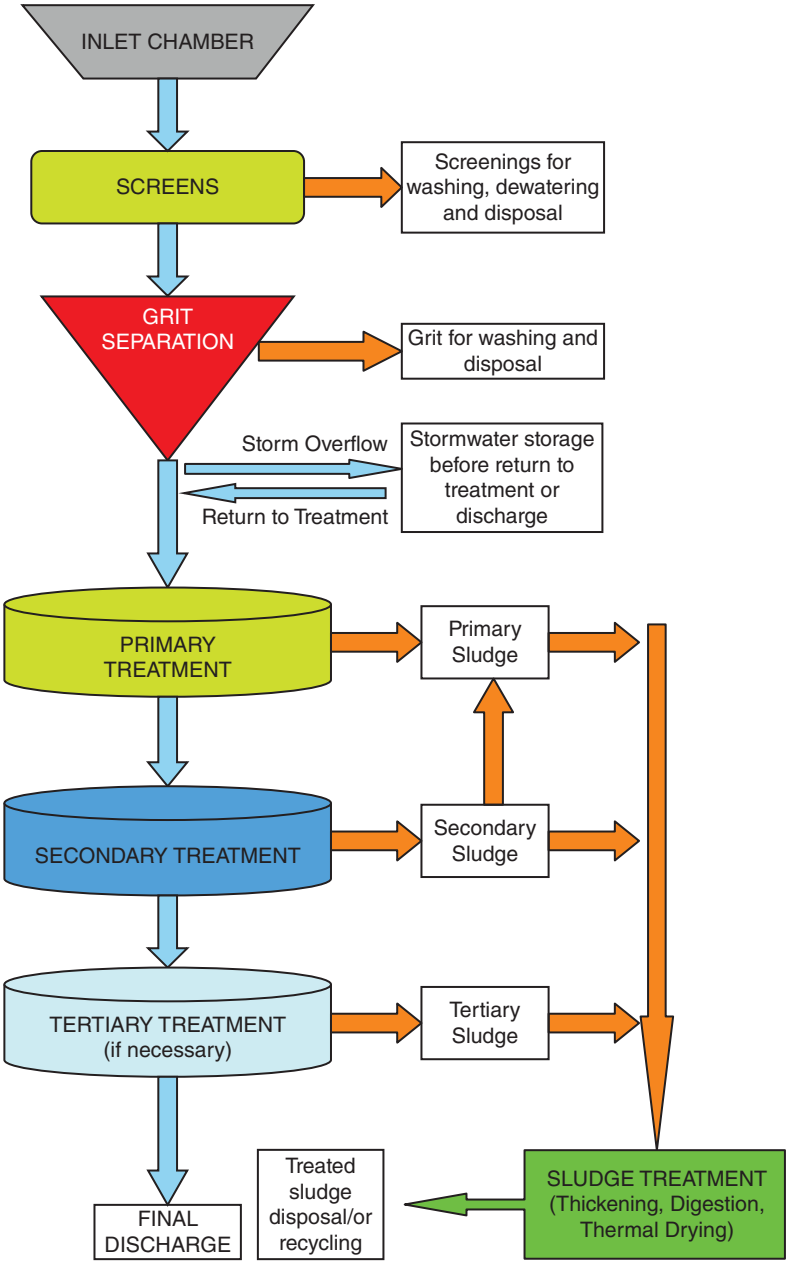


Figure 1.1 *A simplified schematic of the wastewater treatment process.*

Table 1.7 *Typical wastewater qualities.*

Parameter	Unit	Oily wastewater	Stripped sour water	Combined high TDS water (ion exchange waste, boiler blowdown, RO reject)	Cooling tower blowdown
Temperature	°C	30–60	30–35	30–40	—
pH	—	7–8	7–8	7–8	8
TDS	mg/l	150–5000	50–150	500–2500	5000–6000
TSS	mg/l	300–800	10–20	50–100	16 000–19 000
Cl_2 residual	—	—	—	—	0.3–0.5
BOD	mg/l	300–500	100–300	5–150	—
COD	mg/l	300–1200	200–500	100–500	—
TOC	mg/l	—	—	<100	—
Hardness	mg/l as $CaCO_3$	—	—	—	1200–1400
Total alkalinity	mg/l as $CaCO_3$	—	—	—	100–125
Ca^{2+}	mg/l	—	—	—	1000
Cl^-	mg/l	50–2000	—	—	1000–1500
NH_3	mg/l	20–50	40–80	—	<5
Cyanides	mg/l	1–3	—	—	—
Phenols	mg/l	5–20	20–80	—	—
H_2S	mg/l	5–10	10–40	—	—

TDS, total dissolved solids, RO, TSS, TOC.

1.2.1 Sources of Wastewater

Sources of wastewater in the oil, gas, and chemical processing industries include oily wastewater, sour water, stripped sour water, water treatment waste, and blowdown streams (cooling tower, boiler, and gasifier). Each of these sources produces wastewater with slightly different characteristics and treatment requirements.

Table 1.7 shows typical wastewater qualities for some of the wastewater streams in the oil, gas, and chemical processing industries.

1.2.2 Discharge Options and Quality Requirements

Water produced water in oil and gas industry has a complex composition, but its constituents can be broadly classified into organic and inorganic compounds, including dissolved and dispersed oils, grease, heavy metals, radionuclides, treating chemicals, formation solids, salts, dissolved gases, scale products, waxes, microorganisms, and dissolved oxygen.

The following four discharge alternatives are all technically feasible:

- physical and biological treatment followed by discharge to a river
- physical, biological, and chemical treatment followed by discharge to a river
- physical and biological treatment, and recycling with deep well injection, thus no surface discharge
- physical and biological treatment, evaporation, and crystallization, thus no discharge.

The selection of the preferred alternative is a function of the selected process, recycling opportunities, economics, regulatory limitations, and social requirements. Process effects, which relate primarily to dissolved solids concentrations and financial implications, will be examined.

1.2.2.1 Preliminary Wastewater Treatment

Preliminary wastewater treatment is defined as the removal of wastewater constituents that may cause maintenance or operational problems with the treatment operations, processes, and ancillary systems.

Screening and comminution for the removal of debris and rags, grit removal for the elimination of coarse suspended matter that may cause wear or clogging of equipment, and floatation for the removal of large quantities of oil and grease are examples of preliminary operations.

1.2.2.2 Primary Wastewater Treatment

In primary treatment a portion of the suspended solids and organic matter is removed from the wastewater. This removal is usually accomplished with physical operations such as screening and sedimentation.

The effluent from primary treatment will ordinarily contain considerable organic matter and will have a relatively high BOD. The principal function of primary treatment is as a precursor to secondary treatment.

Following primary treatment, the treated water is suitable for use as cooling water and utility water but will require further treatment to be used as boiler feed water.

1.2.2.3 Conventional Secondary Wastewater Treatment

Secondary treatment is directed principally toward the removal of biodegradable organics and suspended solids. Disinfection is frequently included in the definition of conventional secondary treatment.

Conventional secondary treatment is defined as the combination of processes customarily used for the removal of the constituents above and includes biological treatment by activated sludge, fixed film reactors, or lagoon systems and sedimentation.

1.2.2.4 Nutrient Removal or Control

Nutrient removal or control is generally required for:

1) discharge to confined bodies of water where eutrophication may be caused or accelerated
2) discharge to flowing streams where nitrification can tax oxygen resources or where rooted aquatic plants can flourish
3) recharge of groundwater that may be used indirectly for public water supplies.

The nutrients of principal concern are nitrogen and phosphorus, and these may be removed by biological, chemical, or a combination of these processes. In many cases, the nutrient removal processes are coupled with secondary treatment, for example biological denitrification may follow an activated sludge process that produces a nitrified effluent.

1.2.2.5 Advanced Wastewater Treatment/Wastewater Reclamation

Advanced wastewater treatment or tertiary treatment is normally defined as the level of treatment required beyond conventional secondary treatment to remove constituents of concern including nutrients, toxic compounds, and increased amounts of organic material and suspended solids.

In addition to the nutrient removal processes, the unit operations or processes frequently employed in advanced wastewater treatment are chemical coagulation, flocculation, and sedimentation followed by filtration and activated carbon. Less frequently used processes include ion exchange and reverse osmosis for specific ion removal or for reduction of dissolved solids.

Advanced wastewater treatment is also used in a variety of reuse applications where quality water is required, such as for industrial cooling water and groundwater recharge.

1.2.2.6 Toxic Waste Treatment/Specific Contaminant Removal

The removal of toxic substances and specific contaminants is a complex subject and the concentrations of toxic pollutants are usually controlled by pre-treatment prior to discharge to the final treatment system. Many toxic substances, such as heavy metals, are reduced by some form of chemical-physical treatment such as chemical coagulation, flocculation, sedimentation, or filtration.

Some degree of removal is also accomplished by conventional secondary treatment. Wastewater containing volatile organic constituents may be treated by air striping or carbon adsorption. Small concentrations of specific contaminants may be removed by ion exchange. Table 1.8 presents a list of typical pollutants that have an inhibitory effect on the activated-sludge process.

1.2.2.7 Sludge Processing

When a liquid sludge is produced, further treatment may be required to make it suitable for final disposal. Typically, sludges are thickened (dewatered) to reduce the volumes transported off-site for disposal.

Processes for reducing water content include lagooning in drying beds to produce a cake that can be applied to land or incinerated, pressing, where sludge is mechanically filtered, often through cloth screens, to produce a firm cake, and centrifugation where the sludge is thickened by centrifugally separating the solid and liquid. Sludges can be disposed of by liquid injection to land or by disposal in a landfill. For the most part, the methods and systems reported in Table 1.9 are used to process the sludge removed from the liquid portion of the wastewater.

1.3 Effluent Water Pollution Control

Examples of design and procedures which are generally beneficial are as follows:

- recovery of oil spills and hydrocarbons with vacuum trucks to reduce emissions and water effluents
- separation of oily wastes, concentrated wastes, and other process wastes from general effluents for more effective treatment

Table 1.8 *Threshold concentrations of pollutants inhibitory to the activated-sludge process.*

	Concentration (mg/l)	
Pollutant	Carbonaceous removal	Nitrification
Aluminum	15–26	—
Ammonia	480	—
Arsenic	0.10	—
Borate (boron)	0.05–100	—
Cadmium	10–100	—
Calcium	2500	—
Chromium (hexavalent)	1–10	0.25
Chromium (trivalent)	50	—
Copper	1	0.005–0.50
Cyanide	0.1–5	0.34
Iron	1000	—
Manganese	10	—
Magnesium	—	50
Mercury	0.1–5	—
Nickel	1–2.5	0.25
Silver	5	—
Sulfate	—	500
Zinc	0.8–1	
Phenols		
Phenol	200	4–10
Cresol	—	10–16
2,4-Dinitrophenol	—	150

- reduction of shock pollutant loads on treatment facilities through the periodic flushing of process sewers to prevent contaminant build-up and the use of flow and load equalization prior to treatment
- a specialized program for handling oily wastes, sludges, wash water, and other effluents
- maximization of air fan cooling and employing cooling water only for those services in which low process temperatures make air fan cooling impractical or uneconomic
- limiting the amount of water used for process unit washdowns
- converting foul water strippers to reboiler strippers to reduce foul water and recover condensate
- using caustic injection into desalted crude to reduce the amount of NH_3 needed to control corrosion in the crude unit overhead system.

1.3.1 Spill Prevention and Control

Prevention of spills of oil and related petroleum products should be one of the prime objectives of both the design and operation of a proposed facility, and should include, but not be limited to, the siting and design criteria for all facilities, operating procedures, and their periodic review, inspection, and monitoring, personnel training, revision of operating procedures (where required), and redesign (if necessary).

Table 1.9 *Sludge-processing and disposal methods.*

Processing or disposal function	Unit operation, unit process, or treatment method
Preliminary operation	Sludge pumping
	Sludge grinding
	Sludge blending and storage
	Sludge degritting
Thickening	Gravity thickening
	Flotation thickening
	Centrifugation
	Gravity belt thickening
	Rotary drum thickening
Conditioning	Chemical conditioning
	Heat treatment
Disinfection	Pasteurization
	Long-term storage
Dewatering	Vacuum filter
	Centrifuge
	Belt press filter
	Filter press
	Sludge drying beds
	Lagoons
Heat drying	Dryer variations
	Multiple effect evaporator
Thermal reduction	Multiple hearth incineration
	Fluidized bed incineration
	Co-incineration with solid wastes
	Wet air oxidation
	Vertical deep well reactor
Ultimate disposal	Land application
	Distribution and marketing
	Landfill
	Lagooning
	Chemical fixation

Among specific design parameters are impervious dikes around tankage (feedstock and product), containment of storm water from the process area(s), ability to treat contaminated storm water in the wastewater treatment facility, leak detection systems capable of detecting small volume or slow rates of leakage from the pipeline system, and appropriate use of valves to minimize potential spill volumes.

1.3.1.1 Spill Prevention Techniques

Prevention of spills is the first line of defense in protecting life, property, and the environment. Experience has shown that operational or human error and equipment failures are the principal causes of spills. Both of these can be reduced through the involvement and commitment of all staff to spill prevention.

Proper design, inspection, and maintenance of general facilities are of principle importance. Operator capacity is also extremely important and must be periodically tested and upgraded.

Given good equipment, good operators, and good procedures, spills will be reduced. They will not, however, be eliminated.

The difference between a minor event and a catastrophic event depends almost entirely on planning. Such planning includes plant design with spill containment features and alarms, a workable and efficient contingency plan, trained spill control personnel, and adequate spill control equipment.

1.3.1.2 Bulk Storage

Oil storage tank construction and material should be compatible with the oil stored and storage conditions such as pressure, temperature etc.

Impervious secondary containment should be provided for the capacity of the largest single tank plus a sufficient allowance for precipitation and free board.

New metallic tanks buried underground should be protected from corrosion by coatings, cathodic protection, or other effective methods compatible with local soil conditions. The use of non-metallic tanks, if available and practical, should be given consideration.

Above-ground tanks should be subjected to appropriate integrity testing. Appropriate procedures might include hydrostatic testing, visual inspections, or inspection by a system of non-destructive shell thickness gauging.

Plant effluents which are discharged into a watercourse should have disposal facilities that are observed frequently enough to detect any possible system upset that could cause an oil discharge.

1.3.1.3 Facility Drainage

Appropriate containment or diversionary structures should be provided to prevent oil from leaving the property uncontrolled.

1.3.2 Groundwater Pollution Control

Two basic sources of spilled liquid petroleum products are equipment failure and operator error.

- Equipment failure includes corrosion and leaking of both above- and below-ground piping and tanks, valves failure, refinery unit upsets, and sewer and drain leaks. Many of these failures may be avoided through proper inspection and maintenance procedures.
- Operator error includes overfilling tanks and improper alignment of valves and piping. These and other operator errors can best be corrected through developing proven operating procedures, regular training and testing of personnel, and systematic follow-up to assure that procedures are followed.

1.3.2.1 Preventive Measures

The preventive measures to be installed during the construction of a permanent structure must consider the following:

- the type of construction (refinery, storage tank, pipeline, etc.)
- the volume and the nature of the oil likely to pollute the site
- the geology and hydrogeological environment: the nature of the terrain, and the depth, activity, and quality of the aquifer
- the economic environment: proximity to and capacity of water wells and intakes for domestic purposes, risk of pollution of a river, etc.

The preventive system involves four areas: corrosion protection, surface preventive measures, subsurface preventive measures, and monitoring devices to detect and warn of unsuspected pollution not visible from the surface or of a dangerous change in groundwater levels.

Other methods of preventing spilled product from entering the ground and controlling its direction are:

- rendering the soil impermeable where required by means of a concrete paving, a clay or bitumen layer, plastic sheets (PVC sheets covered with gravel, fiberglass reinforced epoxy), and chemical mixed with the soil
- a surface drain system in the plant area carrying all oil and oil-contaminated water to a dirty water sewer, and then to an interceptor or separator, by means of a pipe system with manholes (cast iron, steel, epoxy) and gutters.

1.3.2.2 Types of Devices

- *Trench*
  This system of protection, which is used as a barrier to prevent the horizontal movement of oil, can only be carried out on a practical scale if the water table is situated at a depth of less than about 3–8 m, depending on soil conditions.

  Spread of oil on the groundwater surface is intercepted by digging the trench to about 1 m below the piezometric level. Oil flows onto the water surface, where it can be recovered.
- *Hydrodynamic protection*
  The principle of oil spill control using hydrodynamic methods is to effect a change in the groundwater flow pattern such that the free oil or the contaminated water, as the case may be, can be drawn to a specific control point or points. This can be achieved by discharging or recharging the aquifer, or a combination of both. The success of the method depends on maintaining an artificial gradient in the groundwater surface.
- *Monitoring*
  Groundwater monitoring devices are typically installed to detect and warn of unsuspected contamination not visible from the surface or of a dangerous change in groundwater levels. These devices are installed around petroleum storage areas, waste treatment/disposal facilities (including lagoons, land farms, and landfills), or an entire facility depending on the potential for contamination.

  Care should be taken in choosing monitoring devices to maximize the accuracy and reliability of the system. Monitoring should also be conducted to differentiate between previous and new spills.
- *Mitigation measures*
  After a spill or any contamination is detected, remedial measures such as determination of the extent of contamination (boundaries) and a hydrogeological assessment of

the contamination area to determine the corrective action necessary must be conducted. When an appropriate action is determined, steps including recovery of the oil and oily water, and restoration of the site may be instituted.

- *Recovery measures*
  The principal factor to be considered when recovering free oil from the groundwater surface is to employ the natural water gradient or induce one or by increasing an existing gradient by artificial means. By good use and operation of recovery equipment, free oil can be concentrated at a relatively limited number of selected sites and removed. Wells and trenches are typically used for recovering oil and water.

1.4 Treatment Processes

Industrial wastewater treatment processes cover the mechanisms and processes used to treat water that has been contaminated in some way by anthropogenic industrial or commercial activities prior to its release into the environment or its re-use.

Oil, gas, and chemical industries produce some contaminants in wastewater that have to be removed by physical, chemical, and/or biological means. Figure 1.2 shows a schematic of wastewater treatment in the chemical industry.

Unit operations and processes which may be commonly used in wastewater treatment are listed in Table 1.10. The following guidelines should be taken into consideration for the selection of treatment technologies:

a) Technologies should be categorized into those that work, those that have the potential to work, and those that have no place for the particular application.
b) Technologies should be evaluated based on their effectiveness (ability to reliably attain treatment goals), implementability (availability of materials and services), and costs (capital, and operation and maintenance).

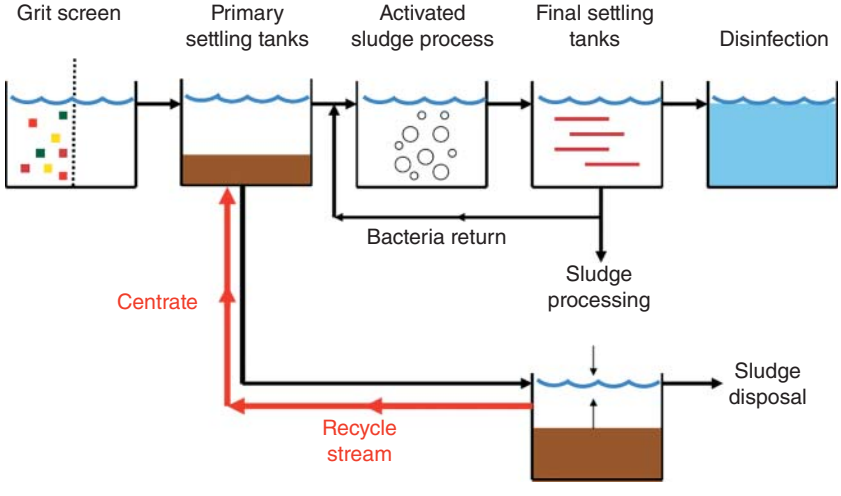


Figure 1.2 *A schematic of wastewater treatment. Source: Reproduced with permission, W. Zhou et al., Bioresource Technology 102 (2011) 6909–6919, ©Elsevier 2011.*

Table 1.10 *Unit operations, unit processes, and systems for waste-water treatment.*

Contaminant	Unit operation, unit process, or treatment system
Suspended solids	Sedimentation
	Screening and comminution
	Filtration
	Flotation
	Chemical polymer addition
	Coagulation/sedimentation
Biodegradable organics	Activated-sludge variations
	Fixed-film: trickling filters
	Fixed-film: rotating biological contractors
	Lagoon and oxidation pond variations
	Intermittent sand filtration
	Land treatment systems
	Physical-chemical systems
Pathogens	Chlorination
	Hypochlorination
	Ozonation
	Land treatment systems
Nutrients	
a) Nitrogen	Suspended-growth nitrification and denitrification variations
	Fixed-film nitrification and denitrification variations
	Ammonia stripping
	Ion exchange
	Breakpoint chlorination
	Land treatment systems
b) Phosphorus	Metal salt addition
	Lime coagulation/sedimentation
	Biological/chemical phosphorus removal
	Land treatment systems
c) Nitrogen and phosphorus	Biological nutrient removal
	Carbon adsorption
Refractory organics	Tertiary ozonation
	Land treatment systems
Heavy metals	Chemical precipitation
	Ion exchange
	Land treatment systems
Dissolved inorganic solids	Ion exchange
	Reverse osmosis
	Electrodialysis

c) Viable technologies should be identified for each of the individual wastewater streams. The streams that use the same technologies should be combined to create composite wastewater treatment trains. These wastewater treatment trains should be compared to the current manufacturing and waste treatment practices to identify possible candidates for waste segregation and independent treatment.

d) The level of wastewater treatment and method of effluent discharge should be established to protect the receiving body of water or water table and its usages. The level of treatment of the facility to be designed should be determined by the ability of the receiving water to accept residual wastes and the allocation set up by effluent standards. The degree of treatment can be determined by comparing the influent wastewater characteristics to the required effluent wastewater characteristics. In case of wastewater reuse applications, the quality of water used as make-up will govern the wastewater treatment needed and the degree of reliability required for the treatment processes and operations. The reliability of the proposed treatment processes and operations must be evaluated to provide a continuous supply of water with consistent water quality.
e) All toxic and highly chemically active materials should be treated at the source and not be discharged in any active state into the sewers loading to the waste treatment plant. This may include removal of soluble and insoluble forms of metals such as lead, zinc, copper, or their derivatives and other similarly dangerous classified metals and their by-products. It should be required that highly active metals, including finely divided magnesium or aluminum alloys, should not be discharged in the sewers but be treated and removed by special methods and equipment at the source. It should be required that all highly toxic inorganic chemicals, including cyanides, fluorides, and related objectionable anions, must be treated and removed from the water at or near the source to the degree specified in the code regulations. This includes the chromates and other special complex anion derivatives. Another group for exclusion from discharge of waste in the sewer includes highly active oxidizing agents, particularly peroxides of organic and inorganic structures. This group should also include the exclusion of other powerful oxidizing agents, including of chlorates, perchlorates, nitric acid, and other similar products. The discharge of volatile organic materials into the waste should also be restricted and these materials should be isolated and treated at the source. This restriction is necessary because explosions may occur in sewer systems where volatilization of the organic matter creates an explosive mixture or some other conditions set off chemical reactions. In general all toxic materials, particularly of organics, that are known to be dangerous to plant, animal, or human life should be treated at the source. All solutions containing radioactive products must also be kept isolated and treated at the source.

1.4.1 Wastewater Pollution Oil Terminals

Wastewater from the petroleum industry are numerous and diverse. They can be process water such as crude oil desalting water or sour water from hydrocracking or hydrotreatment processes, general effluents such as drained oily water, washing water or spent caustics. In order to meet quality requirements for wastewater releases, it is necessary to segregate these different types. Common techniques for wastewater treatment in refineries are described here and then best management practices for process wastewater are described.

The largest source of contaminated wastewater at a crude terminal is the ballast water from tankers. The quantity of ballast water requiring treatment depends upon the ship design, operation, and regulations governing the discharge of ballast water. The ship-design parameters include the amount of segregated ballast, the tank dimensions, and the use of onboard oil/water separators. The operating parameters include the type of previous cargo,

weather conditions, and tank cleaning operations. Optimizing the design and operation of a tanker can reduce the amount of water requiring treatment.

Ballast water treatment usually consists of settling the ballast in shoreside tankage for periods of 10–24 hours, skimming off any oil, and discharging the water. This simple gravity separation is acceptable in some circumstances. For a better quality effluent physical, chemical, and/or biological methods are necessary.

In some locations where shore space is at a premium off-shore, deballasting facilities in the form of converted redundant tankers are utilized. One method to eliminate contaminated ballast water in tankers is the use of segregated ballast.

1.4.2 Simple Gravity Separation

Oil/water separation is the first step in the general treatment of residual refinery water. Its purpose is to eliminate insoluble hydrocarbons and suspended matters. It is classically carried out by gravity. Several separators are available which can be longitudinal [American Petroleum Institute (API) separators], circular, or lamellar.

These treatment systems rely on gravity difference to separate the oil and water. They are capable of removing the bulk of non-dissolved and non-emulsified oil. Examples these systems include storage and settlement, once through storage with skimming, API separators, corrugated plate interceptors (CPI), and holding basins.

1.4.3 Residual Suspended Matter

If it is necessary to reduce the non-dissolved oil content of the effluent below 25 mg/l, there are several processes available which can be added after the chosen simple gravity system.

These methods will also reduce suspended solids to below approximately 30 mg/l. BOD can also be reduced because of the oil and solids removed. These processes have little effect on soluble oil content.

The physical methods include dissolved air flotation, filtration (using gravity or pressure filters), physical separation plus use of chemicals such as inorganic flocculants, and/or demulsifiers or polyelectrolytes, flocculation/sedimentation, flocculation-dissolved air flotation, and induced air flotation.

1.4.3.1 Combination of Simple Gravity Separation Systems

Various combinations of the above individual treatment steps can be used and such combinations may consist of storage and settlement plus API separators or CPI, storage and settlement plus holding basin, or storage and settlement plus API or CPI plus holding basin.

There are several reasons why a combination of steps is often the best choice of treatment process. First, storage and settlement ahead of a CPI or API will remove crude oil and prevent temporary overloading of the downstream separator.

Second, rather than sizing the CPI or API separator to handle the maximum hourly flow rate, costs can be reduced by having a combination of a settling tank and CPI or API separator, with the tank designed for the maximum flow rate and the separator design to deal with the average flow rate. Third, a CPI or API plus holding basin serves as a guard chamber to finally trap any inadvertent discharge of oil from the settling tank.

1.4.3.2 Physical and Chemical Purification

This step is necessary before biological treatment. This technique associates one chemical reaction with a physical separation. The most commonly used techniques are coagulation, flocculation, air flotation, and filtration. Purification allows elimination of colloidal suspended matters and insoluble hydrocarbons.

1.4.3.3 Biological Treatment

After physical and chemical treatment, dissolved pollutants have still to be removed. These pollutants include soluble hydrocarbons, soluble CODs and BODs, phenols, and nitrogen compounds. They are biodegradable and can be removed with biological treatment techniques such as activated sludge or trickling filters. Biological treatment may in some cases be appropriate for removing dissolved biodegradable materials, which are often in low concentrations in normal ballast water. Typical devices used for biological treatment include activated sludge, trickling filters, rotating discs, and lagoons (aerated or not).

1.4.3.4 Spills

A major environmental concern with terminal operations is oil being spilled and the effects on birds and marine life.

Depending upon the type of terminal (offshore or onshore) and the characteristics of the water (such as currents and proximity to open water), the effects of a spill can vary from insignificant to extremely damaging. For example, an enclosed area such as an inlet from the sea, which has been described as the most productive marine environment, may experience accumulation of oil to unacceptable levels over time.

The oil that is spilled offshore will have less impact on the marine environment than an equivalent oil spill within an inlet from the sea (estuary) for three reasons:

1) There are fewer organisms offshore to be affected.
2) The concentration of toxic compounds within the water column is expected to be less because more dilution water is available offshore.
3) The contact time with marine life will generally be shorter for an offshore spill due to the restricted flushing of the inlet from the sea.

In addition to spilled oil, treated ballast water can also affect marine life in an "enclosed" area. Thus, it may sometimes be best to pipe the treated water to another location where good mixing may occur, thereby protecting the "enclosed" area and minimizing the effects on the marine environment.

Spill contaminant is an important feature of a terminal. The most common types of barrier systems used are floating booms and sorbent ropes. Two less frequently used alternatives are air-bubble barrier systems and enclosed berths.

1.4.4 Selection of Treatment Processes

Removing the all wastewater contaminants will be achieved only through various treatment operation units. Selection of the most appropriate treatment sequences will provide better quality treated wastewater.

Table 1.11 *Selective list of unit processes used for particular waste constituents.*

Unit process	Removal mechanism	Waste constituent
Sedimentation/ flotation	Gravity	Solid phase organics/inorganics
Coagulation/ sedimentation	Particle aggregation/gravity	Solid phase organics/inorganics
	Chemical bonding	Colloidal phase organics/inorganics
		Colloidal phase inorganics
Biological treatment	Particle aggregation/biological	Solid phase organics/inorganics
	Metabolism/gravity	Colloidal phase organics/inorganics
		Soluble phase biodegradable organics
Filtration	Entrapment particle aggregation/adsorption	Solid phase organics/inorganics
		Colloidal phase organics/inorganics
Carbon adsorption	Adsorption	Soluble phase adsorbable organics/inorganics
	Entrapment	Solid phase organics/inorganics
	Particle aggregation/adsorption	Colloidal phase organics/inorganics

The two general categories of treatment are physical/chemical treatment and biological treatment. The essential difference between the capabilities of a physical/chemical process and a biological process is the ability of each to remove certain types of organic materials. Physical/chemical processes are subject to apparent inefficiencies caused by a certain amount of non-adsorbable organics in the wastewater. Biological processes are subject to apparent inefficiencies as a result of non-biodegradable organics in the wastewater. A selective listing of unit processes and the waste constituents for which they are generally applied and/or are effective is shown in Table 1.11.

Deciding on the most applicable process is based on full knowledge of the wastewater conditions and constituents. In general, chemical/physical treatment is a suitable alternative:

- for a waste having a high particulate organic concentration, provided the soluble organic concentration, following chemical coagulation, sedimentation, and filtration, is less than 50 mg/l BOD5
- for wastewater treatment systems where no influent flows will be received for substantial periods of time, for example batch treatment or systems experiencing significant flow variations
- if land space is limited or toxic substances are presented in the raw wastewater.

Care should be exercised in the application of physical/chemical treatment systems on medium to high strength wastes (BOD5 greater than 200 mg/l). For this situation, on-site pilot studies are desirable to determine effluent quality that could be obtained and to ascertain if the biological activity anticipated in the carbon column will be more of a detriment (odor, plugging) than an asset (higher organic removal).

Land application of wastewater is viewed as an alternative to other secondary treatment schemes or as a final add-on step for liquid disposal and convenient water use. Alternative

Table 1.12 *Treatment processes used for the removal of toxic compounds.*

Process	Removal application
Activated-carbon adsorption	Natural and synthetic organic compounds including VOCs, pesticides, PCBs, and heavy metals
Activated-sludge-powdered activated carbon	Heavy metals, ammonia, selected refractory priority pollutants
Air stripping	VOCs and ammonia
Chemical coagulation, sedimentation, and filtration	Heavy metals and PCBs
Chemical oxidation	Ammonia, refractory and toxic halogenated aliphatic and aromatic compounds
Conventional biological treatment (activated-sludge, trickling filter)	Phenols, PCBs, selected hydrogenated hydrocarbons

VOCs, volatile organic compounds; PCBs, polychloro-biphenyls.

land disposal methods include various modes of surface and subsurface percolation and deep well injection. Combined land disposal and wastewater reclamation methods include infiltration-percolation, overland flow, irrigation, and groundwater recharge.

Many treatment methods can be used for the treatment of toxic compounds. Because of the complex nature of toxicity, such treatment methods must consider the specific characteristics of the wastewater and the nature of the toxic compounds. Treatment processes used to remove some specific compounds or groups of compounds are summarized in Table 1.12.

Various combinations of unit operations and processes and their interaction for treatment of refinery wastewater are identified in Table 1.13. A summary of treatment methods for petrochemical wastes is presented in Tables 1.14–1.16. The selection of a process train or alternative process trains should be made on the ability of the individual unit processes to remove specific waste constituents.

1.5 Siting and Design

In previous sections, the sources of pollution and control methods were discussed. In the following pages the general outline of pollutant specific for management in the siting and design of a refinery or terminal will be discussed.

A major design requirement for a refinery or terminal is the need to minimize or eliminate the emission of pollutants to the environment. The methods needed to implement this depend on the types of crude oil processed, the types of products, the availability of water fuel and other utilities, and the agreed pollution parameters.

Safety requirements must also be considered at this stage to ensure that the surrounding population and plant personnel are protected from hazards such as fire, explosion, and toxic chemicals.

The items of concern in the siting and design of a facility are briefly reviewed here with the intention of pointing out potential environmental effects.

Table 1.13 *Refinery treatment sequence options.*

Pre-treatment	Primary treatment	Secondary treatment	Tertiary treatment	
Removal of phenolics, S-, NH_3, RSH, F-, acid, sludge, oil, etc., water reuse; waste equalization	Removal of free oil Suspended solids	**Removal of emulsified oil, suspended and colloidal solids**	**Removal of dissolved organics (variable) produced biological sludge**	
Processes				
Unit separators Steam stripping Fuel gas stripping Air oxidation Neutralization Surge ponds	API separators CPI, PPI separators	Chemical coagulation and air flotation Chemical coagulation and filtration pH control Reduction of intermediate oxygen demand Equalization of wastes	Trickling filter Activated oxidation pond Aerated lagoon Rotating biological contactors	Chemical coagulation and air flotation Chemical coagulation and filtration Carbon adsorption Carbon adsorption
Inhibitory contaminant surge control	↓Sludges	↓Sludges	↓Sludges	↓Sludges

RSH, API, CPI, corrugated plate interceptor; PPI, parallel plate interceptor.

1.5.1 Aquatic Ecosystems

A refinery or terminal siting should take into account potential impacts on aquatic ecosystems. The characterization of aquatic systems in a siting should include the location of spawning areas, feeding zones, commercial fishing areas, sport fishing areas, a description of the benthic populations, and an estimate of primary productivity and its limiting factors.

Design considerations should include the facility's water supply requirements. While water use is usually non-consumptive, attention should be given to the intake and discharge zones.

At refineries or terminals there is always the potential for a release of oil or petroleum products. All facilities should have a spill contingency plan and the basic equipment necessary to clean up a spill.

1.5.2 Terrestrial Ecosystems

Impacts on terrestrial ecosystems from the siting of a refinery or terminal include a reduction or loss in total available habitat, destruction, or modification of food webs, and changes in

Table 1.14 *Summary of physical treatment methods for petrochemical wastes classified by plant product.*

	Physical treatment						
Plant product	Suspended-growth nitrification	Suspended-growth nitrification	Suspended-growth nitrification	Suspended-growth nitrification	Suspended-growth nitrification	Suspended-growth nitrification	Suspended-growth nitrification
General chemicals	✓			✓	✓		
Nylon							✓
Nylon chemical intermediates	✓	✓		✓		✓	
Organic chemicals			✓			✓	
Photochemicals		✓					
Resins					✓		
Rocket fuels			✓				
Synthetic rubber			✓				

Table 1.15 *Summary of chemical and biological treatment methods for petrochemical wastes classified by plant product.*

	Chemical treatment		Biological treatment		
Plant product	pH adjustment	Chemical oxidation	Biological filters	Activated sludge	Lagoons
General chemicals	✓	✓			✓
Nylon			✓		
Nylon chemical intermediates		✓	✓		✓
Organic chemicals	✓				
Oxygenated hydrocarbons				✓	
Photochemicals			✓		
Powders			✓		
Resins			✓		✓
Rocket fuels	✓		✓		
Rubber, textiles, and plastics				✓	

Table 1.16 *Summary of ultimate disposal methods for petrochemical wastes classified by plant product.*

	Ultimate disposal						
Plant product	Controlled dilution to streams and bays	At sea	On land surfaces	Dumping or burial	Deep weles	Incinekation	Salvage
Nylon			✓		✓	✓	✓
Nylon chemical intermediates	✓					✓	
Synthetic rubber	✓					✓	

populations. Another concern in the siting should be the sensitivity of plants and animals to pollutants.

1.5.3 Wetland Ecosystems

Where the water table is at, near, or above the land surface for a significant part of most years, the hydrologic regime is such that aquatic or hydrophytic vegetation is usually established, although tidal flats may be non-vegetated. Because wetlands are water systems, any alteration affecting the quality of water in a small area is transmitted to other areas, magnifying potential impacts.

Wetlands may be altered directly by filling, dredging, draining, or creating impoundments. Indirectly, alteration of water flow patterns at locations and changes in adjacent land use can change the functions and values of wetland areas.

In addition to facility construction, the laying of pipelines associated with these facilities can have an impact on wetlands.

1.5.4 Land Use

Part of the siting for a refinery or terminal should consider the existing land use and compatibility with local and regional land use plans.

1.5.5 Water Pollution Control

The siting and design guidelines for water pollution control are as follows:

- *Siting*
  The most important aspect of water pollution control in the siting of a refinery is the effect of the wastewater effluent on the receiving water. Several factors which should be assessed in the siting investigation are heat load, total dissolved solids, heavy metal concentrations, and the effects of organics in the effluent.
- *Design*
  The design of a water pollution control depends on the degree of cleanup required to permit discharge of the wastewater to either a body of water or public wastewater treatment plant, and the characteristics of the refinery. The following design practices are directed primarily toward segregation of process and non-process wastewater, and the recycling and reuse of raw and treated wastewater:
  a) Refinery wastewater should be segregated and treated based on oil content and potential for reuse. Four common divisions are oil-free wastewater, oily cooling water, process water, and sanity wastewater.
  b) Raw and treated wastewater streams should be recycled to reduce the effluent volume and thereby the make-up water required. Specific practices include the use of catalytic cracker accumulator wastewater rich in H_2S (sour water) for make-up to crude desalters after stripping;
  c) Tank farm, process, and product-handling areas should be sloped and graded toward sumps or sewers to permit quick removal and collection of spills.
  d) Check valves and storage tanks should be installed at the ends of pipelines specifically for spill prevention and control.
  e) Seals should be installed on normally closed valves.
  f) Cathodic protection systems should be installed on underground pipelines and tanks or a continuous coating applied around the pipeline to prevent direct contact between the pipe and the soil.
  g) Where feasible, all pipelines should be located above ground to facilitate inspection and identification of leaks.
  h) Concrete ditches leading to either a chemical waste system or a wastewater system should be installed under pipelines.

1.6 Sources of Effluent in the Petrochemical Industry

1.6.1 Water Pollution

In chemical plants, the volume water formed by chemical reaction is generally less than the volume of water evaporated into atmosphere, so the amount of water discharged tends to be less than the water intake. However, most of the intake water is discharged.

In addition, rain water is fouled while flowing through contaminated areas of a plant and is discharged as part of the wastewater.

1.6.2 Cooling Water

Most industrial water is used as cooling water, (for example, for naphtha thermal cracking in making ethylene and ethylene dichloride), for thermal cracking in the manufacture of vinyl chloride, for removal of reaction heat in polymerization and oxidation, and for cooling fractionator condensers. Cooling water is not fouled since an indirect cooling method is generally adopted. However, there are instances of liquid leaking from the tubes of a cooler due to corrosion attack, resulting in contamination of cooling water.

1.6.3 Washing Water and Process Water

Considering the properties of fouled water, washing water is identical to process water, so the former is frequently called "process water." Water is used in washing because it dissolves various substances. For example, carbon dioxide, hydrogen sulfide, hydrochloric acid, etc. in gas are dissolved in dilute alkali water.

The amounts of washing water and process water used in petrochemical plants are small compared with those of cooling water. This wastewater contains a considerable amount of organic substances and dissolved oils, but the COD and BOD values are insufficient to indicate the amounts of organic substance contained in the wastewater from petrochemical processes.

The organic matter in wastewater from petrochemical plants should be indicated using TOC (total organic carbon) and TOD (total oxygen demand) but the TOC and TOD indications themselves are not always considered useful criteria for the detection of toxic substances in wastewater or for the selection of wastewater treating methods. As organic compounds discharged from petrochemical processes have a variety of chemical properties depending on the processes, it is necessary to pursue the emission sources. Table 1.17 shows different types of pollution in plant operations.

1.6.4 Typical Pollutants in the Petrochemical Industry

Aqueous effluents originating from the petrochemical industry are essentially characterized by the presence of the following substances:

organic substances that are not biodegradable, or only slightly so
nitrogen compounds
heavy metals.

Table 1.17 Types of water pollution.

Type of pollution	Plant operation	Examples of pollution
Water pollution (wastewater, waste liquid)	Cooling water	Direct cooling or quenching of decomposed gas: wastewater contains tar dust, hydrogen sulfate, and cyanide
		Breakage of indirect cooler tubes: contamination of cooling water due to liquid inside the tubes
		Steam ejector: steam condensate from ejector contains volatile hydrocarbon
	Boiler feed water	Steam ejector: steam condensate from ejector contains volatile hydrocarbon
	Washing water	Water containing hydrogen sulfate, hydrochloric acid etc. is discharged from the washing of gas
		Water containing hydrochloric acid, etc. is discharged from the washing of liquid
		Dust is contained in discharged water from the dust collector
	Process water	Solvent for suspension and emulsion polymerization contains catalysts, emulsifier, plastic monomer, etc.
	Feed water (chemical reaction, electrolysis)	Steam condensate from steam stripping: dissolves hydrocarbons
		Steam condensate originating from dilution steam for naphtha thermal cracking: contains carbon, phenol, and light oil
	Leakage (loss)	Leakage from pump and agitator shafts, valve stems, and flanges, and due to operational error

1.6.5 Petrochemical Waste Treatment

Petrochemicals have been defined as bulk chemicals derived principally from natural gas, petroleum, or both. A careful check should be made of processes proposed or used for the manufacture of petrochemicals to decrease the possibility of water-soluble organics entering water supplies. The following methods should be considered:

- recycling and reuse of waste streams
- quenching with oil or chemicals other than water that do not produce waterborne wastes
- use of alternative processes that do not produce waterborne wastes
- use of air coolers or of cooling towers in place of once-through cooling water
- elimination of waste products in the manufacturing operation before they become associated with waste streams
- processing of waste streams to reduce the amount of chemicals in wastewater leaving the plant.

The extensive use of automated controls, alarms, and checks by operators to prevent loss of chemicals is also important. It is essential that adequate facilities be installed to prevent uncontrolled release of chemicals and wastes to sewers or receiving water. A very

effective means of quality control is the use of large lagoons capable of holding several days' production of wastewater. This allows the water to be checked before being released to receiving water.

1.6.6 Fertilizer

The liquid effluents arising from a fertilizer factory originate from a variety of sources and may be summarized as follows:

a) Ammonia-bearing waste from ammonia plants.
b) Ammonia and urea waste from urea manufacturing plants.
c) Ammonium salts such as ammonium nitrate, ammonium sulfate, and ammonium phosphate.
d) Phosphates and fluoride waste from phosphate and super phosphate plants.
e) Acidic spillages from sulfuric acid, nitric acid, and phosphoric acid plants.
f) Spent solutions from the regeneration of ion-exchange units:-acid from cation exchange units and alkali from regeneration of anion exchange units.
g) Phosphate, chromate, copper sulfate, and zinc wastes from cooling tower blowdown.
h) Salts of metals such as iron, copper, manganese, molybdenum, and cobalt.
i) Sludge discharged from clarifiers and backwash water from sand filters.
j) Carbon slurry from partial oxidation units.
k) Scrubber wastes from gas purification processes containing contaminants such as:
   - mono and diethanol amines (MEA and DEA)
   - arsenic, as As_2O_3
   - potassium carbonate
   - caustic soda.

The effluents from fertilizer manufacturing are generated from a wide range of unit operations, and considerable variation between wastewater from different factories may be noted. The age, state of repair, operational management, and degree of sophistication of each manufacturing unit will play an important role in determining the degree of in-plant materials loss, and the important factors leading to excessive losses (and subsequent pollution) may be summarized as follows:

- outdated basic manufacturing plant with low efficiency and poor process control
- improper maintenance and repair, with particular emphasis on servicing of control equipment
- variations in feedstock and difficulties in adjusting process plant to cope with these variations effectively
- lack of consideration for pollution abatement and the prevention of materials loss at the original plant design stage.

Overall water requirement for fertilizer manufacturing plants may be high due to process cooling requirements. The total volume of effluent discharged is dependent to a considerable extent on the degree of in-plant recirculation, and in the case of total recycle the raw water is used primarily for make-up purposes.

Plants designed on a once-through cooling system generally give rise to high volumes of effluent, from 1000 m^3/h to volumes in excess of 10 000 m^3/h, consisting primarily of cooling water discharge.

1.6.6.1 Nitrogenous Fertilizers

A complex nitrogenous fertilizer plant based on the production of ammonium nitrate and urea products may give rise to pollutants such as ammonium nitrate, nitric acid, ammonia, urea, sulfuric acid, caustic soda, chromate, oil, grease, and boiler feed additives, contained within the overall effluent stream. The individual effluents from ammonia and urea plants can be categorized as follows:

a) Ammonia plants
   - HCN stripper outlet
   - Catalyst reduction process
   - Shift process condensate.

b) Urea plants
   - Concentrate liquor
   - Cooling water blowdown
   - Additional pollutant discharges may arise from oily water and sanitary sewage effluents.

1.6.6.2 Phosphate Fertilizers

Some examples of the sources of liquid effluents from phosphatic fertilizer manufacture are as follows:
Plant 1: Raw water intake
Effluent sources:

- Superphosphate plant
- Sulfuric acid plant
- Water treatment plant
- Cooling tower
- Other sources

Plant 2: Raw water intake – Sea water (once-through cooling)
Effluent sources:

Ammonia plant
Phosphoric acid plant
Sulfuric acid plant
Utilities plant
Cooling water make-up
Boiler blowdown and washings from ion
Exchange units and floor washing

1.6.6.3 Compound Nitrogen/Phosphorus/Potassium Fertilizers

A major component of nitrogen/phosphorus/potassium (NPK) effluent is the direct loss of fertilizer compounds from granulation units. Examples of the effluents from compound

fertilizer manufacture are as follows:
Plant 1: Raw water intake
Effluent sources:

- Ammonia plant
- Urea plant
- Phosphoric acid and NPK plants
- Water treatment plant
- Cooling tower
- Boiler plant

Plant 2: Raw water intake
Effluent sources:

- Ammonia plant
- Urea plant
- Phosphoric acid and NPK plants
- Sulfuric and nitric acid plants
- Water treatment and steam generation plant
- Methanol plant

1.7 Effect of Pollution

Wastes may be subcategorized into major and minor elements, but it should be noted that in specific instances particular minor waste components may exercise significant polluting effects.

1.7.1 Major Pollutants

General water pollution effects from fertilizer manufacturing wastes are dependent primarily on the elements nitrogen and phosphorus, in their varying chemical forms.

1.7.1.1 Nitrogen: Ammoniacal Nitrogen and Urea

These two compounds are grouped together since urea may be hydrolyzed to ammoniacal nitrogen. The pollution problems which may be attributable to ammoniacal nitrogen include toxicity, oxygen demand, and eutrophication. Ammonia can be toxic to fish and other aquatic life forms at relatively low concentrations, and urea itself may be toxic to some aquatic life.

Ammoniacal nitrogen and urea may both be oxidized biologically. As such, their presence must be considered a potential oxygen demand in a receiving water. In addition, ammoniacal nitrogen may act in its role as a fertilizer in an aquatic environment, leading to excess growth of algae and aquatic macrophytes, and contributing toward accelerated eutrophication.

The presence of high ammonial levels may also cause problems if the receiving water is used for water supply purposes due to chemical interference with chlorination (i.e. formation of chloramine intermediates) and resultant increase in chlorine demand.

1.7.1.2 Nitrate

The water pollution problems resulting from high nitrate levels may be categorized into eutrophication and public health effects. High levels of nitrate can give rise to increased eutrophication, leading to the promotion of growth of algae and macrophytes, adversely affecting water quality and amenity value. Health hazards related to nitrate in water used for supply purposes are considered to be infant methaemoglobinaemia and carcinogenic potential.

1.7.1.3 Phosphate

The presence of significant levels of phosphate has important effects on eutrophication. In terms of inorganic nutrient enrichment of receiving water, phosphate may in many instances be more important than nitrogenous compounds due to the fact that some forms of aquatic plant life may fix atmospheric nitrogen, so removing the absolute requirement for soluble forms of nitrogen to promote growth.

Under these circumstances, phosphate becomes the growth-limiting agent, and programs to control eutrophication have generally sought to reduce available phosphate limits to prevent excessive algal and macrophyte growth, with subsequent increase in nutrient retention.

1.7.1.4 Minor Constituents

In addition to pollution arising from the discharge of nitrogenous or phosphatic elements in liquid waste streams, pollution can be caused by a number of secondary waste components. The most important of these are:

- oil and grease
- hexavalent chromium
- arsenic
- fluoride.

In specific instances, one or more of these individual pollutants may give rise to detrimental effects in a receiving water, due primarily to toxicity, or cause inhibition of nitrification. In addition, oil and grease may adversely affect the oxygen transfer characteristics of a watercourse.

1.8 Olefin Plants

- *Liquid effluents*
  The main liquid effluent streams of olefin plants are oily drains, flare system pump-out, caustic oxidation effluent, dilution steam generator blow down, and fouled condensate.
- *Oily drains*
  The major oily drain sources are water draw-offs from vessels and hydro blast decoking wastewater. Hydro blast wastewater produced during cleaning of coke-fouled equipment

contains entrained coke fines which are screened before discharge to the oily wastewater treatment system.

- *Flare system effluent*
  A flare system is required for safe disposal of hydrocarbons which may be released at pressure during mal-operation and emergency conditions. The hot flare knockout drum is primarily provided in order to receive liquids from the flare seal drum, excess fuel gas, hot relief, and hot blow down.
- *Spent caustic neutralization*
  The cracked gas from the cracking furnaces is scrubbed in a caustic wash tower to remove any remaining gas, including carbon dioxide, hydrogen sulfate, and mercaptans, prior to further processing in the plant cold section. The spent caustic is purged from the wash tower and is laden with sulfidic constituents plus VOCs such as condensed oils and benzene. The spent caustic scrubbing liquor is commonly the most problematic waste stream generated by an olefin plant. This is due primarily to the sulfate concentrations, which can range as high as 6% (expressed as NaHS), depending on the cracking furnace feed stock and wash tower operation. The most effective means for on-side treatment of spent caustic is wet air oxidation, which can achieve the oxidation of reactive sulfate to soluble thiosulfate, sulfate and sulfate.
- *Fouled condensate*
  Suspect condensate consists of all condensate streams from heat exchangers where hydrocarbon side pressure is more than the heating steam. A leakage in one of these heat exchangers will result in hydrocarbon contamination of the condensate. Normally, the condensate flow to the surge tank is zero. The possible constituents in suspect condensate are propane, propylene, butane, butadiene, and pentane, with their concentrations related to the maximum solubility.
- *Dilution steam generator blow down*
  The main sources of wastewater in an olefin plant are:
  - process water below down during normal and upset operating conditions
  - process water from the quench tower
  - surface runoff from possibly contaminated or non- contaminated areas.

  The wastewater components are variable depending on the respective sources, but the major components are oil, phenols, H_2S, and hydrocarbons.

1.8.1 Polymeric Plants

- Poly ethylene plant (HDPE/LLDPE/LDPE)
  - Process wastewater
    The process wastewater discharged from the bottom of the dryer scrubber entrained polymer fines typically has following characteristics:
    temperature < 50 °C
    BOD5 < 100 ppm
    COD < 200 ppm
    Suspended solids 100 ppm max.
  - Rain water and floor-washing water
    Rain water and floor-washing water should be collected and treated separately according to their origin.

- Polymerization area
  The ceiling of the polymerization area may be polluted with polymer powder and oil that can be sometimes spilled from pumps, compressors, and other mechanical equipment.
  Rain water and washing water falling on paved areas may carry away powder and oil, and therefore should be gathered to the basins separately, where the entrained material is retained.
- Extrusion building area
  The floors of the extrusion buildings may be occasionally polluted by polymer/scrapes and lubricating oils.

• Polypropylene plant
Process wastewater effluent
The sources of continues process wastewater effluent are dryer scrubbers and palletizing sections. The wastewater contaminated by trace polymer fines leaves the bottom of the dryer scrubber. It typically has the following characteristics:
pH 6–8
temperature 40–60 °C
contaminant polymer powder.
The wastewater from the palletizing section combined oil and trace suspended solid. It typically has the following characteristics:
pH 7–8
suspended solids 25 ppm
oil content 1 ppm max.
COD 5–10 ppm
temperature 50–80 °C.

1.8.2 Polyvinyl Chloride Plants

Polyvinyl chloride (PVC) is formed by polymerization. During the chemical process of polymerization a lot of heat is generated. To remove the heat two emulsion and suspension PVC processes have been established. The wastewater effluent coming out of an emulsion PVC plant is similar to that from a suspension PVC plant.

The sources of the wastewater effluent are the polymerization reactor additive coating, the vacuum station, and the recovered vinyl chloride monomer. The wastewater streams coming out of these sources are collected in the wastewater settling basin, which has two compartments. The wastewater contaminated with wet PVC and vinyl chloride monomer (VCM) components typically has the characteristics reported in Table 1.18.

Table 1.18 *Wastewater contaminated with wet PVC and VCM characteristics.*

Temperature	40–70 °C
pH	6–7
COD	150–250 ppm wt
BOD5	75–150 ppm wt
Wet PVC	15–20 mg per kg water
VCM	0.5–1 mg per kg water

PVC, poly vinyl chloride; VCM, vinyl chloride monomer.

1.8.3 Aromatic Plants

The effluent in aromatic plants mainly comes from naphtha hydro-treating and catalyst regeneration units under normal operating conditions.

- Naphtha hydro-treating units
  The main effluent is sour water coming from the reactor effluent separator drum.
  Depending on the quality of the naphtha feed, the sour water will contain hydrocarbons, H_2S, and NH_3.
  The typical characteristics of sour water are:
  temperature 45 °C
  HC 100 ppm wt
  H_2S 50 ppm wt
  NH_3 20 ppm wt.
  In this case, the water collected and treated in the batch stage by direct oxidization with hydrogen peroxide in the sour water treatment unit.
- **Catalyst regeneration unit**
  The catalyst regeneration unit, which is part of aromizing section, continuously regenerates deactivated catalyst from the aromizing unit and introduces it to the aromizing reactor.
  The major effluent streams consist of water from the washing drum, liquid from the oxy-chlorination drum, and liquid from the dryer package.

a) *Water from the washing drum*
   The major constituents of water from the washing drum are carbon dioxide dissolved in water with traces of carbonate sodium, hydroxide sodium, chloride sodium, and oxy-chloride sodium.
b) *Liquid from the oxy-chlorination effluent drum*
   The liquid effluent from the oxy-chlorination drum consists of some sodium salts. The specified composition of the liquid includes sodium combinations such sodium hydroxide, sodium carbonate, sodium oxy-chloride, and sodium chloride, which are neutralized with hydrochloric acid.

1.9 Environmental Protection for Industrial Waste

All industrial complexes which produce waste in higher quantity above the standards should have waste treatment facilities before final release of the wastewater to the environment. The dilution of treated wastewater to the standard level is not permitted. A monitoring system in final stage of treatment should be used. Tables 1.19–1.21 illustrate typical standards for municipal waste, effluent permissible concentrations, and characteristics of potable water.

1.9.1 Important Factors in Process Selection

The most important factors that must be considered in evaluating and selecting unit operations and processes are the following:

a) *Process applicability*
   The applicability of a process should be evaluated on the basis of past experience, published data, and data from full-scale plants and pilot plant studies. If new or unusual conditions are encountered, pilot plant studies are essential.

Table 1.19 *Typical maximum effluent standard for municipal waste (daily average).*

Effluent characteristic	Unit	Maximum concentration	Note
BOD5	mg/l	30	BOD5 should not increase to more than 50 mg/l
COD	mg/l	60	COD should not increase to more than 120 mg/l
Cl	mg/l	1	
Chloroform	MPN	100/100 ml	
Color	Color unit	16	
Detergents	mg/l	1.5	Equivalent to ABS
Dissolved oxygen	mg/l	2	
F	mg/l	2.5	
Ammonia (as N)	mg/l	2.5	
Nitrite (as N)	mg/l	50	
Nitrate (as N)	mg/l	10	
Oil and grease	mg/l	10	
pH	—	6.5–8.5	
Phosphate	mg/l	1	
Settleable solid	mg/l	0.1	
Suspended solid	mg/l	40	Should not increase to more than 60 mg/l
Sulfate	mg/l	400	Should not increase the sulfate content of supply water more than 10%
Sulfite	mg/l	1	
Turbidity	NTU	50	

BOD5, biological oxygen demand; COD, chemical oxygen demand; MPN, ABS; NTU, nephelometric turbidity unit; JYU.

b) *Applicable flow range and flow variation*

The process should be matched to the expected range of flow rates, for example stabilization ponds are not suitable for extremely large flow rates. Most unit operations and processes have to be designed to operate over a wide range of flow rates. Most processes work best at a relatively constant flow rate. If the flow rate variation is too great, flow equalization is necessary. Table 1.22 identifies critical design and sizing factors for secondary treatment plant facilities and describes potential performance impacts of flow rate and constituent mass loading variations. Design provisions for flow rate variations, in addition to flow equalization, may include flow splitting and unit process bypassing under certain peak flow rate conditions. Minimum treatment requirements, if permitted by regulatory authorities, may include primary treatment and disinfection of the entire flow and secondary treatment of a portion of the flow. The advantages of a unit process flow-splitting and bypassing strategy are that:

- the biomass the secondary treatment process can be preserved during peak storm conditions and not lost due to washout

Table 1.20 *A typical effluent: permissible concentrations.*

Contaminants	Discharge to surface runoff (mg/l)	Discharge to groundwater (mg/l)	Irrigation and agriculture usage (mg/l)
Al	5	5	5
Ba	2	1	1
Be	0.1	1	0.1
B	2	1	1
Cd	1	0.01	0.01
Ca	75	—	—
Cr^{6+}	1	1	1
Cr^{3+}	1	1	1
Co	1	1	0.05
Cu	1	1	0.2
Fe	3	0.5	5
Li	2.5	2.5	2.5
Mg	100	100	100
Mn	1	0.5	0.2
Hg	0	0	0
Mo	0.01	0.01	0.01
Ni	1	0.2	0.2
Pb	1	1	1
Se	1	0.01	0.02
Ag	1	0.05	0.01
Zn	2	2	2
Sn	2	2	—
V	0.1	0.1	0.1
AS	0.1	0.1	0.1
Cl^{-1}	Amount of chloride in industrial effluents should not exceed 250 mg/l (ppm) for fresh water	Amount of chloride in industrial effluents should not exceed 250 mg/l (ppm) for fresh water	Amount of chloride in industrial effluents should not exceed 250 mg/l (ppm) for fresh water
F	2.5	2	2
P	1	1	—
CN	0.2	0.02	0.02
C_5H_5OH	1	0	1
CH_2O	1	1	1
NH_4^+	2.5	0.5	—
NO_2^-	50	10	—
NO_3^-	50	1	—
SO_4^{2-}	300	300	500
SO_3^{2-}	1	1	1
TSS	30	30	100
SS	0	0	0

(*Continued*)

Table 1.20 *(continued)*

Contaminants	Discharge to surface runoff (mg/l)	Discharge to groundwater (mg/l)	Irrigation and agriculture usage (mg/l)
TDS	Total dissolved solids in industrial effluents should not increase the amount of these materials more than 10% in the underground water/river and any other sources up to a distance of 200 m in which effluent dumped	Total dissolved solids in industrial effluents should not increase the amount of these materials more than 10% in the underground water/river and any other sources up to a distance of 200 m in which effluent dumped	Total dissolved solids in industrial effluents should not increase the amount of these materials more than 10% in the underground water/river and any other sources up to a distance of 200 m in which effluent dumped
Oil and grease	10	10	10
BOD	20	20	100
COD	50	50	200
DO	>2	>2	>2
ABS (detergent)	1.5	0.5	0.5
Turbidity	50	50	50
Color	Color of source water should not exceed more than 16 standard units due to industrial effluent, dumped	75 units of color	75 units of color
Temperature	Temperature of industrial effluent should not change the temperature of source water more than ±3 °C up to a distance of 200 m	—	Temperature of industrial effluent should not change the temperature of source water more than ±3 °C up to a distance of 200 m
pH	6.5–8.5	5–9	5–9
Radio actives	0	0	0
Digestible coliform	400/100 ml	400/100 ml	400/100 ml
MPN	1000/100 ml	1000/100 ml	1000/100 ml

TSS, SS, TDS, total dissolved solids; BOD, biological oxygen demand; COD, chemical oxygen demand; DO, ABS, MPN

- the quality of the treatment plant effluent can be restored shortly after the storm event
- the entire treatment facilities need not be oversized to handle unusual events.

A disadvantage of flow-splitting and bypassing is that the effluent quality may violate the discharge permit for short periods of time. any treatment sequence designed for flow-splitting and unit bypassing should be investigated in advance to ensure it meets environmental regulation requirements.

Table 1.21 *Typical physical characteristics of potable water.*

Characteristic	Desired threshold limit value	Maximum value
Color	5 units	5 units
Odor	2	3
Turbidity	5	25
pH	7–8.5	6.5–9.2

Chemical characteristic of potable water mg/l

Characteristic	Desired threshold limit value	Maximum value
As	0	0.05
Cd	0	0.01
Cn	0	0.05
Pb	0	0.1
Hg	0	0.001
Se	0	0.01
Cr	0	0.05
Ba	0	1
Ag	0	0.05
B	0	1
Hardness	150	500
Ca	75	200
Mg	50	150
Mn	0.05	05
Fe	0.3	1
Zn	5	15
Cr	0.5	1.5
SO_4	200	400
Cl	200	600
N	0.002	0.05
Detergent	0.1	0.2
P	0.1	0.2
Total dissolved solids	500	1500

c) *Influent wastewater characteristics*
The characteristics of the influent wastewater affect the types of processes to be used (e.g. chemical or biological) and the requirements for their proper operation.

d) *Inhibiting and unaffected constituents*
The following should be identified:
- the constituents which are present
- the constituents which may be inhibitory to the treatment processes
- the constituents which are not affected during treatment.

e) *Climatic constraints*
Temperature affects the rate of reaction of most chemical and biological processes. Temperature also affects the physical operation of the facilities. Warm temperatures may accelerate odor generation and also limit atmospheric dispersion.

Table 1.22 *Effect of flowrates and constituent mass loadings on the selection and sizing of secondary treatment plant facilities.*

Unit operation or process	Critical design factor(s)	Sizing criteria	Effects of design criteria on plant performance
Wastewater pumping and piping	Maximum hour flow rate	Flow rate	Wet well may flood, collection system may surcharge, or treatment units may overflow if peak rate is exceeded
Screening	Maximum hour flow rate	Flow rate	Head losses through bar rack and screens increase at high flow rates
	Minimum hour flow rate	Channel approach Velocity	Solids may deposit in approach channel at low flow rates
Grit removal	Maximum hour flow rate	Overflow rate	At high flow rates, grit removal efficiency decreases in flow-through type grit chambers causing grit problems in other processes
Primary sedimentation	Maximum hour flow rate	Overflow rate	Solids removal efficiency decreases at high overflow rates; increases loading on secondary treatment system
	Minimum hour flow rate	Detention time	At low flow rates, long detention times may cause the wastewater to be septic
Activated sludge	Maximum hour flow rate	Hydraulic residence time	Solids washout at high flow rates; may need effluent recycle at low flow rates
	Maximum daily organic load	Food/ microorganism ratio	High oxygen demand may exceed aeration capacity and cause poor treatment performance
Tickling filters	Maximum hour flow rate	Hydraulic loading	Solids washout at high flow rates may cause loss of process efficiency
	Minimum hour flow rate	Hydraulic and organic loading	Increased recycle at low flow rates may be required to sustain process
	Maximum daily organic load	Mass loading/media Volume	Inadequate oxygen during peak load may result in loss of process efficiency and cause odors
Secondary sedimentation	Maximum hour flow rate	Overflow rate or detention time	Reduced solids removal efficiency at high overflow rates or short detention times
	Minimum hour flow rate	Detention time	Possible rising sludge at long detention time
	Maximum daily organic load	Solids loading rate	Solids loading to sedimentation tanks may be limiting
Chlorine contact tank	Maximum hour flow rate	Detention time	Reduced bacteria kill at reduced detention time

f) *Reaction kinetics and reactor selection*
Reactor sizing should be based on the governing reaction kinetics. Data for kinetic expressions usually are derived from experience, published literature, and the results of pilot plant studies.

g) *Performance*
Performance is usually in terms of effluent quality, which must be consistent with the effluent discharge requirements.

h) *Treatment residuals*
The types and amounts of solid, liquid, and gaseous residuals produced should be known or estimated.

i) *Sludge processing*
Any constraints that would make sludge processing and disposal infeasible or expensive should be identified. The extent of recycle loads from sludge processing which affects the liquid unit operations or processes should also be clarified.

j) *Environmental constraints and regulations*
Environmental factors, such as prevailing winds, wind direction, and proximity to residential areas, may restrict or affect the use of certain processes, especially where odors may be produced. Noise and traffic may affect selection of a plant site. Receiving water may have special limitations, requiring the removal of specific constituents. The characteristics of treated water imposed by the final destination and/or environmental regulations will dictate special unit operations and processes for treatment of wastewater.

k) *Chemical requirements*
The resources and amounts must be committed for a long period of time for successful operation of the unit operation or process to be clarified. The effects of the addition of chemicals on the characteristics of the treatment residuals and the cost of treatment should also be determined.

l) *Energy requirements*
The energy requirements, as well as the probable future energy cost, must be known if cost-effective treatment systems are to be designed.

m) *Operating and maintenance requirements*
Special operating or maintenance requirements needed along with the necessary spare parts and their availability and cost should be determined.

n) *Reliability*
The long-term reliability of the unit operation or process under consideration must be determined. Is the operation or process easily disrupted? Can it stand periodic shock loadings? If so, how do such occurrences affect the quality of the effluent? Because of the variations in effluent quality performance, a treatment plant should be designed to produce an average effluent concentration below the permit requirements.

o) *Compatibility*
The unit operation or process should be used successfully with existing facilities. Plant expansion should be accomplished easily.

p) *Land availability*
Sufficient space should be allocated to accommodate either the facilities currently under consideration or possible future expansion.

q) *Equipment availability*
Most of the equipment used in wastewater treatment is custom manufactured, except for items such as small pumps, motors, and valves. Some items of equipment may require special manufacturing techniques or are proprietary and only available from limited sources. The equipment components that make-up the process or system should therefore be considered carefully to determine their potential effects on the design, construction, operation, and maintenance of the facilities.

r) *Personnel requirements*
The selection of a treatment process should consider not only the amount of operating and maintenance personnel needed but also the skills required. The extent and complexity of the control systems and the staffing levels required must be evaluated carefully.

1.10 Chemical Oxygen Demand in Wastewater Systems

This section first discusses the background of the COD method, then the method used to calculate the theoretical oxygen demand. COD is the equivalent amount of oxygen consumed under specified conditions in the chemical oxidation of the organic and oxidizable inorganic matter contained in wastewater, corrected for the influence of chlorides. In American practice, unless otherwise specified, the chemical oxidizing agent is hot acid dichromate.

Micro-organisms in natural water bodies consume oxygen when degrading organic matter to biomass. BOD is a parameter which describes the oxygen consumption when microorganisms "eat" organic mass. The more organic load enters the water body, the more oxygen the micro-organisms will use for conversion. Large amounts of pollutants may cause oxygen loss in a water body and lead to harmful effects in nature so it is useful to know the oxygen consumption of wastewater before discharge.

BOD requires days to get results and COD is used because it is a lot faster. So-called standard methods for COD determination are open and closed reflux systems, where a strong oxidant is added to the water solution and boiled in open or closed reflux for a few hours, then the amount of oxidant used is measured by titration methods. COD determination with standard methods takes usually a few hours but colorimetric determination of COD requires less than an hour. COD measures the organic content of a solution.

Due to its rapidity, COD is used to measure the total amount of pollutants in water media. It is often used in water and wastewater quality determination.

The difference between COD the BOD is that in COD, the amount of oxidant used for oxidation of organic components is measured, but BOD expresses the oxygen consumed by micro-organisms when the sample is kept for 5 days at 20 °C. The dissolved oxygen is measured at the beginning and end of the test, and the oxygen consumption is the difference between amount of dissolved oxygen at the beginning and end of the test. There is a correlation factor between BOD and COD so when COD is known, the biochemical oxygen consumption in nature can be determined.

1.10.1 Determination of COD

Usually a strong oxidant, like potassium dichromate, is used in this measurement. The standard method for determination of COD is titration with open or closed reflux, where the

sample is heated either in a closed or an open vessel in the laboratory. The sample is boiled for 2 hours in the presence of the oxidant.

The amount of dichromate consumed can be determined when the difference in oxidant concentration at the beginning and end of the process is determined. Potassium dichromate is considered to be the best oxidant because it has a strong oxidizing capability, it is applicable to many kinds of organic and inorganic matter, and it is easy to manipulate.

Oxidation of inorganic components interferes with COD determination since they also consume dichromate. In the oxidation process, the dichromate ion (Cr^{6+}) is oxidized to chromate (Cr^{3+}).

Baker et al. (1999) declared that the COD for chemicals in group one and group two well-correlated data group, equals the theoretical oxygen demand (ThOD).

For chemicals in groups three and four (potentially well-correlated data) COD can be estimated from the ThOD. No correlation for chemicals presented in groups five and six could be determined.

1.10.2 Calculation of Theoretical Oxygen Demand

The ThOD can be obtained for different chemicals from different studies. Because ThOD is not usually determined for all the chemicals found in the wastewater, it can be determined for every chemical using the method of Baker et al. (1999).

According to Baker et al. (1999) the amount of oxygen consumed by a single component *i* can be determined using Eqs. (1.1) and (1.2). Letters *n, m, k, j, i, h,* and *e* can be determined with Eq. (1.1). According to Baker et al. (1999) Eq. (1.1) assumes that all compounds are oxidized completely to end products. The letters inform how many molecules there are of element *i* in component *i*.

$$C_nH_mO_eX_kN_jS_iP_h + bO_2 \rightarrow nCO_2 + \left(\frac{m-k-3j-2i-3h}{2}\right)H_2O + kH_x + jNH_3 + iH_2SO_4 + hH_3PO_4 \quad (1.1)$$

$$b = n + \frac{m-k-3j-2i-3h}{4} - \frac{e}{2} + 2i + 2h \quad (1.2)$$

To determine the $ThOD_i$, the oxygen demand for 1 g of component *i* has to be determined. Oxygen demand for 1 g of component *i* is represented by $ThOD_{O,i}$ and determined using Eq. (1.3), where b_i is the amount of oxygen consumed in moles per one mole component *i*, M_i is the molar mass of a single component *i*, M_{O2} is the molar mass of an oxygen molecule and ci is the concentration of component "i" in water.

$$ThOD_{O,i} = b_i\frac{M_{O2}}{M_i} \quad (1.3)$$

$$ThOD_i = ThOD_{o,i} \times c_i \quad (1.4)$$

$$\sum ThOD = \sum_i^n ThOD_i = \sum_i^n (ThOD_{o,i} \times c_i) \quad (1.5)$$

Table 1.23 shows the calculated oxygen demand per 1 mole of component *i*, the molar mass, and ThOD demand for various components.

Table 1.23 *Oxygen demand per one mole component* i*, molar mass, and theoretical oxygen demand.*

Component	Composition	Oxygen demand per one mole component, *i* b	Molecular weight Mi (g/mol)	Theoretical oxygen demand ThODi (gO_2/gi)
Methanol	CH_4O	1.5	32.03	1.5
Phenol	C_6H_6O	7	94.1	2.38
Acetone	C_3H_6O	4	58.07	2.2
2-Aminoethanol	C_2H_7NO	2.5	61.08	1.31
Benzene	C_6H_6	7.5	78.11	3.07
Cumene	C_9H_{12}	12	120.2	3.19
Propanol	C_3H_8O	5	44.1	3.63
Toluene	C_7H_8	9	92.14	3.12
Total nitrogen	NH_3	0	17.03	0
Xylene	C_8H_{10}	10.5	106.17	3.16

For example, the chemical formula of phenol is C_6H_6O. If the concentration of phenol is 360 mg/l in a wastewater sample, the ThOD determination is as follows.

According to Eq. (1.1) : $n = 6$, $m = 6$, $e = 1$, $k = 0$, $j = 0$, $i = 0$, $h = 0$. When n, m, k, j, i, h, and e are put into Eq. (1.2), the amount of oxygen molecules needed to oxidize phenol into end products can be determined:

$$b_{C_6H_6} = 6 + \frac{6 - 0 - 3 - 2 - 3}{4} - \frac{1}{2} + 2 + 2 = 7 \text{ mol } O_2/(\text{mol } C_6H_6)$$

$$ThOD_{O,i} = 7\frac{\text{mol } O_2}{\text{mol } C_6H_6}\left(\frac{31.98}{94.1\frac{g_{C_6H_6}}{mol_{C_6H_6}}}\right) = 2.38\frac{\text{g } O_2}{\text{g } C_6H_6}$$

The total ThOD is determined by summing the individual ThOD values:

$$ThOD_{C_6H_6} = ThOD_{o,C_6H_6} \times C_{C_6H_6} = 2.38\frac{\text{mg } O_2}{\text{mg } C_6H_6} \times 360\frac{\text{mg } C_6H_6}{\text{liter } H_2O} = 856.8\frac{\text{mg } O_2}{\text{liter } H_2O}$$

2

Physical Unit Operations

Those operations used for the treatment of wastewater in which change is brought about by means or through the application of physical forces are known as physical unit operations.

The unit operations most commonly used in wastewater treatment and their applications are shown in Table 2.1.

2.1 Flow Measurement

Important criteria that must be considered in the selection of flow metering devices include type of application, proper sizing, fluid composition, accuracy, headloss, installation requirements, operating environment, and ease of maintenance.

Because of rapid advances in metering device electronics and converters, current information should be obtained from meter manufacturers.

Among the important criteria that must be considered in the selection of flow metering devices accuracy and repeatability are critical, especially where the readings from the metering devices are to be used for process control.

2.2 Screening

Suspended particles greater than 2–6 mm should be removed by screening. A screen should have openings of uniform size of any shape. The screening element should consist of parallel bars, rods or wires, wire mesh, grating or a perforated plate. Figure 2.1 shows a typical screening process.

An adequate number of units should be provided to facilitate continuous screening with permission of maintenance type, size classification, and application of screening devices as shown in Table 2.2.

Figure 2.2 is a typical bar screen that consists of a series of parallel bars or a perforated screen placed in a channel. The flow passes through the screen and the large solids are trapped on the bars for removal. The bar screen may be coarse (2–4 cm openings) or fine (2–5 cm openings). The bar screen may be manually or mechanically cleaned. Manual or mechanical cleaning is performed frequently enough to prevent solids buildup and reduce

Waste Management in the Chemical and Petroleum Industries, Second Edition. Alireza Bahadori.
© 2020 John Wiley & Sons Ltd. Published 2020 by John Wiley & Sons Ltd.

Table 2.1 *Applications of physical unit operations in wastewater treatment.*

Operation	Application
Flow metering	Process control, process monitoring, and discharge reports
Screening	Removal of coarse and settleable solids by interception (surface straining)
Comminution	Grinding of coarse solids to a more or less uniform size
Gravity separation	Settling of oil droplets or solid particles by relative density (specific gravity) differences
Flow equalization	Equalization of flow and mass loadings of BOD and suspended solids
Mixing	Mixing chemicals and gases with wastewater, and maintaining solids in suspension
Flocculation	Promotes the aggregation of small particles into larger particles to enhance their removal by gravity sedimentation
Sedimentation	Removal of settleable solids and thickening of sludges
Flotation	Removal of finely divided suspended solids and particles with densities close to that of water. Also thickens biological sludges
Filtration	Removal of fine residual suspended solids remaining after biological or chemical treatment
Micro-screening	Same as filtration. Also removal of algae from stabilization-pond effluent
Gas transfer	Addition and removal of gases
Volatilization and gas stripping	Emission of volatile and semi-volatile organic compounds from wastewater

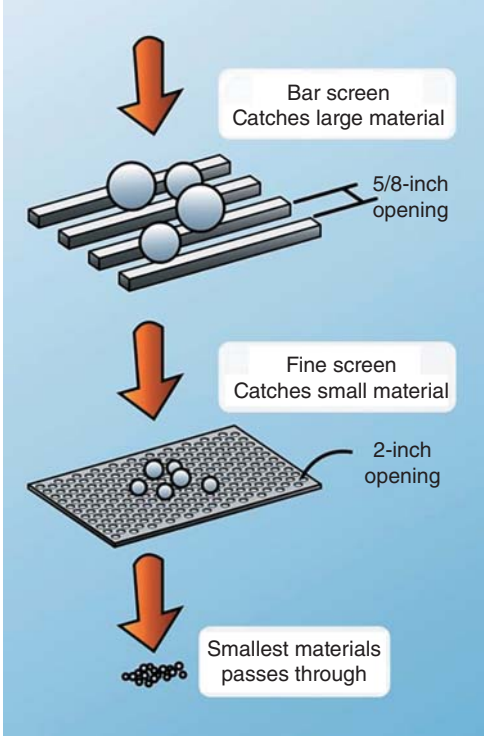


Figure 2.1 *Screening process illustration in water and wastewater treatment.*

Table 2.2 *Screening devices.*

Type of screening device	Size classification	Size range (mm)	Application
Bar rack	Coarse	15–35	Pre-treatment
Screens			
Inclined (fixed)	Medium	0.25–2.5	Primary treatment
Inclined (rotary)	Coarse	0.76 × 2.29 × 50	Pre-treatment
Drum (rotary)	Coarse	2.5–5	Pre-treatment
	Medium	0.25–2.5	Primary treatment
	Fine	6–35 μm	Removal of residual secondary suspended solids
Rotary disk	Medium	0.25–10	Primary treatment
	Fine	0.025–0.5	Primary treatment
Centrifugal	Fine	0.05–0.5	Primary treatment, secondary treatment with settling tank, and the removal of residual secondary suspended solids



Figure 2.2 *A typical bar screen consisting of a series of parallel bars or a perforated screen placed in a channel. Source: Courtesy of the City of Phoenix (Arizona) Water Services Department.*

flow into the plant. The water velocity through the screen is very important and should be around 1.5 ft/s (0.45 m/s). If the velocity decreases below 1 ft/s (0.3 m/s) or slower, grit will drop out of the flow and into the screening channel.

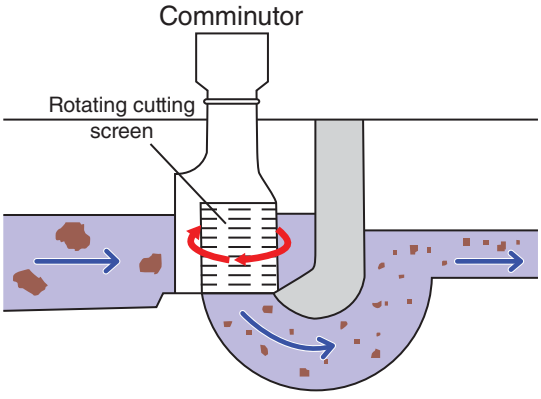


Figure 2.3 A schematic of a comminutor.

2.3 Comminution

As an alternative to racks or coarse screens, comminutors can be used to grind up coarse solids without removing them from the flow.

In this device all of the wastewater flow passes through the grinder assembly. The grinder consists of a screen or slotted basket, a rotating or oscillating cutter, and a stationary cutter. Solids pass through the screen and are chopped or shredded between the two cutters. The comminutor will not remove solids that are too large to fit through the slots, and it will not remove floating objects. These materials must be removed manually. Figure 2.3 shows a schematic of a comminutor.

Comminutors should be constructed with a bypass arrangement so that a manual bar screen is used in case flow rates exceed the capacity of the comminutor or in case there is a power or mechanical failure. Stop gates and provisions for draining should also be included to facilitate maintenance.

Manufacturer's data and rating tables for these units should be consulted for recommended channel dimensions, capacity ranges, upstream and downstream submergence, and power requirements. Because the manufacturer's capacity ratings are usually based on clean water, the ratings should be decreased by approximately 20–25% to account for partial clogging of the screen.

2.4 Grit Removal

Grit removal may be accomplished in grit chambers or by the centrifugal separation of sludge. The removal of grit is essential ahead of centrifuges, heat exchangers, and high pressure diaphragm pumps.

The purpose of grit removal is to remove heavy inorganic solids that could cause excessive mechanical wear. Grit includes sand, gravel, clay, egg shells, coffee grounds, metal filings, seeds, and other similar materials. There are several devices or processes used for grit removal. All these processes are based on the fact that grit is heavier than the organic solids that should be kept in suspension for subsequent treatment. Grit removal processes

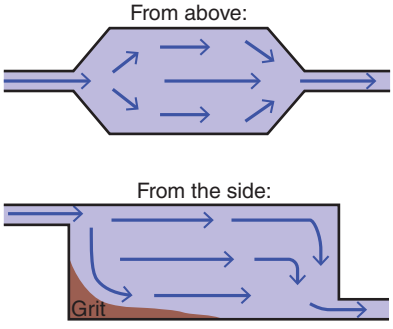


Figure 2.4 *A schematic of a grit chamber in both above and side views.*

use gravity/velocity, aeration or centrifugal force to separate the solids from the wastewater. Figure 2.4 shows a schematic of a grit chamber for grit removal.

2.5 Gravity Separation

2.5.1 General

The American Petroleum Institute (API) separator is normally the first, and arguably the most important, wastewater treatment step in most petroleum refineries. For years, refineries have attempted to use other technologies or treatment scenarios as an alternative to the API separator, but most refineries ultimately select, or return to, the API separator as the technology of choice for their wastewater treatment primary oil–solids separation step.

Gravity differential type separators are used to remove most of the oil from the plant wastewater before discharging the water to the further treating units. The oil–water separator is basically a holdup basin which reduces wastewater velocity and provides holdup time to allow the oil to rise to the surface, where it is removed by skimming.

The primary function of a properly designed API separator is to remove gross quantities of oil and suspended solids from refinery wastewater prior to subsequent downstream wastewater treatment processes, normally a second oil–water separator polishing step and some form of advanced treatment for removal of dissolved organic compounds (typically biological treatment, though other treatment technologies have been used).

In some special cases, oil traps, oil holding basins, and/or water retention basins may be provided in order to lower final the oil–water separator load.

The effectiveness of the treatment facility depends on the design flow rate, water temperature, density and size of the oil globules, and amount of suspended matter. It also relies on good operating techniques and proper supervision and maintenance.

Gravity-type separators will not separate or retain substances in solution and will not remove soluble biochemical oxygen demand (BOD). They will also not break stable emulsions and therefore should not be used for such applications. Oil–water separators will remove only free oil; emulsified and dissolved oils require additional treatment.

Oil–water separators are as follows:

a) conventional, rectangular channel units
b) the parallel-plate separators

c) oil traps
d) oil holding basins
e) other types

In this book, the term "conventional oil–water separator" is used in place of the term "API separator" and refers to rectangular channel units designed in accordance with the criteria published by API. Utilizing of any type of oil–water separators in oil and gas industries should be congruent with local environmental regulations and on approval of the relevant company. For the design of oil–water separators, the latest edition of API-421 should be used in addition to the instructions stipulated in this book.

2.5.2 Application

Oil–water separators are designed to remove free oil only. If emulsified or dissolved oil is present, an oil–water separator will not be able to remove it and additional downstream treatment will be required. A principal function of the oil–water separator is to remove gross quantities of free oil before future treatment.

In this capacity, the oil–water separator protects more sensitive downstream treatment processes from excessive amounts of oil.

Parallel-plate separators require less space than conventional oil–water separators and are theoretically capable of achieving lower concentrations of effluent oil.

In some applications the oil–water separator is provided as a protective device for containment of spills and leaks (e.g. on once-through cooling water).

It should be stressed that whenever an oil–water separator is considered for an application where it must stand alone, the amount of emulsified and dissolved oils in the wastewater stream must be properly quantified because these oils will not be removed by the separators. Figure 2.5 shows a highland rectangular API oil–water separator.



Figure 2.5 *A highland rectangular API oil–water separator. Source: Reproduced with permission from © Can-Am Instruments Ltd.*

2.5.3 Oil–Water Separators: General Design Considerations

The following requirements should be taken into consideration in the design stage.

a) Location:
   - safety distance
   - access from the road
   - prevailing wind (when applicable)
   - possible future extensions.

b) Function:
   - two-way access/escape for operator
   - hand railing and grating
   - easy access to skimmers, pumps, and filters
   - proper ventilation for depressed locations
   - lamp posts
   - surface drainage
   - kerbs around pump foundations
   - water supply for flushing and/or pump seal cooling
   - maintenance access for vacuum truck/mobile crane
   - signboard with unit number and instructions
   - high-level alarm in oil-collecting sumps in the control room
   - heating coils in cold climate conditions.

c) Safety distances:
   - distance to the edge of public roads: 30 m
   - distance to the edge of main roads: 15 m
   - distance to a fixed source of ignition: 15 m.

d) Air pollution control:
   An effective means of control should be instituted to minimize losses of hydrocarbon and other contaminants such as sulfur compounds to the atmosphere from the large exposed surface area of the separators if required by the environmental regulations.

   Control of hydrocarbon or contaminants emissions from oil–water separators may be achieved by covering fore bays or primary separator sections by either fixed roofs or floating roofs. The roof should be vapor tight as much as possible.

e) Screening:
   Screens should be installed at the oily sewer outlet (oil–water separator influent) in order to stop and manually remove rags, stones, and other debris which would interfere with the operation. The screens should be equipped with a hot-dip galvanized steel frame, lateral rails, movable box for solid removal, and stainless-steel removable screen. A hoist for screen removal for cleaning should be provided.

2.5.4 Conventional, Rectangular Channel (API) Separators

2.5.4.1 Basic Design Considerations

Conventional oil–water separators (Figures 2.5 and 2.6) are simple rectangular channel tanks which provide nominal retention time to remove larger oil molecules. This type of

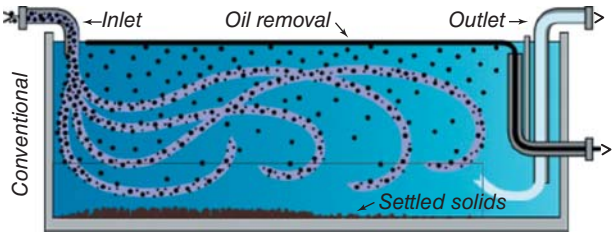


Figure 2.6 *A conventional API oil–water separator. Source: Reproduced with permission from © Brentwood Industries.*

equipment has only been found to remove free oil droplets with a diameter greater than or equal to 150 µm. These separators typically do not achieve effluent oil concentrations of less than 100 ppm because of the abundance of smaller oil droplets, which are harder to remove. Ideal separators are those that have no turbulence, short circuiting, or eddies.

If the particles are falling in the viscous fluid by their own weight due to gravity, then a terminal velocity, also known as the settling velocity, is reached when this frictional force combined with the buoyant force exactly balances the gravitational force. The resulting settling velocity (or terminal velocity) is given by:

$$v_s = \frac{2(\rho_P - \rho_f)gR^2}{9\mu} \tag{2.1}$$

where:

- v_s is the particles' settling velocity (m/s) (vertically downwards if $\rho_p > \rho_f$, upwards if $\rho_p < \rho_f$)
- g is the gravitational acceleration (m/s^2)
- ρ_p is the mass density of the particles (kg/m^3)
- ρ_f is the mass density of the fluid (kg/m^3)
- R is the radius of the spherical object (in m)
- μ is the dynamic viscosity (N s/m^2).

Stokes' law makes the following assumptions for the behavior of a particle in a fluid:

- laminar flow
- spherical particles
- homogeneous (uniform in composition) material
- smooth surfaces
- particles do not interfere with each other.

Free oil can be removed by gravity separation given proper quiescent flow conditions. Gravity oil–water separators exploit the differences in specific gravity between the fluids by providing adequate retention time for the less dense oil globules to rise to the surface of the water. The theory of this type of separation is based on the rise rate of oil droplets in the water and the surface-loading rate of the separator. The surface-loading rate is the ratio of the flow rate to the separator and the surface area of the separator. If the oil globule rises toward the surface of the separator faster than the surface loading rate, the oil will reach the surface and can be skimmed off mechanically.

The required rise rate can be found using Stokes' law.

The design of oil–water separators should carefully consider these characteristics of the wastewater and the oil itself. Additionally, the separator design should take into account the amount of settleable solids in the wastewater and other contaminants, such as surfactants, which might hinder the treatment of the system. Usually many of these characteristics must be assumed based on the type of facility generating the wastewater.

Minimum requirements for the design of API separators should be as per the procedure outlined in API publication 421 (latest edition) and the following design notes:

- A minimum of two parallel channels should be included, so that operation can be continued when one channel is removed from service for repair or cleaning. The separator should be designed for design flow with all the channels in service.
- Provision should be made for separator expansion to meet possible future requirements in the design of separators for new installations.
- The unit should be particularly amenable to expansion, such that additional channels can be added without interruption of service or major construction changes to the existing facility.
- The design of the separators should be performed based on the worst ambient conditions (e.g. minimum ambient temperature, effects of wind velocity, etc.).
- The main separators should be designed to guarantee outlet oil that is susceptible to separation (STS) in the range of 50–70 mg/l in the worst ambient conditions. Maximum outlet oil content should be reduced to 50 mg/l for areas with minimum ambient temperature of about 0 °C or higher. Effluent free oil concentration should be 50 mg/l maximum for crude desalter oil–water separators for all areas.
- The total oil and grease content (only free oil) of the streams concerned should be determined by the United States Environmental Protection Agency's (EPA) methods 413.1 Gravimetric Separation and 413.2 Infrared Spectrophotometry. ASTM method D-3921 Test Method for Oil and Grease for Petroleum Hydrocarbons in Water can also be used in the absence of the EPA's methods. EPA method 413.1 is applicable for an oil concentration range of 50–1000 mg/l and non-volatile hydrocarbons, and method EPA 413.2 is applicable for an oil concentration range of 0.2–1000 mg/l and volatile hydrocarbons.
- The requirement for separator covers and type of coverage (fixed or floating) will be advised in accordance with the environmental pollution regulations. However, special attention should be made for provision of the covers for oil–water separators which receive more than 800 l per day of volatile organic compounds.
- Separators should be installed such that oily water from the industry oily water sewer can flow by gravity to the separators. Influents to the separators should be below grade.
- In order to minimize the emulsification of oil and the remixing of the separated oil in the wastewater flow, pumping of separator influent should be avoided.
- A hold-up basin should be provided upstream of the main separator(s) for dumping of sudden fluctuations in the receiving oily water. The basin should be designed for a minimum capacity of 3 h hold-up of influent oily water to the separator(s) at maximum flow rate conditions.
- The basin should be designed with a suitable coverage for environmental pollution control purposes.

- Each separator should consist of either a pre-separation or an entry flume and two parallel channels. The pre-separation flume will be common to both channels.
- Provision of coalescers in the separators is not acceptable.
- The effective length of the channels should not be less than 40 m for oil and gas processing industry main separator(s). However, the design should be based on separating oil droplets of sizes down to 100 μm in diameter for all oil–water separators.
- The following characteristics of wastewater should be evaluated for the design of oil–water separators as minimum requirement:
  - free oil
  - solids content
  - relative densities (specific gravities) of oil and water phases
  - absolute viscosity of wastewater.

  The relative densities (specific gravities) and viscosity should be evaluated at minimum design temperature.
- The separators should be provided with floors (other than earth). Floors should allow the use of sludge scrapers, provide leakage of groundwater, and avoid contaminating the groundwater.
- In materials selection, consideration should be given to corrosion, leakage, structural strength, buoyancy (height with local water table vs. mass of separator), etc. All parts in contact with fluid should be made of dip galvanized steel and/or red wood.
- Antispark material should be used for metal-to-metal contacts in moving parts.

Figure 2.6 shows a schematic of a conventional API oil–water separator.

2.5.4.2 API Separator Components

Figure 2.7 shows an oil–water separator. API and oil–water separators should consist of, but not be limited to, the following components.

2.5.4.2.1 Inlet Section. This section generally includes a pre-separator flume, trash rack, oil skimmers, retention baffle, and forebay.



Figure 2.7 *An oil–water separator. Source: Reproduced with permission from © Skim oil™, Inc.*

2.5.4.2.2 Pre-Separator Flume. The pre-separator flume is the transition between the end of the inlet sewer and the separator forebay and will be common to both channels. It serves two functions: reduction of flow velocity and collection of floating oil.

The transition and separator sections of the pre-separator flume have to be covered to reduce evaporation loss. For this the vapor space should be enclosed by a barrier or wall at the downstream end of the cover.

The transition between the sewer outlet and the pre-separator section should be designed to accomplish velocity reduction with a minimum of turbulence. The pre-separator section should be designed to reduce the horizontal flow velocity to about 3–6 m per minute (m/min).

The pre-separator section contains two kinds of equipment as minimum: a trash or bar screen and a floating oil skimmer.

2.5.4.2.2.1 Trash Rack. Trash racks or bar screens, which are provided to remove sticks, rags stones and other debris, should consist of a series bars or rods and be located at the entrance to each separator flume. Bars should be 1 mm by 5 mm with clear openings of 1.9–2.5 mm. The bars should be spaced on 25–50 mm centers, at an angle of 45–60° from the horizontal, depending upon the depth of the flume and space availability. A pan or trough should be provided at the top of the trash rack to receive the refuse when the trash rack is cleaned. The refuse pan should be perforated to allow liquid drainage back into the flume.

2.5.4.2.2.2 Oil Skimmer. An oil skimmer should be installed downstream of the trash rack for removal of oil from the inlet section. Both a rotatable slotted-pipe skimmer and a floating type oil skimmer (Section 2.5.4.2.2.2.1) should be employed in the inlet section.

2.5.4.2.2.2.1 Floating Oil Skimmers. Floating oil skimmers are applicable for installation in the pre-separator section, especially when the liquid level is expected to vary significantly. The specifications stipulated below are typical and should be followed for all other types of floating oil skimmers as applicable.

Floating Vortex Oil Skimmer. A floating vortex oil skimmer should be installed in the pre-separation flume and equipped with a vortex oil device. It should have the following characteristics:

- The vortex oil skimmer should remove at least 85% of oil entering each basin.
- The vortex oil skimmer should be of the floating type and each should consist of a vortex generator and drive, generator support structure, float assembly, control station, pump, and pump drive.

  The vortex generator should be equipped with a propeller set on a vertical axis driven by an electric motor to create a vortex to collect floating oil, from which it is recovered by pumping.

  Each unit should be equipped for automatic, unattended operation by addition of a simple reliable oil level indicator electrode control system which serves as an automatic switch to operate the pump when the vortex pocket contains oil. The vortex oil skimmer should be capable of continuous operation.
- The vortex generator should consist of a cylindrical skirt surrounding a vortex generating impeller. The impeller should utilize a conical inlet section and a lower zero-pitched

propeller. The bottom of the generator should consist of a flat plate separated from the skirt section and formed with an annular opening to flow through the generator.

The generator should be mounted on a float structure by three equally spaced support rods. The impeller, skirt, and base plate should be of carbon steel construction and painted with two coats of epoxy for corrosion resistance. A hollow steel pipe should be provided to join the impeller to its drive motor. The pipe should be seated at the base of the impeller in a Teflon bearing mounted on the base plate. The pipe should be perforated at its upper end and fitted with a sleeve for control of flow level into the pipe. The flow into the pipe should be directed through the base plate and piped laterally to the pump mounted on the generator skirt.

- The pump should be a direct coupled centrifugal pump. The pump casing and bearing cover should be of bronze construction. The impeller should be dynamically balanced and keyed to the pump shaft. The pump should have sufficient head to send the oil to the slops tanks.
- The float assembly should consist of three fiberglass float structures attached to the vertical legs of the support structure. The fiberglass floats should be adjustable in the vertical plane to allow for a proper skimming depth below the surface of the water. Changes in waste stream composition, which will cause liquid density variations, should be taken into consideration in the design of the float assembly.
- All electrical equipment and wiring should be fabricated and installed for Class I, Group D Division 1 Area hazardous locations in accordance with API-RP-500A (latest edition). All motors should be furnished with drip covers and lifting lugs. Motor drain plugs should be located at the lowest point so that accumulated moisture may be drained. Each motor should be furnished with a stainless-steel nameplate.

  Control panels should be explosion-proof and suitable for installation within non-ventilated, 220 V, 50 Hz motor control circuitry.

  Space heaters or other means of heating should be provided on both motors and the control panel. The space heating elements should be independently controlled by integral thermostats set at predetermined temperatures to prevent excessive condensation within the control panels during periods of cold weather when the unit is stored and not in use.
- All bolts, nuts, screws, and other necessary connecting devices should be stainless steel.
- Pump discharge should be provided with 6 m of DN 50 (2 in.) poly vinyl chloride (PVC) hose with quick disconnect couplings. A rigid single point lifting fixture should be attached to the assembly for permanent positioning and handling.
- The following requirements should be guaranteed by the vendor when the equipment is operated in accordance with the written operating instructions:
  - The vortex oil skimmers should remove not less than 85% of oil entering each basin.
  - The equipment should be free from fault in design, workmanship, and material to fulfill satisfactorily the specified operating conditions.

Rotary Drum Oil Skimmer. A rotary drum oil skimmer (Figure 2.8) can provide large-scale solutions for pit and sump oil removal for metal foundries and oil refineries, as well as industrial facilities and consumer product manufacturers.

The rotary drum oil skimmer consists of a drum or unslotted pipe mounted in a horizontal position, partially submerged below the surface of the settled oil layer. The drum is rotated



Figure 2.8 *A rotary drum oil skimmer. Source: Reproduced with permission from © Skimoil™, Inc.*

by an external motor; as the drum rotates it picks up a film of oil, which adheres to the drum surface. The oil film is removed by doctor knife and directed to a trough.

A rotary drum oil skimmer may be used in the following applications:

- for continuous and automatic operation
- for minimizing water skimmed off with the oil

Disadvantages of rotary drum oil skimmers are:

- limited oil removed, cannot handle massive spills
- problems with heavy greases and heavy objects, which slide off
- floating debris can interfere with oil pick-up
- require maintenance for rotating machinery
- do not skim floatable solids.

A rotary drum skimmer should not be used if a large amount of oil is expected. When rotary drum skimmers are selected, a variable speed drive and a Teflon wiper blade should be provided.

Horseshoe-type Floating Skimmer. A horseshoe-type floating oil skimmer consists of a floating collecting pan buoyed up by hollow chambers on three sides (see API-421). The

fourth side is open, contains an oil-skimming weir, and faces in the upstream flow direction to skim on-coming oil. This skimmed oil flows out through a pipe or a hose to a sump or other reservoir.

Horseshoe-type floating skimmer advantages and disadvantages are shown in Table 2.3.

A slotted-pipe skimmer is normally the preferred type for separator channel sections. It has the ability to remove the large amount of oil that could be encountered in the event of a massive spill. The recovered oil should be drained to a slop oil pit at one side of the unit.

2.5.4.2.3 Separator Forebay. The pre-separator flume discharges into the separator forebay, which distributes the influent to the separator channels. If an upstream grit collector is lacking, sludge is likely to be deposited in the forebay. In the absence of an upstream grit collector, means should be provided for removing or transferring the sludge to the separator for subsequent removal, particularly if a reaction-jet diffusion device is used. Water jets can be used to flush solids from the forebay into the separator zone. This practice can affect the quality of the effluent unless the separator channel is blocked off.

Alternatively, the reaction-jet diffusion device can be put at the floor level of the forebay to allow solids to be scoured out of the forebay to the separator channels for collection. A slotted-pipe skimmer should be provided in the forebay, depending on whether or not oil is trapped by the flow distribution devices.

2.5.4.2.3.1 Oil Retention Baffle. An oil retention baffle should be located immediately downstream of the slotted-pipe oil skimmer.

The spacing between the oil skimmer and the baffle should not exceed 150 mm. The oil retention baffle should be high enough to prevent oil from flowing or splashing over it. Submergence of this baffle should not exceed 450 mm. The baffle should be extended to the top of the channel.

2.5.4.3 Separation Section

2.5.4.3.1 Gateways. Each channel should be provided with one or more sluice gates at its inlet to allow the flow to the channel to be shut off when desired. A hoist should be provided for gate removal. The gate frame and slots should be made of suitable corrosion-resistant and erosion-resistant materials.

Table 2.3 *Horseshoe-type floating skimmer advantages and disadvantages.*

Advantages	Disadvantages
Simple	Requires manual operation
Economical	Removes relatively large amounts of water with the oil
Low maintenance	Usually not continuous
No utilities required	Operated with only a limited variation in liquid level
High capacity	
Can remove floatable solids in addition to oil	

2.5.4.3.2 Velocity Head Diffusion Devices. Immediately downstream of the inlet gateway should be a diffusion device to distribute the flow equally over the cross-sectional area of the channel and to reuse flow turbulence. Two types of diffusion devices are available: vertical slot baffles and reaction jets. Only the reaction-jet type should be used.

2.5.4.3.2.1 Vertical Slot Baffle. A vertical slot baffle is formed from vertical posts. This type of distributor has suffered from severe fouling and should not be used.

2.5.4.3.2.2 Reaction-Jet Inlet. The reaction-jet inlet is the preferred diffusion device. It introduces and distributes the influent appropriately.

The reaction jet consists of a tube or orifice and a dished baffle; the concave surface of the baffle faces the tube or orifice. Water flows through the tube (orifice), is reversed by the baffle, and impinges on the inlet wall of the separator, dissipating the velocity head and distributing the flow.

Orifices are generally used if the separator forebay is large and the normal direction of flow is toward the inlet wall. Tubes are used when approach velocities in directions not normal to the inlet wall exceed 9 m/min.

Reaction jets have a number of advantages:

- They are less subject to clogging than vertical slot baffles.
- They provide good distribution over a wide range of flow rates.
- They are cheaper than vertical slot baffles.
- They can be shut off easily, since they are relatively small orifices in solid barriers, thus obviating gates or dams for interrupting the flow for maintenance.
- They may result in less oil in the channel effluent than with vertical slot baffles.

Reaction-jet inlets should be designed on the following basis, in addition to the requirements outlined in API-421:

- Reaction jets should be made up of #10 gauge thick stainless-steel plate formed to a proper radius and should be completely mounted in front of inlet pipes.
- At least four reaction jets should be provided for each API channel and two for each oil/water channel.
- Reaction jet wall sleeves and inlet guide vanes to mount the reaction jets to the influent wall should be provided.
- The maximum spacing between reaction jets should be 1.5 m.

2.5.4.3.3 Oil and Sludge Moving Devices. The separator channels contain a mechanical device to move the separated oil and the sludge to the collecting area. The floating oil is moved to the downstream end of the separator and the settled sludge is moved to the upstream end. Two oil and sludge moving devices are available: the traveling bridge (span) type and the flight scraper or chain type.

2.5.4.3.3.1 Traveling Bridge or Span Type. This type of moving device consists of one or two blades extending across the width of the channel hung from a beam or truss spanning the channel.

The span rests on wheels in a carriage arrangement; the wheels rise on rails at the sides of the channel and travel the length of the basin. The wheels are chain driven and the rails are located on top of the channel walls.

The blades are adjusted to sequentially skim oil on downstream travel and scrape sludge on the upstream flight. The one-blade arrangement accomplishes this by adjusting the height of the blade to either the oil level or channel bottom using a hoist or cam mechanism. The blade pivots on the underside of the bridge as the height is changed.

The two-blade arrangement achieves the sequential movement of material by one of two possible means. During oil movement, the sludge blade can be moved out of the channel or it can be feathered parallel to the channel bottom. At the end of the downstream run, the oil-moving blade is raised out of the water and the sludge-moving blade is properly positioned to move sludge upstream on the return trip.

Surface travel is typically on the order of 0.6 m/min and bottom travel is on the order of 0.3 m/min.

This device can span and operate in one or several channels. Operation can be manual or continuous, but is preferably automatic and actuated intermittently by cycle time.

The traveling bridge type oil/sludge moving device offers the following advantages:

- The parts requiring lubrication are located above the water.
- It allows different travel speeds on the forward and reverse runs.

The disadvantages are as follows:

- It is more expensive than other types.
- It requires a movable power cable, usually either a cable reel or a festoon system using a cable looped from a supporting wire.
- It complicates covering the channels.
- The design is not common and has not been used on units equipped with covers.

A design specification for a traveling bridge type device should include the following features:

- full width skimming
- totally enclosed, explosion-proof, weather-proof drivers
- overload protection
- facilities for leveling the blades
- means to raise blades out of the water for maintenance.

2.5.4.3.3.2 Flight Scraper or Chain Type. The flight scraper type of oil and sludge moving device consists of two parallel endless chains, one at each side of the channel, with flights connected to the chains across the channel width. The assembly is moved at a flight speed on the order of 0.3–0.6 m/min by motor-driven sprockets.

Flights can be spaced uniformly along the entire length of the chains, but flights on only one half of the chain length are usually sufficient and are preferred because the smaller the number of flights, the less the turbulence. The flights should span the entire width of the channel. Typically, flights are 200 mm high and spaced on 3 m centers.

Only one oil/sludge moving device per channel should be installed. The motor and speed reducer assembly may be mounted directly on the concrete. Each oil/sludge moving device

in a parallel channel installation should have its own drive unit operating independently of the others. Operation of these devices can be either automatic or manual.

The advantages of the flight scraper type oil/sludge mover are:

- lower initial cost
- can be used on channels equipped with covers.

The disadvantages of this device are:

- requires underwater bearings
- sludge can be accumulated on chain and sprockets
- moves at the same speed on the top and the bottom of the separator
- chain sag can redistribute oil beneath the water surface.

A design specification of flight scraper type oil/sludge moving devices should include the following features:

- full width skimming
- totally enclosed, explosion-proof, weather-proof drivers
- overload protection of driving sprocket
- shaft aligning facilities
- flight leveling facilities
- chain guards for personnel protection on chains above grade or near stairs, ladders, platforms, access-ways, etc.
- chain tighteners
- flight cleaner chains should have an average ultimate strength of 18 200 kg with the plain and attachment links assembled with DN 20 (¾ in.) heat-treated high-carbon steel pins and rivets
- angle tracks for supporting surface run of sludge collectors
- flights to be spaced at 3 m intervals and to be 200 mm high
- squeegees of spark-proof construction on two flights for positive cleaning of the tank wall at the water surface and at the tank bottom
- the flight cleaner should consist of 75 mm × 203 mm (3 in. × 8 in.) nominal size heart redwood scrapers on two strands of chain
- the flights should be provided with wearing shoes to contact bottom rails
- the chains should run over four sets of sprocket wheels to clean sludge from the basin bottoms and move floating oil and material to the downstream end of the separator channel
- the flight cleaner speed should not exceed 36.6 m/h (10.15 mm/s)
- all flights should be accurately drilled and notched at the factory and be carefully grouped and banded together for safe shipment and storage
- rails flush with tank bottom should be provided for wear surfaces
- corrosion-resistant anchor bolts
- sprockets for drive and collector chains should have a hardness of not less than 360 Brinell at the tooth-bearing surfaces, and should be stress relieved before machining, should be keyed firmly to the head shaft
- all flight cleaners should be of the double-life type

- all shafting should be solid, cold-finish steel, straight and true, should extend across the full width of the basin, and should be held in alignment with screwed set collars
- the shafting should contain key ways with fitted keys where necessary and should be of sufficient size to transmit the power required
- all underwater bearings should be babbitted, water lubricated, ball and socket, and self-aligning, especially designed to prevent accumulation of settle solids in their surfaces
- underwater bearings should be bolted directly to the concrete walls in a manner which will permit their easy adjustment
- each motor should have ample power for starting and operating the cleaner mechanism without overloading
- each drive unit speed reducer should be of the worm gear type, fully enclosed, running in oil and of approved make with antifriction throughout
- the reducer unit and the electric motor should be mounted as a common unit directly on the concrete.

2.5.4.3.4 Sludge Collection and Removal. A sludge hopper should be provided independently for each channel at the downstream base of the inlet baffle. A screw conveyor for positive removal of the sludge should be provided for each channel. The hoppers should consist of inverted pyramids with sides sloped at least 45°. With an underdraw system, each hopper contains an exit pipe at the apex. The exits discharge into a sludge withdrawal pipe.

Screw conveyors should include a wet well type drive complete with helical gear reducer and a chain and sprocket drive arrangement. The screw should be at least 9.5 mm thick and should run in water-lubricated bearings and be supported by a suitable diameter pipe shaft. The sludge should be directed to the sludge pit.

The sludge pit will be common for both separator channels. Accumulated sludge should be removed by sludge pumps. The sludge pumps should be started automatically when the level in the sump reaches the high liquid level and should be switched off when the level comes down to the low liquid level. Two vertical sludge pumps (one operating and one spare) should be provided.

High- and low-level alarms in the control room should also be provided for the sludge sump.

2.5.4.3.5 Skimmed Oil Collection. The skimmed oil from the main separator channels as well as from the forebay section should be routed by gravity to a common sump. Both separator channels will have a common oil sump. The sump provides a reservoir for the pump-out pump, and in addition can be used to allow water to be separated from the oil.

The sump should be equipped with two vertical centrifugal pumps (one operating and one spare). All the oil should be pumped to the slops tank. Level controls of the float, electric probe, or air differential pressure type should actuate the pumps at the high level and switch them off at the low level. High- and low-level alarms should also be provided in the control room to guard against sump overflow and pump cavitation, respectively.

The sump and the pumps should be large enough to avoid continuous operation of the pumps, and should also be large enough to handle a large spill. The size of the sump pumps can be estimated on the following basis if data are unavailable:

- Assume incoming oil can reach 2000 ml/m^3 (2000 ppm by volume) on dry weather separator influent.
- Water withdrawn with the skimmed oil can be assumed to be about seven times the skimmed oil volume when a slotted-pipe oil skimmer is used. It can be assumed that the water volume is the same as the skimmed oil volume when a rotary drum oil skimmer is used.
- There should be about 4 h of hold-up time in the sump before pump-out.
- Sump pump-out of oil should occur in 20–30 minutes and sump pump-out of water in ½ to 1 ½ h (when the oil and water pumps are not the same).
- Sump pump-out of oil and water should occur in 1 h when the same pump serves to pump a mixture of oil and to the slops tank.

2.5.4.3.6 Oil Skimming Device. A slotted-pipe oil skimmer should be provided at the end of each separator channel. The requirements of the skimming device should be as outlined in above. The rotatable oil skimmer pipes for each channel should be connected end to end in a line that drains to a slop oil pit at one side of the unit.

2.5.4.3.7 Oil Retention Baffle. An oil retention baffle should be provided just downstream of the oil skimming device, spaced not more than 300 mm downstream of the skimming device. The baffle is installed with a maximum submergence of 55% of water depth. It should extend to the top of the channel.

2.5.4.3.8 Effluent Weir. An effluent weir wall should be located at downstream of the oil retention baffle, located not more than 600 mm downstream of the oil-retention baffle.

The weir wall extends from the channel floor to a height equal to the normal water depth minus the depth of normal flow over the crest (top edge) of the weir. The crest corresponds to the head on the weir. A sharp-crested or notched weir plate is attached to the downstream face of the weir wall along its top. Bolt holes in the plate should be elongated vertically so that the weir plate can be made absolutely level when installed and minor adjustments in elevation can be made.

Provision should be made to prevent leakage between the weir plate and the weir wall.

2.5.5 Parallel-Plate Separators

2.5.5.1 General

Parallel-plate oil–water separators offer improved performance by increasing the horizontal surface area of the separator and creating less turbulent flow. Conventional channel units can often be retrofitted with parallel plates to either improve the wastewater effluent or allow for higher flow rates of wastewater. Separators with parallel plate coalescing media can allow flow rates up to three times that of conventional units. They can also remove free oil droplets with smaller diameters than conventional oil/water separators. Effluent from parallel-plate separators is reported to have up to 60% less oil than that from conventional separators and the oil collected from these units contains less water.

In conventional rectangular oil–water separators, more separation (higher flowrate or better effluent) is accomplished only by added volume in the tank. Adding volume in an

open-channel rectangular tank is the only way to create the necessary surface area for improved treatment.

Since these tanks are traditionally manufactured from welded steel, increased volume translates to increased steel at a tremendous material cost. Adding PVC parallel plate coalescing media is an inexpensive and easy way to increase treatment without adding volume to existing steel separators. Figure 2.9 shows a parallel plate API oil–water separator.

In cases where available space for a separator is limited, the extra surface area provided by a more compact parallel plate unit makes the parallel-plate separator an attractive alternative to the conventional separator. The separator's surface area can be increased by the installation of parallel plates in the separator chamber.

The resulting parallel-plate separator will have a surface area increased by the sum of the horizontal projections of the plates added. Flow through a parallel-plate unit can be two to three times that in an equivalent conventional separator.

In addition to increasing the separator surface area, the presence of parallel plates may decrease tendencies toward short-circuiting and reduce turbulence in the separator, thus improving efficiency. The oil content in the effluent water can be up to 60% lower for parallel-plate systems, with a higher proportion of small oil droplets recovered with respect to the conventional separators. This type of separator is not suitable for removing emulsified or dissolved oils.

2.5.5.2 Design Considerations

- An oil-globule diameter of 60 μm should be assumed for the design of the separator.
- The relative density (specific gravity) and viscosity should be calculated based on the worst ambient conditions for either wastewater or oil in the design of the separator.
- Process problems such as oil and solids removal and clogging should be diagnosed and taken into account in equipment selection and separator design. The plate inclination and plate-to-plate spacing should be selected to avoid any clogging problem. Solids-removal devices should be provided preceding the separator to avoid clogging.
- Mechanical sludge-removal equipment should be provided to avoid raising the plate pack from the separator for sludge removal. The system should also include oil draw-off equipment.
- The plates should be corrugated. However, necessary coordination should be made with well-known vendors for optimizing of the plate spacing and configuration.
- In the oil and gas industries for mainly oily water effluent, a minimum of two parallel separators with one inlet in combination with a flow diverter (sluice gate) and

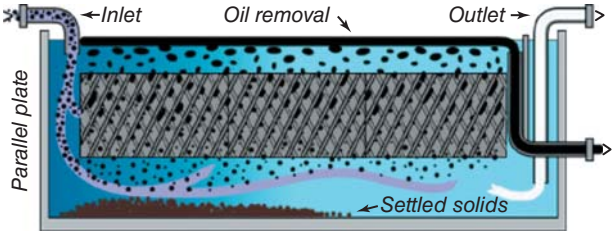


Figure 2.9 *A parallel plate API oil–water separator. Source: Reproduced with permission from © Brentwood Industries.*

independent outlets should be provided, so that operation can be continued when one separator is removed from service for repair or cleaning. The separators should be designed to handle the design flow rate when all separators are in service.
- The separator should be designed to guarantee outlet oil that is susceptible to separation (STS) to be 40 mg/l in worst case ambient conditions.
- The separators should be installed such that oily water from the industry oily water sewer can flow by gravity to the separators. Pumping of separator influents should be avoided.
- A pre-separator/pre-sedimentation basin is often required. Pre-separators are normally constructed in two bays and consist of an overflow weir, a retention baffle, a sedimentation zone, and an overflow into the inlet channels of the parallel-plate separator.
- Floating oil skimmers should be installed in front of the retention baffle, one per bay. The recommended overflow rate under maximum flow conditions is 10 mm/s. The retention time for the maximum flow rate should be about 15 minutes. It should be noted that the composition of the effluent may vary by location. Samples should be taken and tested to verify the above flow and retention time values. The bottom slab of the pre-separator should have a slope of 1 : 50 to simplify cleaning by vacuum truck.

2.5.6 Oil Traps

2.5.6.1 General

An oil trap is a facility designed to retain floating oil only and should not be used for segregation of dispersed oil. The necessity of installing an oil trap should be assessed based on regulations. The oil trap can be used as:

a) an inlet to a storm water pond to keep the surface clean
b) an outlet of, for example, a lagoon where separated oil is prevented from entering public water.

2.5.6.2 Design

Oil trap construction consists of:

- an approach channel with a minimum length of 60 m in which the velocity should be limited to 0.25 m/s under normal conditions and 0.45 m/s during maximum rainfall
- a transition part
- a final weir section in which the velocity should be limited to 0.20 m/s under normal conditions and 0.35 m/s during maximum rainfall. The velocity underneath the baffle should not exceed 0.08 and 0.15 m/s, respectively.

For calculation purposes using the above velocities, a sediment layer with a depth of 0.30 m on the bottom of the complete oil trap should be taken into consideration.

2.5.6.3 Construction

The weir section should be constructed in a V-shape, each leg forming one compartment. However, depending on the throughput, construction of one leg only may be considered. In the transition part the cross-section of the approach channel should change gradually into

the cross-section(s) of the weir section. The underside of the baffle wall should be at least 0.60 m below the water level in the oil trap.

The oil trap approach channel and transition part should preferably be built in two bays in order to facilitate its cleaning and repair when required.

2.5.7 Oil Holding Basins

A holding basin should be designed to hold the amount of oil spilled by a large accidental spillage. This amount of oil should be assumed to be at least 100 cubic meters for one spillage. The holding basin should be constructed at the end of the accidental drainage system.

2.5.7.1 Design

The maximum velocity of effluent through the holding compartment should not exceed 0.05 m/s under normal conditions and 0.075 m/s during maximum rainfall. The velocity underneath the baffle should in no circumstances exceed 0.15 m/s. When calculating the velocities, a sediment layer of 0.30 m on the bottom of the entire holding basin should be taken into consideration.

The overflow rate (i.e. the discharge quantity of the oil holding basin divided by its horizontal surface) should be 0.005 m/s unless otherwise specified. It is recommended that a theoretical design water depth of 1.20 m is assumed. The underside of the baffle should be at least 0.60 m below the water level in the holding basin.

2.5.7.2 Construction

The holding compartment should be preceded by an oil-retention baffle, oil skimmer, and oil sump in the transition part in order to keep the surface of the holding basin free from oil under normal conditions. The underside of the oil-retention baffle should be 0.20 m below the water level. The holding compartment should preferably be built in two or more bays in order to facilitate its cleaning and repair when required.

2.6 Flow Equalization

The equalization basin (Figure 2.10) is used to steady the flow throughout the day. The flow coming into a wastewater plant is very inconsistent. As the flow comes into the plant during the day at a high rate, the equalization basin will fill up. When the flow drops off at night, the equalization basin will start to drain.

The equalization basin is used to overcome operational problems caused by flow rate variations, to improve the performance of the downstream processes, and to reduce the size and cost of downstream treatment facilities.

2.6.1 Application and Location

Flow equalization is used for damping flow rate variations so that a constant or nearly constant flow rate is achieved. The design of equalization basins must take into account both dry and wet weather flows, as well as variations caused by operational problems.



Figure 2.10 *An equalization basin. Source: Reproduced with permission from © Hickory wastewater treatment.*

Sufficient mixing and aeration must be provided in the equalization basin(s) to equalize various wastewater streams and prevent solids deposition, septicity, and odor problems.

In order to achieve an equalized flow and a considerable amount of constituent concentration and flow rate damping, the equalization basin(s) should be provided in an in-line arrangement so that all of the flow passes through the basin(s).

Depending on the type of treatment and the characteristics of the collection system and the wastewater, detailed studies should be performed to optimally locate the equalization basin(s). In refineries and petrochemical plants the appropriate location is downstream of the oil–water separators and upstream of the floatation units. However, locating the basin(s) in any places or in the off-line arrangement should take into account all economical and operational points of view and should meet the company's approval.

Application of flow equalization will result principally the following benefits:

- biological treatment is enhanced because shock loadings are eliminated or can be minimized, inhibiting substances can be diluted, and pH can be stabilized
- the effluent quality and thickening performance of secondary sedimentation tanks following biological treatment is improved through constant solids loading
- effluent filtration surface-area requirements are reduced, filter performance is improved, and more uniform filter-backwash cycles are possible
- in chemical treatment, damping of mass loadings improves chemical feed control and process reliability.

2.6.2 Volume Requirements

The following factors should be taken into account in determining the required volume for the equalization basin(s):

- sufficient depth of liquid in the basin(s) should be provided to allow continuous operation of aeration and mixing equipment
- sufficient volume must be provided to accommodate the concentrated plant recycle streams that are expected
- additional volume should be provided for unforeseen changes in diurnal flow and additional damping of the BOD mass-loading rate
- The volume should be sufficient to accommodate a minimum of 16 hours of retention time for all incoming wastewater flow rates to the plant based on the daily average flows.

2.7 Mixing

2.7.1 Description and Type

Mixing is an important unit operation in many phases of wastewater treatment, including:

- the mixing of one substance completely with another
- the mixing of liquid suspensions
- the blending of miscible liquids
- flocculation
- heat transfer.

Most mixing operations in wastewater can be classified as:

a) continuous rapid (30 s or less) mixing, which is used most often where one substance is to be mixed with another
b) continuous mixing, which is used to maintain the contents of a reactor or holding tank or basin in a completely mixed state.

Typical mixers used in wastewater treatment plants are:

- propeller mixers
- turbine mixers
- static in-line mixers
- in-line turbine mixers
- pneumatic mixers.

2.7.2 Application

Mixers should be selected on the basis of laboratory or pilot plant tests or similar data provided by manufacturers. Mixers with small impellers operating at high speeds are best for dispersing gases or small amounts of chemicals in wastewater. Mixers with slow-moving impellers are best for blending two fluid streams for flocculation.

Paddle mixers should be used as flocculation devices when coagulants, such as aluminum or ferric sulfate, and coagulant aids, such as polyelectrolytes and lime, are added to wastewater or sludges. Mechanically, flocculation is promoted by gentle stirring with slow-moving paddles.

A paddle-tip speed of approximately 0.6–0.9 m/s achieves sufficient turbulence without breaking up the floc. In-line static mixers are commonly used for mixing chemicals, whereas

over and under baffled channels are used for flocculation. In dissolved air-floatation units, flocculation is achieved by introducing air bubbles into the bottom of the tank (pneumatic mixing).

2.8 Sedimentation

Sedimentation, or clarification, is the process of letting suspended material settle by gravity. Suspended material may be particles, such as clay or silts, originally present in the source water.

More commonly, suspended material or floc is created from material in the water and the chemical used in coagulation or in other treatment processes, such as lime softening.

Sedimentation is accomplished by decreasing the velocity of the water being treated to a point below which the particles will no longer remain in suspension. When the velocity no longer supports the transport of the particles, gravity will remove them from the flow.

2.8.1 Sedimentation Theory

As shown in Figure 2.11 for a discrete spherical particle, the settling velocity/terminal velocity is obtained when the gravitational force (F) is equal to the frictional drag force (FD), giving

$$(\rho_S - \rho_W)gV = C_D A_C \rho_W v_S^2/2 \tag{2.2}$$

The settling velocity is:

$$v_S = \sqrt{\frac{2gV(\rho_S - \rho_W)}{C_D \rho_W A_C}} \tag{2.3}$$

where:

V = volume of particle = $\frac{\pi d^3}{6}$

A_C = cross-sectional area of particle = $\frac{\pi d^2}{4}$

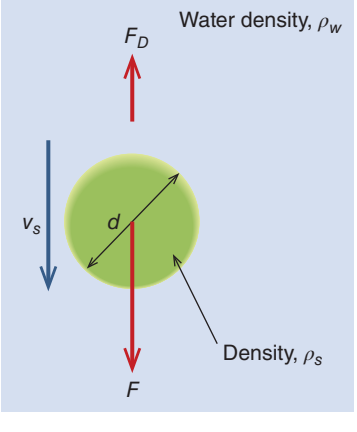


Figure 2.11 Force balance on a discrete spherical particle.

v_S = settling velocity
C_D = drag coefficient.
After revising Eq. (2.3) we have:

$$v_S = \sqrt{\frac{4g(\rho_S - \rho_W)d}{3C_D\rho_W}} \tag{2.4}$$

2.8.1.1 *Determination of the drag coefficient*

The drag coefficient (C_D) can be estimated using the chart in Figure 2.12.
Typical Reynolds number for particles in water treatment:

$$C_D = 24/\mathrm{Re} \text{ for } \mathrm{Re} < 1 \tag{2.5}$$

$$C_D = 24/\mathrm{Re} + 3/\mathrm{Re} + 0.34 \text{ for } 1 < \mathrm{Re} < 10\,000 \tag{2.6}$$

$$C_D = 0.4 \text{ for } 10\,000 < \mathrm{Re} < 100\,000 \tag{2.7}$$

Stokes' law makes the following assumptions for the behavior of a particle in a fluid:

- laminar flow
- spherical particles
- homogeneous (uniform in composition) material
- smooth surfaces
- particles do not interfere with each other.

$$v_S = \frac{g(\rho_S - \rho_W)d^2}{18\mu} \tag{2.8}$$

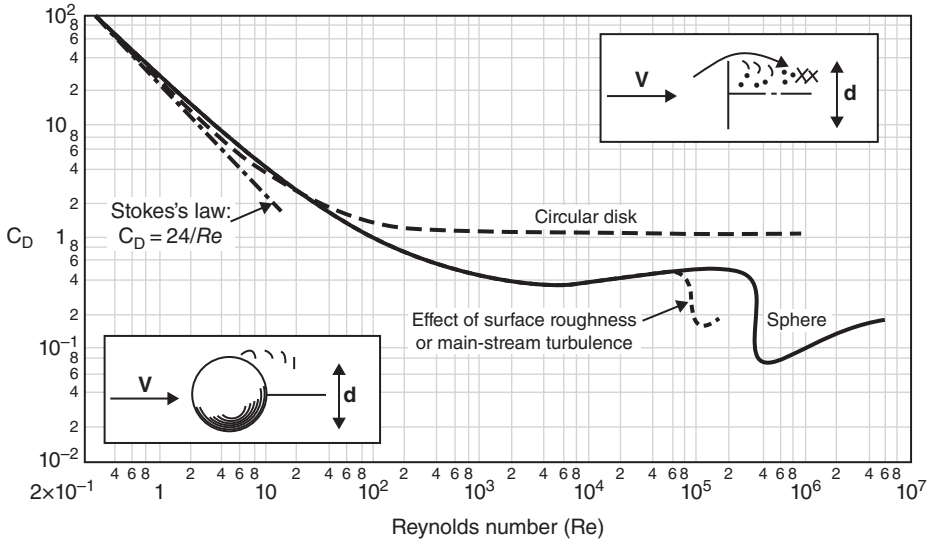


Figure 2.12 *Chart to estimate the drag coefficient.*

where:

- v_s is the particles' settling velocity (m/s) (vertically downwards if $\rho_p > \rho_f$, upwards if $\rho_p < \rho_f$)
- g is the gravitational acceleration (m/s^2)
- ρ_S is the mass density of the solid particles (kg/m^3)
- ρ_w is the mass density of the fluid (kg/m^3).
- d is the diameter of the spherical object (in m)
- μ is the dynamic viscosity (N s/m^2).

2.8.1.2 Ideal Sedimentation Basin

Figure 2.13 shows an ideal sedimentation basin. In an ideal sedimentation basin an overflow rate identifies the smallest settling velocity attributable to the class of particles which experience complete removal:

$$v_O = h_O/t_O = h_O Q/V = Q/A \tag{2.9}$$

For $v_S < v_O$, the removal percentage will be $100(v_S/v_O)$ because:

$$h/h_O = v_S/v_O \tag{2.10}$$

2.8.2 Application and Type

Sedimentation is the separation from water, by gravitational settling, of suspended particles that are heavier than water. Sedimentation may be used for grit removal, particulate matter removal in the primary settling basin, biological floc removal in the activated-sludge settling basin, and chemical floc removal when the chemical coagulation process is used.

It is also used for solids concentration in sludge thickeners. However, in most cases, the primary purpose is to produce a clarified effluent. In designing sedimentation basins, consideration must be given to production of both a clarified effluent and a concentrated sludge.

On the basis of the concentration and the tendency of particles to interact, four types of settling can occur: discrete particle, flocculent, hindered (also called zone), and compression (see Table 2.4 for a description of these settling phenomena).

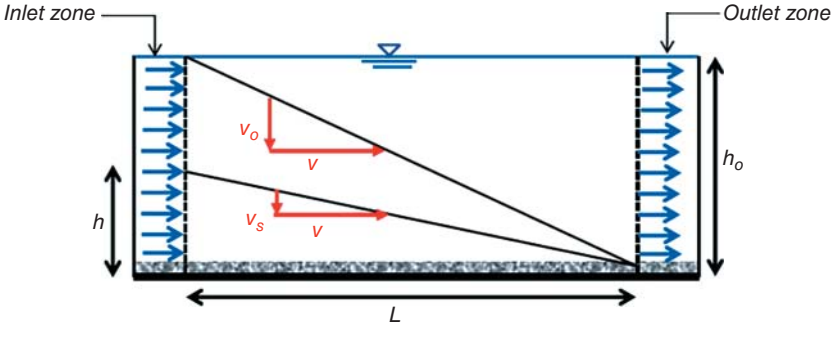


Figure 2.13 Ideal sedimentation basin.

Table 2.4 *Types of settling phenomena involved in wastewater treatment.*

Types of settling phenomenon	Description	Application/occurrence
Discrete particle (type 1)	Refers to the sedimentation of particles in a suspension of low solids concentration Particles settle as individual entities, and there is not significant interaction with neighboring particles	Removes grit and sand particles from wastewater
Flocculant (type 2)	Refers to a rather dilute suspension of particles that coalesce, or flocculate, during the sedimentation operation. By coalescing, the particles increase in mass and settle at a faster rate	Removes a portion of the suspended solids in untreated wastewater in primary settling facilities and in upper portions of secondary settling facilities. Also removes chemical floc in settling tanks
Hindered, also called zone (type 3)	Refers to suspensions of intermediate concentration, in which interparticle forces are sufficient to hinder the settling of neighboring particles. The particles tend to remain in fixed positions with respect to each other, and the mass of particles settles as a unit. A solids–liquid interface develops at the top of the settling mass	Occurs in secondary settling facilities used in conjunction with biological treatment facilities
Compression (type 4)	Refers to settling in which the particles are of such concentration that a structure is formed, and further settling can occur only by compression of the structure Compression takes place from the mass of the particles, which are constantly being added to the structure by sedimentation from the supernatant liquid	Usually occurs in the lower layer of a deep sludge mass, such as in the bottom of deep secondary settling facilities and in sludge-thickening facilities

2.8.3 Design Considerations

a) Pre-sedimentation basins may be constructed in excavated ground or out of steel or concrete. However, the basins should be equipped with a continuous mechanical sludge-removal apparatus. The minimum detention time for pre-sedimentation should be 4 h. Chemical feed equipment should be provided ahead of pre-sedimentation to provide pre-chlorination or partial coagulation.
b) Settling basins are usually provided for chemical coagulation or softening in a wide variety of shapes and flow mechanisms. The selection of the particular form or shape for a given plant depends upon area available and conformity with adjacent structures. The

basins should preferably be circular in shape and of reinforced concrete construction. However, rectangular or square basins can also be used depending on space availability and the company's approval.

c) The basins should be provided with sloping bottoms to facilitate the removal of deposited sludge. The bottom slopes should be 1% in rectangular tanks and 8% in circular or square tanks. The water depth is recommended to be in the range of 3.5–5.3 m. The length to width ratio for rectangular basins should be in the range of 3 : 1–5 : 1.

d) To minimize the effects of short-circuiting and turbulent flow, care should be taken in the effective hydraulic design of inlet and outlet structures in all tanks. Inlet structures should be designed to:
   1) uniformly distribute flow over the cross-section of the settling zone
   2) initiate parallel or radial flow
   3) minimize large-scale turbulence
   4) preclude excessive velocities near the sludge zone.

e) Flow through a sedimentation basin normally enters at the top of the basin, but in the circular basins the flow may enter a central flocculating chamber of the basin. Effluent flows vertically out over perimeter weirs. An efficiently designed vertical tank is more stable than a horizontal one.

   The rating of a vertical tank as related to the bulk settling velocity is usually 1–3 m/h. The volumetric capacity can be increased with the introduction of inclined tubes into the basins.

f) Sedimentation processes should be proceeded by coagulation and followed by filtration.

g) Each clarifier should consist of a scraped clarifier mechanism with a bridge with drive moving along the length/circumference (depending on the type of the basin) to scrape the accumulated scums on the surface of water. Rotating blades just above the clarifier floor should be provided to collect the separated sludges from the mixed liquor. Each blade should have hard rubber squeegees that scrape the basin bottom on each revolution to push the sludge toward the discharge hopper.

2.8.4 Number of Basins

The following considerations should be taken into account in the selection of the number of sedimentation basins:

1) the effect upon the production of treated wastewater if one basin is removed from service for cleaning, repairs, or any other reason
2) the largest size which can be expected to produce satisfactory result.

For any supply which requires coagulation and filtration for the production of safe water, a minimum of two basins should be provided.

2.8.5 Inlet Arrangements

The inlets should be arranged such that the coagulated water is distributed uniformly among the basins and uniformly over the cross-section of each sedimentation basin and avoids

short-circuiting through the basin. The permissible velocity range for any water and floc can be determined by tests, but the recommended velocities are between 0.20 and 0.55 m/s.

Where inlet pipelines or flumes are required, the head loss at each opening should be large compared to the maximum difference of energy head available at the inlets. However, velocities must be kept sufficiently low to prevent breaking up of floc.

2.8.6 Short-Circuiting

In arranging baffles in sedimentation basins for reduction of short-circuiting and improving settling efficiency special attention should be given to avoiding the formation of dead spaces, producing eddy currents, and causing disturbance of the deposited solids.

2.8.7 Outlet Arrangements

Water leaving the sedimentation basin should be collected uniformly across the width/circumference of the basin to prevent high velocities of approach and consequent lifting of the settled sludge over the weir. Weirs may be constructed across the basin, or slots or provided effluent ports.

Combinations of effluent orifices ahead of the submerged weir provide efficient outlet arrangements and reduce short-circuiting. Special attention should be given to provision of sufficient weir length in the construction of the basins to avoid excessive overflow rates and consequent high velocity of approach to the weir.

2.8.8 Detention Time

The time theoretically required for a unit volume of water to flow through a mixing or sedimentation basin is called the detention time. It is equal to the time required to fill the basin at a given rate of flow and can be computed by dividing the volume of the basin by the rate of flow through it.

Detention time must be distinguished from retention time, which is the minimum time required for a particle of water to pass through the basin. Depending on the purpose of the basin, a detention time of 2–4 h should be applied. The detention time should be higher where a high degree of suspended solids removal is desired.

2.8.9 Surface Loading Rate

The surface overflow rate for any given sedimentation tank can be determined by jar test studies wherein the best coagulant, optimum dosage, and the best flocculation are used. The maximum surface loading rate for suspended solids removal should be 25 $m^3/day/m^2$ when proper coagulant and flocculation are used.

2.8.10 Factors Affecting Sedimentation

Several factors affect the separation of settleable solids from water. Some of the more common types of factors to consider are described below.

2.8.10.1 Particle Size

The size and type of particles to be removed have a significant effect on the operation of the sedimentation tank. Because of their density, sand or silt can be removed very easily. The velocity of the water-flow channel can be slowed to less than 1 ft./s, and most of the gravel and grit will be removed by simple gravitational forces.

In contrast, colloidal material, small particles that stay in suspension and make the water seem cloudy, will not settle until the material is coagulated and flocculated by the addition of a chemical, such as an iron salt or aluminium sulfate.

The shape of the particle also affects its settling characteristics. A round particle, for example, will settle much more readily than a particle that has ragged or irregular edges.

All particles tend to have a slight electrical charge. Particles with the same charge tend to repel each other. This repelling action keeps the particles from congregating into flocs and settling.

2.8.10.2 Water Temperature

Another factor to consider in the operation of a sedimentation basin is the temperature of the water being treated. When the temperature decreases, the rate of settling becomes slower. The result is that as the water cools, the detention time in the sedimentation tanks has to increase.

As the temperature decreases, the operator must make changes to the coagulant dosage to compensate for the decreased settling rate. In most cases temperature does not have a significant effect on treatment.

A water treatment plant has the highest flow demand in the summer when temperatures are highest and settling rates are best. When the water is colder, the flow in the plant is at its lowest and, in most cases, the detention time in the plant is increased so the floc has time to settle out in the sedimentation basins.

2.8.10.3 Sedimentation Basin Zones

Most sedimentation tanks are divided into the following zones (Figure 2.14):

- Inlet zone
  The inlet or influent zone should provide a smooth transition from the flocculation zone and should distribute the flow uniformly across the inlet to the tank. The normal design includes baffles that gently spread the flow across the total inlet of the tank and prevent short-circuiting in the tank. (Short-circuiting is the term used for a situation in which part of the influent water exits the tank too quickly, sometimes by flowing across the top or along the bottom of the tank.) The baffle could include a wall across the inlet, perforated with holes across the width of the tank.
- Settling zone
  The settling zone is the largest portion of the sedimentation basin. This zone provides the calm area necessary for the suspended particles to settle.
- Sludge zone
  The sludge zone, located at the bottom of the tank, provides a storage area for the sludge before it is removed for additional treatment or disposal.

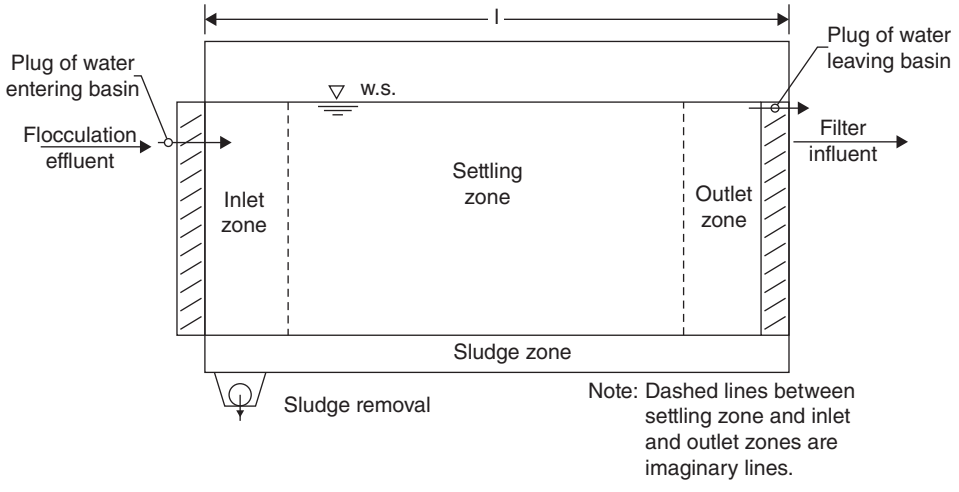


Figure 2.14 Sedimentation basin zones.

2.9 Dissolved Air Flotation

2.9.1 General

DAF is a liquid/solid separation process in which microscopic air bubbles (10–100 µm) become attached to solid particles suspended in liquid, causing the solid particles to float. In a DAF system air is dissolved into liquid under pressure. The dissolved air remains in solution until the pressure is released to atmospheric pressure, causing the air to come out of solution in the form of microscopic air bubbles.

The bubbles are mixed intimately with the wastewater and become attached to the solids in the waste stream, causing the air solids agglomerate to float to the liquid surface where a solids (float) blanket is formed. Surface skimmers then remove the float blanket.

DAF is a flotation process in which air is dissolved in the water at 350–750 kPa (ga) and subsequently released to atmospheric pressure in the floatation tank, where air bubbles precipitate upon particles of suspended matter and float them to the surface. In general, a DAF unit is used to reduce the level of free oil and other suspended matter from wastewater to below that attainable in an API separator.

Figure 2.15 shows a conventional DAF unit. It is designed to produce an effluent containing less than 15 mg/l (max.) of free oil with chemical aids. Reduction of oil content below the solubility level of hydrocarbons in water should not be expected in DAF units.

Dissolved gas flotation (DGF), in which gas (such as natural gas) is employed instead of air, can be applied to maintain a reducing action or otherwise to avoid oxidation of waste material.

The primary purpose of further oil removal by DAF units is to meet desired effluent quality and/or pre-treatment for a downstream biological unit. DAF units are normally located downstream of API separators and upstream of biological oxidation units.

A key application of dissolved air flotation (DAF) units includes the removal of free and emulsified hydrocarbons from petrochemical and similar wastewater upstream of biological

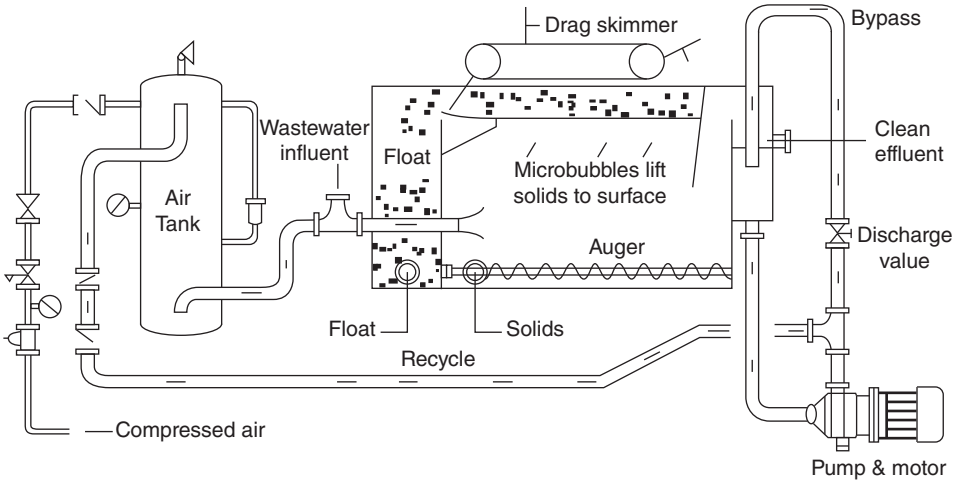


Figure 2.15 *A schematic of a conventional DAF system. Source: Reproduced with permission from © Skimoil, Inc.*

processes. This is done in an effort to prevent toxic or inhibitory materials from hindering the biological processes downstream of the DAF unit.

Other industrial applications of DAF systems include the treatment of concentrated fish farming wastewater, the pre-treatment of food and meat processing effluents, and the treatment of effluents generated by the pulp and paper industries. In certain circumstances DAF can also be a substitute for gravity settlement of solids generated by a biological treatment process.

Advantages linked with DAF systems include the fact that they are high-rate processes when compared with more traditional gravity-based settlement systems. This means that a reduction in space requirements can be achieved, and in terms of sludge thickening, a thicker sludge can be produced. Additionally, DAF systems offer the operator some degree of flexibility, subject to design, with regard to the system's operating parameters.

2.9.2 System Configuration

DAF units should be constructed in concrete tanks located partially or totally above grade. A minimum of two parallel units, each designed for 50% of the total design flowrate as fresh feed plus the pressurized recycle water flowrate, should be provided. The water recycled to each unit should be designed to be in the range of 50–75% of each DAF unit fresh feed flowrate. Multiple DAF units should be supplied when the dimension of a rectangular unit would exceed 6 m width or 30 m length, or when the diameter of a circular flotator would exceed 24 m.

Each DAF unit should consist of, but not be limited to, the following facilities:

- pressurized flow control system and pressure retention tank
- flocculation chamber
- control valves and instrumentation for effective control of all flow conditions throughout the recycle system

- telescopic valves
- scum skimmer, including drive and supports
- scum screw conveyor and scum trough
- scum retention baffles
- bottom sludge collector and drive
- perforated recycle pipe and baffle for distribution of the pressurized recycle across the flotation channel
- deflection baffle out of stainless steel
- scum pit agitator and drive
- effluent weir and scum retention baffles
- all booster and pressurizing pumps, including motors and drivers
- air compressors
- inlet sluice gates of 0.1 square meter free area
- adjustable outlet weirs.

2.9.3 Variables Affecting DAF Efficiency

2.9.3.1 Influent Characteristics

Certain characteristics of the influent affect DAF efficiency, for example globule size, pH, surface activity, and suspended solids concentration. Coagulation agents can significantly affect globule size, the chemicals used may alter surface activity, and floating all the suspended solids can be achieved by introducing enough air bubbles through the water.

The pH should be adjusted to within the proper range prior to the addition of coagulating chemicals. The pH adjustment facilities should be provided upstream of DAF units.

2.9.3.2 Design Variables

The following major design variables should be taken into account:

- overflow rate (rise rate)
- recycle rate
- air pressure.

2.9.3.3 Operating Variables

The unit should be sized such that sufficient operating flexibility can be provided to allow effluent quality to be maintained with the expected variations in influent characteristics. The operator should be able to adjust the following major operating variables:

- pH
- coagulant type and dose
- coagulant aid type and dose
- air pressure
- recycle rate.

2.9.4 Treatability Testing

Studies should be made on the wastewater to determine if it is amenable to be cleaned up by the DAF process. If it is established that DAF is a suitable technique for the particular

waste, pilot plant tests or laboratory bench-scale tests can be used to establish the following design parameters (refer to API, Manual on Disposal of Refinery Wastes, Volume on Liquid Wastes, 1969 for bench-scale treatability test procedures for the DAF process):

- overflow rate or rate of particles of mass
- optimum recycle rate
- pressure level in the air-water mix drum
- type of chemical conditioning required, such as:
  - type and number of chemicals
  - optimum dosages of chemicals
  - best points of chemicals
  - best points of chemicals application
  - flash-mix and flocculation detention times.

If the wastewater cannot be tested before design, data from a similar refinery or plant should be used if possible.

2.9.5 Design Considerations

The hydraulic loading rate (HLR) is an important characteristic of unit operations in a WTP as it is directly related to the tank size required for the utility to meet water demand. The HLR for a DAF clarifier is calculated as shown in Eq. (2.11):

$$\text{HLR} = \frac{\text{treated flow}}{\text{total clarifier footprint}} \tag{2.11}$$

where:

HLR = hydraulic loading rate (m/h)

treated flow = clarifier effluent flow, not including recycle flow (m^3/h)

total clarifier footprint = footprint area including contact and separation zones of clarifier (m^2).

DAF is a high-rate clarification process with nominal HLRs ranging from 5 to 40 m/h, as opposed to sedimentation loading rates which are 0.5–5 m/h, both depending on factors such as water quality, temperature, and basin configuration.

Temperature affects water viscosity such that at warm temperatures higher rise velocities can be achieved. The theoretical floc-bubble aggregate rise rate has been derived from Stokes' law (Eq. (2.12)) and is shown below in Eq. (2.13). Ensuring floc-bubble aggregate rise velocities are sufficient to reach the top of the clarifier before being drawn into the subnatant effluent flow is crucial to DAF performance.

$$v_b = \frac{g(\rho_w - \rho_b)d_b^2}{18\mu_w} \tag{2.12}$$

$$v_{fb} = \frac{4g(\rho_w - \rho_b)d_{fb}^2}{3K\mu_w} \tag{2.13}$$

where:

v_b = rise velocity of bubble

v_{fb} = rise velocity of floc-bubble aggregate

g = gravitational constant

ρ_w = density of water

ρ_b = density of air
μ_w = water dynamic viscosity
d_b = diameter of bubble
d_{fb} = diameter of floc-bubble aggregate
K = coefficient: varying from 24 for flocs <40 µm to 45 for 170 µm.

2.9.5.1 System Design

a) The system should be designed for a continuous service and an uninterrupted operation of 2 years (minimum).
b) All equipment should be suitable for unsheltered outdoor installation for the specified climatic zone.
c) Enclosure for electrical equipment should be appropriate for the specific area classification and environment.
d) Effluent from the flocculation tank to the DAF unit and the float/sludge from the DAF unit to the receiver tank should be moved by gravity.
e) The design retention time should be a minimum as follows:
   - Neutralization tank: 3 minutes
   - Flocculation tank: 20 minutes (influent feed)
   - Floatation basin: 40 minutes (influent feed + recycle)
   - Air/water mix drum: 3 minutes at maximum recycle rate.
f) The design flow rate should be 1.5 l/s/m^2 (max.) based on the DAF flotation area.
g) A continuous supply of air to the pressure retention tank should be provided at a pressure not less than 500 kPa (ga) or more than 700 kPa (ga).

2.9.5.2 DAF Section

a) The side water depth (SWD) should be minimum 2.5 m and maximum 3.0 m. In addition to the water depth, 500 mm of free board should also be provided.
b) A perforated recycle distribution pipe and baffle should be provided to uniformly distribute the flow across the depth and width of the flotation compartment. The perforations should be spaced and designed for proper flow distribution across the width of the chamber. The pipe should be flanged at one end for connection to the recirculation piping.
c) The unit should be designed to remove floatable free oil and/or suspended solids with a rise rate of 7.2 m/h or greater when the unit is working at design flow rate.
d) Fluid velocity in the flotation chamber should not exceed 36 m/h.
e) The scum skimmer should consist of two stands of chain running above the liquid surface over two sets of sprockets with pivoted skimming flights. The flights should enter the floated material blanket at the effluent end of the tank and skim toward the influent end. The skimmer should be driven by a suitable variable speed drive. Skimmer chains should be supported where required.

   The skimmer blade should include a depth adjustment feature. Skimmer chains should be provided with a self-lubricating device for rectangular units. For circular units, blades should be interconnected with transverse bracing to reduce potential for excessive blade horizontal deflection and rebound.

f) A helical flight screw conveyor should be provided in the flotation basin to remove the floatable solids from the scum trough to a sump beyond the basin wall. The conveyor should be 225 mm in diameter with full pitch flights mounted on a standard mass (weight) steel pipe. The conveyor should be driven by a suitable electric drive. An agitator and drive should be provided at the scum sump to keep the slurry in suspension.

g) The bottom sludge collector should consist of a 50 mm × 152 mm nominal size redwood scraper, mounted on two strands of chain and not more than 3000 mm apart. The collector chains should run over three sets of sprocket wheels and be driven by a suitable variable speed drive. The chains should be C720, heavy pintle type with the plain and attachment links assembled with heat-treated high-carbon steel pins and rivets. At least 25# tee rails (as per Table 3 of DIN 997) should be provided for the tank bottom for the collector. Tracks for the return run of the scraper, where required, should be made of 76 mm × 51 mm × 9.5 mm thick steel angles with 6.25 mm steel supporting brackets.

h) The skimmer/sludge scraper tip speed should be maximum 0.025 m/s for circular units and 0.015 m/s for rectangular units.

i) The use of belt transmissions for skimmers and scrapers should be approved by the company. Limitations on the use of belt transmissions should be as follows:
   - maximum drive power rating: 110 kW
   - drive service factor: 1.5
   - belt type: jointed (multiple V-belt).

   Belts should be of heavy duty or premium quality with oil-resistant, static conducting characteristics. Use of variable speed transmissions should be approved by the company. Couplings should be of forged steel, flexible type.

j) Float skimmer and sludge scrapers should have cycle timers with on/off switches. A remote torque indicator and a manual torque lifting device should be provided for circular scrapers. If the design load is reached, the drive motor should shut off and visual and audible alarms should be actuated. A shear pin should be furnished on the skimmer/scraper drive shaft.

k) Provisions should be included to remove settled sludge from the flotation tank. Generally, a number of hoppers or a trough at the inlet end of the tank may be provided. Settled sludge is usually scraped into the hoppers or trough and periodically removed either by pumping or by allowing the hydrostatic head in the flotation tank to pressure the sludge out.

l) The float/sludge receiving tank should be sized to accommodate a minimum of 3 h retention of a float production based on 0.5 vol.% of raw wastewater feed. The tank should include facilities for steam or air injection, or both. Float boxes should be sized to accommodate the maximum amount of float produced. A minimum of two float boxes should be provided. The vendor's design basis, including the number of boxes, should be approved by the company.

m) Float/sludge transfer pumps should have the following characteristics:
   - A minimum of two screw pumps (one operating and one spare) should be provided. If single-screw type pumps are used, spare stators should be provided for each pump.
   - Pump suction strainers should be provided to screen out any solid particles which the pump cannot handle. Screen material should be a copper alloy. Strainers should be provided with flushing connections.

2.9.5.3 Neutralization/Flocculation Section

2.9.5.3.1 Neutralization Section.

a) Neutralization tank design requirements are:
   - The tank should be baffled.
   - For circular tanks, liquid height should be approximately equal to the diameter.
   - For other than circular tanks, liquid volume should have approximate cubical dimensions.
b) The feed stream inlet piping layout should allow for a free fall of about 600 mm above liquid level to promote premix condition.
c) Influent and effluent connections should be diametrically opposite each other. The effluent connection should be per API 650 low type.
d) Acid and caustic injection into the neutralization tank should be adjacent to raw wastewater influent.
e) The mixer should be propeller or axial flow type. The liquid pumping or moving capacity should be 10–20 times the feed flow rate with the flow directed toward the bottom of the tank.
f) Neutralization facilities should preferably be located downstream of the equalization basin.
g) The pH control system should incorporate the following:
   - At least proportional plus reset feedback control mode to be provided
   - The pH analyzer should have a self-cleaning feature. The pH control probe should be located on the neutralization tank effluent line as close as practicable to the tank.
   - pH indicator and alarm high in the control room should be provided.
   - pH control system should be automatic.

2.9.5.3.2 Flocculation Section. The flocculation equipment should be installed in an adequately sized compartment. A freeboard of 610 mm at the head of each unit should be provided. The equipment should consist of a paddle wheel mounted on a shaft and driven by a suitable variable speed drive. Each paddle assembly should consist of nominal size, clear, all-heart redwood blades supported by steel angle arms.

The flocculation tank should incorporate the following:

a) circular tanks should be baffled
b) the mixer should have maximum tip speed of 0.6 m/s
c) the tank should include an air sparger.

A manually operated rack and pinion scum collection pipe should be installed in the flocculator compartment for the removal of floating material trapped in the coalescing area. The scum pipe should be capable of being rotated backward as well as forward to insure the removal of scum between the pipe and the basin wall.

A 60° slot should be cut symmetrical about the vertical axis of the pipe with the edges of the slot serving as a weir over which the scum flows into the pipe when the pipe is rotated. A suitable watertight seal should be provided for the open end of the pipe. The seal should be renewable without removing the pipe from the supporting brackets and should not bind or impede the smooth action of the revolving pipe.

2.9.5.4 Pressurized Flow Recycle System

a) Each pressurized flow recycle system should consist of a pressurized tank, pressurizing pump, flow meter, regulating valves for water and air, and necessary instrumentation such as indicators, alarms, on/off valves, etc.

   Individual pressurized flow systems comprising individual pressurized tank, flow meter, regulating valve, connecting piping, instrumentation, etc., should be provided to serve each DAF unit. When two DAF systems are provided, three pressurizing pumps should be used such that each pump is capable of serving both DAF units. In this case, each pressurized flow system should also be designed to be operable for both flotation basins.

   Each pressurized recycle system with all components such as pressurized tank, pump, piping, etc., should be designed to handle at least 75% of the design fresh feed to each DAF unit. The recycle pumps should be horizontal centrifugal types.

b) The pressurized tank should be designed to ensure that a minimum of 80% saturation at operating conditions is achieved. An air sparger on the air inlet line and water spray nozzles on the water inlet line should be provided. The equivalent liquid hold-up time should be 3 min. A minimum 1 m of outage should be provided between the normal liquid level and the internals to allow for frothing and for the air to disengage. A means to drain the drum should be provided.

c) Float switches and solenoid valves mounted on the pressurized tank should maintain the proper air–liquid ratio in the tank. The float switches should activate an alarm in the event of high or low water levels. The pressure tank should also have a pressure gauge, level gauge, low pressure alarm, air vent with needle valve, and pressure relief safety valve. The level and pressure control system proposed by the vendor should be submitted to the company for approval. Any proposed level control should be the external type.

d) Suitable packing should be provided in the pressurized tank to increase the water surface and improve air solubility.

e) The air–water mix drum should be made of killed carbon steel with 3 mm corrosion allowance and a suitable coating or lining. The mechanical design pressure of the drum should be sufficiently high to permit future operation at a process pressure higher than that initially anticipated.

f) Back pressure (let-down valve) should be located as close to the flotation tank and to the influent stream as possible. The valve must be suitable for the mechanical design pressure of the system, should not be easily plugged by solids, and should minimize turbulence.

   The valve should not impart high shear in order to prevent the floc from breaking. Downstream of the back-pressure valve at the entrance to the flotation chamber, a proper inlet distributor with suitable sized nozzles should be provided.

g) Injection of air to the suction and/or interstage of the recycle pump is not accepted. When the air is added to the discharge side of the recycle pump, it should be injected through a porous diffuser.

h) Take-offs for recycle and effluent should be oriented to satisfy recycle feed water requirements so that on loss of raw feed, the DAF unit should go into total recycle.

i) The recycle line should ensure full flow so that air entrainment will not bind the pump. The recycle line should be fabricated of corrosion-resistant material.

j) The air supply should provide at least 0.12 Nm^3/m^3 of raw wastewater feed. If plant air is unavailable and a separate compressor is included with the system, a 100% installed spare should be furnished.
k) Final configuration of the air–water mix drum control and instrumentation systems should be approved by the company.

2.9.5.5 Effluent Chamber

Effluent water should leave the effluent chamber by gravity. A common effluent chamber should be provided for the flotation units. Minimum residence time for the chamber should be 12 minutes. An adjustable weir plate at the end of each flotation chamber should be provided to permit the regulation of the water level to control penetration of the skimmer blades into the scum blanket in the flotation area.

A scum retention baffle should be provided to prevent flotation solids from passing under and out of the flotation chamber. A wiper should be provided to clean the skimmer blades. Recycle flow should be designed to be delivered to the suction side of the pressurizing pump from the effluent chamber at a rate of equal to 50–75% of the design fresh feed to the flotation basin.

2.9.6 Instruments and Control

a) All instrumentation for furnished equipment should be suitable for the service and electrical area classification.
b) All instruments should be tagged with identifying tag numbers which will be assigned by the company. A stainless-steel nameplate should be furnished stamped or engraved with this tag number and permanently mounted with stainless-steel drive screws.
c) The following instruments should be provided in addition to the instruments specified in Section 2.9:
   - flowrate recorder for fresh influent
   - ratio controllers to control chemical dosages
   - recycle flowrate meter
   - air flowrate meter (usually a rotameter)
   - oil-in-water detector on effluent water
   - turbidity meter for effluent total suspended solids.

2.9.7 Piping

a) Gravity line(s) between the flocculation tank and the DAF should be sized for a maximum velocity of 0.6 m/s.
b) Sample connections and relevant valves should be DN 20 for the wastewater lines, DN 50 for the sludge line, and DN 25 for the feed recycle sample line. Connections should be located for easy accessibility.
c) The float and sludge line to the float/sludge receiver tank should include rodding and flushing connections.
d) Facilities should be provided for blow-down of the let-down system to the flotation tank with compressed air.

e) Drains should be included for all vessels and tanks.
f) Corrosion allowances should be specified.
g) All lines and accessories in contact with aerated water should be carbon steel with corrosion-resistant lining. The minimum acceptable lining for corrosion protection is coal tar epoxy.

2.9.8 Chemicals Facilities

a) When feasible, the types and quantities of chemicals to be added to a DAF feed should be determined by tests before the chemicals facilities are designed.
b) In addition to the chemicals (acid, caustic, etc.) used for the neutralization section, chemical facilities should be provided for at least two chemicals: a coagulant and a coagulant aid. Necessary equipment for chemicals storage, solution or dilution, addition, metering, flash mixing, and flocculation should be provided. If solid chemicals are handled, a suitable enclosure or shed to protect the solids and their addition facilities from the weather should be provided.
c) The floc must not be pumped, and lines carrying the floc should be sized to avoid both break-up and settlement of the floc. Design for a velocity of about 0.6 m/s.
d) A flash-mixing drum should be designed for a hold-up time of 4–5 min, and should be provided with rapid agitation. The length to diameter ratio should be about 1.0.
e) The flocculation tank should be provided with gentle agitation by a slow-speed mixer with a maximum tip speed of 0.6 m/s.
f) A suitable shelter or building should be provided to cover chemicals facilities.

2.9.9 Material

The material for vessels, piping, and all other equipment should be selected in accordance with the company's relevant standards unless otherwise specified below:

a) Carbon steel tanks and vessels should have at least 3 mm corrosion allowance and a protective coating system of two coats of coal tar-polyamide epoxy. Surface preparation for the protective coating should be by white metal blast cleaning. The nominal dry thickness for each coat should be 200 μm (8 mm).
b) Carbon steel float/sludge receiver tank(s) that include facilities for live steam should be lined with gunite of 25 mm thickness. Coal tar-polyamide epoxy is not acceptable.
c) All internals of the vessels/tanks contacting aerated water should be stainless steel.
d) Piping contacting aerated water should be carbon steel with a minimum corrosion allowance of 3 mm.
e) Rubber and plastic parts should be resistant to attack by aromatic solvents.
f) Bolting for skimmer and weir adjustment should be type 316 stainless steel.
g) Antispark material should be used for metal-to-metal contacts in moving parts.

2.9.10 Estimation of Air Concentration in DAF Systems

DAF is a water treatment process that clarifies wastewater (or other water) by the removal of suspended matter. The removal is achieved by dissolving air in the water or wastewater

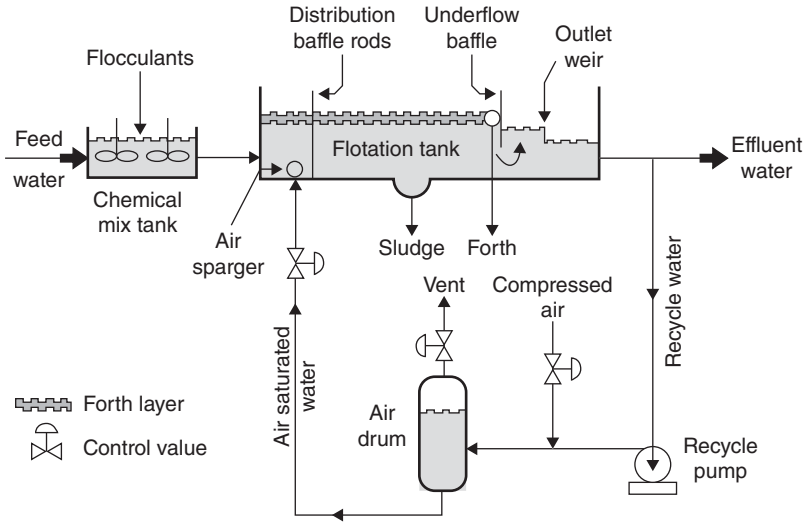


Figure 2.16 *Schematic of a DAF system. Source: Reproduced with permission, A. Bahadori et al., Chemical Engineering Research and Design, 2013 91 (1), pp. 184–190 © Elsevier 2013b.*

under pressure and then releasing the air at atmospheric pressure in a flotation tank or basin. Figure 2.16 shows a schematic of a DAF system. Like other gravity separation processes, raw water is coagulated and flocculated prior to entering the DAF basin.

The water is introduced into the contact zone of the basin near the floor. A baffle wall separates the contact zone from the clarification zone and limits short-circuiting. In the DAF basin, a cloud of air bubbles called white water, typically 10–100 μm in diameter, adheres to floc particles, causing them to float by reducing the net specific gravity of the floc–bubble aggregate below that of surrounding liquid.

Air bubbles are introduced near the bottom of the basin containing the water to be treated. As the bubbles move upward through the water, they become attached to particulate matter and floc particles, and the buoyant force of the combined particle and air bubbles will cause the particles to rise to the surface.

The released air forms tiny bubbles which adhere to the suspended matter, causing it to float to the surface of the water where it can be removed by a skimming device. Thus, particles that have a higher density than the liquid can be made to float. Particles that rise to the surface are removed for further processing as residuals, and the clarified liquid is filtered to remove any residual particulate matter.

The increased dissolved air concentration in water at elevated pressure is the fundamental principle that allows the formation of micro-bubbles. In this section a simple predictive tool is developed to estimate air saturated concentration in dissolved air flotation (DAF) systems.

Effluent turbidity declines with increasing air loading until a breakpoint is reached where the application of additional air provides no corresponding increase in process performance. The mass concentration of air released can be calculated from Eq. (2.14):

$$C_b = \frac{C_r - C_{fl}}{1 + r} r \tag{2.14}$$

The air concentration in the saturator can be expressed either as the bubble number concentration (N_b) or the bubble volume concentration (ϕ_b). These values can be determined from Eqs. (2.15) and (2.16):

$$\phi_b = \frac{C_b}{\rho_{air}} \tag{2.15}$$

$$N_b = \frac{10^{12} \times 6\phi_b}{\pi d_b^3} \tag{2.16}$$

where C_b is mass concentration of air released, C_{fl} is mass concentration of air in the floc tank effluent, C_r is mass concentration of air in recycle flow, and d_b is mean bubble diameter.

It has been found that flotation performance increases as N_b increases because there are more collision and attachment opportunities between the bubbles and particles. Attached air bubbles provide lower floc particle density and larger volume, producing floc particle–bubble aggregates that have high upward velocities.

In view of the above, it is necessary to develop an accurate and simple correlation that is easier than existing approaches, less complicated and requires fewer computations to predict air saturated concentration.

Equation (2.17) represents the proposed governing equation in which four coefficients are used to correlate dissolve air concentration in DAF as a function of pressure and temperature, where the relevant coefficients are reported in Table 2.5.

$$\ln(x) = a + \frac{b}{P} + \frac{c}{P^2} + \frac{d}{P^3} \tag{2.17}$$

Table 2.5 *Tuned coefficients used in Eqs. (2.18)–(2.21).*

Coefficient	Value
A_1	$5.112\,376\,352\,927 \times 10^{1}$
B_1	$-3.767\,964\,895\,874 \times 10^{-1}$
C_1	$1.060\,069\,664\,864 \times 10^{-3}$
D_1	$-1.011\,565\,521\,006 \times 10^{-6}$
A_2	$-3.283\,012\,529\,565 \times 10^{5}$
B_2	$3.360\,561\,486\,772 \times 10^{3}$
C_2	$-1.150\,208\,224\,506 \times 10^{1}$
D_2	$1.311\,220\,065\,117 \times 10^{-2}$
A_3	$1.021\,345\,559\,148 \times 10^{8}$
B_3	$-1.048\,743\,022\,561 \times 10^{6}$
C_3	$3.594\,675\,738\,720 \times 10^{3}$
D_3	$-4.104\,275\,097\,337$
A_4	$-7.036\,559\,254\,429 \times 10^{9}$
B_4	$7.218\,196\,550\,836 \times 10^{7}$
C_4	$-2.473\,400\,471\,536 \times 10^{5}$
D_4	$2.824\,070\,339\,246 \times 10^{2}$

where:

$$a = A_1 + B_1T + C_1T^2 + D_1T^3 \tag{2.18}$$

$$b = A_2 + B_2T + C_2T^2 + D_2T^3 \tag{2.19}$$

$$c = A_3 + B_3T + C_3T^2 + D_3T^3 \tag{2.20}$$

$$d = A_4 + B_4T + C_4T^2 + D_4T^3 \tag{2.21}$$

In Eqs. (2.14)–(2.21) the symbols are:
A, B, C, and D = tuned parameters
C_b = mass concentration of air released (mg/l)
C_{fl} = mass concentration of air in floc tank effluent (mg/l)
C_r = mass concentration of air in recycle flow (mg/l)
d_b = mean bubble diameter (μm)
N_b = bubble number concentration (no./Ml)
P = pressure (kPa(abs))
r = recycle ratio (dimensionless)
T = temperature (K)
x = dissolved air concentration (mg/l)
ϕ_b = bubble volume concentration (l/l)
ρ_{air} = density of air saturated with water vapor (mg/l).

These optimum tuned coefficients help to cover temperature up to 40 °C and pressure up to 700 kPa (abs).The optimum tuned coefficients given in Table 2.5 can be further retuned quickly according to the proposed approach if more data become available in the future.

In this work, our efforts were directed at formulating a correlation which can be expected to assist engineers for rapid calculation of dissolved air concentration in DAF systems as a function of pressure and temperature using an exponential function. The proposed novel tool developed in the present work is a simple and unique expression which is non-existent in the literature. Furthermore, the selected exponential function to develop the tool leads to well-behaved (i.e. smooth and non-oscillatory) equations enabling reliable and more accurate predictions.

Figure 2.17 shows the proposed method results in comparison with data in the literature. Figures 2.18 and 2.19 show the results from the proposed method and its smooth performance in the prediction of dissolved air concentration in DAF systems as a function of pressure and temperature.

It is expected that our efforts in formulating a simple tool will pave the way for arriving at an accurate prediction of dissolved air concentration in DAF systems which can be used by water treatment practitioners and process engineers for monitoring the key parameters periodically. A typical example is given below to illustrate the simplicity associated with the use of the proposed correlation.

Example 2.1: A DAF plant is operating at 10% recycle with a saturator pressure of 500 kPa at 10 °C. Flocculated water enters the contact zone with a floc particle concentration (N_p) of 2000 particles/ml and a floc volume concentration (φ_p) of 2×10^{-6} l/l (2 ppm). Calculate the air mass concentration (C_b), the bubble zone volume concentration (φ_b), and the bubble number concentration (N_b) in the contact zone of the DAF tank and compare

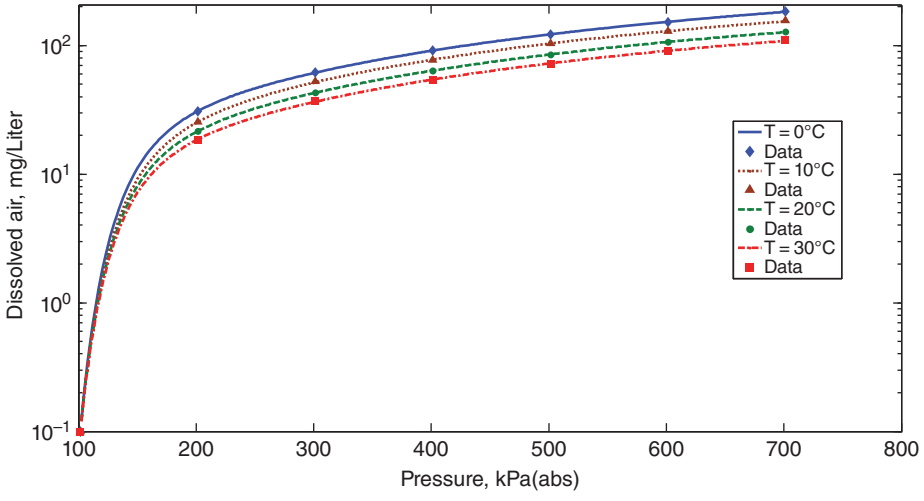


Figure 2.17 *The performance of a predictive tool in comparison with data for calculating dissolved air concentration in DAF systems. Source: Reproduced with permission, A. Bahadori et al., Chemical Engineering Research and Design 91 (1), pp. 184–190 © Elsevier 2013b.*

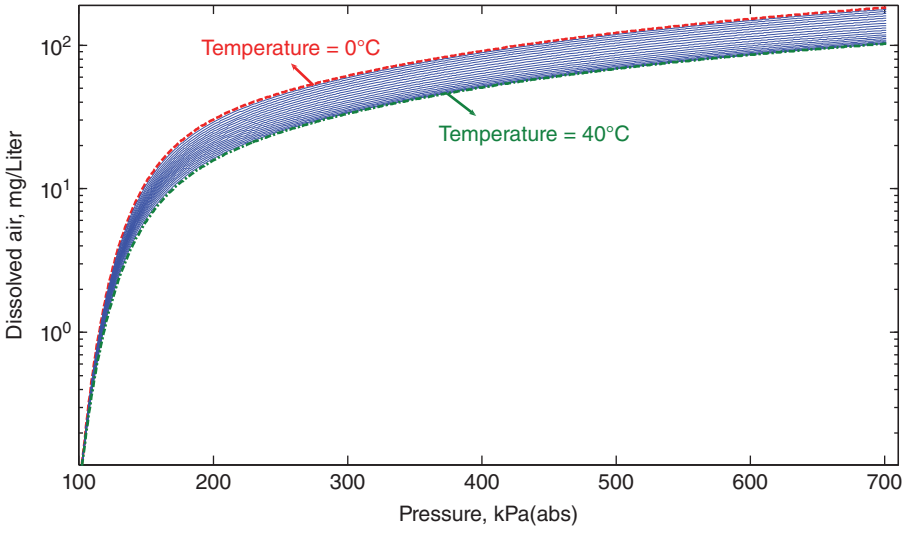


Figure 2.18 *The smoothness of results for the predictive tool for the estimation of dissolved air concentration in DAF systems. Source: Reproduced with permission, A. Bahadori et al., Chemical Engineering Research and Design 91 (1), pp. 184–190 © Elsevier 2013b.*

the concentrations of bubbles to floc particles. Assume the water temperature is 10 °C (ρair = 1.20 kg/m^3 = 1200 mg/l), the flocculated water has no oxygen deficit, so the air concentration in water is 24 mg/l, and the mean bubble diameter is 40 μm. Determine the mass of air in the recycle water.

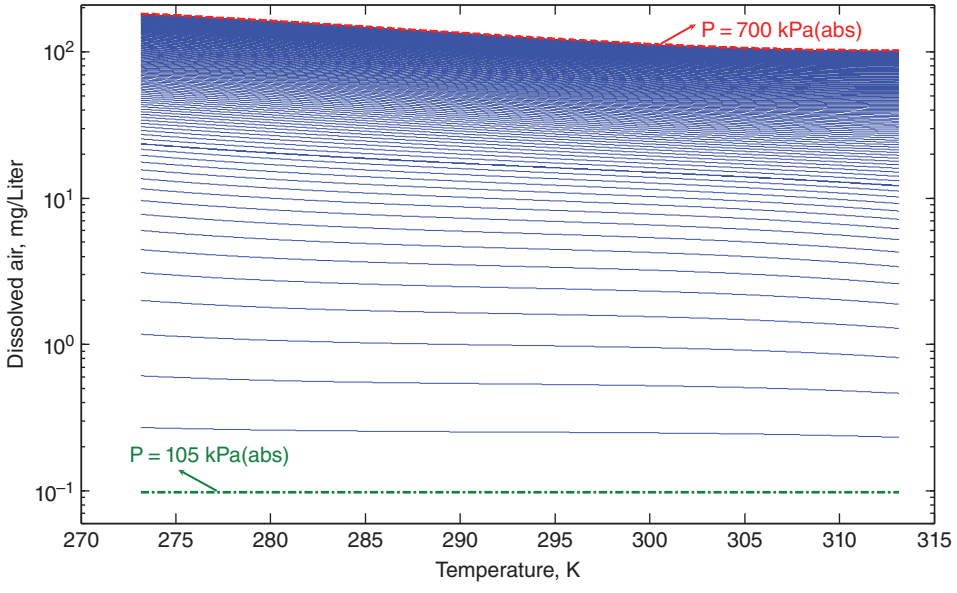


Figure 2.19 *The smoothness of results for the predictive tool for the estimation of dissolved air concentration in DAF systems from another view point. Source: Reproduced with permission, A. Bahadori et al., Chemical Engineering Research and Design 91 (1), pp. 184–190 © Elsevier 2013b.*

Solution Calculate the mass concentration of air in the DAF tank. The dissolved air in the water through the saturator is calculated using new predictive tool.

$a = 6.4599$
$b = -1.262\,02 \times 10^3$
$c = 2.1006 \times 10^5$
$d = -1.7465 \times 10^7$
$x = 129.26$ mg/l

The mass of air in the recycle water is about 129.26 mg/l for 601 kPa (500 kPa gauge pressure plus 101 kPa atmospheric). Based on the air mass balance in the contact zone of the DAF tank, the concentration of air released can be calculated:

$$C_b = \frac{C_r - C_{fl}}{1+r} r = \frac{(129.26 - 24)}{1 + 0.1}(0.10) = 9.64 \text{ mg/l}$$

Then, the bubble volume concentration φ_b is calculated:

$$\phi_b = \frac{C_b}{\rho_{air}} = \frac{9.64}{1200} = 8033 \times 10^{-6} \text{ 1/l (8033 ppm)}$$

After that, the bubble number concentration N_b is calculated:

$$N_b = \frac{10^{12} \times 6\varphi_b}{\pi d_b^3} = \frac{(10^{12})(6)(0.008033)}{\pi 40^3} = 2.4 \times 10^5 \text{ bubbles/ml}$$

Now we can compare the concentrations of bubbles to floc particles. The ratio of the concentration of bubbles to floc particles is calculated for the bubble number concentration and the bubble volume concentration:

$$\frac{N_b}{N_p} = \frac{2.4 \times 10^5}{2\,000} = 120$$

Because the ratio of bubbles to particles is high, there is a lot of opportunity for particle collision and attachment:

$$\frac{\varphi_b}{\varphi_p} = \frac{8033}{2} = 4017$$

Because the ratio of bubble volume to particle volume is high, the floc–bubble density is low, resulting in high rise velocities of the particle–bubble aggregate.

In this work, simple-to-use equations, which are easier than existing approaches, with fewer computations and suitable for process engineers are presented for the estimation of dissolved air concentration in DAF systems as a function of pressure and temperature.

Unlike complex mathematical approaches for estimating dissolved air concentration in DAF systems, the proposed correlation is simple to use and would be of immense help for process engineers, especially those dealing with water and wastewater treatment operations. Additionally, the level of mathematical formulations associated with the estimation of dissolved air concentration in DAF systems can be easily handled by process engineers or water treatment practitioners without any in-depth mathematical abilities.

The example shown for the benefit of engineers clearly demonstrates the simplicity and usefulness of the proposed tool. Furthermore, estimations are quite accurate, as evidenced from the comparisons with literature data (with average absolute deviation being less than 0.5%), and would help with attempting faster engineering and operations in the water treatment industry.

The proposed method has a clear numerical background in which the relevant coefficients can be retuned quickly if more data become available in the future. The solubility of air in water increases in a linear fashion with increasing pressure. In addition, the solubility of air in water is reduced at elevated temperatures, as shown by the proposed predictive tool. In DAF designs in tropical areas, or anywhere where raw-water temperatures routinely exceed 25 °C, it is sometimes necessary to adopt higher than normal design recycle rates to ensure sufficient air can be delivered to the process at warmer temperatures.

2.10 Granular-Media Filters

2.10.1 General

Granular-media filtration is the process of removal of suspended solids by the passage of water through a porous medium. Filtration is commonly the final polishing step in the conventional water treatment process, designed to meet final treated water turbidity limits. Figure 2.20 shows a granular-media filter.

The filtration process results in a gradual accumulation of entrapped solids within the granular media, which require intermittent removal by means of a filter backwash cycle.



Figure 2.20 *A granular-media filter system. Source: Reproduced with permission from © Environmental Products and Solutions (EPS).*

This cycle typically comprises both air scour and water wash phases to effectively loosen and flush out the retained solids to waste.

Granular-media filters are facilities that separate undissolved (free) oil and solid suspended matter from the wastewater by filtering the water through a bed of granular media such as sand. Granular-media filters do not remove phenol, H_2S, soluble BOD or other soluble constituents. They remove solids from the water stream by straining through the filter bed and by other mechanisms such as sedimentation between the media particles and adsorption upon them.

As impurities are removed, bed pressure drop increases, thus the filters should periodically be taken out of service and backwashed in the upflow direction to reduce pressure drop. Backwashing should be accomplished by expanding or fluidizing the bed with filter influent or effluent at a relatively high flow rate and injecting air to scour the particles. Occasionally, a detergent wash or steaming may be employed to more thoroughly clean the bed.

2.10.2 Filter Types and Applications

Granular-media filters are differentiated by:

- Mode of operation:
  a) downflow
  b) upflow
- Number of media:
  a) monomedia
  b) mixed-media:
    b.1) dual-media (e.g. sand and anthracite)
    b.2) tri-media (e.g. garnet, sand, and anthracite)

- Material of media:
  a) sand
  b) anthracite
  c) garnet or ilmenite
- Driving force for flow:
  a) gravity
  b) pressure
- Depth of penetration:
  a) shouldow-bed
  b) deep-bed.

Granular-media filters can remove oil and suspended solids from wastewater with or without the use of chemicals. In chemical applications, a chemical flocculent is often added to the wastewater prior to granular-media filtration to enhance oil removal.

Additionally, granular-media filters can be designed and operated as simple coalescers, without chemicals, causing the small oil droplets to coalesce into larger ones as they pass through the filter bed.

When filters are operated in this manner, the oil is subsequently removed from the water by gravity separation. This technique can be used on oil-field produced water, but should not be used for refinery or petrochemical plant wastewater. Use of gravity filters due to high water demand and large bed areas should be avoided.

When possible, the design basis contaminant removal efficiency for granular-media filters should be determined by tests using the particular waste stream of interest. With an existing wastewater stream, pilot-plant work to establish effluent purity, cycle time, pressure drop, pressure drop build-up, chemicals, and dosages should precede design.

For grassroots and/or other installations where tests cannot be conducted, the following typical contaminant removal efficiencies in Table 2.6 can be used for granular-media filters.

Deep-bed, downflow, and sand filters produce about the same quality of effluent as an upflow sand filter or a downflow, dualmedia filter, but with a shorter cycle time. Downflow filters can operate with more flowrate variation than upflow filters because the media will not fluidize at high flowrates. However, deep-bed downflow sand filters may not be feasible with flocculents because of the low solids retention capacity of these filters. Shallow-bed, downflow, gravity sand filters are conventionally used for polishing in domestic water treatment.

Table 2.6 *Typical contaminant removal efficiencies for granular-media filters.*

Filter location	API separator efficiency	Biological efficiency
Residual oil level	Less than 20 mg/l 80–90% free residual	80–90% free
Suspended solids removal	80–90%	80–90%
5-day BOD removal	30% (based on the removal of insoluble BOD when the filter is used as a pretreatment process; this BOD reduction should not be expected when the filter is used for polishing. Granular-media filters do not remove soluble BOD or other soluble constituents.)	—

In general, in refinery or petrochemical plants, the following types of filters are preferred for wastewater treating purposes:

- deep-bed, pressure, down-flow, sand filter
- deep-bed, pressure, up-flow, sand filter.

Use of any other types should be approved by the company:

2.10.3 System Design Parameters

a) The feed system should be designed to minimize flow surges.
b) Multiple units should be provided to allow continuous operation at maximum design capacity with one unit out of service for backwashing.
c) Units should be designed for continuous service and uninterrupted operation for a minimum period of 2 years.
d) Filters should be vertical cylindrical with dished head ends supported on four legs. However, if horizontal type filters are used (with the approval of the company), the effective filtration area should be the area of the interface between the underdrain systems and the bottom media.
e) All equipment should be suitable for unsheltered, outdoor installation for the specified climatic zone.
f) Type of operation (manual or automatic) backwash as well as provision of automatic programmable controllers should be specified by the company.
g) Headers for feed water distribution, effluent collection, backwash water, and air scour should be provided.
h) Sufficient storage capacity with all necessary accessories should be provided for backwashing purposes.
i) Deep-bed, pressure filters, both up-flow and down-flow, may be used either with or without chemical addition depending on the quality requirements of the effluent water requested by the company. However, use of these chemicals should be proposed by vendor based on the effluent water quality and should be approved by the company.

2.10.3.1 Down-Flow Sand Filters

Down-flow sand filters should consist of a bed of sand supported on several layers of gravel resting on a backwash distributor which supports the entire bed. The sands should be 1–2 mm in diameter. The minimum and maximum depths of the sand bed should be 1.2 and 2 m, respectively. The gravel layers should be graded particle size, with the coarsest layer on the bottom.

The backwash distributor should be designed such that it supports the gravel and allows proper simultaneous distribution of air and water during backwashing.

Down-flow filters offer a more positive protection against breakthrough than up-flow filters. Down-flow filters also offer the advantage of not fluidizing during filtration, and thus can operate with a relatively large temporary increase in flow.

2.10.3.2 Up-Flow Sand Filters

An up-flow sand filter should consist of a bed of sand supported by several layers of gravel of various sizes, resting on a bed support/distributor. A hold-down grid should be located near the top of the bed to prevent fluidization during filtration. Use of open-top vessels is not acceptable. The filters should be composed of pressure vessels containing sands 1–2 mm in diameter.

The filter bed support should be designed such that simultaneous addition and distribution of air and water during backwashing is allowed. The minimum and maximum depths of the sand bed should be 1.2 and 2 m, respectively.

The media in up-flow sand filters should be fine sand (fine relative to the other material in the filter) and should consist of a layer of coarse sand and two layers of gravel, each of a different size. All of the media should be of the proper size and shape. The shape should approach spherical (at least 0.8) to allow effective movement of the grains during backwashing. The uniformity coefficient (U) should be 1.2 minimum.

2.10.3.3 Backwashing Considerations

a) The water used to backwash the filter must be clean. It can be a portion of the filtrate or clean water from another source. When filtrate is used, a holdup tank should be provided to retain the necessary amount. Alternatively, if there are enough filters and the pressure is sufficient, the backwash water can be taken directly from the filter effluent.
b) Two backwash pumps (one operated and one spare) should be provided. The backwash water rate depends upon the size of the sand particles and the temperature of the water and should be advised by the vendor. The recommended backwash water rate is 39 m^3/h per square meter of the filter bed.
c) A restriction orifice, about 45–50 m^3/h per square meter of the filter bed, should be provided in the backwash water line to each filter to limit the quantity of backwash water to avoid washing the sand from the bed. A hand-control valve with a local indicator should be provided at the backwash pump discharge line.
d) Air should be injected during backwashing to cause movement, tumbling, and rotation of the media to scour off the retained material. The air rate will be advised by the vendor. Air pressure should be at least 300 kPa (ga). No deliberate back pressure is maintained on the filter beds during air blowing or backwashing. If safety problems (explosivity) can be encountered during air blowing, due to the presence of light components, inert gas or nitrogen should be used in place of air.
e) If plant air is unavailable, air blowers (with 100% spare capacity) to supply air for air scour during backwash operation should be provided.
f) The backwash storage tank should have adequate capacity at least for 20 min working of the backwash pumps at design throughput.
g) When a bed is cleaned, the discharge from the backwash will contain the bulk of the contaminants and should be sent to a sludge removal facility.

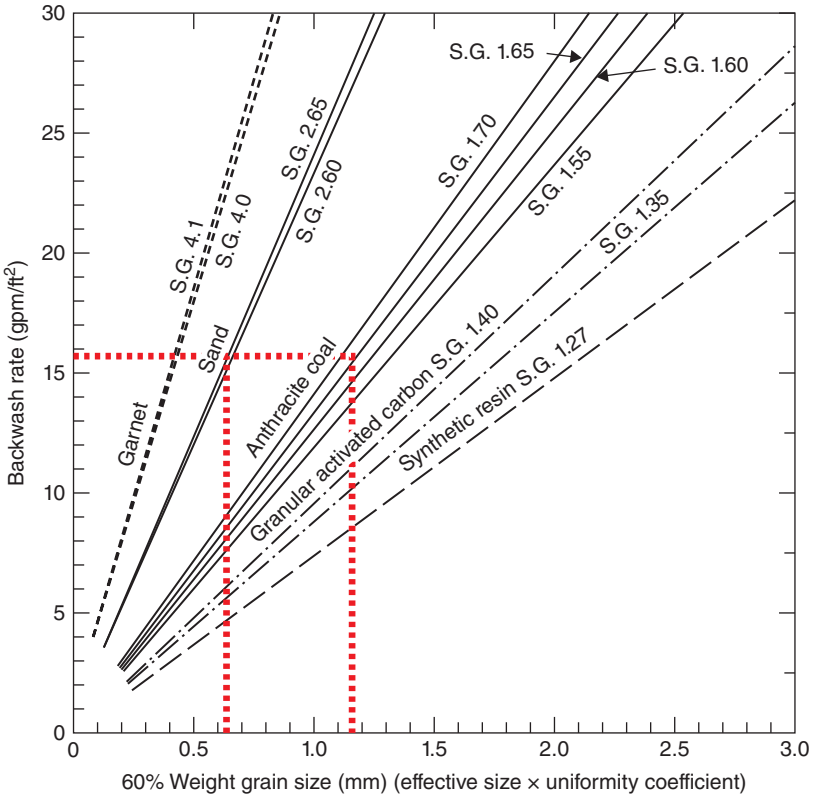


Figure 2.21 *Estimation of the backwash rate in a granular-media filter system at 20 °C. Source: Reproduced with permission from © AECOM.*

h) If automatic backwashing is desirable and required by the company, the automated backwash should be actuated by a cycle timer, but should have overrides that activate the backwash procedure at high pressure drops across a filter and at low flow through one. Additional overrides for high oil content in the effluent water and for high effluent turbidity should also be considered.
i) Figure 2.21 provides rapid estimation of the backwash water rate at 20 °C.

2.10.4 Cycle Time

The on-stream filtration time depends on the solids loading, oil content, and contaminant characteristics of the stream being filtered and, when possible, should be determined by tests. Filtration run lengths on the order of 8–24 h can be expected if chemicals are used; longer runs would be expected if chemicals are not used. Pressure drop may play a part in the retention of the oil and solids, so the flow to these filters should not be suddenly reduced or stopped and then increased or restarted, otherwise oil breakthrough or high pressure drops may ensue.

2.10.5 Vessels and Appurtenances

a) The filter vessel must be high enough to accommodate the required depth of filter media and an inlet distributor, and to allow freeboard for bed expansion during backwashing. The manufacturer determines the space required under the inlet distributor. The filter media should be minimum 1.2 m for vertical vessels.

   The freeboard should be a minimum of two-thirds of the total bed depth, measured from the top of the filter media to the tangent line at the top of vessel but not less than 1.2 m.

   Filter media retainers should be furnished above the bed of each filter vessel in up-flow filters to prevent fluidization of the bed during filtration.

b) Sand filters not subject to steaming should be designed for a minimum mechanical design temperature of 93 °C and a mechanical design pressure of at least equal to the shut-off pressure of either the filter feed pumps or the backwash water circulation pumps, whichever is greater. If steam is connected to the filter, the mechanical design pressure and temperature of the steam system should also be considered in addition to the above conditions. Pressure vessels should be designed and fabricated per ASME Code Section VIII Div. 1.

c) The filter bed should rest on a perforated baffle. Holes in the baffle should be covered by devices to retain the filter media in the bed. Devices should be equipped with slots or holes smaller than the particle dimension of the filter media.

d) The total required filtration area will be determined by dividing the flowrate to be filtered by the filter hydraulic loading (allowable filtration rate per unit of the area with one unit out of service for backwashing). The maximum hydraulic loading for a deep bed pressure, down-flow type filter should be 12.2 $m^3/h/m^2$ when one filter is in backwash operation.

e) Maximum media loss should be 5% of the media volume per year.

f) Filter media traps should be furnished on the outlet of each pressure filter unit to indicate loss of media in the event of underdrain failure. The maximum pressure drop through the trap should be 35 kPa (ga) when the unit is operating at maximum design flowrate.

g) Units 900 mm diameter and larger should have one 500 mm manhole in the top head and one at the same size below the media support. Units smaller than 900 mm diameter should have one 250 mm diameter handhole located in the top head and another one below the media support. Manholes, 500 mm (20 in.) minimum diameter, should be provided for access to compartments of units, as required. Manhole covers should be equipped with handling davits. In every case, access for removal of the internals should be provided.

h) A filter media discharge connection should be furnished close to the vessel bottom. It should be DN 150 (6 in.) minimum size and furnished with a blind flange.

i) Drains should be provided to dewater each unit. The minimum size of drains should be DN 50 (2 in.) for units up to 750 mm (30 in.) diameter and 75 mm (3 in.) for larger units.

j) Cleaning connections should be provided for each vessel.

k) A manual air relief valve should be provided for each vessel.

l) Sample valves should be furnished on the inlet and outlet of each vessel. Units operating above 65 °C should have a common sample cooler to cool the sample below 38 °C.

m) A pressure safety valve for each pressure vessel should be provided.
n) The filter vessels should be constructed of killed carbon steel with a minimum corrosion allowance of 3 mm. Where lining is required, the lining material should be compatible with the water quality and media abrasiveness. The vendor's proposals for coatings and linings should be submitted to the company for approval. Vessel internals should be stainless steel.
o) Winterizing should be provided for filters if required by the site climatic conditions.

2.10.6 Instrumentation and Controls

2.10.6.1 Pressure

a) A differential pressure gauge, with an adjustable high-pressure alarm announced in the control room, should be furnished to monitor the differential pressure across the combined inlet and outlet headers. Additional pressure gauges are required on the inlet and the outlet backwash headers for use during backwashing.
b) For each vessel, facilities should be provided to measure the pressure at the inlet and the pressure drop across the vessel during either filtration or backwashing operation. A high DP alarm in the control room should be provided for each vessel. These instruments will not show if a filter is plugged so individual flow instruments are also required.

2.10.6.2 Flow

Adjustable flow controls and flow indicators should be provided to control and indicate service, air scour or subsurface wash, backwash, and effluent flow from each vessel.

2.10.6.3 Level

A means (preferably sight glass) must be provided to detect the water level in the vessels when they are drained to the top of the sand prior to backwashing.

2.10.6.4 Temperature

Some means should be provided to measure and control the temperature of the backwash water.

2.10.6.5 Venting

Air vents should be DN 20 (¾ in.) minimum, piped to the nearest drain. When units are operated automatically, air vents should also operate automatically. In addition, an auxiliary, manually operated vent valve should be furnished. Automatically operated vent valves should be installed with a block valve to permit removal of the vent valve without shutting down the unit.

2.10.6.6 Analyzers

If specified by the company, the following in-line analyzers with indicators and alarms in the control room should be provided for the effluent water from the unit:

- turbidity analyzer (surface scatter type)
- oil analyzer.

2.10.6.7 Programmable Controller for Automatic Operation

If provision of a programmable controller for automatic operation is specified by the company, it should be provided in accordance with the following requirements:

a) The number of programmable controllers required should be specified.
b) The control mode (automatic/step/manual) should permit selection and control of every step within the sequence of operation.
c) The control system should provide for status selection (service/standby/power off) and identification.
d) Interlocks should be provided to prevent:
   - more than one unit from backwashing simultaneously
   - a filter backwash where the levels in either the clean or the dirty backwash storage tank are insufficient for complete backwash.
e) A means positively to verify that a step has been completed within a specified time should be provided. If a step fails, an alarm should be actuated and either the sequence stopped or another contingency step initiated.
f) Programmable controllers should have provisions for manual operation from a locally mounted solenoid cabinet in the event of a programmable controller malfunction.
g) Local solenoid cabinets containing solenoids for manual operation of automatic valves should be located adjacent to the units. Operation of the solenoids should be by means of switches mounted outside the cabinet. Switches should be protected by a hinged, weatherproof cover.
h) A remote interface should be provided in the control room. This interface should include graphics in the form of either a hard-wired graphics panel or displays presented on a video screen, as specified. The minimum graphics display for each unit should be as follows:
   - control mode (automatic/step/manual)
   - unit status (service/standby/power off)
   - programmable controller malfunction
   - indication of each step of the backwash sequence
   - on/off indication of pumps and compressors
   - position of each automatic valve
   - valve malfunction during the sequence
   - a schematic of a filter unit to display the status.
i) Programmable controller input and output circuits should be individually isolated and protected against transitions in field wiring affecting the internal logic.

3

Chemical Treatments

3.1 Introduction

Chemicals are used during wastewater treatment in an array of processes to expedite disinfection. These chemical processes, which induce chemical reactions, are called chemical unit processes and are used alongside biological and physical cleaning processes to achieve various water standards. There are several distinct chemical unit processes, including chemical coagulation, chemical precipitation, chemical oxidation and advanced oxidation, ion exchange, and chemical neutralization and stabilization, that can be applied to wastewater during cleaning.

3.1.1 Chemical Precipitation

Chemical precipitation is the most common method for removing dissolved metals from wastewater solution containing toxic metals. To convert the dissolved metals into solid particle form, a precipitation reagent is added to the mixture. A chemical reaction, triggered by the reagent, causes the dissolved metals to form solid particles. Filtration can then be used to remove the particles from the mixture. How well the process works is dependent upon the kind of metal present, the concentration of the metal, and the kind of reagent used. In hydroxide precipitation, a commonly used chemical precipitation process, calcium or sodium hydroxide is used as the reagent to create solid metal hydroxides. However, it can be difficult to create hydroxides from dissolved metal particles in wastewater because many wastewater solutions contain mixed metals.

3.1.2 Chemical Coagulation

This chemical process involves destabilizing wastewater particles so that they aggregate during chemical flocculation. Fine solid particles dispersed in wastewater carry negative

Waste Management in the Chemical and Petroleum Industries, Second Edition. Alireza Bahadori.
© 2020 John Wiley & Sons Ltd. Published 2020 by John Wiley & Sons Ltd.

electric surface charges (in their normal stable state), which prevent them from forming larger groups and settling. Chemical coagulation destabilizes these particles by introducing positively charged coagulants that then reduce the negative particles' charge. Once the charge is reduced, the particles freely form larger groups. Next, an anionic flocculant is introduced to the mixture. Because the flocculant reacts against the positively charged mixture, it either neutralizes the particle groups or creates bridges between them to bind the particles into larger groups. After larger particle groups are formed, sedimentation can be used to remove the particles from the mixture.

3.1.3 Chemical Oxidation and Advanced Oxidation

With the introduction of an oxidizing agent during chemical oxidation, electrons move from the oxidant to the pollutants in wastewater. The pollutants then undergo structural modification, becoming less destructive compounds. Alkaline chlorination uses chlorine as an oxidant against cyanide. However, alkaline chlorination as a chemical oxidation process can lead to the creation of toxic chlorinated compounds, and additional steps may be required. Advanced oxidation can help remove any organic compounds that are produced as a byproduct of chemical oxidation through processes such as steam stripping, air stripping, or activated carbon adsorption.

3.1.4 Ion Exchange

When water is too hard, it is difficult to use to clean and often leaves a gray residue. (This is why clothing washed in hard water often retains a dingy tint.) An ion exchange process can be used to soften the water. Calcium and magnesium are common ions that lead to water hardness. To soften the water, positively charged sodium ions are introduced in the form of dissolved sodium chloride salt, or brine. Hard calcium and magnesium ions exchange places with sodium ions, and free sodium ions are simply released in the water. However, after softening a large amount of water, the softening solution may fill with excess calcium and magnesium ions, requiring the solution be recharged with sodium ions.

Ion exchange resins are classified according to their specific application as per Table 3.1.

3.1.4.1 Design Criteria for an Ion Exchange System

Design criteria for an ion exchange system should be based on [5–8]:

- the required flow rate
- influent water quality
- desired effluent water quality
- exchange capacity and hydraulic characteristics of the exchanger
- period between regenerations
- type of operation-manual or automatic
- flexibility required, that is the number of softener units.

Ion exchangers are not economically suitable for demineralizing water containing more than 1000–2000 mg/kg of dissolved solids, except in a few specialized industrial applications.

Table 3.1 *Classification of ion exchange resins.*

Type	Application	Ionic form in ready-to-use condition	Aqueous solution of regenerating agent
Cation exchange resins Strongly acidic	Reduction of calcium ion concentration	Na	NaCl
Cation exchange resins Strongly acidic	Reduction of salt content	H	HCl, H_2SO_4
Weakly acidic	Reduction of hydrogen carbonate concentration	H	HCl, H_2SO_4, CO_2
Weakly acidic	Reduction of heavy metal ion content	Na, H	HCl, H_2SO_4, NaOH
Anion exchange resins Strongly basic	Reduction of salt content	OH	NaOH
Anion exchange resins Strongly basic	Reduction of content of certain ions, e.g. nitrate ions, sulfate ions	Cl, HCO_3	NaCl, $NaHCO_3$
Anion exchange resins Strongly basic	Reduction of organic substance content, e.g. humic acids	Cl, OH	NaCl, NaOH
Weakly basic	Reduction of salt content	Free base	NaOH
Weakly basic	Reduction of heavy metal ion content	Free base	NaOH
Weakly basic	Reduction of organic substance content, e.g. humic acids	Free base	NaOH

The process of ion exchange for softening water is preferable to the precipitation process when one or more of the following conditions exist:

- less than 100 mg/kg of hardness expressed as calcium carbonate is present in the water
- an extremely low dissolved solids content is required
- only a limited volume of treated water is required.

The relative exchange capacity of cation exchangers and regenerative salt dosage are as shown in Table 3.2.

Anion exchangers have typically an exchange capacity calculated as $CaCO_3$ of 27.4–57.2 g/l at a sodium dosage of 1.05–7 kg/kg removed. Interstate degasification in demineralization systems should be considered at flow over 22.7 m^3/h and alkalinity over 100 mg/kg.

When ultra-pure water is required, using a mixed bed demineralizer is recommended.

The demineralized water storage(s) should be designed to store the produced demineralized water and to cover the following uses:

Table 3.2 Relative exchange capacity of cation exchangers.

Cation exchanger	Nominal exchange capacity (g/l)	Regenerative salt dosage	
		Volumetric ($kg/m^{3)}$	Effective hardness removed (kg/kg)
Greensand	6.4	20.2	3.1
Processed greensand	12.6	39.5	3.1
Synthetic siliceous zeolite	25.2	79.2	3.1
Resin, polystyrene	73.2	201.7	3.1
Resin, polystyrene	50.3	80	1.7

- make-up to deaerators
- process units
- regeneration of condensate treatment.

3.1.5 Chemical Stabilization

This process works in a similar fashion to chemical oxidation. Sludge is treated with a large amount of a given oxidant, such as chlorine. The introduction of the oxidant slows down the rate of biological growth within the sludge and also helps deodorize the mixture. The water is then removed from the sludge. Hydrogen peroxide can also be used as an oxidant and may be a more cost-effective choice.

3.2 Definition and Application

Those processes used for the treatment of wastewater in which change is brought about by means of or through chemical reaction are known as chemical unit processes. In the field of wastewater treatment, chemical unit processes are usually used in conjunction with physical unit operations and biological unit processes to meet treatment objectives.

Applications of chemical unit processes in wastewater treatment are presented in Table 3.3. In considering the application of the following chemical unit processes, the inherent disadvantages associated with most chemical processes (activated carbon adsorption is an exception), as compared with the physical unit operations, are that they are additive processes and cause an increase in the total dissolved-solids concentration of the wastewater. If the treated wastewater is to be reused, this can be a significant factor. Another disadvantage of chemical unit processes is that they are all intensive in operating costs.

For additional chemical applications in wastewater collection, treatment, and disposal, reference can be made to Table 3.4.

3.2.1 Activated Carbon Adsorption

Activated carbon has been used for a long time in water and wastewater treatment. The adsorption capacity of activated carbon is of special interest due to its large surface area. The surface properties of activated carbon depend upon both the initial material used to

Table 3.3 *Applications of chemical unit processes in wastewater treatment.*

Process	Application
Chemical precipitation	Removal of phosphorus and enhancement of suspended solids removal in primary sedimentation facilities used for physical-chemical treatment
Chemical flocculation	Removal of free oil and suspended solids from wastewater
Adsorption	Removal of organic material not removed by conventional chemical and biological methods Also used for dechlorination of wastewater before final discharge for treated effluent
Disinfection	Selective destruction of disease-causing organisms (can be accomplished in various ways)
Disinfection with chlorine	Selective destruction of disease-causing organisms Chlorine is the most used chemical
Dechlorination	Removal of total combined chlorine residual that exists after chlorination (can be accomplished in various ways)
Disinfection with chlorine: dioxide, bromine chloride, ozone, or ultraviolet light	Selective destruction of disease-causing organisms
Other chemical applications	Various other chemicals can be used to achieve specific objectives

produce the carbon and the exact production procedure. Generally, granular carbon from bituminous coal has small pore size, large surface area, and the highest bulk density. Lignite carbon has the largest pore size, least surface area, and the lowest bulk density.

The ability of activated carbon to adsorb pollutants is a function of both the characteristics and concentration of the pollutants and the temperature. Generally, the amount of material adsorbed is determined as a function of concentration at a constant temperature, and the resulting function is called an adsorption isotherm. The most common adsorption isotherm equations used in water and wastewater treatment are the Freundlich isotherm and Langmuir isotherm.

- Freundlich isotherm:

$$\frac{x}{m} = K_f C_e^{1/n} \tag{3.1}$$

where:
x/m = amount of adsorbate adsorbed per unit of carbon
C_e = equilibrium concentration of adsorbate in solution after adsorption
K_f, n = empirical constants.

- Langmuir isotherm:

$$\frac{x}{m} = \frac{abC_e}{1 + bC_e} \tag{3.2}$$

where:
x/m = amount of adsorbate adsorbed per unit of carbon
C_e = equilibrium concentration of adsorbate in solution after adsorption
a, b = empirical constants.

Table 3.4 *Applications of chemical unit processes in wastewater treatment.*

Application	Chemicals used	Remarks
Collection		
Slime-growth control	Cl_2, H_2O_2	Control of fungi and slime-producing bacteria
Corrosion control (H_2S)	Cl_2, H_2O_2, O_3	Control brought about by destruction of H_2S in sewers
Corrosion control (H_2S)	$FeCl_3$	Control brought about by precipitation of H_2
Odor control	Cl_2, H_2O_2, O_3	Especially in pumping stations and long, flat sewers
Treatment		
Grease removal	Cl_2	Added before pre-aeration
BOD reduction	Cl_2, O_3	Oxidation of organic substances
pH control	KOH, $Ca(OH)_2$, NaOH	—
Ferrous sulfate oxidation	Cl_2	Production of ferric sulfate and ferric chloride $[6(FeSO_4 \cdot 7H_2O) + 3Cl_2 \rightarrow 2FeCl_3 + Fe_2(SO_4)_3 + 42H_2O]$
Filter-ponding control	Cl_2	Residual at filter nozzles
Filter-fly control	Cl_2	Residual at filter nozzles, used during fly season
Sludge-bulking control	Cl_2, H_2O_2, O_3	Temporary control measure
Digester supernatant oxidation	Cl_2	—
Digester and Imhoff tank foaming control	Cl_2	—
Ammonia oxidation	Cl_2	Conversion of ammonia to nitrogen gas
Odor control	Cl_2, H_2O_2, O_3	
Oxidation of refractory organic compounds	O_3	
Disposal		
Bacterial reduction	Cl_2, H_2O_2, O_3	Plant effluent, overflows, and stormwater
Odor control	Cl_2, H_2O_2, O_3	

Cl_2, chlorine; H_2O_2, hydrogen peroxide; O_3, ozone; KOH, potassium hydroxide; $Ca(OH)_2$, calcium hydroxide; NaOH, sodium hydroxide.

Activated carbon can be classified into two types: powdered activated carbon (PAC), which has a diameter of less than 200 mesh, and granular activated carbon (GAC), which has a diameter greater than 0.1 mm. GAC is usually used in a fixed bed column while PAC is added to the effluent from secondary biological treatment to serve as a polishing process. Another application of PAC is direct addition of PAC to the aeration basin of the activated sludge process.

3.3 Chemical Precipitation

Chemical precipitation in wastewater treatment involves the addition of chemicals to alter the physical state of dissolved and suspended solids and to facilitate their removal by sedimentation. Chemical processes, in conjunction with the various physical operations, can be used in the secondary treatment of untreated wastewater, including the removal of either nitrogen or phosphorus, or both. The most common chemicals used in wastewater treatment are listed in Table 3.5. The degree of clarification obtained depends on the quantity of chemicals used and the care with which the process is controlled. It is possible by chemical precipitation to obtain a clear effluent, substantially free from matter in suspension or in the colloidal state. From 80% to 90% of the total suspended matter, 40–70% of the BOD5, 30–60% of the chemical oxygen demand (COD), and 80–90% of the bacteria can be removed by chemical precipitation. In comparison, when plain sedimentation is used, only 50–70% of the total suspended matter and 30–40% of the organic matter settles out.

3.4 Chemical Flocculation

To meet the requirements of potable, industrial, and agricultural water, the immediate need is to treat wastewater, particularly sewage sludges and slimes from municipal and chemical oil and gas industrial effluents, respectively. These effluents are highly undesirable and unsafe. The removal of contaminants from wastewater is a must before they can be reused.

The removal of contaminants from these effluents involves the processes of flocculation and coagulation. Colloidal particles in nature normally carry charges on their surface, which lead to the stabilization of the suspension.

By addition of some chemicals, the surface property of such colloidal particles can be changed or dissolved material can be precipitated so as to facilitate the separation of solids by gravity or filtration. Conversion of stable state dispersion to the unstable state is termed destabilization and the processes of destabilization are coagulation and flocculation. Often the terms coagulation and flocculation are used synonymously in spite of there being a

Table 3.5 *Chemicals used in wastewater treatment.*

Chemical	Formula	Molecular mass	Density (kg/m^3)	
			Dry	Liquid
Alum	$Al_2(SO_4)_3 \cdot 18H_2O$	666.7	960–1200	1250–1280 (49%)
	$Al_2(SO_4)_3 \cdot 14H_2O$	594.3	960–1200	1330–1360 (49%)
Ferric chloride	$FeCl_3$	162.1	—	1345–1490
Ferric sulfate	$Fe_2(SO_4)_3$	400	—	1120–1153
	$Fe_2(SO_4)_3 \cdot 3H_2O$	454		
Ferrous sulfate (copperas)	$FeSO_4 \cdot 7H_2O$	278	993–1057	—
Lime	$Ca(OH)_2$	56 as CaO	560–800	—

subtle difference between the two. If destabilization is induced through charge neutralization by addition of inorganic chemicals, the process is called coagulation.

On the other hand, the process of forming larger agglomerates of particles in suspension or small agglomerates already formed as a result of coagulation through high molecular weight polymeric materials is called flocculation. No substantial change of surface charge is accomplished in flocculation.

The agglomerates formed by coagulation are compact and loosely bound, whereas the flocs are of larger size, strongly bound, and porous in flocculation.

3.4.1 Definition and Applications

Chemical flocculation can be used to remove suspended matter and free oil from water. The coagulating agent hastens the settling of suspended material and often allows the removal of solids not separated by conventional sedimentation.

Chemical flocculation consists of the following four steps:

- Coagulation
  The formation of flocculent particles from added chemicals. This is sometimes termed flash-mixing or rapid mixing (Figure 3.1).
- Flocculation
  The provision of retention time with gentle agitation to allow the floc particles or precipitate, associated with the impurities, to increase in size by agglomeration. This step is sometimes called slow-mix (Figure 3.2).
- Sedimentation
  The gravity settling of the floc (Figure 3.3).
- Removal of the settled material
  After coagulation, flocculation, and settling, the floc is removed as a sediment or sludge.

The chemical flocculation units normally serve to protect a downstream biological oxidation unit from the excessive influxes of oil. Other potential uses for chemical flocculation are:

- to protect downstream carbon adsorption columns from excessive oil and solids
- to increase the cycle time of downstream deep-bed sand or mixed media filters

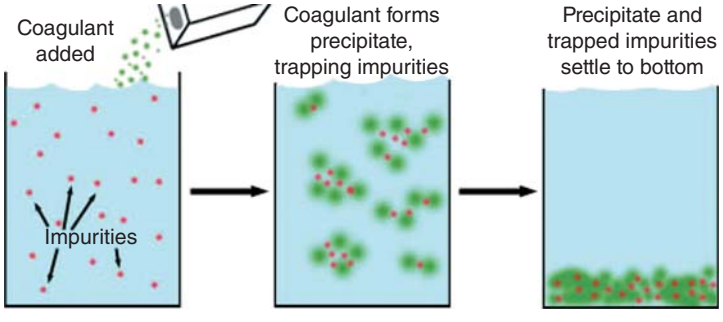


Figure 3.1 *The coagulation process. Source: Reproduced with permission, © Bahadori, A. et al. 2013a* Essentials of water systems design in oil, gas and chemical processing industries, *Springer.*

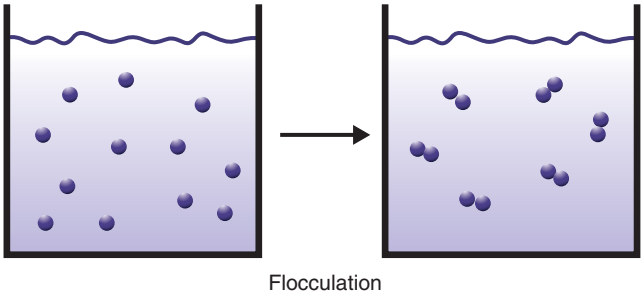


Figure 3.2 *The flocculation process. Source: Reproduced with permission, © Bahadori, A. et al. 2013a* Essentials of water systems design in oil, gas and chemical processing industries*, Springer.*

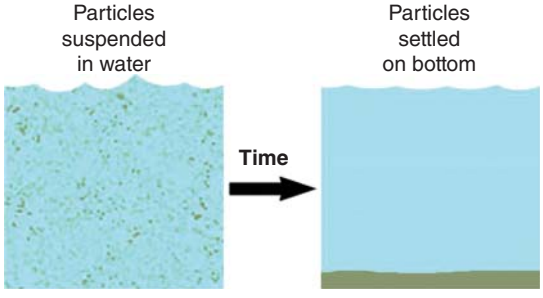


Figure 3.3 *Sedimentation mechanism in wastewater treatment. Source: Reproduced with permission, © Bahadori, A. et al. 2013a* Essentials of water systems design in oil, gas and chemical processing industries*, Springer.*

- to reduce the oil content of American Petroleum Institute (API) separator effluent prior to final discharge
- to reduce color and turbidity
- to remove stabilized, fine oil droplets that are ineffectively removed by gravity separation
- to remove some COD and biochemical oxygen demand (BOD) associated with the non-dissolved material (usually the BOD of the water is hardly affected by the chemical flocculation process)
- to reduce the concentration of sulfides (by using iron salts).

A chemical flocculation unit should include the following major items:

- chemicals storage, metering, and addition units
- flash-mixing
- flocculation
- clarification
- sludge handling, treatment, and disposal.

Design contaminant removal efficiencies for a chemical flocculation unit are shown in Table 3.6.

Table 3.6 Design contaminant removal efficiencies for chemical flocculation units.

Contaminant	Removal efficiencies
Oil	5–25 mg/l residual (depending on the pre-treating facilities of the feed), measured by extraction and infrared analysis
Suspended solids	50–80% removal with a minimum residual of 20 mg/l
Hydrogen sulfide	10% removal
Phenol	10% removal
Five-day BOD	10% removal (based on removal of insoluble BOD)

3.4.2 Design Considerations

- A chemical flocculation unit operating on refinery or petrochemical plant wastewater should generally be preceded by pre-treatment and flow equalization. The type of pre-treatment and the amount of flow equalization vary with the waste and installation, and must be studied for each case. Pre-treatment should include at least sulfides and ammonia stripping facilities, and settling in an API-type or other gravity settler to remove oil and settleable solids.
- Pumping of the flocculated water or subjecting it to any other turbulence should be avoided.
- The flocculation chamber should contain a slow speed mixer which gently agitates the fluid. The mixer should be of a variable speed, mechanical agitator type.
- High temperature can upset the clarifier, so a high temperature alarm in the control room on the sewer water to warn of excessive influent temperature should be provided. In addition, provision of high temperature alarms on critical streams into the sewer should be taken into consideration. pH swings can also upset the clarifier and therefore meters to measure both alkalinity and free mineral acidity, or pH meters with attendant alarms on the sewer water should be provided.
- The alarms should allow diversion to avoid excessive swings in temperature, acidity, alkalinity, or pH.
- Chemicals addition equipment should be designed with sufficient flexibility to allow the addition of acids, alkali, coagulant, and coagulant aid over a range of rates.
- Special attention should be paid to covering the flocculation chamber if required by either air pollution regulations or the relevant company's instructions.

3.4.3 Clarifiers

Secondary circular clarifiers for wastewater (Figure 3.4) are designed to provide a high-quality effluent suitable for discharge to the environment or further treatment. The secondary clarifier effectively separates the biological floc and colloidal solids to produce wastewater with very low levels of organic material and suspended matter.

3.4.3.1 Design Considerations

Solids from the aeration basin settle out in the secondary clarifiers. Some of the solids are recirculated back to the aeration basin to increase the rate of organic decomposition. Solids



Figure 3.4 *Secondary circular clarifier. Source: Reproduced with permission from © Hickory Wastewater Treatment.*

are also pumped out from the secondary clarifiers to control the age of the bugs in the aeration basin.

The treated wastewater runs over the edges of secondary clarifiers. A part of the settled sludge is returned to aeration tanks, where is mixed with "fresh" primary treated wastewater and the bio-oxidation process occurs.

The settled sludge goes to further treatment – anaerobic decomposition in controlled conditions with biogas (methane) production.

(a) A minimum of two clarifiers should be provided. Each clarifier should be designed to operate under the following conditions:
   - Total retention time should not be less than 2 hours, including recycling.
   - The clarifier overflow (rise) rate should not be greater than 2.4 l/day/cm^2.
   - Oil 5–25 mg/l residual (depending on the pre-treating facilities of the feed), measured by extraction and infrared analysis.
   - Suspended solids 50–80% removal with a minimum residual of 20 mg/l.
   - Hydrogen sulfide 10% removal.
   - Phenol 10% removal.
   - Five-day BOD 10% removal (based on removal of insoluble BOD).
   - The system should be designed for a recycle flow rate equal to 100% of the fresh feed to the clarifier.
   - Sludge withdrawal should be designed based on the continuous handling of a flow rate equal to 100% of the fresh feed.

(b) The basins should preferably be circular in shape and of reinforced concrete construction with a bottom slope of 8%. However, rectangular or square basins can also be used depending on space availability and the company's approval.

(c) The minimum side water depth should be 4.5 m. At least 600 mm freeboard above the water depth should be provided.

(d) The unit must be capable of effective operation at all rates from 40% of design to 100% of design.

3.4.3.2 Clarifier Components

- A conical hood should be included in the center of circular clarifiers to separate the flocculation chamber from the clarification chamber.
- The outlet weirs should be level to promote even distribution. Level weirs and the capability to be leveled after installation should be specified. Submerged weirs should be specified where freezing problems are anticipated. Multiple weirs can be employed to reduce the weir rate in both rectangular and circular clarifiers. In circular clarifiers, multiple weirs should be of radial type and should be at least equivalent in length to a circumferential weir. Weirs should be arranged to uniformly collect the effluent over a substantial portion of the surface to promote full utilization of the settling area and reduce short-circuiting.
- The clarified water flows over the weir(s) into a collecting trough or launder which leads it to the outlet pipe. Peripheral effluent launders should be flat-bottomed and sized to result in a velocity of around 0.6 m/s.
- Sludge scrapers should be provided to move the settled floc and contaminants to an outlet in the bottom of the tank. Scrapers in circular clarifiers should move the sludge to a central outlet in the cone bottom of the tank. Sludge scrapers in circular units should be rotated from a central shaft. The rotary mechanism should operate at a relatively low speed (tip speed of around 2.5 cm/s) to avoid disturbance of the settled solids. Circular sludge scrapers should be designed for continuous operation and constant speed driven.
- The sludge should be removed from the clarifiers by the hydrostatic pressure in the tank to a pit outside the clarifier.
- Sludge discharged from the clarifier is usually intermittent and should be controlled by an automated blow-off valve. Provisions should be made in the sludge outlet for back-flushing with water under pressure prior to sludge discharge.
- The frequency and duration of the back-flush and blow-off can be automatically controlled by cycle timers. The sludge withdrawal rate should be frequently regulated by a manually set timing sequence. The setting should be based on the amount of floc that is being formed and the amount of silt and dirt entering the chemical flocculation system. The accumulated sludge in the sludge sump should be recycled back by the sludge pumps to the clarifier influent. Two to five percent of the sludge should be routed to the aerobic digester, sludge thickener, and/or sludge basin.
- The clarifier should be equipped with an oil skimmer in conjunction with an oil moving device. When the chemical flocculation unit is followed by a biox plant, it is particularly important to avoid sending large slugs of oil to the biox unit. The oil moving device usually consists of slowly moving blades that direct settled oil to the skimmer for removal. In circular clarifiers, the oil-moving device should be rotated by a common shaft with the sludge scraper. In rectangular clarifiers, the oil moving device should be of the continuous, flight scraper type.

3.4.4 Chemical Addition Systems

3.4.4.1 Type of Chemicals

- pH adjustment
  Either a basic material or an acid should be consistently added for pH adjustment of the wastewater. Liquid caustic is normally used to raise pH; sulfuric acid is often used to lower it. Acid is normally added with a metering pump, and the acid addition rate is regulated by the pump speed or pump stroke, which is set by the pH controller. A pH meter/controller to control the addition of the basic or acidic material should be provided.
- Coagulants
  Alum is the most commonly used coagulant. It can be used as a solid and as a water solution. If the alum solution requires dilution, it should be diluted to the optimum concentration (determined by testing) with the water to be treated. Dilution water should be added when delivered alum solution is being unloaded, in order to get good mixing. Alum is corrosive, and piping and equipment in alum solution service should be fabricated of corrosion resistant materials.
- Coagulant aids
  Polyelectrolytes are the most commonly used coagulant aids. Jar tests should be performed to determine the most suitable form of polyelectrolyte (cationic, acidic, or neutral) for a particular waste and contaminant. Activated silica may also be used as a coagulant aid. Utilizing of activated silica due to the extremely short self-life is not recommended. Facilities should be provided to add the coagulant aid to both the flash-mix and the slow-mix (flocculation chamber) sections.

3.4.4.2 Polyelectrolyte Handling and Mixing System

Polyelectrolyte handling and mixing system requirements should be a minimum as per the following list. The requirements outlined here are also applicable to any other chemical handling system (where required) and/or liquid polyelectrolyte plus activator.

(a) The polyelectrolyte should be used as a coagulant aid at the influent of the dissolved air flotation unit and the clarifier.
(b) Equipment and facilities should receive the input plant water from the plant source and polyelectrolyte from the concentrated polyelectrolyte containers for ratio balancing and transfer as separate streams to the tank and should also include the control system and electrical terminals. The design concentration of the dilute polyelectrolyte solution should be 1% mass (using liquid) and 0.2% mass (using dry powder).
(c) Tanks should be completed with gauge glass, a hinged cover, and level control connections for drain and pump suction.
(d) The control system should be provided to sequence water and polyelectrolyte flush cycles to prevent undispersed polyelectrolyte from entering the system. Safety circuits should be provided to monitor normal operating conditions and shut down the unit in the event of a component failure. A low-level switch should also be provided on all tanks to stop the relevant pumps when the tank is in low-level conditions.
(e) The system should be located inside a suitable shelter or building.

(f) Suitable material should be used for all equipment and piping.
(g) The system should include but not be limited to the following equipment:
- water pumps (one operating and one spare)
- polyelectrolyte metering pumps (one operating and one spare)
- polyelectrolyte solution tank with minimum capacity of 3 m^3
- activator supply tank with minimum capacity of 2 m^3
- water tank with minimum capacity adequate for 24 hours
- polyelectrolyte inline static mixer(s)
- polyelectrolyte dosing screen conveyor
- polyelectrolyte concentrate tank with minimum capacity of 60 l
- calibration pots on the activator metering pumps suction line
- polyelectrolyte injection pumps to clarifier (one operating and one spare), including a calibration pot on the suction line
- polyelectrolyte injection pumps to a dissolved air floatation (DAF) unit (one operating and one spare), including a calibration pot on the suction line
- polyelectrolyte premix water pumps to a DAF unit (one operating and one spare)
- all necessary instrumentation, including a local control panel.

3.5 Disinfection

Primary, secondary, and even tertiary treatment cannot be expected to remove 100% of the incoming waste load and as a result many organisms still remain in the waste stream. To prevent the spread of waterborne diseases and minimize public health problems, the destruction of pathogenic organisms in wastewater is required. While most of these microorganisms are not pathogens, pathogens must be assumed to be potentially present.

Thus, whenever wastewater effluents are discharged to receiving water that may be used for water supply, or any other purposes, the reduction of bacterial numbers to minimize health hazards is a very desirable goal. When all of the disease-causing organisms are not destroyed during the process, disinfection should be used. In wastewater treatment, disinfection should be accomplished through the use of chemical agents, physical agents, mechanical means, and radiation.

3.5.1 Chemical Agents

Chemical agents that should be used as disinfectants include alcohols, iodine, chlorine and its compounds, bromine, ozone, dyes, soaps and synthetic detergents, quaternary ammonium compounds, hydrogen peroxide, and various alkalis and acids. The characteristics of an ideal chemical disinfectant are shown in Table 3.7.

3.5.2 Mechanical Means of Disinfection

Typical removal efficiencies for various treatment processes are listed in Table 3.8.

Table 3.7 *Characteristics of an ideal chemical disinfectant.*

Characteristics	Remarks
Toxicity to microorganisms	Should have a broad spectrum of activity of high dilutions
Solubility	Must be soluble in water or cell tissue
Stability	Loss of germicidal action on standing should be low
Non-toxic to higher forms of life	Should be toxic to organisms and non-toxic to humans and animals
Homogeneity	Solution must be uniform in composition
Interaction with extraneous material	Should not be absorbed by organic matter
Toxicity at room temperature	Should be effective in environmental temperature range
Penetration	Should have the capacity to penetrate through surfaces
Non-corrosive and non-staining	Should not disfigure metals or stain clothing
Deodorizing ability	Should deodorize while disinfecting
Detergent capacity	Should have cleansing action to improve effectiveness of disinfectant
Availability	Should be available in large quantities and reasonably priced

Table 3.8 *Removal or destruction of bacteria by different treatment processes.*

Process	Percent removal
Coarse screens	0–5
Fine screens	10–20
Grit cambers	10–25
Plain sedimentation	25–75
Chemical precipitation	40–80
Trickling filters	90–95
Activated sludge	90–98
Chlorination or treated sewage	98–99
Fine screens	10–20
Grit cambers	10–25

3.6 Chlorination

Chlorination is by far the most common method of wastewater disinfection and is used worldwide for the disinfection of pathogens before discharge into receiving streams, rivers or oceans. Chlorine is known to be effective in destroying a variety of bacteria, viruses, and protozoa, including Salmonella, Shigella, and Vibrio cholera. Today, wastewater chlorination is widely practiced to reduce microbial contamination and potential disease risks to exposed populations.

Figure 3.5 shows a chlorine contact chamber. The contact chamber is maze shaped to allow the chlorine to completely mix with the water. Extra chlorine residual is removed by sulfur dioxide. Chlorination plays a key role in the wastewater treatment process by removing pathogens and other physical and chemical impurities. Chlorine's important benefits to wastewater treatment are:

- disinfection
- controlling odor and preventing septicity
- aiding scum and grease removal
- controlling activated sludge bulking
- controlling foaming and filter flies
- stabilizing waste-activated sludge prior to disposal
- foul air scrubbing
- destroying cyanides and phenols
- ammonia removal.

The principal uses of chlorine and its compounds are listed in Table 3.9.

3.6.1 Chlorine Dosages

Typical chlorine dosages for disinfection are shown in Table 3.10.



Figure 3.5 *Chlorine contact chamber. Source: Reproduced with permission from © Hickory wastewater treatment.*

Table 3.9 *Chlorination applications in wastewater collection and treatment.*

Application	Dosage range (mg/l)	Remarks
Collection		
Slime-growth control	1–10	Control of fungi and slime-producing bacteria
Corrosion control (H_2S) (per mg/l of H_2S)	2–9	Control brought about by destruction of H_2S in sewers
Odor control (per mg/l of H_2S)		Especially in pump station and long flat sewer
Treatment		
Grease removal	2–10	Added before preparation
BOD reduction (per mg/l of BOD, destroyed)	0.5–2	Oxidation of organic substance
Ferrous sulfate oxidation, $6FeSO_4$, $7H_2O + 3Cl_2 \rightarrow 2FeCl_3 + 2Fe2(SO_4)3 + 42H_2O$	Based on reaction stoichiometry	Production of ferric sulfate and ferric chloride
Filter-pounding control	1–10	Residual at filter nozzles
Filter-fly control	0.1–0.5	Residual at filter nozzles, used during fly season
Sludge-bulking control	1–10	Temporary control measure
Digester supernatant oxidation	20–140	—
Digester and Imhoff tank	2–15	—

3.6.2 Design Considerations

(a) Each chlorinator unit should include a chlorinator, any necessary manifold valving for the chlorinator cylinders, an ejector, a chlorinator flowrate indicator and adjusting valve, a strainer and all necessary solution feed and vacuum tubing, valves, adapters, check valves, etc.
(b) Separate housing for the chlorination system with forced ventilation that has start-up bottom at room entrance should be supplied.
(c) Chlorine cylinders with handling equipment should be provided.
(d) A space heater should be provided for the room.
(e) The chlorinators should be manually operated on an intermittent push-button start-up basis, with all vacuum gauges and a rotameter located on the front of the panel. The rate of chlorine feed should remain constant until manually changed.
(f) The chlorine feed rate, when set, should be maintained within less than 3% error. Operation should be continuous and intermittent.

Table 3.10 Typical chlorine dosages for disinfection.

Effluent from	Dosage range (mg/l)
Untreated wastewater (prechlorination)	6–25
Primary sedimentation	5–20
Chemical precipitation	2–6
Trickling filter plant	3–15
Activated sludge plant	2–8
Multimedia filter following activated sludge plant	1–5

(g) The chlorinator should be equipped with an ejector assembly of the chlorine water solution type utilizing water pressure to produce the vacuum in the chlorine system. The ejector should be constructed of corrosion-resistant plastic and the ejector nozzle should be of the fixed throat orifice type. The ejector nozzle should be precisely engineered for given hydraulic conditions such that the chlorinator should operate efficiently over the full range of its operating capacity. The ejector should contain a diaphragm-type check valve to prevent water from entering the chlorinating system when water flow is shut down.

(h) The chlorinator should be constructed of materials suitable for wet and dry chlorine gas service. All springs used in the chlorinator should be of hastelloy C.

(i) The cabinet should be of plastic fiberglass, floor-mounted, self-supporting, and suitable for indoor installation.

(j) All necessary chlorine valves, flexible connectors, fittings, etc. and any additional items as required for an operable unit should be provided. The basic instruments should be as follows:
- gas inlet pressure gauge
- outlet vacuum gauge
- rota-meter (easily visible for flow adjustment from the front of the unit)
- spring-loaded diaphragm actuated pressure relief valve (for use if pressure is excessive or when excessive air develops)
- chlorine gas shut-off valve for interrupted water flow or loss of vacuum.

(k) The chlorinator should be provided with a heated trap.

(l) The chlorinator should be provided with an indicator in the cabinet to indicate when chlorine supply is exhausted or shut-off.

(m) The following accessories should be included:
- header valves and double unions at each chlorinator inlet
- auxiliary valves, flexible connections, and header valves at each chlorine container
- in-line chlorine pressure switch with adjustable contacts.

3.7 Water Monitoring

Monitoring may be necessary for a number of reasons:

(a) to measure water problems (what, where, why, when)

(b) to measure waste parameters for use in calculation of waste treatment charges for a municipal or regional treatment system
(c) to measure waste parameters to allow detection and triggering of emergency actions in case of spills or process upsets
(d) to measure the effect of wastewater discharge on the quality of a receiving body of water
(e) to measure the quantity and quality of all process wastes as well as influent liquid raw materials
(f) to gather enough information on water used and contamination to allow design of pre-treatment and/or reclamation systems.

Oil, gas, and chemical industries discharging to municipal or regional treatment systems must monitor their wastewater discharges or allow monitoring by others.

3.7.1 Design Considerations for a Water Monitoring System

The following questions should be addressed when preparing to establish a water monitoring program:

(a) What must be or should be monitored?
(b) When should samples be collected and monitoring equipment located?
(c) How should monitoring be done (collection of samples, storage, analysis)?

These four questions cannot always be completely answered in the sequence shown; usually information is gathered and tabulated and several questions are answered simultaneously. Conflicts may arise with selection of a monitoring station at a hazardous location because the proper type of explosion-proof equipment necessary for the area is not available or is prohibitively expensive. In this case the "where" and "how" are not compatible and a compromise must be made. The parameters and equipment that should be monitored are covered in the following sections.

3.8 On-Site Portable Instruments for Water Pollution Control

An effort has been made to present the most appropriate methods and equipment that apply as generally as possible for monitoring surface water, groundwater, cooling or circulating water, boiler water, boiler feed water, wastewater effluents after varying degrees of treatment, and untreated municipal or industrial wastewater.

An effort has been made to present methods and equipment of the widest possible application, but when samples of highly unusual composition are encountered, this equipment may require modification or may be wholly inappropriate.

All parameters mentioned in previous sections of this chapter could be monitored by excluding organic and radioactive substances.

This equipment has been developed to meet the need for a simplified, convenient, accurate means of testing water in the field. Colorimetric tests are made with a colorimeter using pre-calibrated meter scales for direct read-out.

Volumetric tests are conducted by titration using a unique burette and titration stand with a precision screw plunger. This dispenses titration solution so that accurate, reliable results are obtained from test to test.

3.8.1 Alternative Current Colorimeter

As mentioned above the basic of measurement is colorimetric which some reagent could be added to water sample to produce colored solution. This should be tested later. The type of portable instrument can be determined by the relevant authorities.

See also the technical data in Table 3.11 for more information:

3.8.1.1 Calibration and Inspection

- In general this type of instrument is factory calibrated, but it can also be calibrated by a competent person in accordance with the manufacturer's recommended standard.
- All reagents and chemicals must be fresh or in case of changing color and precipitation replaced by new one.

3.8.2 Online Fixed Measurement or Continuous Monitoring

The use of continuous monitoring equipment permits the frequent measurement of several water quality parameters and the recording of this data at the measurement site or transmission to another location.

3.8.3 Continuous Water Sampling and Clarification System

Monitoring instruments should contain a sampling module, the sensors, a signal conditioning module, and a data logging or transmission module. A continuous flow of sample must be provided to the sensors by a submersible pump.

Each sensor in the instrument should be supplied with its own signal conditioner, which converts the input to a standard electrical output. See Table 3.12 for more detail on sensors and ion selective electrodes.

A typical electrode placement for continuous monitoring is shown in Figure 3.6. Further information is given in ASTM Volume 11.01, 1989.

3.8.3.1 Calibration and Inspection

Calibration of the sensor signals should be carried out by adjustment of the controls on the signal conditioner.

The sample intake should be shielded with a screen and must be inspected according to manufacturer's instructions to prevent debris from clogging the system or damaging the pump.

3.8.4 Laboratory Instruments

All parameters described in the following sections could be monitored in laboratory using instrumental or wet chemical methods.

Table 3.11 *Technical data.*

Alkalinity
Titration for phenolphthalein and total alkalinity
Enough of each indicator for 100 tests
Enough titrant for 100 average (125 ppm) tests

Carbon dioxide
Standard titration procedure; enough reagent for approximately 100 tests

Chloride
Mercuric nitrate titration
Colorimetric range: 0–1.5 ppm N, 100 tests; 0–15 ppm N
Enough reagent for approximately 100 tests

Chlorine
Improved orthotolidine method
Colorimetric range: 0–1 ppm
Enough reagent for 60 tests

Diphenylcarbohydrazide method
Improved Winkler method
Alkaline colorimetric range: 0–1.5 ppm
Enough reagent for approximately 100 titration 1 drop = 1 ppm tests

Color
Colorimetric range: 0-500 APHA
Platinum-cobalt units
No reagents required

Copper
Cuprethol method
Colorimetric range: 0–3 ppm
Enough reagent for approximately 100 tests

Fluoride
SPADNS method
Colorimetric range: 0–2 ppm
Enough reagent for approximately 10 tests

Hardness, calcium
EDTA titration method
Enough reagent for approximately 100 tests

Hardness, total
EDTA titration method
Enough reagent for approximately 100 tests

Hydrogen sulfide
Screen test color chart comparison 1–5 ppm
Enough test papers for 100 tests

Iron
Simplified phenanthroline method
Colorimetric range: 0–3 ppm
Enough reagent for approximately 100 tests

Manganese
Cold periodate oxidation method
Colorimetric range: 1–10 ppm
Enough reagent for approximately 100 tests

Nitrate, nitrogen
Cadmium reduction-diazotization method
Colorimetric range: 0–1.5 ppm N, 0–150 ppm N
Enough reagent for 100 tests

Nitrite, nitrogen
Diazotization method
Colorimetric range: 0–0.2 ppm N
Enough regent for approximately 100 tests

Oxygen dissolved
Improved Winkler method
Alkaline colorimetric range: 0–1.5 ppm
iodide-azide modification
Enough reagent for approximately 100 titration 1 drop = 1 ppm tests, 1 drop = 0.2 ppm
Enough reagent for approximately 100 tests

pH, wind range
Colorimetric range: 4.0–10
No reagents required
Enough reagent for approximately 100 tests

Phosphate, ortho and meta
Stannous reduction method
Colorimetric range: 0–3 ppm
Colorimetric range 0–2 ppm and 0–8 ppm
Enough reagent for approximately 100 tests

Silica
Heteropoly blue method
Colorimetric range: 0–3 ppm
Enough reagent for approximately 100 tests

Sulfate
Turbidimetric method
Range: 0–300 ppm
Enough reagent for approximately 100 tests

Turbidity
Absorption method
Range: 0–500 JTU
No reagents required

Table 3.12 *Electrodes and ion-selective.*

Ion determined	Recommended reference electrode
Ammonia	Not applicable
Ammonium	Calomel
Barium	Calomel
Bromide	Double junction
Cadmium	Calomel
Calcium	Calomel
Chloride	Double junction
Copper	Calomel
Cyanide	Double junction
Fluoride	Double junction
Fluoroborate	Not applicable
Iodide	Double junction
Lithium	Double junction
Nitrate	Double junction
Oxygen	Not applicable
Potassium	Double junction
Silver/sulfide	Double junction
Sodium	Double junction
Sulfur	Not applicable

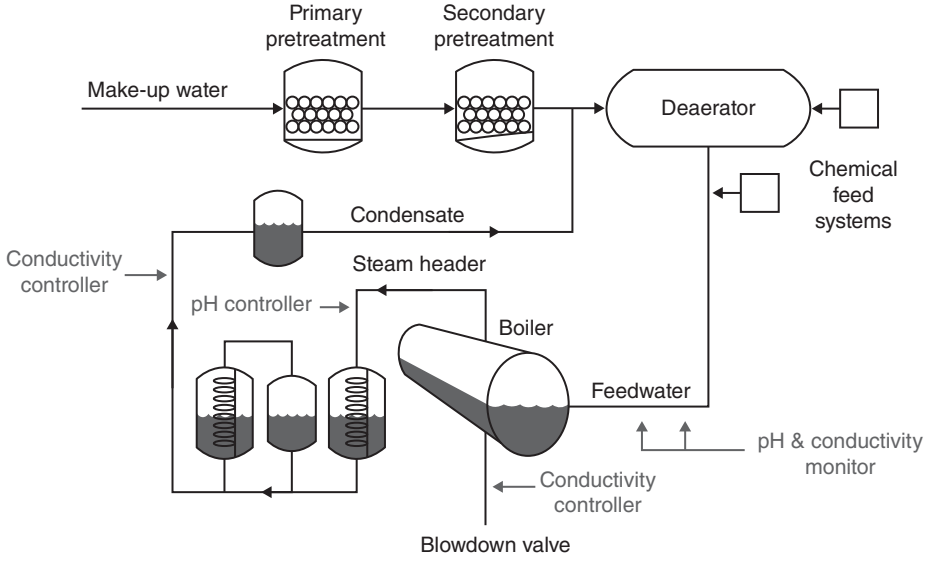


Figure 3.6 *Continuous water sampling and monitoring system.*

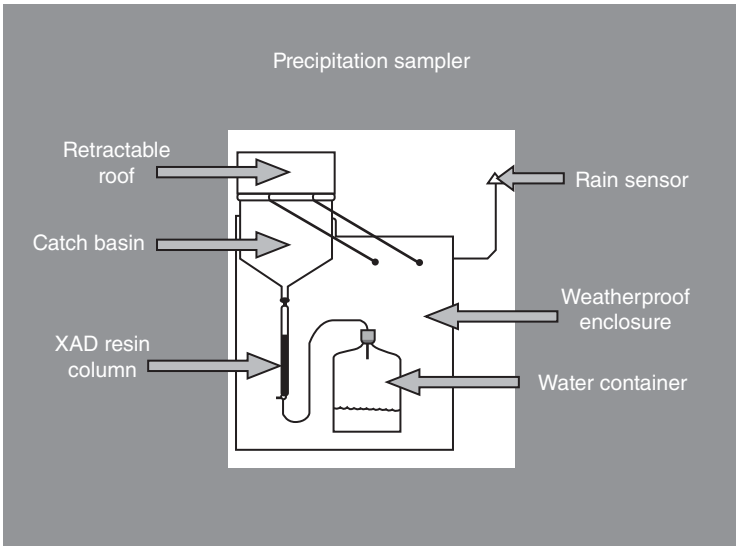


Figure 3.7 *Sampling of atmospheric precipitation.*

3.8.4.1 Collection and Preservation of Samples

- Sampling of different sources
  A summary of different kinds of sampling is given here. For more details see BS 6068-6.2, Water Quality Sampling.
- Sampling of atmospheric precipitation
  Atmospheric precipitation usually occurs in discrete events of limited duration.
- Sampling precipitation equipment
  Equipment for sampling precipitation includes a polyethylene polypropylene bucket and a stand.
- Construction
  The basic equipment is shown in Figure 3.7. It can be operated manually or automatically.
- The equipment must be designed to minimize pollution during its operation. It should be manufactured from chemically inert materials to avoid contamination.
- Surface water samples are usually taken directly into the sample container. It is not possible to take the sample by submerging the container by hand; laboratory forceps or a holder with a sliding sleeve should be used. For such sampling the container, which should have a volume of at least 2 l is usually made of stainless steel.

3.8.5 Soil Water Sampling

Soil water is defined as being all of the water contained in the soil.

- Soil water sampling system
  A common soil sampling system comprises a ceramic vessel with two pressure (vacuum) hoses inserted into it. The system operates by developing a vacuum through one hose, which causes the soil water to be drawn in through the porous walls of the vessel.

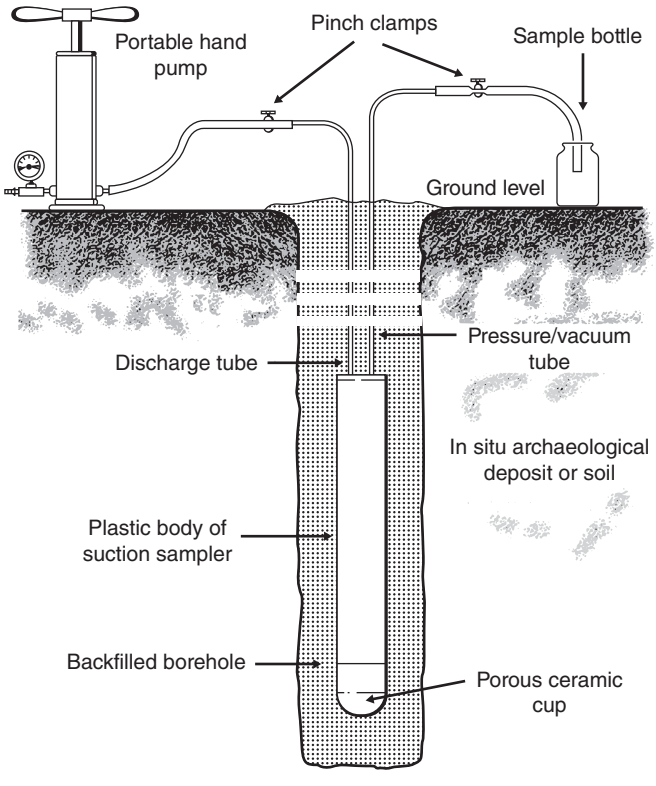


Figure 3.8 *The installation of a suction sampler. Source: Intarch.*

- Construction
  A schematic of a soil water sampler is shown in Figure 3.8.

3.8.6 Groundwater Sampling

The sampling of groundwater is usually carried out with devices and equipment very similar to that used for surface water.

Similar containers are used for groundwater, mainly glass or polythene bottles.

3.9 Physical Examination

3.9.1 Color

Color in water may result from the presence of metallic ion humus and peat materials, plankton, weed, and industrial waste.

The unit of color produced by 1 mg/l platinum in the form of the chloroplatinate ion.

For color monitoring see ASTM D 1882-00 and BS 2690: Part 9, 1970.

3.9.2 Conductivity

Conductivity is a numerical expression of the ability of a water sample to carry an electric current and is measured in μ moh/cm^2. The magnitude of the conductivity depends on the total concentration of ionized substances dissolved in the water. See also BS 2690: Part 9, 1970.

- Conductivity instruments
  Measurement of electrical conductance is usually based on the use of conductivity bridges (e.g. Whetstone bridge). The bridge circuit should always be arranged so that at the balance point the detector indicates either zero or minimum potential.
- Determination of the conductivity of the solution
  We know that conductivity is the reciprocal of resistance and the resistance is frequently determined by means of some form of Wheatstone bridge circuit. However, when direct current is passed through the solution following difficulties arise:
  (i) The concentration of the charges.
  (ii) The polarization set in due to the substance liberated at electrodes. With the result, a back E.M.F. is set up and the resistance of the electrolyte is altered. These difficulties can be avoided as follows:
    (a) *By using an alternating current*. The polarizing effects of the deposition of substances due to the current in one direction are neutralized by the effect of the current in the other direction.
    (b) *By increasing the surface of the electrodes*. Polarization is decreased further if the surface of the electrodes is increased. This is done by coating the electrodes in the cell with finely divided platinum.
    (c) *By using an oscillator*. To obtain better results the induction coil is replaced by an oscillator with a frequency of 2000–4000 cycles per second.
- Method:
  The solution of an electrolyte whose conductivity is to be determined is put into a conductivity cell. This is made of pyrex glass and is fitted with platinum electrodes. The electrodes usually consist of stout platinum plates sealed into glass tubes which pass through mercury placed in the tubes. The relative positions of the electrodes are fixed by cementing the tubes to the ebonite cover. The electrodes are coated with finely divided platinum. To maintain a constant temperature it is placed in a thermostat. Copper wires are dipped in mercury placed in glass tube to make connections.
- Determination of specific conductivity
  The cell is connected to a resistance box, R on one side and thin uniform wire AB of meter bridge on the other secondary of induction coil is connected to the ends of the V bridge while the primary is connected to a battery. The headphone, G is connected to a sliding key, P and the binding screw in between the cell and resistance box.

  The sliding key, P is placed near the middle. When the circuit is complete, a buzzing sound is heard in the headphone. Plugs are taken out from the resistance box. The sliding key is moved along the wire until the sound in the headphone is reduced to a minimum. Thus point H is recorded. The observed conductivity of solution is then calculated by applying the following formula:

$$\text{resistance of solution} = (\text{BH}/\text{AH}) \times \text{R}$$

or

$$1/(\text{obs.conductivity}) = (\text{BH}/\text{AH}) \times \text{R}$$

AH and BH are measured on a graduated scale and R is measured in ohms from the resistance box.

3.9.3 Turbidity

Turbidity is an expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through a sample.

Turbidity in water is caused by the presence of suspended matter, such as clay, silt, finely divided organic and inorganic matter, plankton, and other microscopic organisms. See also BS 2690: Part 9, 1970.

3.9.4 Determination of Metals

The presence of metals in potable water, domestic wastewater, and industrial effluents is a matter of serious concern. Metal content can be monitored by atomic absorption spectroscopy, polarography, inductively coupled plasma, and colorimetric methods.

3.9.4.1 Atomic Absorption Spectroscopy

In atomic absorption the sample is atomized into a flame, producing atomic vapor of the elements in question. The atoms absorb radiation from a light source and the amount of light absorbed is proportional to the amount of the element.

- Atomic absorption instrument
  Figure 3.9 shows schematic diagram of an atomic absorption spectrometer. A mechanical modulated chopper alternately passes and reflects the light beam. One beam by-passes the sample and its intensity is measured as I_0 the sample's beam is measured as I_1. The absorbed light is as $I_0 - I_1$.
- Calibration
  The instrument should be calibrated according to the manufacturer's manual. Toxic pollutants such as Pb, As, and Hg with low concentrations (parts per billion, ppb) should be monitored using a special device (vapor Generation and Hydride Generation) that can be installed on the spectrometer.

3.9.5 Polarography

Electrochemical methods are used for analysis of raw water and wastewater. Polarography measurement is based on determining the time-averaged current of a dropping mercury electrode (DME) under diffusion conditions.

- Chloride: Chloride, in the form of Cl ions, is a major inorganic anion in water and wastewater. It can be monitored by titrimetric, potentiometric, and ion selective electrode methods. More detail can be found in ASTM D 512-2004.

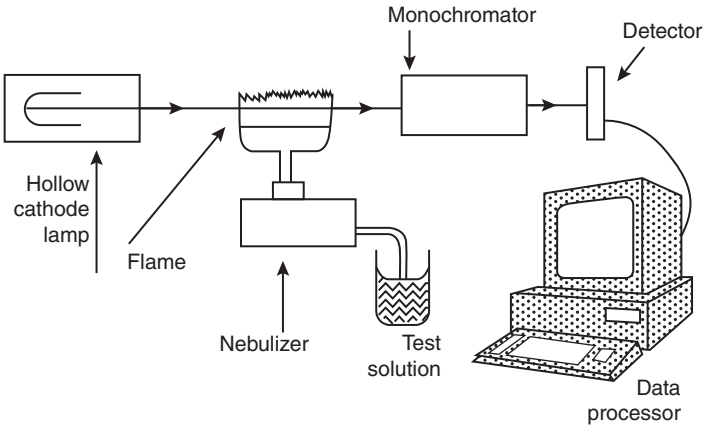


Figure 3.9 Atomic absorption spectrometer.

- Chlorine (Residual): The chlorination of water supplies and polluted water destroys or deactivates disease, producing microorganisms. Chlorination improves water quality by reaction with ammonia, iron, manganese, sulfide and some organic substances. Chlorination is monitored by titrimetric colorimetric techniques. More detail can be obtained in ASTM D 1253-2003.
- Cyanide, Fluoride, and Iodide: These three pollutants can be measured by titrimetric and/or colorimetric methods (UV-VIS spectroscopy) and ion selective electrodes.
- Nitrogen (Ammonia, Nitrate, and Organic): Nitrogen can be monitored by titrimetric and/or colorimetric methods.
- Ozone: Ozone can be measured by a titrimetric method, as described in ASTM Volume 11.02.
- pH Value: The pH of a solution is defined as the logarithm of the reciprocal of the hydrogen ion concentration. Detail on effect of pH could be provided in API, manual on disposal of refinery wastes volume on liquid wastes, Chapter 2. pH can be monitored using an electronic pH meter. The pH meter is calibrated using standard buffer solution with known pH.
- Phosphate: Phosphate content should be monitored by the colorimetric method. For more detail see ASTM 11.02 and BS 6068 Section 2.28 (1986).
- Silica: Silica concentration can be measured by calorimetric or gravimetric methods. For more detail see ASTM 11.02.
- Sulfate: Sulfate can be measured by the gravimetric method.
- Sulfide: Sulfide can be measured by colorimetric and titrimetic methods.

3.9.6 Determination of Organic Constituents

3.9.6.1 Grease and Oil

- Solvent extraction infrared absorption
  The oil is extracted from sample and the infrared absorption of the oil in solution is then measured.

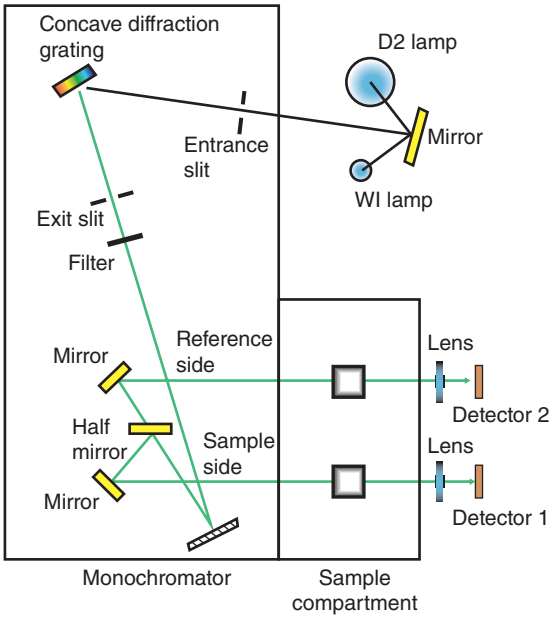


Figure 3.10 *Double-beam spectrophotometer. Source: Instrumentation Analog.*

- Infrared spectrophotometry
  Radiation from the source is split into two beams, half passing into the sample cell and the other half into the reference cell. The reference beam then passes through an attenuator and onto a chopper. After dispersion by a prism or grating, the alternating beams fall on the detector and are converted to an electrical signal. A double-beam spectrophotometer is shown in Figure 3.10. Calibration of instrument should be according to the manufacturer's manual.

3.9.7 Combustible Gas Indicator

The partial pressure of methane can be determined using a combustible gas indicator. An equilibrium is established between methane in solution and the partial pressure of methane in the gas phase above the solution. The heat generated by the oxidation of the gas increases the electrical resistance of the filament. The resulting imbalance of the electrical circuit causes deflection of a milliammeter.

3.9.8 Total Organic Carbon

Total organic carbon (TOC) can be monitored by a carbon analyzer in the range of 1–150 mg/l in water and wastewater. A microportion of sample is injected into a heated packed tube in a stream of oxygen or purified air. The water is vaporized and the organic matter is oxidized to carbon dioxide, which is measured by means of a nondispersive type of infrared analyzer.



Figure 3.11 COD analyzer.

3.9.9 Biochemical Oxygen Demand

The BOD is a test in which standardized laboratory procedures are be used to determine the relative oxygen requirements of wastewater, effluent, and polluted water. See ASTM Volume 11.02 and BS 6068 Section 2.3 (1984).

3.9.10 Chemical Oxygen Demand

COD is an important parameter for stream and industrial waste control. Dry CO_2 carries the organic matter through a platinum catalytic combustion furnace which oxidizes it to CO and H_2O. Following water removal and passage through a second catalytic treatment, the CO concentration is measured using an infrared analyzer. A COD analyzer is shown in Figure 3.11.

3.9.11 Examination of Water and Wastewater Radioactivity

The radioactivity in water and wastewater can originate from either natural or artificial sources. Artificial sources of radioactivity include fission, fusion, and particle acceleration, giving rise largely to alpha, beta and gamma radioactivity.

The room in which the radioactivity is to be measured should be free of any dust and fumes that may affect the electrical stability of instrument. The background should be stabilized and lowered considerably by making the walls, floor, and ceiling out of several centimeters of concrete. Generally, the temperature should be constant within 3 °C and should not exceed 30 °C.

Samples containing appreciable activity should be stored at a distance so as not to affect instrument background counting rate.

3.9.11.1 Alpha Particle Counter

An alpha particle counter consists of either a proportional detector or a scintillation detector, plus a scaler conforming to the following requirements. For the method of use see ASTM 11.02 1989.

- Proportional detector
  This may be one of several commercially available types. The material used in the construction of the detector should be free from detectable radioactivity. The manufacturer should supply voltage plateau and background counting rate data. The voltage plateau data should show the threshold voltage, slope, and length of plateau for a particular input sensitivity.
- Scintillation detector
  This consists of an "activated" zinc sulfide phosphor with a minimum effective diameter of 36.5 mm. The phosphor should be mounted so that it can be attached and optically coupled to a multiplier photo tube.
- Scaler
  A mechanical register, a power supply, and an amplifier are contained in a single chassis, generally termed the scaler.
- Sample mounting disks or dishes
  These should have a flat bottom of a diameter slightly less than the inside diameter of the detector. Flat disks are preferred, but dishes could be used that have 3.2 mm high side walls. Platinum and stainless steel have been used to make these disks.
- Calibration and standardization for general monitoring
  Place a known amount of alpha standard into a volume of water sufficient to dissolve salts equivalent to those of the test samples and prepare for counting.

3.9.11.2 Beta Particle Counter

The beta particle radioactivity of water and wastewater is monitored by a beta particle counter, which consists of the following components:

- Detector
  The end-window Geiger-Muller tube and the internal or external proportional gas-flow chamber are the two most widely available types of detector.
- Detector shield
  The detector assembly should be surrounded by an external radiation shield of massive metal equivalent to approximately 51 mm of lead and lined with 3.2 mm thick aluminum.

3.9.11.3 Gamma-Ray Monitoring

Gamma-ray emitting radionuclides are monitored in water or wastewater by means of gamma-ray spectrometry.

- Gamma-ray instrument
  Gamma-ray spectra are measured with modular equipment consisting of a detector, analyzer, memory, and permanent data storage device. Lithium-drifted detectors, P-type or N-type, are used. A multichannel pulse-height analyzer should be used to determine the amplitude of each pulse originating in the detector.

3.10 Automated Laboratory Equipment for Monitoring Water and Wastewater

Automated instruments are available and can be used to monitor individual samples at rate of 10–60 samples/hour. The same instruments can be modified to simultaneously analyse for multiple constituents from one sample. The read-out system includes sensing elements with indicators, alarms, and recorders.

Appropriate methodology can be supplied by the manufacturer for many common constituents of water and wastewater.

3.10.1 Loading Losses

3.10.1.1 Total Volatile Organic Compound Estimation

Emissions from the loading petroleum liquid can be estimated (with a probable error of ±30%) using the following equation:

$$LL = 0.12 \times SPM/T \tag{3.3}$$

where:

LL = volatile organic compound loading loss (kg/m^3 of liquid loaded)
S = a saturation factor (see Table 3.13)
P = true vapor pressure of liquid loaded (kilopascals, kPa)
M = molecular weight of vapors (kg/kg-mole)
T = temperature of bulk liquid loaded (K, i.e. °C + 273).

The saturation factor S accounts for the variations observed in emission rates from different loading and unloading methods. Table 3.13 lists suggested saturation factors.

Table 3.13 *Saturation(s) factors for calculating petroleum liquid loading losses.*

Cargo carrier	Mode of operation	*S* factor
Tank trucks and rail	Submerged loading of a clean cargo tank	0.5
Tank cars	Submerged loading: dedicated normal service	0.6
	Submerged loading: dedicated vapor balance service	1
	Splash loading of a clean cargo tank	1.45
	Splash loading: dedicated normal service	1.45
	Splash loading: dedicated vapor balance service	1
Marine vessels	Submerged loading: ships	0.2
	Submerged loading: barges	0.5

Emissions from controlled loading operations can be calculated by multiplying the uncontrolled emission rate (determined using the equation above) by a reduction efficiency term:

$$\text{controlled emission} = \text{uncontrolled emission} \times (1 - \text{efficiency}/100) \quad (3.4)$$

The overall reduction efficiency should account for the capture efficiency of the collection system, as well as both the efficiency and any downtime of the control device. This data should be obtained from the supplier or manufacturer of the collection system.

3.10.2 Emissions to Water

This section is divided into two parts:

- point source wastewater discharges as released by refinery treatment plants
- diffuse wastewater that arises through stormwater and other miscellaneous runoff from the refinery site that is not captured and treated prior to discharge.

3.10.2.1 Point Source Discharge

The following tables provide "default" emission data for refinery effluent discharges that are not classified as transfers (transfers include discharging to sewers).

Based on discussions with the petroleum refining industry, the dissolved organic carbon (DOC) content of refinery effluents is a known parameter. Hence, the speciation factors for organic compounds in Table 3.14 are based on this parameter.

The document from which the data in Table 3.14 were derived indicates a DOC/COD ratio of 0.267. In the absence of site-specific information regarding the DOC, this ratio can be used to determine the DOC from measurements of COD.

A similar parameter to DOC was not identified for trace elements and other inorganics in wastewater effluent. Therefore, trace elements and inorganic compound emissions are expressed as default emission factors in Table 3.15.

Table 3.14 *Default speciation factors for organics in refinery effluent.*

Substance	Weight percent of DOC
Toluene	9.2×10^{-4}
Benzene	9.1×10^{-4}
Xylenes	1.4×10^{-3}
Phenol	6.9×10^{-4}
1,2-Dichloroethane	2.7×10^{-4}
Hexachlorobenzene	4.4×10^{-6}
PAHs	1.6×10^{-3}
Styrene	1×10^{-4}
Ethylbenzene	1.2×10^{-4}
1,1,2-trichloroethane	3.6×10^{-5}
Chloroform	2.5×10^{-3}

Table 3.15 *Default emission factors for trace elements and inorganics in refinery effluent.*

Substance	Emission factors (kg/m^3 of flow)
Zinc	4.4×10^{-4}
Phosphorous	4.1×10^{-7}
Arsenic	6.7×10^{-6}
Chromium (VI)	7.7×10^{-6}
Selenium	3.1×10^{-6}
Nickel	3.6×10^{-6}
Copper	2.9×10^{-6}
Antimony	5.8×10^{-7}
Cobalt	1.6×10^{-6}
Mercury	1.1×10^{-8}
Cadmium	3.3×10^{-7}
Lead	1.9×10^{-6}
Cyanide	7.6×10^{-9}
Ammonia	1.3×10^{-6}

These speciation factors are applied to this effluent parameter in the following manner:

$$WWE_i = DOC \times (WP_i/100) \times \text{flow} \tag{3.5}$$

where:

WWE_i = wastewater emission of component i from the treatment plant (kg/h)
DOC = DOC content of the treated effluent discharged by the plant (kg/m^3)
WP_i = weight percent of component i
flow = wastewater flowrate discharged to the receiving body of water (m^3/h).

The emission factors in Table 3.15 are applied in the same way as factors are applied to air emissions, with the exception that they are based on the flow of effluent from the treatment plant (i.e. the emission factors are kg/m^3 of wastewater flow).

4

Biological Treatments

Biological treatment – the use of bacteria and other microorganisms to remove contaminants by assimilating them – has long been a mainstay of wastewater treatment in the chemical process industries. Many biological treatment options are effective and widely used today.

They are, however, not all created equal, and the decision to install a biological-treatment system requires ample thought. When considering biological wastewater treatment for a particular application, it is important to understand the sources of the wastewater generated, typical wastewater composition, discharge requirements, events, and practices within a facility that can affect the quantity and quality of the wastewater, and pre-treatment ramifications.

4.1 Theory

The objectives of the biological treatment of wastewater are to coagulate and remove the non-settleable colloidal solids and stabilize the organic matter. For domestic wastewater, the major objective is to reduce the organic content and, in many cases, nutrients such as nitrogen and phosphorus.

In many locations, the removal of trace organic compounds that may be toxic is also an important treatment objective. For industrial wastewater, the objective is to remove or reduce the concentration of organic and inorganic compounds. Pre-treatment will be required because many compounds in industrial wastewater are toxic to microorganisms.

Depending on the type of wastewater being treated, as well as its level of biodegradability and toxicity, a series of physical, chemical, and biological processes are combined in order to remove different forms of carbon, nitrogen, and phosphorus present in the water, among other elements, in order to achieve the maximum possible efficiency in the treatment. Compared with physical and chemical processes, biological processes are considered to be efficient and cost-effective; in most cases they will be the treatment of preference for a diverse range of wastes.

Waste Management in the Chemical and Petroleum Industries, Second Edition. Alireza Bahadori.
© 2020 John Wiley & Sons Ltd. Published 2020 by John Wiley & Sons Ltd.

All biological treatment reactors are designed using mass balance calculations. These are calculated for each of the "electron donor" constituents of interest that are entering or leaving the system, along with their rates of depletion or production within the system, as well as the flow rates crossing a defined volume, which are measured as mass per unit volume per unit time. Reactors are designed to operate with high microorganism concentrations, but their overall rate of metabolism is controlled by the limiting substrate concentration.

Monod kinetics are most commonly used to model the relationship between the residual concentration of substrate that limits the microbial specific growth rate and the maximum specific growth rate of biomass obtained as a function of the substrate utilization. This is given by the equation:

$$\mu = \mu_{\max} \frac{S}{K_S + S} \tag{4.1}$$

where:

μ = specific growth rate (per day)
$\mu_{\max}$ = maximum growth rate at saturation concentration of growth limiting substrate (per day)
S = substrate concentration (mg/l)
K_s = half saturation constant (mg/l), which is the concentration of limiting substrate at which the specific growth rate equals one-half of the maximum specific growth rate ($\mu = \mu_{\max}/2$).

The specific growth rate μ corresponds to the change in biomass per day (related to the amount of biomass present) and is a function of the substrate concentration. The maximum bacterial specific growth rate relates to the maximum specific substrate utilization rate and occurs at high substrate concentrations. Hence when cells grow rapidly in the presence of non-limiting substrate concentrations they make their maximum investment of energy in cell synthesis. However, when the substrate concentration (electron donor) is limited, a larger portion of the energy obtained from the substrate oxidation must be used for cell maintenance.

A loss term not explicitly included in the standard Monod equation (Eq. (4.2)) is endogenous decay. Endogenous decay includes cell mass losses derived from the oxidation of internal storage products for energy used for cell maintenance, cell death and lysis, and predation by organisms higher in the food chain. As the endogenous decay may also affect the specific growth rate μ, in practice the endogenous decay is also commonly considered by engineers in the Monod equation as follows:

$$\mu = \mu_{\max} \frac{S}{K_S + S} - K_d \tag{4.2}$$

where:

μ = specific growth rate (per day)
$\mu_{\max}$ = maximum growth rate at saturation concentration of growth limiting substrate (per day)
S = substrate concentration (mg/l)

K_s = half saturation constant (mg/l), which is the concentration of limiting substrate at which the specific growth rate equals one-half of the maximum specific growth rate ($\mu = \mu_{max}/2$)
K_d = endogenous decay.

The ratio of the amount of biomass produced to the amount of substrate (electron donor) consumed is defined as the biomass yield coefficient Y and is expressed as mass (or mole) of organism produced per mass (or mole) of substrate consumed. As a definitive stoichiometric relationship exists between the substrate removed and the observed biomass yield, the expression of yield can also be combined with the Monod equation to give the rate of substrate utilization as follows:

$$\frac{ds}{dt} = -\frac{\mu}{Y}X \tag{4.3}$$

where:

s = concentration of substrate (mg/l)
t = time (days)
μ = specific growth rate (per day)
Y = yield coefficient
X = concentration of microorganisms (mg/l).

In summary, the performance and efficiency of biological processes are directly linked to the dynamics of substrate utilization and microbial growth. Therefore the effective operation of biological systems requires an understanding of the types of microorganisms that are involved, the specific reactions that they perform and their nutritional needs and kinetics.

In addition, knowledge and control of environmental conditions such as temperature, pH, dissolved oxygen (DO), and other relevant factors that affect organisms of interest is also essential. By taking into account all these factors, organic and inorganic chemicals may then be effectively removed from water and thus the best treatment possible may be implemented.

4.1.1 Biological Activated Carbon Process

Biological activated carbon (BAC) is the modification of conventional biological processes. In the process, activated carbon is added to the biological tank. The functions of activated carbon are adsorbency and attaching media for bacterial growth.

The advantages of biological activated process have been widely proved:

- stable system during shock loadings
- reduction of refractory compounds
- color and ammonia removal
- improved settleability.

Normally, bacteria are very sensitive to organic loading. Adding granular activated carbon (GAC) in a biological treatment reduces the impact of shock loading by its adsorption property. If the biofilm is generated in the BAC system, the adsorbate adsorbed in the activated

carbon can be degraded by the microorganism attached to the surface of the activated carbon through the biofilm process. Thereby, it extends the time for activated carbon regeneration. Furthermore, some compounds that are non-biodegradable can be adsorbed on activated carbon and subsequently metabolized by attached microorganisms.

One of the important considerations in the quantity of added activated carbon is sludge age. Eq. (4.4) (Metcalf and Eddy 2003) illustrates the dependence of GAC and mixed liquor GAC suspended solid dosage on solid residence time and hydraulic retention time:

$$X_p = \frac{X_i.\theta_c}{\theta} \tag{4.4}$$

where:

X_p = equilibrium GAC mixed liquor suspended solid (MLSS) content (mg/l)
X_i = GAC dosage (mg/l)
θ_C = solid residence time (days)
Θ = hydraulic retention time (days).

The quantity of activated carbon addition is different from one process to another but higher sludge age means better organic removal per unit of carbon, which results in higher removal efficiency.

4.1.2 Biokinetic Theoretical Model

The effectiveness of biological treatment is governed by the growth of microorganisms. The following sections cover the basic equations concerned with bacterial growth, substrate utilization rate, and yield coefficient in growth with and without inhibition.

4.1.2.1 Growth Without Inhibition

Growth of bacteria can be expressed into two ways: numbers and mass. The kinetics consideration of bacterial growth is very important to control the growth rate of the microorganism. Experimentally, the effect of a limiting substrate or nutrient on bacterial growth can usually be defined adequately using two well-known Monod's equations:

- Specific growth rate:

$$\frac{dX}{dt} = \mu X \tag{4.5}$$

$$\mu = \mu_{max}\frac{S}{K_S + S} \tag{4.6}$$

where:

X = biomass concentration (mg/l)
S = growth-limiting substrate concentration (mg/l)
μ_{max} = maximum growth rate (per day)
μ = specific growth rate (per day)
K_S = half-velocity constants (mg/l).

From Eq. (4.6), it can be seen that the growth rate of bacterial is limited even the substrate is available.

- Substrate utilization rate:
  The substrate utilization rate is the amount of biomass produced per 1 mg of substrate removed per day and can be expressed as:

$$U = \frac{(S_0 - S)}{\theta X} \tag{4.7}$$

where:

U = substrate utilization rate (mg substrate removed/mg MLSS/day)
S_o = initial substrate concentration (mg/l)
X = biomass concentration (mg/l)
S = final substrate concentration (mg/l)
θ = hydraulic retention time (days).

- Growth yield coefficient (Y):
  In biological treatment, a portion of substrate is converted to new cells and the relation between bacterial growth rate and substrate consumption is represented by the growth yield coefficient:

$$\frac{dX}{dt} = -Y\frac{dS}{dt} \tag{4.8}$$

where:

Y = growth yield coefficient (g SS/g substrate removed/day)
X = biomass concentration (mg/l)
S = substrate concentration (mg/l).

- Growth with inhibition
  In complex or particular wastewater, some compounds which inhibit biological treatment are present, which changes the growth kinetics. Some researchers have developed models for growth kinetics in these cases. Table 4.1 shows some kinetic models for growth with inhibitory substances.

  If the substrate is an inhibitor at a critical point a model for the inhibition of growth on acetic acid as substrate has been determined (Table 4.2).

Table 4.1 *Kinetic models for inhibition growth (Han and Levenspiel 1988).*

Equations (equation number)	Model name
$\mu = \mu_{max}\left(1 - \frac{I}{K_I}\right)\frac{S}{S + K_S}$ (4.9)	Ghose and Tyagi
$\mu = \mu_{max}\left(1 - \frac{I}{K_I}\right)^{0.5}\frac{S}{S + K_S} = \mu_{obs}\frac{S}{S + K_S}$ (4.10)	Bazua and Wilke
$\mu = \mu_{max}\left(1 - \frac{I}{K_I}\right)^{n}\frac{S}{S + K_S} = \mu_{obs}\frac{S}{S + K_S}$ (4.11)	Han and Levenspiel

I, concentration of inhibitor; K_i, critical inhibitor concentration above which reactions stop; μ_{max}, maximum specific growth rate at zero concentration of inhibitor ($I = 0$); μ_{obs}, observed maximum specific growth rate at certain concentration of inhibitor.

Table 4.2 *Growth models for inhibitor as substrate.*

Equations (equation number)	Model name
$\mu = \mu_{max} \frac{S}{K_S + S}\left(1 - \frac{S}{S_C}\right)$ (4.12)	
$\mu = \mu_{max} \frac{S}{(K_S + S)\left(1 + \frac{S}{K_i}\right)}$ (4.13)	
$\mu = \mu_{max} \frac{S}{K_S + S + \frac{S^2}{K_i}}$ (4.14)	

K_i, critical inhibitor concentration above which reactions stop; μmax, maximum specific growth rate at zero concentration of inhibitor ($I = 0$); μobs, observed maximum specific growth rate at certain concentration of inhibitor; Sc, critical substrate concentration above which reactions stop.

The primary purpose of wastewater purification is not cell multiplication and biomass production but removal of organic compounds from solution. Combining Eqs. (4.5), (4.7) and (4.8) leads to:

$$-\frac{dS}{dt}\frac{1}{X} = \frac{\mu_{max}}{Y_{obs}}\frac{S}{K_S + S} \tag{4.15}$$

$$r_x = r_{x,m}\frac{S}{K_S + S} \tag{4.16}$$

Where:

$r_x = -(dS/dt)/X$ is the actual substrate removal rate (1/time)
$r_{x,m} = \mu_{max}/Y_{obs}$ is the maximum substrate removal rate (1/time).

Equation (4.16) shows the dependence of the substrate removal rate on the actual concentration of a single component substrate and its relative value to K_s. In order to control the operation of a treatment system and thus produce good efficiency from a practical point of view, it is important to know the biokinetic data of a particular wastewater. One of the easiest ways to find this is respirometry.

4.2 Biological Treatment Processes

The major biological processes used for wastewater treatment are identified in Table 4.3. All of these processes are derived from processes occurring in nature.

By controlling the environment of the microorganisms, the decomposition of wastes is speeded up. Regardless of the type of waste, the biological treatment process consists of controlling the environment required for optimum growth of the microorganisms involved.

The principal applications of these processes are:

- removal of carbonaceous organic matter in wastewater, usually measured as biochemical oxygen demand (BOD), total organic carbon (TOC), or chemical oxygen demand (COD)
- nitrification
- denitrification
- phosphorus removal
- waste stabilization.

Table 4.3 *Major biological treatment processes used for wastewater treatment.*

Type	Common name	Use
	Aerobic processes	
Suspended growth	Activated sludge process	Carbonaceous BOD removal (nitrification)
	Conventional (plug flow)	
	Complete mix	
	Slop aeration	
	Pure oxygen	
	Sequencing batch reactor	
	Contact stabilization	
	Extended aeration	
	Oxidation ditch	
	Deep tank (27.5 m)	
	Deep shaft	
	Suspended growth nitrification	Nitrification
	Aerated lagoons	Carbonaceous BOD removal (nitrification)
	Aerobic digestion	Stabilization, carbonaceous BOD removal
	Conventional air	
	Pure oxygen	
Attached growth	Tricking filters	Carbonaceous BOD removal, nitrification
	Low-rate	
	High-rate	
	Roughing filters	Carbonaceous BOD removal
	Rotating biological contactors	Carbonaceous BOD removal (nitrification)
	Packed-bed reactors	Carbonaceous BOD removal (nitrification)
Combined suspended and attached growth processes	Activated biofilter process, trickling filter solids contact process, biofilter activated sludge process, series trickling filter activated sludge process	Carbonaceous BOD removal (nitrification)
	Anoxic processes	
Suspended growth	Suspended growth denitrification	Denitrification
Attached growth	Fixed-film denitrification	Denitrification
	Anaerobic processes	
Suspended growth	Anaerobic digestion	Stabilization, carbonaceous BOD removal
	Standard rate, single-stage	
	High-rate, single-stage, two-stage	
	Anaerobic contact process	Carbonaceous BOD removal
	Upflow anaerobic sludge blanket	Carbonaceous BOD removal
Attached growth	Anaerobic filter process	Carbonaceous BOD removal, waste stabilization (denitrification)
	Expanded bed	Carbonaceous BOD removal, waste stabilization

(*Continued*)

Table 4.3 *(continued)*

Type	Common name	Use
	Combined aerobic, anoxic, and anaerobic processes	
Suspended growth	Single- or multi-stage processes, various proprietary processes	Carbonaceous BOD removal, nitrification, denitrification, phosphorus removal
Combined suspended and attached growth	Single- or multi-stage processes	Carbonaceous BOD removal, nitrification, denitrification, phosphorus removal
Pond processes	Aerobic ponds	Carbonaceous BOD removal
	Maturation (tertiary) ponds	Carbonaceous BOD removal (nitrification)
	Facultative ponds	Carbonaceous BOD removal
	Anaerobic ponds	Carbonaceous BOD removal (waste stabilization)

Note: Major uses are presented first; other uses are identified in parentheses.

Biological processes are affected by environmental conditions. The environmental conditions can be controlled by pH and/or temperature regulation, nutrient or trace element addition, oxygen addition or exclusion, and proper mixing. Biological processes are classified by the oxygen dependence of the primary microorganisms responsible for the waste treatment. The processes are usually referred to as aerobic, anaerobic, or facultative.

4.2.1 Major Differences in Aerobic and Anaerobic Treatment

Before we go into discussions of various aerobic biological treatment processes, it is important to briefly discuss the terms aerobic and anaerobic. Aerobic, as the title suggests, means in the presence of air (oxygen), while anaerobic means in the absence of air (oxygen). These two terms are directly related to the type of bacteria or microorganisms that are involved in the degradation of organic impurities in a given wastewater and the operating conditions of the bioreactor. Therefore, aerobic treatment processes take place in the presence of air and utilize those microorganisms (also called aerobes) that use molecular/free oxygen to assimilate organic impurities, i.e. convert them into carbon dioxide, water, and biomass. Anaerobic treatment processes, on other hand, take place in the absence of air (and thus molecular/free oxygen) using those microorganisms (also called anaerobes) which do not require air (molecular/free oxygen) to assimilate organic impurities. The final products of organic assimilation in anaerobic treatment are methane, carbon dioxide gas, and biomass.

Table 4.4 summarizes the major differences in these two types of processes. From the summary in Table 4.4, it can be concluded that it is not anaerobic or aerobic treatment, but a combination of the two types of technology that gives an optimum configuration for those wastewater treatment applications where the organic impurities are at a relatively high concentration.

Table 4.4 *Major differences in aerobic and anaerobic treatment.*

Parameter	Conventional ASP system	Cyclic activated sludge system	IFAS system	MBR
Treated effluent quality	Meets specified discharge standards with additional filtration step	Meets/exceeds specified discharge standards without additional filtration step	Meets/exceeds specified discharge standards with additional filtration step	Exceeds specified discharge standards without additional filtration step Very good for recycling provided TDS level permits
Ability to adjust to variable hydraulic and pollutant loading	Average	Very good	Very good	Very good
Pretreatment requirement	Suspended impurities, e.g. oil and grease and TSS removal	Suspended impurities, e.g. oil and grease and TSS removal	Suspended impurities, e.g. oil and grease and TSS removal	Fine screening for suspended impurities like hair and almost complete oil and grease removal
Ability to cope with ingress of oil	Average	Good	Average	Poor and detrimental to membrane
Secondary clarifier requirement	Needed	Aeration basin acts as clarifier	Needed	Clarifier is replaced by membrane filtration
Complexity to operate and control	Simple, but not operator friendly	Operator friendly	Operator friendly	Requires skilled operators
Reliability and proven-ness of technology	Average	Very good	Very good	Limited references in industrial applications
Capital cost	Low	Low	High	Very high
Operating cost	Low	Low	High	Very high
Space requirement	High	Low	Average	Low

4.2.2 Aerobic Processes

The aerobic environment is achieved by the use of diffused or mechanical aeration. The reactor contents are referred to as the mixed liquor. Temperature dependence of the biological reaction rate constant is very important in assessing the overall efficiency of a biological treatment process.

In aerobic photosynthetic ponds, the oxygen is supplied by natural surface aeration and by algal photosynthesis. Only a portion of the original waste is actually oxidized to low-energy compounds, such as NO_3, SO_4, and CO_2; the remainder is synthesized into cellular material.

The most important inorganic compound is ammonia because its presence in the plant effluent can stimulate the lowering of the DO in the receiving stream through the biological process of nitrification. In nitrification, ammonia is biologically oxidized to nitrite. The nitrite is then oxidized by another group of microorganisms to nitrate. Nitrate is the final oxidation state of the nitrogen compounds, and as such represents a stabilized product.

There are multitudes of aerobic biological treatment processes and technologies in literature and practice, such as activated sludge, trickling filter, and aerobic stabilization ponds. The activated sludge process (ASP) is used almost exclusively in large units. However, in this section, four biological treatment technologies are described.

4.2.2.1 Conventional ASP System

This is the most common and oldest bio-treatment process used to treat municipal and industrial wastewater. Typically, wastewater after primary treatment, i.e. suspended impurities removal, is treated in an ASP-based biological treatment system comprising an aeration tank followed by a secondary clarifier. The aeration tank is a completely mixed or a plug flow (in some cases) bioreactor where a specific concentration of biomass is maintained along with sufficient DO concentration (typically 2 mg/l) to effect biodegradation of soluble organic impurities measured as BOD5 or COD.

Figure 4.1 shows a conventional ASP system. The aeration tank has fine bubble diffused aeration pipework at the bottom to transfer required oxygen to the biomass and also ensure a completely mixed reactor. A roots-type air blower is used to supply air to the diffuser pipework. The aerated mixed liquor from the aeration tank overflows by gravity to the secondary clarifier unit to separate out the biomass and allow clarified, treated water to the downstream filtration system for finer removal of suspended solids. The separated biomass

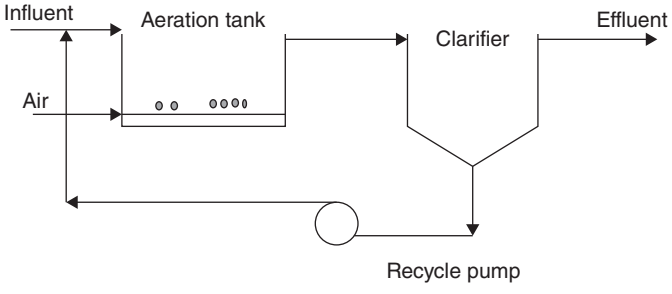


Figure 4.1 *Conventional activated sludge process system.*

is returned to the aeration tank by means of a return activated sludge (RAS) pump. Excess biomass (produced during the biodegradation process) is wasted to the sludge handling and dewatering facility.

4.2.2.2 Cyclic Activated Sludge System

The cyclic activated sludge system (CASS™), as the name suggests, is one of the most popular sequencing batch reactor (SBR) processes employed to treat municipal wastewater and wastewater from a variety of industries including refineries and petrochemical plants.

The CASS™ incorporates a high level of process sophistication in a configuration that is cost and space effective, and offers a methodology that has operational simplicity, flexibility, and reliability that is not available in conventionally configured activated sludge systems. Its unique design provides an effective means for the control of filamentous sludge bulking, a common problem with conventional processes and other activated sludge systems.

System design is such that the sludge return rate causes an approximate daily cycling of biomass in the main aeration zone through the selector zone. No special mixing equipment or formal anoxic mixing sequences are required to meet the effluent discharge objectives. The basin configuration and mode of operation enables combined nitrogen and phosphorous removal mechanisms to take place through a simple "one-shot" control of the aeration.

Important reasons for choosing CASS™ over a conventional constant volume activated sludge aeration and clarifier process include:

- it operates under continuous reduced loading through simple cycle adjustment
- it operates with feed-starve selectivity, So/Xo operation (control of limiting substrate to microorganism ratio), and aeration intensity to prevent filamentous sludge bulking and ensures endogenous respiration (removal of all available substrate), nitrification, and denitrification together with enhanced biological phosphorus removal
- it uses simultaneous (co-current) nitrification and denitrification by variation of aeration intensity
- it tolerates shock load caused by organic and hydraulic load variability.
- The system is easily configured and adjusted for short-term diurnal and long-term seasonal variations.
- it has inherent ability to remove nutrients without chemical addition by controlling the oxygen demand and supply.

4.2.2.3 Integrated Fixed Film Activated Sludge System

There are several industrial installations that use a two-stage biological treatment comprising stone or plastic media trickling filters (also known as packed bed biotowers) followed by a ASP-based aeration tank, followed by secondary clarifier.

Another modification of this configuration that has been implemented in newer industrial wastewater treatment systems uses a fluidized media bioreactor (also known as a moving bed bioreactor [MBBR]) in lieu of the biotower followed by ASP. In some industries (e.g. refineries and petrochemical plants, where the existing wastewater treatment system was single-stage conventional ASP based on an aeration tank and clarifier unit) that underwent capacity expansion and/or faced stricter discharge regulations, the up-gradation of ASP by

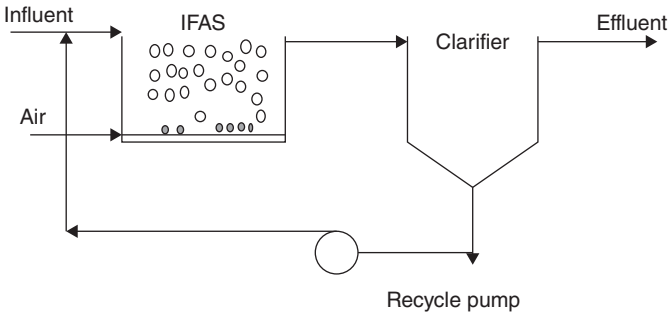


Figure 4.2 *Integrated fixed film activated system.*

the addition of fluidized bio-media has been implemented to meet these requirements. This hybrid process of fluidized media and ASP taking place in a single aeration tank is known as the integrated fixed film activated sludge (IFAS) process (Figure 4.2).

The common advantages of all the above configurations are:

- fixed film media provide an additional surface area for the biofilm to grow on and degrade the organic impurities that are resistant to biodegradation or may even be toxic to some extent
- the overall efficiency of the two-stage biotreatment system is better than that of ASP alone
- fixed film processes are more effective in nitrification of the wastewater than ASP
- the overall footprint for a fixed film process system is smaller than that for an ASP system
- due to less sludge wastage, the sludge handling and dewatering facility is smaller compared to that for ASP.

4.2.2.4 Membrane Bioreactor

The membrane bioreactor (MBR) is the latest technology for biological degradation of soluble organic impurities. MBR technology has been in extensive usage for treatment of domestic sewage, but for industrial waste treatment applications its use has been somewhat limited or selective. The MBR process is very similar to conventional ASP, in that both have mixed liquor solids in suspension in an aeration tank. The difference in the two processes lies in the method of separation of bio-solids. In the MBR process, the bio-solids are separated by means of a polymeric membrane based on a microfiltration or ultrafiltration unit, as against the gravity settling process in the secondary clarifier in conventional ASP. Therefore, the advantages of an MBR system over a conventional activated sludge system are obvious, as listed below:

- Membrane filtration provides a positive barrier to suspended bio-solids so they cannot escape the system, unlike gravity settling in ASP, where the bio-solids continuously escape the system along with clarified effluent and sometimes a total loss of solids is also encountered due to process upsets causing sludge-bulking in the clarifier. As a result, in an MBR process the bio-solids concentration measured as MLSS/mixed liquor volatile suspended solid (MLVSS) can be maintained at three to four times (~10 000 mg/l) that in ASP (~2500 mg/l).
- Because of the membrane filtration MBR, the aeration tank size in the MBR system can be one-third to one-fourth the size of the aeration tank in an activated sludge system.



Figure 4.3 Aerobic basin. Source: Reproduced with permission from © Žika Rech – Subotica Wastewater Treatment Plant.

Further, instead of a gravity settling based clarifier, a much more compact tank is needed to house the membrane cassettes in case of submerged MBR and skid-mounted membrane modules in case of non-submerged, external MBR system.

- Thus, the MBR system requires only 40–60% of the space required for an activated sludge system, therefore significantly reducing the concrete work and overall footprint.
- Due to membrane filtration (micro/ultrafiltration), the treated effluent quality in an MBR system is far superior compared to conventional activated sludge, so the treated effluent can be directly reused as cooling tower make-up, gardening etc. Typical treated water quality from an MBR system is:
  - BOD5 < 5 mg/l
  - turbidity <0.2 NTU (Figure 4.3).

4.2.3 Anaerobic Waste Treatment

Anaerobic waste treatment should be involved in the decomposition of organic and/or inorganic matter in the absence of molecular oxygen. The major application is in the digestion of the concentrated sewage sludges and the treatment of some industrial wastes. Another application of anaerobic treatment is in anaerobic lagoons or ponds. The usual mode of operation of an anaerobic waste treatment unit receiving a concentrated sewage sludge is use of a complete-mix reactor system with minimum cellular recycle for the purpose of heating and mixing the tank contents.

4.2.4 Aerobic-Anaerobic (Facultative) Waste Treatment

Stabilization ponds of facultative bacteria are known as aerobic-anaerobic ponds. Such ponds have an aerobic upper layer and an anaerobic bottom layer. In practice, oxygen is maintained in the upper layer by the presence of algae or by the use of surface aerators. Where surface aerators are used, algae are not required.

4.3 Activated Sludge Units

The activated sludge unit is a multi-chamber reactor unit that makes use of (mostly) aerobic microorganisms to degrade organics in wastewater and to produce a high-quality effluent. To maintain aerobic conditions and to the keep the active biomass suspended, a constant and well-timed supply of oxygen is required. Activated sludge systems (see Figures 4.4 and 4.5) normally make use of bar screens and/or comminutors, grit chambers, primary settling tanks, secondary settling tanks, and digesters, which are operated in the same manner as those in trickling filter systems. They differ from trickling filter systems in that they make use of an aeration tank instead of a trickling filter.

Different configurations of the ASP can be employed to ensure that the wastewater is mixed and aerated (with either air or pure oxygen) in an aeration tank. Microorganisms oxidize the organic carbon in the wastewater to produce new cells, carbon dioxide, and water.

Although aerobic bacteria are the most common organisms, aerobic, anaerobic, and/or nitrifying bacteria along with higher organisms can be present. The exact composition

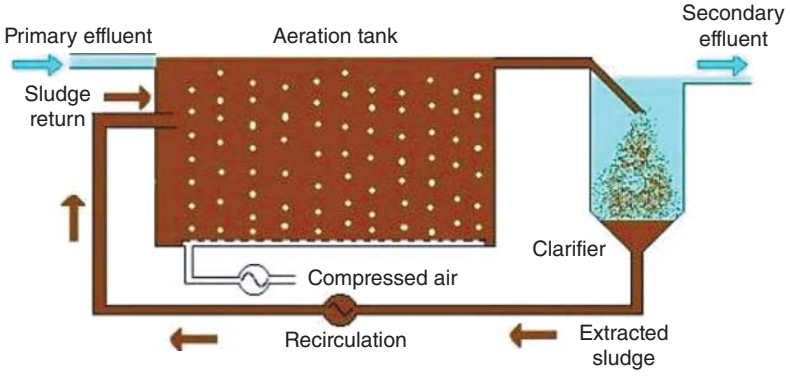


Figure 4.4 *Activated sludge system (example 1).*

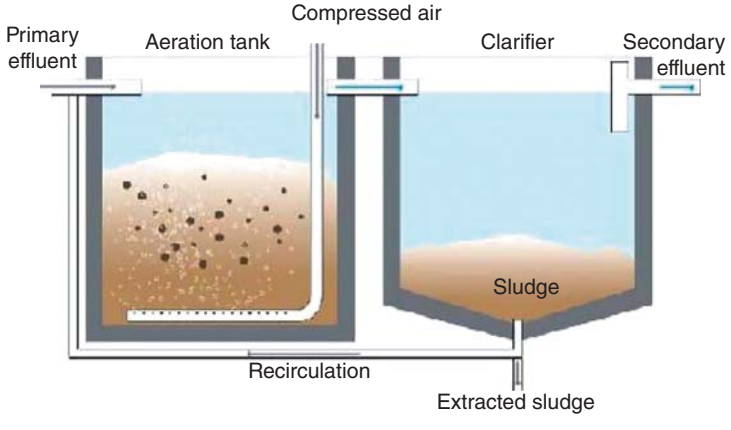


Figure 4.5 *Activated sludge system (example 2).*

depends on the reactor design, environment, and wastewater characteristics. During aeration and mixing, the bacteria form small clusters, or flocs. When the aeration stops, the mixture is transferred to a secondary clarifier where the flocs are allowed to settle out and the effluent moves on for further treatment or discharge. The sludge is then recycled back to the aeration tank, where the process is repeated.

Compressed air is continually diffused into the sewage as it flows through the aeration tank. This provides both a source of oxygen for the aerobic bacterial floc that forms in the tank and the turbulence necessary to bring the waste and the bacteria into contact. Aerobic bacteria attack the dissolved and finely divided suspended solids not removed by primary sedimentation. Some of the floc is removed with the sewage that flows out of the aeration tank and carried into the secondary settling tank. Here the floc settles to the bottom of the tank, and is later pumped back into the aeration tank. The liquid portion then flows over a weir at the surface of the settling tank to be chlorinated and released to a receiving stream.

To achieve specific effluent goals for BOD, nitrogen, and phosphorus, different adaptations and modifications have been made to the basic activated sludge design. Aerobic conditions, nutrient-specific organisms (especially for phosphorus), recycle design, and carbon dosing, among others, have successfully allowed ASPs to achieve high treatment efficiencies.

4.3.1 Applications

The ASP and its modifications, the extended-aeration ASP and the oxygen ASP, are used to decompose organic matter and stabilize soluble organic wastes in water. An activated sludge unit achieves more BOD reduction than a trickling filter, and it requires shorter liquid retention times and smaller plot areas than stabilization ponds or lagoons. Equalization should be considered to stabilize loads for wastewater with widely varying BOD. In general, the benefits of the biological treatment of wastewater are reduction of oxygen demand, reduction of oil content, reduction of toxicity to the aquatic life in receiving water, improvement in odor, and improvement in appearance.

4.3.2 Effects of Activated Sludge

An activated sludge plant can be designed to produce an effluent with a total (soluble plus insoluble) BOD5 of 10–20 mg/l. However, the COD of the effluent is usually considerably higher because of the presence of compounds resistant to biological oxidation.

a) The residues from an activated sludge system can include the following:
   a.1) Soluble BOD, which is composed of the following:
      - Any of the soluble BOD in the wastewater not removed by the process. The concentration of these residues decreases with retention time in the aeration basin.
      - Organic by-products produced by the microorganisms and not metabolized. These residues increase with retention time.
      - Organic material produced by the decomposition of cells during endogenous respiration (auto-oxidation, oxidation by microorganisms of material from

bacterial cells). A residual BOD5 of 5–15 mg/l will persist from these residues as long as active cells are present in the system.

a.2) Biological solids
Although the biological solids (cells) are removed in the settler following aeration, the settling step is not perfect and some solids overflow with the clarifier effluent. These solids often hold some oil. In addition, these solids will contribute a BOD on the order of 0.3–0.7 mg BOD5/mg suspended solids depending on the age of the sludge.

a.3) Non-biodegradable residues
Some soluble wastes are not biodegradable. These will exhibit a COD or TOC, but not a BOD. In addition, some solid metabolic by-products which are non-biodegradable are produced.

a.4) Non-biological organic suspended material
Some of the insoluble organic material originally present in the wastewater may carry through with the settled effluent. This unstabilized material could include oil, plastics, rubber, etc.

a.5) Inorganic, non-volatile suspended matter
Most of the inorganic suspended matter (e.g. silt) will settle with the floc and will be purged with wasted sludge. Some, however, may not settle and so may appear as non-volatile suspended solids in the clarifier effluent.

b) Free oil
An activated sludge unit is designed to remove soluble organic compounds and not free oil. Free oil above about 50 mg/l must be first removed in a pretreatment step. The small amount of free oil remaining after pretreatment (5–20 mg/l) will be further reduced in the activated sludge unit, primarily by adsorption onto the floc.

c) Ammonia
A small amount of ammonia (equal to 1–3% of the BOD5 removed) can be removed from water by activated sludge treatment in the usual case where nitrification does not occur. Thus, activated sludge treatment is not a practical way to remove ammonia from wastewater due to too small removal efficiency.

4.3.3 Feed Composition

Certain materials in the feed and other environmental factors affect the operation of an activated sludge plant. Table 4.5 gives criteria for pre-treatment of activated sludge feed. In Table 4.5 shock loads as well as continuous loads are considered, and the values given are for satisfactory operation of the activated sludge unit. Pre-treatment may be required to reach more restrictive values to meet discharge requirements.

Pre-treatment of feed to an activated sludge or extended-aeration plant should be provided when the feed is outside the limits shown in Table 4.5.

In addition to feed pre-treatment, a holding basin to which the biox influent can be diverted in the event of toxic shocks or organic shocks is recommended.

4.3.3.1 Oil Content

Pre-treatment of the wastewater to remove free oil should be provided if the oil content of the wastewater to be treated in an activated sludge system is over 50 mg/l.

Table 4.5 *Criteria for pretreatment of activated sludge feed.*

Constituent	Limiting concentration	Appropriate pretreatment	Remarks
Oil	50 mg/l	Dissolved air flotation, granular media filtration, chemical flocculation	Limiting concentration varies with the solids retention time
Sulfides	10 mg/l max.	Stripping, precipitation with iron salts	—
Ammonia	500 mg/l max.	Stripping, dilution	—
Phenols	500 mg/l max.	Stripping	Although the activated sludge unit will operate satisfactorily within the indicated range, the size will be affected by the indicated parameter Determine if there is an economic incentive to provide pretreatment to adjust this parameter in order to reduce the cost of the activated sludge or extended-aeration plant The concentration given applies if the concentration is relatively constant Only a lesser concentration can be tolerated if it occurs as a non-steady variation
Chlorides	100% sea water max.	Dilution, de-ionization	Although the activated sludge unit will operate satisfactorily within the indicated range, the size will be affected by the indicated parameter Determine if there is an economic incentive to provide pretreatment to adjust this parameter in order to reduce the cost of the activated sludge or extended-aeration plant The concentration given applies if the concentration is relatively constant Only a lesser concentration can be tolerated if it occurs as a non-steady variation De-ionization and ion exchange are seldom practical for refinery or petrochemical plant wastewater
Suspended solids	150 mg/l max.	Sedimentation, granular media filtration, chemical flocculation, DAF unit	–

Copper	1 mg/l max.	Precipitation, ion exchange	De-ionization and ion exchange are seldom practical for refinery or petrochemical plant wastewater
Heavy metals	1–10 mg/l max.	Precipitation, ion exchange	De-ionization and ion exchange are seldom practical for refinery or petrochemical plant wastewater
Dissolved salts	30 000 mg/l max.	Dilution, stream segregation	Although the activated sludge unit will operate satisfactorily within the indicated range, the size will be affected by the indicated parameter Determine if there is an economic incentive to provide pretreatment to adjust this parameter in order to reduce the cost of the activated sludge or extended-aeration plant The concentration given applies if the concentration is relatively constant Only a lesser concentration can be tolerated if it occurs as a non-steady variation
Cyanides	5 mg/l max.	Stripping, oxidation (ozone, alkaline chlorination)	—
Thiocyanides	30 mg/l max.	Retention, equalization	Depends on the wastewater
Organic load Variation (Based on 4 h composite)	max. of 2 to 4		
pH	6.5–8.5	Neutralization	
Alkalinity	Max. of 0.2 kg alkalinity as $CaCO_3$ per 0.4 kg BOD removed	Neutralization	
Free mineral acidity	Zero free mineral acidity, maximum	Neutralization	Although the activated sludge unit will operate satisfactorily within the indicated range, the size will be affected by the indicated parameter
Temperature	10–40 °C or 46–60 °C	Cool, dilute, heat	Determine if there is an economic incentive to provide pre-treatment to adjust this parameter in order to reduce the cost of the activated sludge or extended-aeration plant Avoid operation in the 40–46 °C temperature range

4.3.3.2 Nutrients

Any nutrient not already present in sufficient quantity should be supplied. Ammonia is most readily assimilated by bacteria in the form of nitrogen. The source of ammonia can be either free ammonia in the wastewater or ammonia formed in the activated sludge unit by the bio-degradation of organic nitrogen compounds such as mono-ethanolamine (MEA) and di-ethanolamine (DEA). Both refinery and petrochemical plant wastewater is usually deficient in phosphorus, although phosphorates enter the wastewater from boiler and cooling tower blow-down and from spent phosphoric acid catalyst from polymerization units.

The needs for nitrogen and phosphorus should be determined by pilot-plant testing. If this has not been done, an analysis of the feed wastewater is required. Based on this analysis, the contractor should provide nutrient addition facilities, if necessary, to result in a ratio of N:P:BOD metabolized of 5 : 1 : 100, and, in addition, provide for residual concentrations of 0.1 mg/l of the phosphate phosphorus (PO_4^{3-}) and 0.5 mg/l ammonia nitrogen in the effluent.

4.3.3.3 Toxic and Inhibitory Materials

The presence of toxic materials in the wastewater can seriously impair the performance of an activated sludge unit and reduce its efficiency. Toxicants either kill microorganisms or inhibit their growth. The effect depends on concentration, contact time, and the environment (e.g. pH).

A number of toxic materials are potentially present in refinery and petrochemical plant wastewater, including zinc, chromium, copper, cyanide, sulfide, biocides, furfural, and certain other organic compounds. In addition, highly alkaline or acid discharges may be toxic. Besides being toxic, sulfides preferentially consume oxygen and can create an anaerobic environment.

Table 4.5 gives guidance on the limiting concentrations for certain materials. Heavy metals, in general, inhibit the ASP. Dissolved heavy metal ions (cadmium, cobalt, copper, dichromate, ferric iron, lead, manganese, nickel, silver, vanadium, and zinc), above certain concentrations, impede biological metabolism. The effect of any particular concentration of these depends on the environment, therefore it is not possible to give exact concentration limits for most of these heavy metals. Microorganisms can tolerate only 1 mg/l or less of some heavy metals (cadmium, copper, silver), but other metal ions (ferric iron, manganese, nickel, vanadium) have been successfully handled at 10 mg/l with little or no loss in efficiency.

Organic compounds which are toxic to the microorganisms will inhibit their utilization of other materials. Hence, intermittent slugs of many organic compounds or sudden, large changes in their concentration can disrupt the biological process. When feasible, laboratory studies to evaluate toxic limits should be made before wastes from a new process are introduced into an existing activated sludge system.

4.3.3.4 Organic Compounds

Organic compounds differ in their biodegradability; some are readily degraded by the microorganisms normally present, some are degraded if the organisms have become acclimated to the compound, and others are practically non-biodegradable. Table 4.6 lists organic compounds that are biodegradable by acclimated organisms and compounds generally resistant to biological degradation.

Table 4.6 *Relative biodegradability of certain organic compounds.*

Acrylic acid	Diethanolamine
Aliphatic acids	Ethers
Aliphatic alcohols (normal, iso, secondary)	Ethylene chlorohydrin
Aliphatic aldehydes	Insoluble oil
Aliphatic esters	Isoprene
Aromatic amines	Methyl vinyl ketone
Benzaldehyde	Morpholine
Dichlorophenols	Polymeric compounds
Ethylene glycol	Selected hydrocarbons
Ketones	Aliphatics
Linear alkyl benzene sulfonates	Aromatics
Methacrylic acid	Alkyl-aryl groups
Methyl methacrylate	Tertiary aliphatic alcohols
Monochlorophenols	Tertiary benzene sulfonates
Monoethanolamine	Tetrapropylene and other polypropylene benzene
Nitriles	Sulfonates
Phenols	Trichlorophenols
Primary aliphatic amines	Triethanolamine
Styrene	
Vinyl acetate	

Note: Some compounds can be degraded biologically only after an extended period of acclimation.

4.3.3.5 Organic Shocks

An organic shock is a sudden increase in the organic content of the incoming wastewater. Organic shocks can be caused by a number of materials, including phenols, alcohols, detergents, solvents, MEA, DEA, hydrocarbons, etc. The concentration of each component in the feed to an activated sludge unit should not vary by more than 50% per hour. In any case, retention or equalization hold-up should be provided to avoid any organic shock.

4.3.3.6 Salt Content

Rapid changes in salt concentration can devitalize the microorganisms; salt concentrations about 3000 mg/l (ppm) total dissolved solids (TDS) retard sludge settling and any concentration of dissolved solids reduces the solubility of oxygen in water and increases the rate of transfer of oxygen to water. In any case, shock loads of salt, as from occasional releases of salt-water ballast, should be avoided.

4.3.3.7 Suspended Solids

High concentrations of influent suspended solids decrease efficiency by reducing the fraction of active biological solids, create an excessive oxygen demand, and may result in a sludge less amenable to dewatering.

4.3.3.8 pH, Alkalinity, and Acidity

The pH of the aeration basin determines which microorganisms predominate in the system and also affects the rate of reaction. Facilities to adjust the pH of the feed to the activated sludge unit should be provided. The pH of the aeration basin should be kept in the range of 6.5–8.5, the optimum pH range is 7–8. An aeration basin pH outside the range of 5–9 may result in destruction of microorganisms.

4.3.3.9 Temperature

The temperature in the aeration basin affects the reaction rate in the aeration basin and the settling characteristics of the sludge. Either of two ranges of temperature can be maintained in the aeration basin.

The growth of a different type of microorganism predominates in each of these ranges: mesophilic microorganisms grow in the range of 10–40 °C and thermophilic microorganisms grow in the range of 46–60 °C. An activated sludge plant should not be designed to operate in the 40–46 °C temperature range. Winterization facilities should be foreseen in cold climates. Temperature changes should be kept smaller than 10 °C per hour so as not to retard performance. An activated sludge plant should not be designed to operate below 15 °C.

4.3.3.10 Oxygen Concentration

The design value for DO concentration should be minimum 2 mg/l. This should be sufficient to maintain a minimum DO residual of 0.5 mg/l throughout the aeration chamber with normal fluctuations in incoming BOD and COD load. If shock BOD loads are expected, design should be made for more than 2 mg/l DO to avoid a DO of less than 0.3 mg/l during or after the shock load period.

4.3.4 Process Design

The biological oxidation unit should utilize the completely mixed recycle ASP of the treatment. For the design of the unit, influent wastewater specifications should be based on either daily average or maximum figures extracted from the specified conditions. However, the unit should be checked for the expected maximum concentrations of the contaminants in the influent water in order to meet the guaranteed effluent wastewater quality. The effluent from the aeration basin should be routed to the activated sludge clarifier.

A portion of the activated sludge from the clarifier underflow should be recycled to the aeration basin and mixed with the influent waste. A portion of the clarifier underflow should be wasted to the aerobic sludge digester to maintain proper concentration of MLSSs in the aeration basin. Floatable solids from the scum trough in the clarifier should flow to a scum pit. Effluent from the clarifier should flow to a surge tank and be pumped to the deep bed filters for final treatment.

Effluent from the clarifier should contain 10 mg/l(ppm) maximum of dissolved BOD5 and 25 mg/l(ppm) maximum of TDSs unless otherwise specified.

4.3.5 Design Considerations

4.3.5.1 Biological Oxidation Basin(s)

Adequate numbers of aeration basins should be provided based on the optimum size of the basin and the fresh feed design flowrate. Adequate hours of retention time should be provided by each aeration basin. Basin walls should have a 1.5 to 1 slope and a freeboard of not less than 500 mm. The basins should be surrounded by guard rails to prevent personnel from falling into them.

The inlet line should allow the influent to be added to the aeration basin both at the head end of the basin and under each aerator. The recycle sludge should enter at the head end. The aeration basins should be designed so that the air is disengaged from the microbial floc and the skimming of foam, scum, or floating sludge is minimized in the discharge. An overflow weir and baffles extended 500 mm below and 300 mm above the water surface should be provided.

4.3.5.2 Mechanical Aerators

Low-speed mechanical aerators should be provided for each aeration basin to supply oxygen required into the basin. The numbers will be determined based on the total oxygen requirement. The circles of influence of adjacent aerators should just touch but not overlap. The aerators should be of the easily adjusted, variable weir platform mounted type driven by a gear box consisting of a stationary base, ball race, and internal gear. The latter should be provided with a mounting rim for attaching the drive shaft.

The internal gear should be rotated by a pinion, keyed to a first-stage speed reducer, connected with an electric motor. The aerobic sludge digester aerator should be of the floating type. Each unit should be complete with impeller shaft and assembly and all necessary anchor bolts and accessories for a complete unit. Each unit should be ready for easy on-site assembly requiring only bolting the base plate to the appropriate platform or poles. A platform with a vertical access ladder should be provided to the aerobic sludge digester.

The drive assembly should be designed for continuous duty and heavy shock loads. The impeller assembly should be of suitable design to provide oxygen transfer and mixing, withstand design loads, and be easily removable from drive assembly. Each impeller should be statically balanced prior to shipment. The impeller shaft should be of suitable material and of proper size to withstand all operating and static stresses.

4.3.5.3 Nutrient Feed Systems

The nutrient feed systems should be designed to provide a sufficient amount of nitrogen and phosphorous to sustain growth of the biological mass in each aeration basin. The nutrients should be injected to a single point upstream of the aeration basin(s). Each nutrient feed system should include a chemical solution tank, an agitator and two chemical feed pumps (one as spare). The chemical solution tank capacity should be based on at least 24 hours of operation.

The tank should be equipped with level indicator, sight glass, bag breaker, necessary pump controls, and agitator. The pumps should have facilities to permit adjustment of capacity from 0% to 100% of the maximum specified. Accessories of the pumps should include coupling guard and strainer.

4.3.5.4 Aerobic Sludge Digester

The aerobic sludge digester should be of adequate size to provide minimum 16 days retention time based on a design input of at least 3% of the sludge withdrawal rate from the clarifiers. Floating-type low-speed mechanical surface aerators should be provided. The tank should be equipped with a platform (including ladder) and poles to fix the mechanical aerators. The vendor should specify the oxygen requirement for the aerobic sludge digester.

4.3.5.5 Control and Instrumentation

The design of the biological oxidation units should incorporate the necessary instrumentation for a minimum amount of operator observance. Alarms should be installed on all critical water levels and for over-torque condition on the clarifiers. DO and total organic content (TOC) analyzers should be provided at appropriate locations in the biological oxidation unit. The following instrumentation should be specified as minimum requirement:

- A flow controller (indicating or recording) on sludge recycle.
- A flow controller (indicating or recording) on sludge wastage.
- An indicator or recorder for DO in the aeration basin.
- An indicator or recorder for TOC of feed and effluent.
- A recorder of the pH of the feed.
- An indicator or recorder of the pH in the aeration basin.
- An indicator of the temperature of the influent and aeration basin.
- An indicator or recorder of DO in the final effluent.

4.3.5.6 Supplemental Dissolved Oxygen Using Hydrogen Peroxide

Hydrogen peroxide has been used to reduce BOD and COD in refinery wastewater for many years. This includes:

- supply of supplemental DO when biological treatment systems experience temporary overloads or equipment failure. Figure 4.6 shows a typical aeration basin with a supply of supplemental DO.
- pre-digestion of wastewater which contains moderate to high levels of compounds that are toxic, inhibitory or recalcitrant to biological treatment.

As indicated by these examples, hydrogen peroxide can be used as a standalone treatment or as an enhancement to existing physical or biological treatment processes, depending on the situation.

The BOD/COD removal efficiency of aerobic biological treatment processes depends on a number of factors including (but not limited to) influent BOD/COD loading, temperature, nutrient levels, and DO concentrations. Many biological treatment facilities use hydrogen peroxide to supplement DO levels when oxygen-limited conditions in aeration basins result in poor BOD/COD removal.

These conditions can be brought about by unexpected peaks in influent BOD/COD loading, seasonal variations in BOD/COD loading, and hot weather, which reduces the efficiency of oxygen transfer by mechanical aeration equipment (i.e. O_2 solubility decreases as temperature increases). These conditions may or may not be accompanied by filamentous bulking.



Figure 4.6 *Aerobic basin with supplemental DO system. Source: Reproduced with permission from © U.S. Peroxide, LLC.*

When hydrogen peroxide is used to supplement DO, it is metered directly into the aeration basin of a biological treatment system to provide an immediate source of DO. The conversion of hydrogen peroxide to DO in an activated sludge mixed liquor proceeds according to the following reaction:

$$\text{catalase enzyme}: \; 2H_2O_2 \rightarrow O_2 + 2H_2O$$

Catalase enzyme is a natural decomposition catalyst for hydrogen peroxide and is found in all activated sludge mixed liquors, being produced by most aerobic organisms. Because this enzymatic decomposition of hydrogen peroxide is very rapid, the oxygen supplied by hydrogen peroxide is immediately available for uptake by the aerobic organisms.

The above reaction shows that two parts of hydrogen peroxide will yield one part of DO. Therefore, the amount of hydrogen peroxide required to oxygenate the wastewater is surprisingly small. In actual practice, the requirement may be higher due to side reactions with oxidizable compounds.

4.4 Trickling Filters

A trickling filter (see Figures 4.7 and 4.8) is a fixed-bed, biological filter that operates under (mostly) aerobic conditions. Pre-settled wastewater is "trickled" or sprayed over the filter. As the water migrates through the pores of the filter, organics are degraded by the biomass covering the filter material.

The trickling filter is filled with a high specific surface-area material such as rocks, gravel, shredded polyvinyl chloride (PVC) bottles, or special pre-formed filter-material. A material with a specific surface area between 30 and 900 m^2/m^3 is desirable. The filter is usually 1–3 m deep but filters packed with lighter plastic filling can be up to 12 m deep. Pre-treatment is essential to prevent clogging and to ensure efficient treatment. The

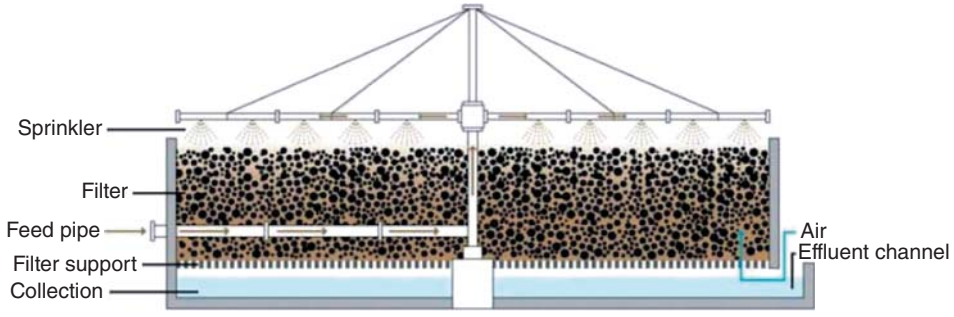


Figure 4.7 Diagram of a trickling filter.



Figure 4.8 Examples of trickling filters.

pre-treated wastewater is "trickled" over the surface of the filter. Organisms that grow in a thin bio-film over the surface of the media oxidize the organic load in the wastewater to carbon dioxide and water while generating new biomass.

The incoming wastewater is sprayed over the filter with the use of a rotating sprinkler. In this way, the filter media goes through cycles of being dosed and exposed to air. However, oxygen is depleted within the biomass and the inner layers may be anoxic or anaerobic.

The ideal filter material has a high surface to volume ratio, is light, durable, and allows air to circulate. Whenever it is available, crushed rock or gravel is the cheapest option. The particles should be uniform such that 95% of the particles have a diameter between 7 and 10 cm. Both ends of the filter are ventilated to allow oxygen to travel the length of the filter. A perforated slab that allows the effluent and excess sludge to be collected supports the bottom of the filter.

The bed consists of crushed rock or slag (1–2 m deep) through which the sewage is allowed to percolate. The stones become coated with a zoogloea film (a jelly-like growth of bacteria, fungi, algae, and protozoa) and air circulates by convection currents through the bed. Most of the biological action takes place in the upper 0.5 m of the bed. Depending on the rate of flow and other factors, the slime will slough off the rocks at periodic intervals or continuously, whenever it becomes too thick to be retained on the stones. A secondary settling basin is necessary to clarify the effluent from the trickling filter. The overall reduction of BOD for a complete trickling filter system averages around 80–90%.

4.4.1 Trickling Filter Process Design

The first process design approach to use fundamental principles was published by Velz in 1948. His equation expressed BOD removal as a first-order function of filter depth:

$$\ln\left(\frac{L_e}{L_o}\right) = -kd$$

where

L_o = BOD of filter influent
L_e = BOD at any depth in filter
d = filter depth (m)
k = coefficient.

4.4.1.1 Wetting Rates

The overall application rate of wastewater to the trickling filter, including recirculation, expressed as gpm/ft^2 (or m^3/m^2/h) of the filter area, is known as the wetting rate. The desired wetting rate ranges from 0.05 gpm/ft^2 (0.12 m^3/m^2/h) to a maximum of 3 gpm/ft^2 (7.32 m^3/m^2/h), but is typically in the range of 0.25–1 gpm/ft^2 (0.61–2.44 m^3/m^2/h) for BOD removal systems and 0.75–2 gpm/ft^2 (1.83–4.88 m^3/m^2/h) for nitrification trickling filters.

If the average wetting rate is too low, the water may not penetrate the depth of the filter bed uniformly. It may channel away from some areas and leave damp unwetted areas that can act as incubators for pests like filter flies and snails (in nitrification towers). Also, biological populations not continuously wetted and fed by wastewater become ineffective. Those areas of the filter tower will not be available to provide effective treatment of wastewater during periods of higher flow. Semi-dry biomass can also putrefy and create odor problems. Recycling of treated wastewater is an effective method of keeping all areas and depths of the trickling filter biologically active when the influent flow is too low for proper wetting.

4.4.1.2 Instantaneous Wetting Rate

From the work of the German wastewater treatment industry, a term has been developed that identifies the instantaneous application rate. This term is the SpülKraft rate, or SK rate, which has units of millimeters of water per pass of the distributor arms:

$$SK = -kd\left(\frac{q+R}{a\times n}\right)\left(\frac{1000}{6}\right)$$

where:

SK = flushing intensity (mm/pass)
$q + R$ = influent and recycle hydraulic loading, (m^3/m^2. h)
a = number of arms
n = distributer (rpm).

Hydraulically-driven rotary distributors in the normal operating mode usually rotate at a rate of 1 revolution per 0.75 to 1.5 minutes and have two or four arms. The SK rate may be in the range of 0.3–0.5 mm per pass in rock filters and from 5 to 30 mm per pass in more modern filters.

If the recycle capacity is minimal and the operator has the ability to slow the rotation speed of the distributor, it is possible to compensate somewhat for low wetting rates by using higher SK values. Higher SK values will provide more complete penetration of the filter media depth and keep the bulk of the filter wetted.

Short cycle times of dryness between flushing will not be as detrimental to the biomass as a general starvation for water in pockets of media that are by-passed at low wetting rates.

4.5 Rotating Biological Contactor System

Rotating biological contactor (RBC) systems (see Figures 4.9–4.11) normally make use of bar screens and/or comminutors, grit chambers, primary settling tanks, secondary tanks, and digesters, which are operated in the same manner as those of trickling filter systems. The RBC is a simple, effective method of providing secondary wastewater treatment. The system consists of biomass media, usually plastic, that is partially immersed in the wastewater.

As it slowly rotates, it lifts a film of wastewater into the air. The wastewater trickles down across the media and absorbs oxygen from the air. A living biomass of bacteria, protozoa, and other simple organisms attaches and grows on the biomass media. The organisms then remove both DO and organic material from the trickling film of wastewater. Any excess biomass is sloughed-off as the media is rotated through the wastewater. This prevents clogging of the media surface and maintains a constant microorganism population.

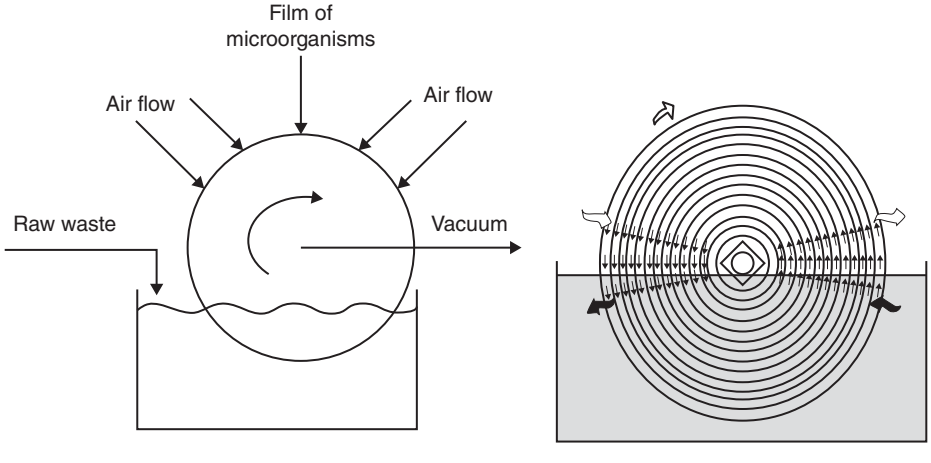


Figure 4.9 *Diagram of a rotating biological contactor.*

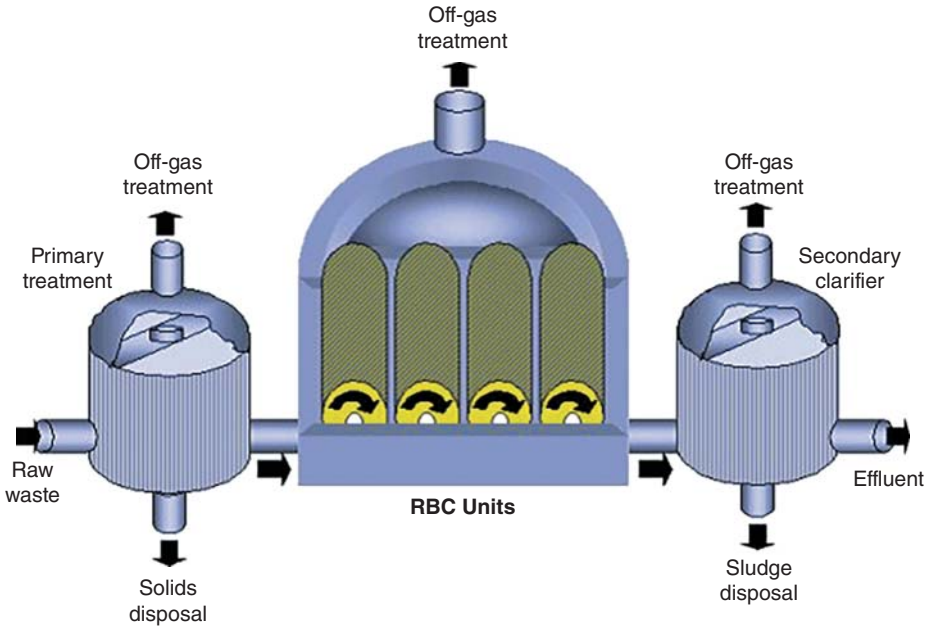


Figure 4.10 *Rotating biological contactors preceded by pre-treatment and followed by secondary sedimentation.*



Figure 4.11 *Example of a rotating biological contactor.*

The sloughed-off material is removed from the clear water by conventional clarification. The RBC rotates at a speed of 1–2 rpm and provides a high degree of organic removal.

4.6 Sewage Oxidation Ponds

Sewage oxidation ponds are 0.8–1.2 m in depth and may be used singly, in parallel, or in a series following primary treatment (see Figures 4.12 and 4.13). Their use is particularly suited to locations with available land and warm climates. Their ability to absorb

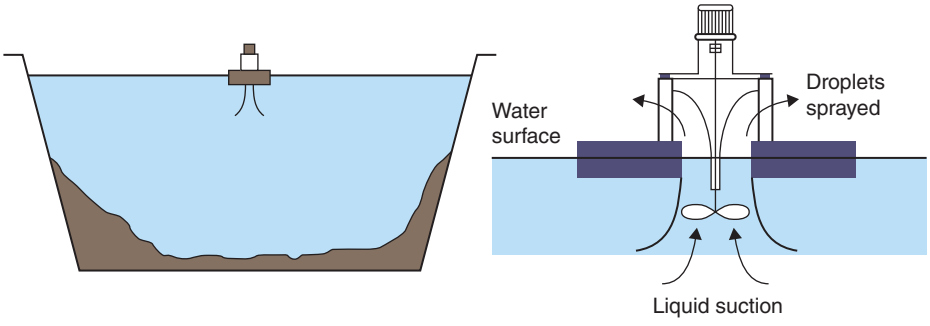


Figure 4.12 *Diagram of a sewage oxidation pond.*



Figure 4.13 *Sewage oxidation ponds.*

shock loads and ease of operation and maintenance make them desirable treatment units. Biological life in ponds uses the organic and mineral matter in the sewage for food to produce more stable products.

The products often stimulate abundant growth of algae and other vegetation. Solution of oxygen from the atmosphere, and the ability of vegetation to produce oxygen when exposed to sunlight, help maintain aerobic conditions. The lagoons will develop an odor similar to freshwater ponds in wooded areas. Allowable loading can vary from 125 to 2000 persons per hectare depending upon the location. Where complete treatment is to be provided by ponding, the cells are known as raw sewage lagoons, with depths of 1–1.5 m and reduced loading.

5

Wastewater Treatment in the Unconventional Oil and Gas Industries

The intent of this chapter is to identify issues associated with the proper environmental management of waste formation water from exploration and production activities in the unconventional oil and gas industries.

Furthermore, this will outline treatment and disposal options to produce and manage formation wastewater to meet or exceed environmental performance and responsible care requirements.

5.1 Background

Exploration and extraction of petroleum hydrocarbons – specifically natural gases (coal seam gas [CSG], shale gas, etc.) – is not a new industry worldwide. However, the resource potential has only been gaining attention in the past two decades as more conventional resources become depleted.

Marcellus shale is of commercial interest because it is an organic-rich shale containing high quantities of natural gas. Thus, there is enormous interest in commercial exploitation of the shale formation for natural gas production using drilling technologies such as the generally used hydraulic fracturing or directional drilling.

Because shales ordinarily have insufficient permeability to allow significant fluid flow to a well bore, most shales are not commercial sources of natural gas. Shale gas is one of a number of unconventional sources of natural gas; others include coal bed methane (CBM), tight sandstones, and methane hydrates. Shale gas areas are often known as resource plays (as opposed to exploration plays).

Waste Management in the Chemical and Petroleum Industries, Second Edition. Alireza Bahadori.
© 2020 John Wiley & Sons Ltd. Published 2020 by John Wiley & Sons Ltd.



Figure 5.1 *Used frack water from drilling operation around a shale gas drilling rig. Source: Reproduced with permission from © Kate Ausburn.*

Shale has low matrix permeability, so gas production in commercial quantities requires fractures to provide permeability. Shale gas has been produced for years from shales with natural fractures; the shale gas boom in recent years has been due to modern technology in hydraulic fracturing (fracking) to create extensive artificial fractures around well bores.

The market-changing growth of shale gas production in recent years has resulted in the emergence of pressing environmental and water management challenges. Treating large quantities of water used in the hydraulic fracturing process is a major concern for operators. Fracking, or hydraulic fracturing, is the process of drilling sideways into subterranean shale and blasting it open with millions of gallons of water to release natural gas. Figure 5.1 shows a used frack water from the drilling operation around a shale gas drilling rig.

The technology innovation targeted toward wastewater treatment from shale gas operations has escalated rapidly. After a well is drilled, water mixed with various chemicals and sand is forced down the well to fracture the shale and release the gas. This process is called hydraulic fracturing, or "fracking." The tainted water that returns to the surface is called "flow back."

Disposal of the tainted water is a relatively new and evolving industry. In common with other young technology markets, we observe transfer and adaptation of technologies from other industries – in this case from utilities water treatment and the desalination space. As the market matures, we expect increased development of water treatment technologies specific to shale gas extraction.

In the CSG industry, there are wide variations of water production rates from coals in any basin. Ease of dewatering any well depends on the coal's permeability, interference with other wells or mines, and link to an aquifer or meteoric water. Past mining in the area, even though presently inactive, may have depleted water in the seams.

Quantity and chemical content are the two important considerations of water produced from coal seams. Some treatment at the surface is necessary regardless of the disposal method. Total dissolved solids (TDS), oxygen content, and suspended solids must be

controlled for discharge into surface streams and conformance to the environmental regulations. Chloride content, TDS, particulate matter, and formation compatibility must be established for water disposal by well injection.

Besides establishing disposal requirements, water composition gives some insight into the permeability of the formation. The bicarbonate ion (HCO_3^-) exists in larger concentrations in those formations having meteoric water continually replenishing the coal seams. The chloride ion (Cl^-) occurs in greater concentration in more stationary coal bed water. Therefore, HCO_3^- is indicative of good permeability in the coals and of continuity in the seams that allows water circulation along an uninterrupted path. Cl^-, on the other hand, suggests a discontinuity in the seams or a lack of permeability that leaves the water uncirculated.

Generally, the water produced is composed of dissolved and dispersed oil components, dissolved formation minerals, production chemicals, dissolved gases (including CO_2 and H_2S), and produced solids. There is a wide variation in the level of its organic and inorganic composition due to geological formation, lifetime of the reservoir, and type of hydrocarbon produced.

5.1.1 Dissolved and Dispersed Hydrocarbon Components

Dispersed and dissolved components are a mixture of hydrocarbons including benzene, toluene, ethylbenzene, and xylene (BTEX), polyaromatic hydrocarbons (PAHs), and phenols. BTEX, phenols, aliphatic hydrocarbons, carboxylic acid, and low molecular weight aromatic compounds are classified as dissolved hydrocarbons, while less-soluble PAHs and heavy alkyl phenols are present in produced water as dispersed liquid hydrocarbons. Dissolved and dispersed oil content in produced water is dangerous to the environment and the concentration of this can be very high at some fields.

5.1.2 Dissolved Minerals

Dissolved inorganic compounds or minerals are usually high in concentration, and classified as cations and anions, naturally occurring radioactive materials, and heavy metals. Cations and anions play a significant role in the chemistry of produced water. Na^+ and Cl^- are responsible for salinity, ranging from a few milligrams per liter to ~300 000 mg/l. Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-, Na^+, K^+, Ca^{2+}, Ba^{2+}, Mg^{2+}, Fe^{2+}, and Sr^{2+} affect conductivity and scale-forming potential. Typical oilfield produced water contains heavy metals in varied concentrations, depending on the formation geology.

^{226}Ra and ^{228}Ra are the most abundant naturally occurring radioactive elements present in the produced water. The radioactivity of produced water results primarily from radium that is co-precipitated with barium sulfate (scale) or other types of scales. The concentration of barium ions in produced water gives a strong indication of the radium isotopes present in it. Table 5.1 lists the typical composition and properties of oilfield produced water.

5.1.3 Production Chemicals

Production chemicals can be pure compounds or compounds containing active ingredients dissolved in a solvent or a co-solvent, and used for inhibition of corrosion, scale deposition, bacterial growth, and emulsion breaking in order to improve the separation of oil and water.

Table 5.1 Oxygen in coal bed waters.

Parameter	Value
Oxygen in water from coal seam	0
Oxygen required in discharged water	≥5 mg/l
Oxygen for ferrous ion oxidation	1 mg/l O_2 per 7 mg/l Fe^{2+}
Oxygen for manganese ion oxidation	1 mg/l O_2 per 3 mg/l Mn^{2+}
Per 1.0 g of BOD	1.2 g O_2
7.6–11.3 mg/l O_2 dissolves in H_2O	At 50–86 °F w/o Cl

These chemicals enter produced water in traces and sometimes significant amounts and vary from platform to platform. Active ingredients partition themselves into all phases present depending on their relative solubilities in liquid hydrocarbons, gas, or water. The fate of these chemicals is difficult to determine because some active ingredients are consumed within the process

5.1.4 Produced Solids

Produced solids include clays, precipitated solids, bacteria, carbonates, sand and silt, corrosion and scale products, proppant, formation solids, and other suspended solids (API Standard 650, 1988). Their concentrations vary from one platform to another.

5.1.5 Dissolved Gases

The major dissolved gases in produced water are carbon dioxide, oxygen, and hydrogen sulfide. They are formed naturally by the activities of bacteria or by chemical reactions in the water (Figure 5.2).

Currently, oil and gas operators treat produced water via one or more of the following options:

- Avoid production of water: water fractures are blocked by polymer gel or downhole water separators, but this option is not always possible.
- Inject into formations: produced water may be injected back to its formation or into other formations. This option often requires transportation of water, and treatment to reduce fouling and bacterial growth. In the long term, the stored produced water may pollute underground water.
- Discharge to the environment: produced water may be discharged to the environment as long as it meets onshore and offshore discharge regulations.
- Reuse in oil and gas industry operations: minimally treated produced water may be used for drilling and workover operations within the petroleum industry.
- Apply in beneficial uses: produced water may be consumed for irrigation, wildlife consumption and habitat, industrial water, and even drinking water. However, beneficial uses of produced water may involve significant treatment.



Figure 5.2 *A holding pond at Woodview, west of Casino, used by a coal seam gas company to store wastewater. Source: Reproduced with permission from © Green-left, NSW, Australia.*

5.2 Toxicity Limitations of Coal Bed Water

Coal bed water is regulated to specify the following chemical contents and conditions:

- dissolved oxygen (DO)
- biochemical oxygen demand (BOD)
- iron
- manganese
- total dissolved solids (TDS).

The first four of these are dependent on adequate oxygen being added to the water from the coal beds before the water can be disposed of in surface streams.

Dissolved oxygen must be input to the produced water because the water from the coal seams are devoid of oxygen.

Upon aerating the water at the surface, iron and manganese are oxidized and precipitate as solids. Additionally, aerating supplies the oxygen for BOD; about 1.2 g oxygen is required for 1 g BOD. Therefore, supplying oxygen is a primary requirement for surface treatment of produced water, and 5 mg/l of O_2 is required for water discharged from the treating process. Table 5.1 summarizes important characteristics of oxygen in water.

Note from Table 5.1 that oxygen solubility in water is naturally limited to 7.6–11.3 mg/l under ordinary conditions. As temperature or chloride content increases, oxygen solubility

is more diminished. In the hot months, therefore, O_2 solubility in Alabama's surface water decreases, and supplying or maintaining the oxygen in produced water becomes more difficult.

Despite the freedom of surface disposal, strict regulations are imposed on the treatment, disposal, and monitoring of water in surface streams. A series of treating ponds in any producing field of the basin serves as staging points for the treatment process.

The first treatment must be to provide oxygen to the water collected in the ponds using one of three methods:

- *Spraying*: The surface area of the water is increased to absorb oxygen from the air.
- *Agitating mechanically*: The surface area of water in contact with air is renewed constantly. The new surface absorbs more oxygen; the concentration gradient is increased for more rapid absorption of the oxygen.
- *Pumping air beneath the water surface*: A primary objective in the initial treatment is to transfer oxygen to the water to feed the growth of microorganisms that degrade organic matter in the water.

These methods increase the surface area of water exposed to air to enhance absorption of oxygen. Then agitation is supplied to bring bacteria, oxygen, and organic matter into contact. Bates et al. give the rate of oxygen transfer across the gas and liquid films of the liquid/air interface in Eq. (5.1):

$$dC/dt = k_L a(C_s - C) \tag{5.1}$$

where:

C = concentration of oxygen
C_s = saturation concentration of oxygen in water
a = area of interface per unit volume of liquid
t = time
k_L = proportionality constant.

BOD results from the bacteria that degrade organic compounds in the water. It is this oxygen that must be supplied to the bacteria to degrade the mass of organic matter in the water within a certain length of time.

The microorganisms increase their activity exponentially with temperature so that a standard temperature must be set. The standard is 20 °C. BOD5 – the biochemical oxygen demand over a 5-day test period at 20 °C – must not exceed 30 mg/l in the disposal water.

The organic constituents of the produced coal seam water that the microorganisms feed upon may come from organic compounds of the coal or from decaying organic matter in the treatment ponds.

However, the greatest amounts of organic matter that must be biodegraded come from fracturing fluids expelled from the formation. Consequently, the fracturing fluids place a heavy periodic demand on the water for oxygen.

After fracturing, these stimulation fluids continue to be returned for several months during production of the methane. The hydroxypropyl guar and other water-soluble polymers used in fracturing are the main culprits.

To correct the heavy surge of BOD5 at the start-up of a field, hydrogen peroxide is added to supply oxygen demand as a temporary fix to a problem that could require large capital expenditures for more facilities. The start-up BOD5 demand results from return of stimulation fluids used to fracture wells in the field.

Removal of manganese and iron is more straightforward than TDS removal. The oxidized manganese and iron form precipitate in the holding ponds. Their oxidation is much faster at higher pH, which should be maintained above 7.2. Manganese content in the effluent water must be less than 2 mg/l as a monthly maximum 2.8. Total iron must be less than 3.0 mg/l monthly maximum.

The TDS are the most troublesome chemical content of produced water and the most damaging to plant life. Sodium chloride is the main constituent of the dissolved solids.

Considerable environmental concern exists with regard to the potential impact of discharged untreated formation water from exploration and extraction operations on aquatic ecosystems, groundwater resources and soils. Other jurisdictions have experienced problems with certain disposal methods for these types of wastewater.

In order to understand the potential environmental impacts of formation water, their physical/chemical properties must first be understood. To this end a brief description of formation water is given below.

Formation water is the naturally occurring water that is contained within the geological formation itself. In order to extract the methane/natural gas resource within the formation, often large volumes of water must be pumped to the surface. The quantity and quality of the formation water can both be problematic. Depending on the formation, each well can produce in the range of 3–100 l of water per minute, which equates to 4500–140 000 l per day per well.

Over time, the water volume should decrease as the gas volumes increase. Formation water has been found to contain high levels of chlorides, arsenic, iron, barium, manganese, and may even contain naturally occurring radioactive materials (NORMS). Chlorides in some cases have been found to be in excess of four times the level of concentrations found in the ocean.

Discharge of this water into streams which are not saline would be lethally toxic to aquatic life. Discharge onto the land can have an adverse effect on soil structure and negatively impact vegetative growth. Sodium-induced dispersion can cause reduced infiltration, reduced hydraulic conductivity, and surface crusting of soils.

Excess salinity in soil water can decrease plant-available water and cause stress to vegetation. Livestock or humans cannot utilize water with high levels of chlorides due to cellular disruption. High levels of arsenic and barium can be lethally toxic to animal and aquatic life. Elevated levels of iron and manganese can cause accelerated bacteria growth in freshwater systems and reduce ground and surface water quality.

Some jurisdictions have permitted discharge of untreated formation water directly into surface water. Pollution caused by these discharges has been common. Many of these jurisdictions have since amended their regulations and policies to prohibit direct discharge of untreated formation water into any surface water body. Discharge of highly saline formation water led to serious pollution of surface water. In the meantime, leakage of lagoons holding highly saline mine formation water may led to serious contamination of a potable aquifer.

5.3 Shale Gas and CSG Produced Water: Treatment, and Disposal

In general, four techniques are possible to dispose of produced coal bed water: (i) well injection, (ii) discharge into surface streams, (iii) land application, and (iv) membrane processes. All CSG (CBM) produced water that is sent through a treatment facility is discharged into a drainage. Thus water treatment is generally used when the well field is in close proximity to a large river or stream. While water treatment is sometimes used farther from a drainage system, it then requires large-scale pumping and piping infrastructure to move the water to the treatment facility and then to the discharge point.

Formation water in most places, typically, cannot meet these requirements without prior treatment before discharge. The following is a list of commercially available treatment technologies currently used by the industry. This list does not represent a hierarchy of options; it is expected that the generators of the waste will choose the treatment option which is best suited to the characteristics of the formation water they are dealing with and within what is economically achievable for the project.

The industry is also not limited to the technologies listed in this chapter. As technology advances and more is learned about the potential environmental effects of formation water, it can be expected that new technologies will emerge and standards will change.

5.3.1 Evaporation Ponds

An evaporation pond is an artificial pond that requires a relatively large space of land and is designed to efficiently evaporate water by solar energy. Evaporation ponds are designed to prevent either subsurface infiltration of water or the downward migration of water, depending on produced water quality.

Evaporation ponds are a favorable technology for warm and dry climates because of the potential for high evaporation rates. They are typically economical and have been employed for the treatment of produced water onsite and offsite.

Ponds are usually covered with nettings to prevent potential problems for migratory waterfowl caused by contaminants in produced water. All water is lost to the environment when using this technology, which is a major setback when water recovery is an objective for water treatment.

5.3.2 Surface-Stream Disposal

A flow diagram of the surface treating facilities for coal bed water is shown in Figure 5.3. The water pass through an aeration pond, a sedimentation pond, and possibly a storage pond before being disposed of through a diffuser into the surface stream.

Aeration of the “dead” coal bed water having no dissolved oxygen is an important step in processing because the introduction of oxygen into the water has multiple beneficial effects. Foremost of these benefits is the oxidation and resulting precipitation of the suspended solid iron and manganese.

Oxidation of the two metals in the aeration and sedimentation ponds removes these metals from the water and from further consideration. (After several years, the solid sediments must be removed from the bottom of the pond.) Volatile organic matter is lost during

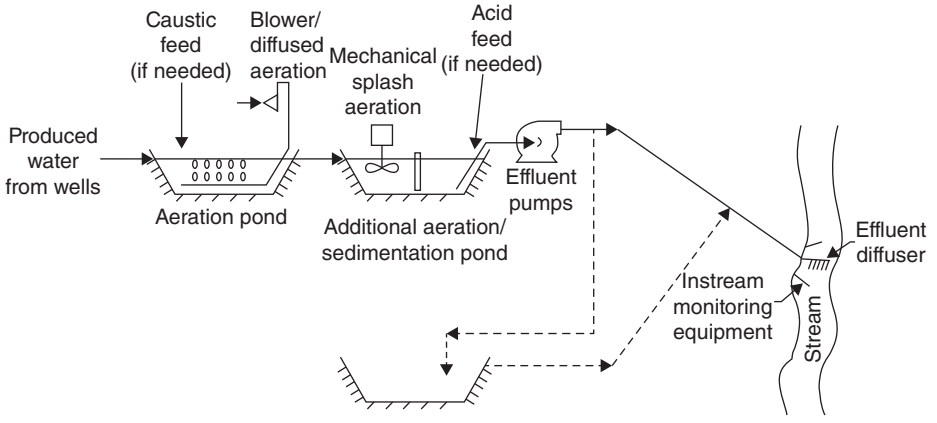


Figure 5.3 *Surface treatment of coal bed water.*

aeration in the holding pond. Also, aeration adds dissolved O_2 and decreases BOD by as much as 50–90%. The aeration process, however, decreases neither the chloride content nor the TDS of coal bed water.

In emergencies, the storage and transfer pond of Figure 5.3 is designed to hold water temporarily, primarily during the low flow of surface streams in the dry summer months.

Chloride removal would require a more expensive and higher technology treatment, specifically ion exchange, reverse osmosis, or electrodialysis; evaporation is also feasible. Consequently, the most difficult problem for any type of surface disposal lies with meeting the TDS specifications, primarily for chlorides. The options are to remove chlorides at considerable expense or to dilute the water to acceptable chloride concentration levels. Upon addition of production water, the content of the natural stream becomes the sum of innate TDS and Cl^- plus TDS and Cl^- added from CBM water.

Timing of CBM water disposal in streams must allow for the prescribed dilution, a feat dependent upon the highly variable seasonal surface stream flow. Four parameters are necessary to develop the surface disposal plan: (i) the water quality of the produced and natural streams, (ii) the well start-up schedule, (iii) the projected flow history of the well, and (iv) natural stream capacities.

$$Q_s = Q_e \frac{C_e - C_m}{C_m - C_s} \tag{5.2}$$

where:

C_m = in-stream quality limitation
C_s = background stream concentration
Q_s = minimum surface stream natural flow to accommodate (cubic feet per second, cfs)
Q_e = effluent from CBM wells (barrels per day, bpd)
C_e = effluent water concentration of TDS.

Environmental regulations set C_m. The assimilative capacities of streams can therefore be calculated. If consistent units of C are used, if Q_e is given in units of barrels of water

per day (BWPD), and if Q_s is wanted in units of cubic feet per second, the relationship becomes:

$$Q_s = 6.5 \times 10^{-5}\ Q_e \frac{C_e - C_m}{C_m - C_s} \tag{5.3}$$

Example 5.1: The "A" Creek in the month of August has an average minimum monthly flow rate of 12 cfs (184 814 bpd). Inherent background TDS in its water amounts to 15 mg/l. Government regulations limit raising the TDS to a maximum of 200 mg/l. CBM wells in the adjacent field produce water having an average TDS content of 1800 mg/l. What maximum volumetric rate of the produced water in BWPD could be disposed of in "A" Creek in August?

Solution

$$Q_e = Q_s \frac{C_m - C_s}{C_e - C_m}$$

where:

Q_e = coal bed well effluent (bpd)
Q_s = 12 cfs
C_e = 1800 mg/l
C_m = 200 mg/l
C_s = 15 mg/l.

Therefore, during the low-flow period of August (assuming an average river flow rate for the month) 21 369 BWPD of the coal bed produced water could be disposed in "A" Creek without exceeding the TDS' limit of the stream. September, October, and November would be the low-flow months, so the low allowable in August would be expected to decrease further in the subsequent 3 months.

5.3.3 Ion Exchange

Ion exchange is conventionally used to describe the purification, separation, and decontamination of aqueous and other ion-containing solutions using solid ion exchangers. Commercial ion exchange is used in many locations for formation water treatment. The technology is capable of treating water of varying quality, which makes it one of the more flexible treatment options.

The finished water quality is high enough to allow it to be used for irrigation, livestock, or watering in some jurisdictions. A waste brine is also produced which, depending on the chemistry, must be disposed of at an approved facility. Ion exchange has proven to be economically viable under appropriate conditions.

5.3.4 Membrane Filtration Technology

Membranes are microporous films with specific pore ratings which selectively separate a fluid from its components. There are four established membrane separation processes: microfiltration (MF), ultrafiltration (UF), reverse osmosis (RO), and nanofiltration (NF). RO separates dissolved and ionic components, MF separates suspended particles, UF

separates macromolecules, and NF is selective for multivalent ions. MF and UF can be used as a standalone technology for treating industrial wastewater, but RO and NF are usually employed in water desalination. Membrane technology operates two types of filtration processes, cross-flow filtration or dead-end filtration, which can be a pressure (or vacuum)-driven system.

5.3.4.1 Reverse Osmosis

Reverse osmosis is a separation process that uses pressure in excess of osmotic pressure to force a solvent through a membrane that retains the solute on one side and allows the purified solvent to pass to the other side.

The process is used most often for desalination but is also effective in removal of all particles larger than 1 Å. Pre-treatment is required as membranes cannot be backwashed because of the design, which allows water to flow through in only one direction.

Waste brine is typically piped to a storage pond for further evaporation and eventual disposal at an approved facility. This process has been effectively utilized worldwide for various types of water and wastewater treatment. This process is energy consumptive due to the high pressures required to force the solvent through the membrane. Figure 5.4 shows a typical RO treatment process.

5.3.4.2 Microfiltration and Ultrafiltration

MF has the largest pore size (0.1–3 μm) and is typically used for the removal of suspended solids and turbidity reduction. It can operate in either cross-flow or dead-end filtration. UF pore sizes are between 0.01 and 0.1 μm. UF is employed in the removal of color, odor, viruses, and colloidal organic matter. UF is the most effective method for liquid hydrocarbon removal from produced water in comparison with traditional separation

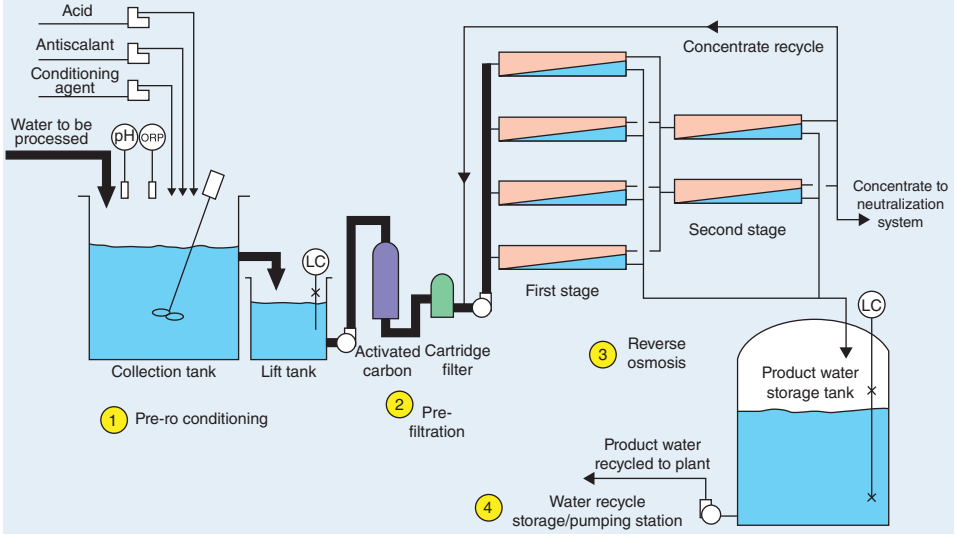


Figure 5.4 *A typical reverse osmosis treatment process.*

methods, and it is more efficient than MF for the removal of hydrocarbons, suspended solids, and dissolved constituents from oilfield produced water. Both MF and UF operate at low trans membrane pressure (1–30 psi) and can serve as a pre-treatment to desalination but cannot remove salt from water.

5.3.4.3 Polymeric and Ceramic Membranes

Polymeric and ceramic membranes are used for UF/MF treatment of water. Polymeric MF/UF membranes are made from polyacrylonitrile and polyvinylidene, and ceramic membranes from clays of nitrides, carbides, and oxides of metals. Ceramic UF/MF membranes have been used in a full-scale facility for the treatment of produced water. Product water from this treatment was reported to be free of suspended solids and nearly all non-dissolved organic carbon. Ceramic UF/MF membranes can operate in both cross-flow filtration and dead-end filtration modes and have a lifespan of >10 years. Chemicals are not required for this process except during periodic cleaning of membranes and pre-coagulation (used to enhance contaminants removal).

5.3.5 Freeze-Thaw Evaporation

Freeze-thaw evaporation may be utilized when the ambient air temperature is below 0 °C. The contaminated water is sprayed or dripped onto a freezing pad to create an ice pile.

During sub-freezing conditions runoff from the ice pile will have elevated concentrations of chemical constituents compared to the original wastewater. The result is a higher concentrated solute, which will be required to be stored for later disposal of at an approved facility. Once temperatures increase to allow for thaw conditions, the melt water can be suitable for beneficial uses such as irrigation.

There are also implications for soil contamination associated with this method of treatment. While this may be feasible in jurisdictions with large land areas that are isolated from population bases.

5.3.6 Adsorption

Adsorption is generally utilized as a polishing step in a treatment process rather than as a standalone technology since adsorbents can be easily overloaded with organics. It has been used to remove manganese, iron, total organic carbon (TOC), BTEX, oil, and more than 80% of heavy metals present in produced water. There are a variety of adsorbents, such as activated carbon, organoclays, activated alumina, and zeolites.

5.3.7 Chemical Oxidation

Chemical oxidation destroys organic contaminants which are either dissolved in water or present in free phase. Chemical oxidants are introduced to the wastewater to react with organic compounds such as amines, phenols, chlorophenols, cyanides, halogenated aliphatic compounds, and mercaptans. Chemical oxidation can be combined with other treatment technologies to maximize clean-up results.

Treated water quality is high. A waste brine is also produced which, depending on the chemistry, must be disposed of at an approved facility. The efficiency of the process is reduced with reduced water quality. Capital and operating costs are typically high.

Chemical oxidation is an established and reliable technology for the removal of color, odor, chemical oxygen demand (COD), BOD, organics, and some inorganic compounds from produced water.

Chemical oxidation treatment depends on oxidation/reduction reactions occurring together in produced water because free electrons cannot exist in solution. Oxidants commonly used include ozone, peroxide, permanganate, oxygen, and chlorine. The oxidant mixes with contaminants and causes them to break down. The oxidation rate of this technology depends on chemical dose, type of oxidant used, raw water quality, and contact time between oxidants and water.

5.3.8 Filtration

Filtration technology is extensively used for the removal of oil, grease, and TOC from produced water. Filtration can be accomplished by the use of various types of media such as sand, gravel, anthracite, walnut shell, and others. Walnut shell filters are commonly used for produced water treatment.

This process is not affected by water salinity and may be applied to any type of produced water. Media filtration technology is highly efficient for the removal of oil and grease, and efficiency of more than 90% has been reported. Efficiency can be further enhanced if coagulants are added to the feed water prior to filtration. Media regeneration and solid waste disposal are setbacks to this process.

5.3.9 Constructed Wetlands

Constructed wetlands are artificially constructed wastewater treatment systems which utilize wetland vegetation to promote natural chemical and biological processes to achieve effective treatment of wastewater. There are two principle categories of constructed wetland systems: free water surface and subsurface flow.

Constructed wetland systems are very effective in removing nutrients such as nitrogen and phosphorous. Depending on the vegetation incorporated, wetlands can also remove organic or inorganic contaminants given sufficient retention time.

The efficiencies of the process have been shown to be in the 95% range. Efficiencies are highly dependent the characteristics of the wastewater and the type of vegetation which is utilized.

Constructed wetland technology is considered a new technology with respect to formation water treatment. However, this technology has been successfully employed for treatment of coal mine discharge water which has similar chemistry to that of formation water. Use of an existing natural wetland or a wetland which has been created as part of a compensation plan is strictly prohibited.

5.3.10 Electrodialysis and Electrodialysis Reversal

Electrodialysis (ED) and ED reversal (EDR) are mature electrochemically driven desalination technologies. These processes involve separation of dissolved ions from water through ion exchange membranes. They use a series of ion exchange membranes containing electrically charged functional sites arranged in an alternating mode between the anode and the cathode to remove charge substances from the feed water (Figure 5.5). If the membrane is

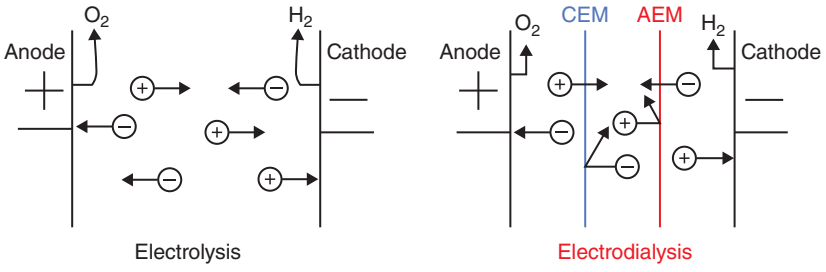


Figure 5.5 *Comparison of electrolysis and electrodialysis. CEM, cation exchange membrane; AEM, anion exchange membrane.*

positively charged, only anions are allowed to pass through it. Similarly, negatively charged membranes allow only cations to pass through them. EDR uses periodic reversal of polarity to optimize its operation.

5.3.11 Deep Well Injection at Dedicated Onshore Sites

Disposal of wastes through injection down wells into pores, fissures, and caverns in underground strata has been a favored strategy in many areas. These disposal sites often take advantage of exploratory wells that did not find commercial quantities of natural gas or oil and therefore represent a non-performing asset to the drilling company or have been evacuated of the oil or gas resource. Using such sites for waste disposal therefore allows some cost recovery.

The technical rationale for using deep well disposal is that the materials are deposited in impermeable strata which is hydraulically isolated from potable aquifers and surface water. In addition, since the particular fluids used in drilling were considered safe enough to use during the original construction of the well, it should be reasonable to assume that more of these materials placed permanently would not pose additional risk.

The arguments against this form of disposal are also persuasive. Injection is a form of dumping since no treatment has occurred or is likely to occur at depth. This results in an area that is permanently impacted and withdrawn from potential beneficial use. There is also additional risk if the underlying geology is not perfectly understood, since leakage may occur and monitoring is difficult and expensive to install.

Since many locations do not have an extensive history of land-based petroleum exploration and therefore do not have preexisting wells or land areas that are impacted by drilling fluids, it does not appear reasonable at this time to establish deep well injection as a disposal option for formation water.

5.3.12 Biological Aerated Filters

Biological aerated filtration (BAF) is a class of biological technologies which consists of permeable media that use aerobic conditions to facilitate biochemical oxidation and removal of organic constituents in polluted water. The media should be not more than 4 inches in

diameter to prevent clogging of pore spaces when sloughing occurs. BAF can remove oil, ammonia, suspended solids, nitrogen, COD, BOD, heavy metals, iron, soluble organics, trace organics, and hydrogen sulfide from produced water. It is most effective for produced water with chloride levels below 6600 mg/l.

This process requires upstream and downstream sedimentation to allow the full bed of the filter to be used. Removal efficiencies of up to 70% nitrogen, 80% oil, 60% COD, 95% BOD, and 85% suspended solids have been achieved with BAF treatment.

Solids disposal is required for accumulated sludge in sedimentation basins and can account for up to 40% of the total cost of this technology.

5.3.13 Macro-porous Polymer Extraction Technology

Macro-porous polymer extraction (MPPE) is one of the best available technologies and best environmental practices for produced water management on offshore oil and gas platforms. It is a liquid–liquid extraction technology where the extraction liquid is immobilized in the macro-porous polymer particles. These particles have a diameter of ~1000 μm, pore sizes of 0.1–10 μm, and porosity of 60–70%. Polymers were initially designed for absorbing oil from water but applied to produced water treatment in 1991. Table 5.2 shows a summary of different produced water membrane treatment technologies.

5.3.14 Thermal Technologies

Thermal water treatment technologies are employed in regions where the cost of energy is relatively cheap. Thermal separation was the technology of choice for water desalination before the development of membrane technology. Multistage flash (MSF) distillation, vapor compression distillation (VCD), and multi-effect distillation (MED) are the major thermal desalination technologies. Hybrid thermal desalination plants, such as MED–VCD, have been used to achieve higher efficiency. Although membrane technologies are typically preferred to thermal technologies, recent innovations in thermal process engineering make thermal process more attractive and competitive in treating highly contaminated water.

5.3.14.1 Multistage Flash

MSF distillation is a mature and robust technology for brackish and sea water desalination. Its operation is based on evaporation of water by reducing the pressure instead of raising the temperature. Feed water is pre-heated and flows into a chamber with lower pressure, where it immediately flashes into steam. Water recovery from MSF treatment is ~20% and the recovered water often requires post-treatment because it typically contains 2–10 mg/l of TDS. A major setback in operating MSF is scale formation on heat transfer surfaces, which often means this process requires the use of scale inhibitors and acids. Overall costs vary depending on the size, site location, and materials of construction. The energy requirement is between 3.35 and 4.70 kWh/bbl.

Globally, MSF market share has significantly decreased due to competition from membrane technologies, but it is a relatively cost-effective treatment method with plant life expectancy of more than 20 years and can be employed for produced water treatment.

Table 5.2 *Comparison of produced water membrane treatment technologies (Igunnu and Chen 2012).*

Method	Reverse osmosis (RO)	Nano filtration (NF)	Polymeric microfiltration/ ultrafiltration (MF/UF) membrane	Ceramic microfiltration/ ultrafiltration membrane
Disadvantages	(1) Highly sensitive to organic and inorganic constituents in the feed water (2) Membranes cannot withstand feed temperatures in excess of 45 °C	(1) Highly sensitive to organic and inorganic constituents in the feed water (2) Membranes cannot withstand feed temperatures in excess of 45 °C (3) Requires several backwashing cycles	(1) Membrane requires periodic cleaning (2) Waste generated during backwash and cleaning processes requires disposal/recycling or further treatment	(1) Irreversible membrane fouling can occur with significant amount of iron concentration in feed water (2) Membrane requires periodic cleaning (3) Waste generated during backwash and cleaning processes requires disposal/recycling or further treatment
Advantages	(1) High pH tolerance (2) System can be operated automatically, leading to less demand for skilled workers (3) Energy costs can be reduced by implementing energy recovery subsystems (4) Performs excellently for produced water treatment with appropriate pre-treatment (5) Does not require concentrate treatment as brine generated is usually disposed of into the sea (6) Product water recovery in SWRO is between 30% and 60%, and between 60% and 85% in BWRO	(1) High pH tolerance (2) System can be operated automatically, leading to less demand for skilled workers (3) Energy costs can be reduced by implementing energy recovery subsystems (4) Does not require solid waste disposal (5) Water recovery between 75% and 90%	(1) Product water is free of suspended solids (2) Product water recovery range from 85% to 100%	(1) Product water is totally free of suspended solids (2) Can be operated in cross-flow or dead-end filtration mode (3) Product water recovery range from 90% to 100% (4) Ceramic membranes have a longer lifespan than polymeric membranes

Life cycle	3–7 years	3–7 years	7 years or more	>10 years
Pre/post-treatment	Extensive pre-treatment is required to prevent fouling of membrane Product water may require remineralization or pH stabilization to restore SAR values	Extensive pre-treatment is required to prevent fouling of membrane Product water may require remineralization to restore SAR values	Cartridge filtration and coagulation are usually used as a pre-treatment Post-treatment may be required for polishing depending on the product water	Cartridge filtration and coagulation are usually used as a pre-treatment Post-treatment may be required for polishing depending on the product water
Overall cost	Capital costs of BWRO vary from \$35 to \$170/bpd and operating costs are \$0.03/bbl Capital costs of SWRO vary from \$125 to \$295/bpd and operating costs are \$0.08/bbl	Capital costs range from \$35 to \$170/bpd Operating cost is \$0.03/bbl	Capital costs depend on feed water quality and size of the polymeric membrane system Approximate capital cost is \$0.02–0.05/bpd Approximate operation and maintenance costs ARE \$0.02–0.05/bpd	
Chemical use	Caustic and scale inhibitors are required to prevent fouling NaOH, H_2O_2, Na_2SO_4, H_3PO_4, HCl, or Na_4EDTA are required for cleaning the system	Caustic and scale inhibitors are required to prevent fouling NaOH, H_2O_2, Na_2SO_4, HCl, or Na_4EDTA are required for cleaning the system	Ferric chloride, polyaluminum chloride, and aluminum sulfate are common coagulants used for pre-coagulation Acids, bases, and surfactants are used in cleaning process	Ferric chloride, polyaluminum chloride, and aluminum sulfate are common coagulants used for pre-coagulation Acids, bases, and surfactants are used in cleaning process

(*Continued*)

Table 5.2 *(continued)*

Method	Reverse osmosis (RO)	Nano filtration (NF)	Polymeric microfiltration/ ultrafiltration (MF/UF) membrane	Ceramic microfiltration/ ultrafiltration membrane
Energy consumption	RO uses electrical energy for its operation SWRO requires 0.46–0.67 KWh/bbl if energy recovery device is integrated BWRO requires less energy than equivalent SWRO system BWRO requires 0.02–0.13 KWh/bbl of energy to power the system's pumps	Uses electrical energy and its energy requirement is less than what is required in RO systems Approximately NF system requires 0.08 KWh/bbl to power its high-pressure pump	Not available	Not available
Feasibility	This is a robust technology for seawater desalination and has been employed in produced water treatment For this technology to be effective in produced water treatment, extensive pre-treatment of feed water is necessary Several pilot studies failed due to poor pre-treatment and insufficient system integration	This technology is used for water softening and removal of metals from wastewater It is specifically efficient for feed water containing TDS ranging from 500 to 25 000 mg/l NF is a poor technology for produced water treatment and is inappropriate as a standalone technology	Applicable to water with high TDS and salt concentrations and also has the potential to treat produced water, but it is extensively used in the municipal water treatment	Ceramic membranes have been used to treat oilfield produced water and extensively used in other industrial water treatments They are applicable to all types of produced water irrespective of their TDS and salt concentrations, but produced water with high concentrations may be problematic

SWRO, BWRO; SAR, sodium adsorption ratio.

5.3.14.2 Multi-effect Distillation

MED involves application of sufficient energy to convert saline water to steam, which is condensed and recovered as pure water. Multiple effects are employed to improve the efficiency and minimize energy consumption. A major advantage of this system is the energy efficiency gained through the combination of several evaporator systems. Product water recovery from MED systems is in the range of 20–67% depending on the type of the evaporator design employed. Despite the high water recovery from MED systems, this process has not been extensively used for water production, like MSF, because of the scaling problem associated with old designs. Recently, falling film evaporators have been introduced to improve heat transfer rates and reduce the rate of scale formation.

5.3.14.3 Vapor Compression Distillation

VCD is an established desalination technology for treating seawater and RO concentrate. Vapor generated in the evaporation chamber is compressed thermally or mechanically, which raises the temperature and pressure of the vapor. The heat of condensation is returned to the evaporator and utilized as a heat source. VCD is a reliable and efficient desalination process and can operate at temperatures below 70 °C, which reduces scale formation problems. Table 5.3 summarizes the various produced water thermal treatment technologies.

5.4 Re-thinking Technologies for Safer Facing

With water treatment predicted to increase, the advancement of innovative and ground-breaking technologies will expand to meet the industry's need. There are a number of companies working to revolutionize fracking through innovative water treatment processes:

- Some companies have developed a high-energy electrocoagulation technology that addresses heavy metals, biological matter, and hydrocarbons, but is limited to areas where salt levels are moderate.
- A group of companies are working on oxidation technologies. They use catalyzed UV to achieve many of the same results, but also removes metals. Though this is still an early-stage start up, it ranks as a high potential player.
- Some researchers are using propane to fracture gas wells. Shell, Husky, and others are testing the technology.
- Some environmental active companies have deployed a proven mobile wastewater treatment system in the field with great success.

As companies set out to revolutionize the industry with new water treatment solutions, it looks like the most cost-effective treatment systems could be based on a mobile platform. Mobile wastewater treatment systems allow drilling companies to operate off the grid, which is a valuable time- and money-saving strategy. Mobile just makes a lot of sense in an industry where jobsites are constantly moving.

Another solution is on the brink of revolutionizing the industry. Some companies have teamed together to commercialize a geographic information system (GIS) that will help predict – and prevent – ecological harm from drilling operations. The system will enable

Table 5.3 *Comparison of produced water thermal treatment technologies (Igunnu and Chen, 2012).*

Method	MSF	MED	Vapor compression distillation technology	Multi effect distillation–vapor compression hybrid	Freeze thaw evaporation
Disadvantages	(1) Low product water recovery usually between 10 and 20% (2) Not flexible for varying water flow rates (3) Scaling and corrosion can be a problem	(1) Typically low product water recovery usually between 20% and 35% (2) Not flexible for varying water flow rates (3) Scaling and corrosion can be a problem (4) High level of skilled labor required	(1) Typically low product water recovery usually around 40% (2) Not flexible for varying water flow rates (3) Scaling and corrosion can be a problem (4) High level of skills required to operate system	(1) Not applicable to produced water wells point source (2) Being a hybrid design, requires very highly skilled labor	(1) Cannot treat produced water with high methanol concentration (2) Moderate product water quality containing around 1000 mg/l TDS (3) Can only work in winter time and in places with below freezing temperatures (4) A significant amount of land is required (5) Generates secondary waste streams

Advantages	(1) Requires less rigorous pre-treatment and feed condition compared with membrane technologies (2) Has a significantly long lifespan (3) MSF system can withstand harsh conditions (4) Can easily be adapted to highly varying water quality (5) Cost of labor is cheaper than using membrane technology (6) Good for high TDS produced water treatment (7) Product water quality is high with TDS levels between 2 mg/l and 10 mg/l	(1) Requires less rigorous pre-treatment and feed condition compared with membrane technologies (2) Has a long lifespan (3) Energy requirement is cheaper than using MSF (4) Can easily be adapted to highly varying water quality (5) Cost of labor is cheaper than using MSF or membrane technology (6) Good for high TDS produced water treatment (7) Product water quality is high (8) Does not require special concentrate treatment (9) Product water recovery of up to 67% can be achieved using stacked vertical tube design	(1) Applicable to all types of water and water with high TDS, 40 000 mg/l (2) Is a smaller unit compared with MS F and MED (3) Has high ability to withstand harsh conditions (4) Does not require special concentrate treatment (5) Pre -treatment is less rigorous compared with membrane treatment	(1) High product water quality (2) Excellent treatment technology for produced water with high TDS and zero liquid discharge (3) System can withstand harsh conditions	(1) Excellent for zero liquid discharge (2) Requires low skilled labor, monitoring, and control (3) Highly reliable and can be easily adapted to varying water quality and quantity

(*Continued*)

Table 5.3 *(continued)*

Method	MSF	MED	Vapor compression distillation technology	Multi effect distillation–vapor compression hybrid	Freeze thaw evaporation
Life cycle	Typically 20 years but most plants operate for more than 30 years	Typically 20 years	Typically 20 years but may operate for more years	Typically 20 years but may be longer if made of materials with high corrosion resistance	Expected lifespan is 20 years
Pre/post-treatment	Pre-treatment is done to remove large suspended solids This requires screens and rough filtration Product water stabilization is required because of its low TDS	Pre-treatment is done to remove large suspended solids similar to MSF This requires screens and rough filtration Product water stabilization is required because of its low TDS	Pre-treatment and post-treatments are required in order to avoid fouling and because of low TDS level in product water, respectively	Requires a less rigorous pre-treatment compared with membrane technologies Lime bed contact post-treatment is required because of low TDS of product water	Requires minimal pre- and post-treatment depending on product water quality and discharge standards
Overall cost	Capital costs vary between $250 and $360 bpd Operating costs are $0.12/bbl and total unit costs are $0.19/bbl	Overall cost is lesser than in MSF Capital costs range from $250 to $330 per bpd Operating costs are $0.11/bbl and total unit costs are $0.16/bbl	Capital costs of vapor compression for sea water desalination ranges from $140 to $250 per bpd depending on various factors Operating costs are $0.075/bbl and total unit costs are $0.08/bbl for seawater desalination	Capital cost is $250 per bbl per day Operation costs depend on the amount of energy consumed	Depends on location

Chemical use	EDTA, acids, and other antiscaling chemicals are used to prevent scaling pH control is also necessary to prevent corrosion	Scale inhibitors are required to prevent scaling Acid, EDTA, and other antiscaling chemicals are required for cleaning and process control	Scale inhibitors and acids are required to prevent scaling EDTA and other antiscaling chemicals are required for cleaning and process control Corrosion is prevented by pH control	Scale inhibitors are required to prevent scaling Acids, EDTA, and other antiscaling chemicals are required for cleaning and process control Corrosion is prevented by pH control	None
Energy consumption	Electrical energy required ranges from 0.45 kWh/bbl to 0.9 kWh/bbl Thermal energy required is estimated at 3.35 kWh/bbl Overall energy required for MSF ranges from 3.35 to 4.70 kWh/bbl	MED requires both thermal and electrical energy types Electrical energy consumed is approximately 0.48 kWh/h/bbl and power consumption is 1.3–1.9 kWh/bbl	VCD requires both thermal and electrical energy For desalination, power energy consumption is around 1.3 kWh/bbl Electricity consumption is 1.1 kWh/bbl for mechanical vapor compression (MVC) and to achieve zero-liquid discharge energy demand is 4.2–10.5 kWh/bbl	Uses both thermal and electrical energy Power consumption for desalination is around 0.32 kWh/bbl To achieve zero-liquid discharge energy consumption is around 4.2–10.5 kWh/bbl	Uses electrical energy, but data are not available

(*Continued*)

Table 5.3 *(continued)*

Method	MSF	MED	Vapor compression distillation technology	Multi effect distillation–vapor compression hybrid	Freeze thaw evaporation
Feasibility	This is a mature and robust desalination technology that can be employed for produced water treatment MSF is applicable to all types of water with high TDS range up to 40 000 mg/l	This is a mature and robust desalination technology that can be employed for produced water treatment MED is applicable to all types of water and a wide range of TDS	This is a mature and robust seawater desalination technology It is applicable to all types of wastewater with TDS level greater than 40 000 mg/l Various enhanced VCD have been applied in produced water treatment	A mature desalination technology that has been employed in produced water treatment It is usually employed for treating water with high TDS In future product, water quality may be increased, for example product water recovery of 75% was achieved by GE using brine concentrator and analyzer	This is a mature and robust technology for produced water treatment It does not require infrastructure It requires favorable soil conditions, a significant amount of land, and a substantial number of days with temperatures below freezing

the formulation of land-use benchmarks to assist in the optimal placement of wells, roads, gathering lines, and other necessary infrastructure. The point is, with withering public opinion, companies are searching for ways to improve the drilling process by building faster, better, and cheaper technologies.

There are numerous types of other treatment methods that can be marketed as viable treatment methods for CBM water prior to discharge, including the following:

1. CBM-WTS is marketed as a CBM water treatment technology that is designed to treat the specific feed specifications of numerous incoming chemical compositions and chemical removal of sodium ions, with throughput ranging from 50 gal per minute to over 1000 gal per minute, thus producing a secondary waste of salt concentrate which must be stored and disposed of.
2. Submerged combustion is marketed as a water treatment technology for the CBM industry that can be utilized to heat liquids in order to treat wastewater. This system is touted for the mining industry, pulp and paper industry, ethanol and glycol reduction, and many more industrial applications.
3. Catalyx fluid solutions (CFS) is marketed as a water treatment technology for the CBM industry.
4. A continuous counter-current ion exchange (CCIX) method can remove sodium (Na) and other cations from CBM produced water. This CCIX system is based on Higgins loop technology. The produced water containing high Na levels enters into the adsorption zone within the Higgins loop where it contacts a strong acid cation resin that loads Na^+ ions in exchange for hydrogen ions. The loop extracts 95% of the cations. Concurrent with adsorption and in the lower section of the Higgins loop, Na-loaded resin is regenerated with hydrochloric acid and a small, concentrated spent brine stream is produced. Regenerated resin is rinsed with water prior to re-entering the adsorption zone to remove acid from its pores. As resin in the adsorption zone becomes loaded with Na, the flows to the Higgins loop are momentarily interrupted to allow "pulsing" of the resin bed through the loop in the opposite direction to the liquid flow. Liquid flows restart after the resin pulsing is complete.
5. There are operator owned chemical treatment plants. While it is possible to alter the chemistry of sodic water by adding calcium and magnesium. This does not eliminate or reduce sodium, but changes the ratio of sodium to other salts, thus decreasing the sodium adsorption ratio (SAR). The net result is more saline water with the sodium salt still dissolved in the water. This approach is not likely to work with CBM product water because the added calcium will combine with carbonate from the CBM water and precipitate out as calcium carbonate (lime). To make this process work, CBM product water must be de-gassed of carbonate by addition of acid, or additional calcium must be made available in the soil by acidification from sulfur additions.

5.5 Water Treatment for Oil Sands Mining

To produce oil from oil sands fields a huge amount of water is used. Specifically, water is used to separate bitumen from the sand at a high water to oil ratio – it is estimated that around 2 to 4.5 barrels of fresh water are used to produce a barrel of synthetic crude oil.

The water is used for in situ recovery of bitumen, i.e. water is converted to steam to heat up the bitumen underground and then pump it to the surface through wells. Wastewater is usually alkaline, slightly brackish, and toxic to aquatic biota due to high concentrations of organic acids. Strong regulation, i.e. a zero discharge policy, has led to mostly water recycling as practiced by the oil sand producers. The other alternative is to tap an underground aquifer hosting non-potable saline water for bitumen recovery.

5.5.1 Recycling and Water Treatment Options

Despite the aggressive recycling of wastewater by oil sand producers for re-use in the recovery process, repeated extraction cycles have resulted in the deterioration of water quality, which could upset the bitumen extraction process through scaling, fouling, increased corrosivity, and interference with extraction chemistry.

Furthermore, with a zero discharge policy, oil sand producers have to treat and properly dispose of millions of cubic meters of toxic process water and tailings, which are currently held in large tailings ponds. With reclamation depending on the natural detoxification of process water in tailings ponds, the viability is uncertain.

To meet the concerns on wastewater management in general, and ensure supply of recycled water for bitumen processing in particular, oil producers could use various water treatment technologies, including:

1. adsorption
2. membranes – microfiltration and ultrafiltration
3. nanofiltration and RO
4. biological treatment
5. advanced oxidation
6. constructed wetlands.

Adsorbents are used to remove a wide variety of pollutants associated with oilfield produced water, especially organic carbon compounds, oil and grease, and heavy metals. Adsorbents can be activated carbon, natural organic matter, zeolites, clays, and synthetic polymers.

Micro- and ultrafiltration are pressure-driven membrane processes that reject particles as small as 0.1 μm and 0.01 μm, respectively. Laboratory- and pilot-scale studies using membranes to treat produced water have shown over 90% oil rejection with permeate concentrations of less than 20 ppm. On a wider scale, problems such as fouling and membrane durability could occur. Nanofiltration has the potential for partial demineralization, softening, and removal of soluble organic compounds from produced water as it can reject divalent ions, dissolved organic matters, pesticides, and other macromolecules.

RO, on the other hand, requires the feedwater to be forced against a concentration gradient though a semi-permeable membrane. Studies have showed that using RO, rejection of hardness typically exceeds 98% (residual concentration of <2 ppm $CaCO_3$) and rejection of monovalent ions exceed 90%.

Other projects have also used RO to convert produced water from an oilfield to freshwater for agricultural and potable use.

Biological treatment (the use of microorganisms to remove contaminants) in one pilot study has been shown to remove 98–99% of total petroleum hydrocarbons from produced

water but the microorganisms have to get used to the saline conditions before certain treatment efficiency (>95%) can be achieved.

Advanced oxidation could be either photocatalytic oxidation or sonochemical oxidation. Laboratory-scale experiments have shown that photocatalytic oxidation can decompose organic and inorganic pollutants in oilfield produced water. The degradation rates are dependent on efficient adsorption of pollutants into the catalyst, which could then be affected by the feedwater pH.

Sonochemical oxidation involves the formation and collapse of bubbles when ultrasound is applied to a liquid, i.e. produced water. This collapse of the microbubbles produces cavities (cavitation) of high temperature and pressure that can break or destroy particles or molecules. Used with an oxidant such as hydrogen peroxide, the cavitation process in some studies has been demonstrated to degrade phenols, organic acids, and PAH.

Constructed wetlands, since their earlier use to treat municipal and storm water, are becoming popular in the oil sector. The processes of pollutant removal in wetlands include sedimentation, adsorption, denitrification, photo-oxidation, plant uptake, and volatilization. Wetlands have proven to be effective in removing contaminants in produced water but treatment performance is variable, as shown in various pilot and full-scale studies, i.e. 55–85% for BOD5, 53–86% for COD, 54–94% for oil and grease, and 10–94% for phenols.

Table 5.4 summarizes the different treatment processes and their potential applications to treat produced water from oilsands mining.

This section shows that many water treatment technologies have shown potential to treat, i.e. de-oil, soften, detoxify, and demineralize, oilfield-produced water on a small scale, but their effectiveness has yet to be proven at the bench or pilot levels.

It is suggested that further preliminary studies are needed on pre-treatment requirements, performance on target pollutants, energy consumption, and costs among other factors to be able to compare these technologies to existing/conventional technologies.

There is a strong need to further understand how these technologies would perform given the unique physical and chemical nature of produced water from oil sands mining on a the larger scale.

5.5.2 Oily Water Treatment in Oil Sands Mining

Oil sands extraction can affect water resources by its requirement for large quantities of water during separation of the oil and sand. The majority of oily wastewater is produced in oil sands mining.

Heavy metals such as vanadium, nickel, lead, cobalt, mercury, chromium, cadmium, arsenic, selenium, copper, manganese, iron, and zinc are naturally present in oil sands and may be concentrated by the extraction process. The technologies reported in Section 5.3 could be considered for oil sand mining wastewater treatment after careful evaluation.

There are currently two methods for recovering bitumen. The first is surface mining of oil sands ores with subsequent separation of bitumen from the other constituents by an alkaline hot water extraction process.

The second method is an in situ thermal process for extracting bitumen from oil sands that are too deep to mine. In surface mining operations, alkaline hot water extraction produces large volumes of surface-mining water that must be stored in onsite tailing ponds to prevent environmental pollution.

Table 5.4 *Water treatment processes: problems and potentials.*

Processes	Problems associated with treatment of produced water	Significant technological advances	Target chemicals in oil sands process water
Adsorption	Incomplete pollutant removal; fouling from oil; cleaning and regeneration costs; low adsorption capacity	Organic modifications to clay adsorbents; natural and synthetic polymers with improved adsorption and regeneration properties	Napthenic acids, bitumen, aromatic hydrocarbons, trace metals
Microfiltration and ultrafiltration	Fouling from oil and solids; membrane durability; disposal of retentate	Surface chemistry modifications to reduce fouling and permeate flux decline; chemical additives, aeration, and ultrasound to reduce fouling	Bitumen, suspended solids
Nanofiltration and RO	Fouling from oil, dissolved organics, and algal growth; membrane replacement costs; brine disposal	Membrane modifications to reduce fouling from organics; ultra-low pressure membranes; lower energy consumption	Napthtenic acids, hardness, TDS, aromatic hydrocarbons
Biological treatment	Feedwater toxicity; incomplete pollutant removal; sludge disposal	Membrane bioreactors facilitate oxidation of recalcitrant compounds and protect biofilm from influent toxicity	Napthenic acids, ammonium, bitumen, aromatic hydrocarbons
Advanced oxidation	Incomplete pollutant removal; high energy costs; radical scavengers; oxidation by-products	Solar photocatalytic systems; photo electrocatalytic process to reduce the effect of radical scavengers	Napthenic acids, ammonium, aromatic hydrocarbons
Constructed wetlands	Flow capacity; feedwater toxicity; removal of salinity; bioaccumulation of toxicants by wetland biota; cold water operation	Subsurface designs for operation in cold climates; implementation of large-scale wetlands to treat oil-contaminated water; improved understanding of degradation pathways	Napthenic acids, ammonium, bitumen, aromatic hydrocarbons

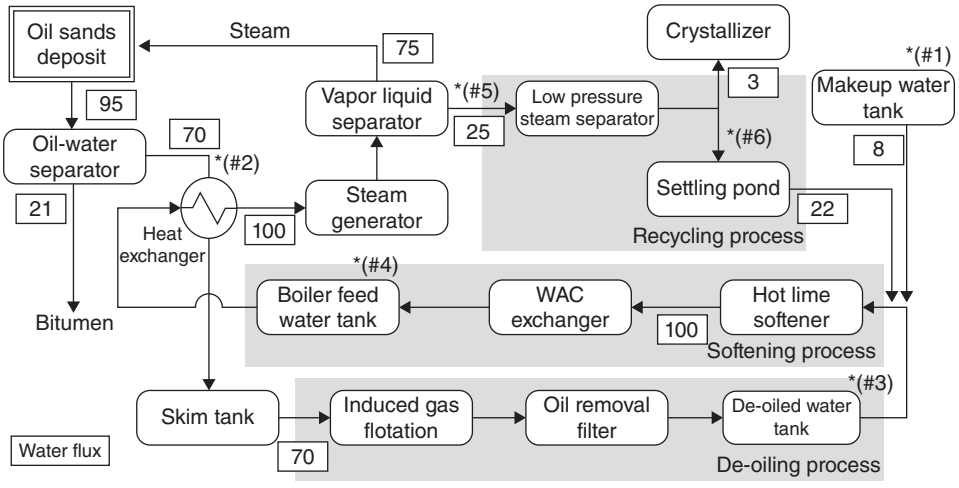


Figure 5.6 *Water treatment system in the SAGD process operated by Japan Canada Oil Sands Ltd. Water sampling points: #1, groundwater; #2, produced water; #3, de-oiled water; #4, softened water; #5, boiler blowdown; #6, recycled water. Source: Reproduced with permission from Kawaguchi et al. Water Research (2012) 5566–5574 © Elsevier.*

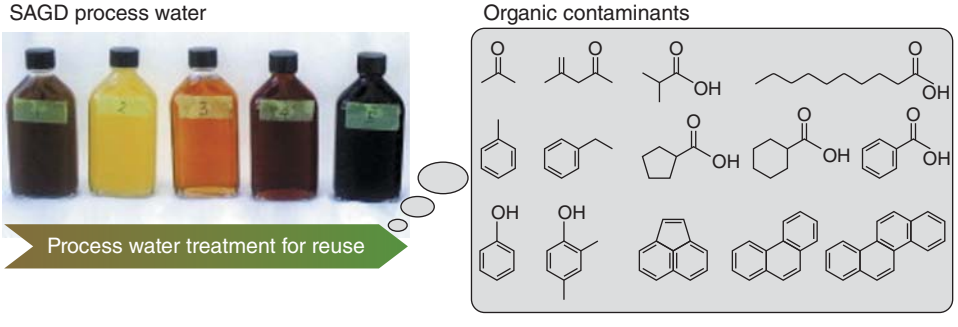


Figure 5.7 *Samples of water takes from sample points in Figure 5.36. Source: Reproduced with permission from Kawaguchi et al. Water Research (2012) 5566–5574 © Elsevier.*

The in situ oil sands production method, called steam-assisted gravity drainage (SAGD), reuses process wastewater following treatment. Figure 5.6 shows the water treatment system in the SAGD process operated by Japan Canada Oil Sands Ltd. The asterisks in Figure 5.6 indicate water sample collection points. Below is a SAGD process water for each sample point.

The treatment and reuse processes that concentrate contaminants in the process water determine the concentration and dynamics of inorganic and organic contaminants, makeup water, and process water from six process steps are shown in Figure 5.7 for facility shown in Figure 5.6 employing the SAGD process in Alberta, Canada.

Table 5.5 *Oily water qualitative characteristic ranges and the treatment capabilities of each piece of equipment.*

		API separator		
Parameter	Untreated range	Inlet range	Reduction %	Outlet range
Temperature, °C	30–60	30–60	—	30–60
pH	7–8	7–8	—	7–8
TDS, mg/l	150–5000	150–5000	—	150–5000
TSS, mg/l	300–800	300–800	67–75	100–200
Oil and grease, mg/l	3000–5000	3000–5000	90	200–500
BOD, mg/l	300–500	900–1400	50	450–700
COD, mg/l	300–1200	1700–3400	50	850–1700
Cl^-	50–2000	50–2000	0	50–2000
NH_3	20–50	50–100	0	50–100
P	—	—	0	—
Cyanides	1–3	1–3	0	1–3
Phenols	5–20	5–20	0	5–20
H_2S	5–10	5–10	0	5–10

	IGF/DGF			Conventional activated sludge		
Parameter	Inlet range	Reduction %	Outlet range	Inlet range	Reduction %	Outlet range
Temperature, °C	30–60	—	30–60	30–40	—	30–40
pH	7–8	—	7–8	7–8	—	7–8
TDS, mg/l	150–5000	—	150–5000	150–5000	—	150–5000
TSS, mg/l	100–200	75–80	20–50	20–50	75–80	5–10
Oil and grease, mg/l	200–500	90	10–30	10–30	95–90	2–5
BOD, mg/l	450–700	30	300–500	300–500	90	20–30
COD, mg/l	850–1700	30	600–1200	600–1200	73–80	80–100
Cl^-	50–2000	0	50–2000	50–2000	0	50–2000
NH_3	50–100	0	50–100	50–100	85–94	<3
P	—	0	—	—	0	<0.5
Cyanides	1–3	0	1–3	1–3	95–98	<0.05
Phenols	5–20	0	5–20	5–20	80–95	<0.5
H_2S	5–10	0	5–10	5–10	>99	<0.05

	Activated sludge with UF + RO		
Parameter	Inlet range	Reduction %	Outlet range
Temperature, °C	30–40	—	30–40
pH	7–8	—	7–8
TDS, mg/l	150–5000	95	15–300
TSS, mg/l	5–10	>95	<1
Oil and grease, mg/l	2–5	>97	<1
BOD, mg/l	20–30	90	<15
COD, mg/l	80–100	73–84	<80
Cl^-	50–2000	90	5–200
NH_3	50–100	85–94	<3
P	<0.5	80	<0.1
Cyanides	1–3	95–98	<0.05
Phenols	5–20	80–95	<0.5
H_2S	5–10	>99	<0.05

The results of the analysis of the samples in Figure 5.7 revealed the chemical abundance and dynamics of organic contaminants found in the recycling of process water using the SAGD method. The contaminants were mainly derived from the oil sands deposits, although traces of saturated fatty acids were contained in the groundwater used as makeup water, which became concentrated in the water recycling system.

Polar organics such as organic acids, phenols, and ketones were selectively concentrated as the water treatment progressed, whereas nonpolar or low-boiling components such as PAHs and BTEX were removed. These results suggest that the removal of such polar components is important for improving process water recycling efficiency and further work may elucidate other factors that obstruct process water recycling.

To identify and handle the potential risks of these contaminants from oil sands deposits to the environment, analytical methods with a higher resolution should be further developed for widespread use and adopted as environmental guidelines for protecting aquatic biota and human society as well as for sustaining emerging oil sands development with alternative approaches to minimize fresh water use.

In general, the treatment of oily wastewater is a standard process common across industry. Oily water is first sent to an API gravity separator, followed by dissolved air (or gas) or induced air (or gas) flotation, which generates tiny air (or gas) bubbles. The bubbles adhere to small oil particulates and float to the top of the tank, where they are skimmed off. Following floatation, oily wastewater can be combined with other waste streams and treated biologically. Table 5.5 lists the oily water qualitative characteristic ranges and the treatment capabilities of each piece of equipment.

6

Wastewater Sewer Systems

Effluents in the form of wastewater are a combination of the liquid and water-carried wastes from buildings and industrial plants, plus groundwater, surface water, or storm water. Wastewater may be grouped into the following classes:

- Class 1
  Effluents that are nontoxic and not directly polluting but liable to disturb the physical nature of the receiving water. They can be improved by physical means.
- Class 2
  Effluents that are nontoxic but polluting because they have an organic content with high oxygen demand. They can be treated for removal of objectionable characteristics by biological methods.
- Class 3
  Effluents that contain poisonous materials and therefore are often toxic. They can be treated by chemical methods.
- Class 4
  Effluents that are polluting because of organic content with high oxygen demand and, in addition, are toxic. Their treatment requires a combination of chemical, physical, and biological processes.

  In general, the aim of any drainage/effluent disposal system should be to segregate uncontaminated water from contaminated water or effluents and to segregate different types of effluents in order to reduce the size, complexity, and costs of any treatment units which may be required for handling the contaminated water and effluents before they are discharged from the company property.

  All wastewater effluents from industry which are discharged to public and/or natural water sources or directed to recycling purposes inside the industry and may contain a wide variety of matters in solution or suspension should be controlled according

Waste Management in the Chemical and Petroleum Industries, Second Edition. Alireza Bahadori.
© 2020 John Wiley & Sons Ltd. Published 2020 by John Wiley & Sons Ltd.

to the requirements imposed by the final destination. However, in any case elimination of the waste or the hazard potential of the waste should be the ultimate goal in the management of hazardous wastes.

6.1 Storm Water Sewer System

This system consists of pipes and open ditches collecting clean and/or oily storm water, and fire and washing water from non-polluted areas. The storm water should be disposed to the oily storm water basin located in the wastewater treatment area through the storm water network. It should mainly collect clean water from the following non-polluted areas:

- diked and undiked tank areas
- unpaved areas
- process and utilities non-polluted paved areas (excluding concrete paved areas)
- roads, yards, and roofs.

The collected storm water after oil removal in the oily storm water basin should be stored in the clean storm water basin. The final disposal of such clean water will be to:

- a wastewater treating unit at an American Petroleum Institute (API) separator(s) effluent for further oil removing
- an evaporation pond(s)
- an ocean/river if it complies with the local conditions of effluent waste streams.

6.2 Oily Water Sewer System

This sewer should collect:

- process spillages and drainage
- drains from all hydrocarbon equipment
- pump and compressor cooling water
- oily condensate
- cooling water drains which have a chance of becoming polluted with oil
- water coming from all hydrocarbon pollutable paved areas, including:
  - process units
  - utilities
  - non-volatile product truck loading stations
  - workshops
  - transport and mobile plant garages
  - pump stations
- pipe trench drains
- sample point drains
- drainage from level gauges, cocks, and similar equipment

Drains of the following fluids are excluded because of flowing in pit for truck disposal:

- heavy viscous fluids such as asphalt
- any fluid containing hazardous materials with concentrations more than allowable figures set out by the environmental and/or biological treatment restrictions.

The system should consist of drains, funnels, underground piping, clean-outs, catch basins, manholes, sealed manholes, and vent pipes. The final main of the oily water sewer should flow into the API separator(s) in the wastewater treating area through a dedicated underground gravity flow network.

Open ditches should be avoided. Leakages of manifolds can be collected in a suitable collecting basin located underneath the manifold.

The basin should drain into a sump located outside the manifold/piping area. The sump can be emptied intermittently (e.g. by vacuum truck) or it can be connected to the continuously oil-contaminated drain system.

6.3 Non-Oily Water Sewer System

This system should collect special oil free water containing high total dissolved solids such as:

- boiler blow-down
- desalination unit blow-down
- brine drainage
- neutralized effluents from all neutralization sumps through the plant
- storm, fire, and washing runoff water from the sulfur solidification and crushing area after removal of sulfur particles through a sedimentation sump
- tempered water system drains
- cooling water (circulated) blow-down and drains, provided that there is no possibility of oil contamination.

The system consists of drains, funnel, underground piping, clean-outs, catch basins, manholes, sealed manholes, and vent pipes. The non-oily water sewer system can be directed to the following disposals where required:

(a) Wastewater treatment plant effluent, if it is intended to reuse the treated wastewater:
as cooling tower make-up (in this case, the recycled treated water should meet the cooling)
tower make-up minimum requirements.
If needed, total hardness removal facilities should be provided on the non-oily water system before any disposal (see also (b)).

(b) Wastewater treatment plant influents (at the API separator outlet), if non-oily water need further physical and/or biological treatment in order to meet the final disposal requirements. In this case the following conditions should be met:
   i. Non-oily water should be treated for total hardness removal before any disposal to the API separator(s) effluent (if required).
   ii. All materials which will suffer the biological treatment activities should be removed from the non-oily water.

(c) Evaporation pond(s).

(d) Public water (if non-oily water is complied with environmental regulations).

However, a non-oily water sewer system should be investigated for appropriate disposal considering the following aspects:

- environmental regulations
- availability of refinery/plant raw water

- economical concerns
- operability of equipment furnished.

6.4 Chemical Sewer System(s)

In this book all sewer systems containing acids, alkalides, chemicals, and all other special organic materials such as Furfural, etc. are designated as chemical sewers. The number and route of chemical sewer systems in a plant should be studied based on the geographical location of various units and the feasibility of the gathering and disposal systems.

Chemical sewer streams should include but not be limited to:

- polluted drains from chemical additives dosing pumps (excluding tetraethyl lead [TEL])
- laboratory building drains (excluding oily drains)
- drainage and storm water polluted by acid and/or other chemicals
- caustic drains (caustic dissolving unit drains are excluded and should have a closed circuit network inside the unit)
- all water contaminated with acids and/or chemicals.

6.4.1 Disposal of Chemical Sewers

In general, disposal of any chemical sewer before neutralization/treatment to the environment should be avoided. Segregated chemical sewer network(s) should be provided depending on the variety of the chemicals disposed. Neutralization ponds effluent should be connected to the non-oily sewer.

The volume of the neutralization pond should be minimum equal to the highest batch volume among the streams disposed. Chemical effluents from the laboratory building should flow into a dedicated neutralization pit near the laboratory itself.

6.4.2 Neutralization Systems

Adequate facilities for acid and caustic injection systems, agitator, pumps, eductor (if required), steam coil (if required for winterization), etc. should be provided for each neutralization pond.

Necessary instrumentation such as acid and caustic flow indicator, pH indicator, pH low and high alarm in the control room, temperature controller, etc. to be foreseen for each pond.

The type of operation (manual or automatic) for the neutralization ponds will be instructed by the company. All acid and caustic handling facilities such as pipes, tanks, pumps, etc. should be traced for proper temperature maintaining.

6.4.3 Types of Chemical Waste

Chemical waste should include all waste contaminated with acids, alkalides, chemicals and additives, and water containing hazardous liquids. Disposal of any stream containing hazardous materials to the oily sewer and/or non-oily sewer systems should be avoided before implementation of the necessary treatment processes for removal of the hazards.

The method and extent of treatment will be instructed based on the authorities' approval. The final treated water specifications should be complied in conjunction with the environmental pollution requirements set out by the authorities concerned.

6.5 Sanitary Sewer System

This sewer should collect non-polluted raw sanitary waste from sanitary facilities of all buildings as required.

The final main should flow into sanitary sewage treatment units. The sanitary sewage treatment plant effluent, if it complies with the required effluent characteristics, can be routed to the wastewater treating plant (at the biological treatment outlet) for recycling purpose.

6.6 Special Sewer Systems

Special sewer systems should be provided where required. In general, all fluids containing poisonous/hazardous materials and/or fluids subject to recovery should be segregated and handled apart from all the other sewer systems mentioned in this book. The systems should include but not be limited to the following streams:

- caustic drains inside the caustic dissolving unit
- amine drains
- solvent drainage
- motor gasoline drainage contaminated with toluene or methyl tert-butyl ether (MTBE)
- hydrocarbon drains containing benzene in concentrations more than allowed by the environmental regulations
- all drains contaminated with toxic components such as cyanide, phenol, lead, etc.
- aluminum chloride drainage
- hydrofluoric acid drainage
- spent catalysts.

6.7 Effluent Sources and Disposal

The majority of effluent source streams can be broadly characterized as one or more of the following types:

(a) high or low dissolved solids content
(b) oily or non-oily
(c) high or low in phenols and/or sulfides
(d) chemical or non-chemical
(e) high or low in suspended solids.

Using these broad characteristics, the effluent source streams should be investigated for suitable disposal.

- Unpaved areas
  The effluent from unpaved, non-process, and non-tank areas will be clean storm water. The word "clean" is defined as meaning non-oily.

- Undiked tank areas
  The effluents from undiked tank areas will be oily storm water.
- Diked tank areas
  The normal effluent from diked hydrocarbon tank areas will be oily storm water. If a tank should rupture, the residual oil after clean-up will probably be washed down and routed to the oily storm water sewer. Diked area drains should be valved at the outlet of the dike so that any accumulation of oily water or oil can be impounded and released under controlled conditions.
- Tank bottom draws
  The water periodically drained from hydrocarbon tanks will be "oily foul water" and these drains should be valved.

  This water may contain salt and other dissolved solids if the tanks are storing crude oil, sulfides, and/or phenols, or if the tanks are storing untreated intermediate products, and free or emulsified oils.

  This water is normally discharged to the oily water sewer except when the drains are rich in hazardous materials such as phenols or lead, which should be segregated from the ordinary sewer systems. Drains of slops and any other tanks which are rich in H_2S should be routed to the sour water stripper unit for treatment.
- Concrete paved process and utility areas drains
  The effluent from concrete paved process and utility areas which are contaminated from various sources of oily drips and drains should be connected to the oily water sewer system unless otherwise specified in this book.
- Process and utility paved areas
  Drains from all clean areas adjacent to the streets around process and utilities areas and/or other clean paved areas which are not subject to any oil spillage should be routed to the storm water sewer system.
- Pump and compressor cooling
  Some amount of water cooling will usually be used for hot pump pedestals and glands and compressor jackets. Additionally, some water and/or oil may be used in pump and compressor seals. The drips and drains from these systems should constitute another source of the oily sewer system. Should the utility area include a pump or compressor, then the drain of such areas which will be subject to oil contamination should be connected to the oily water sewer system.
- Boiler blow down and water treating rinses
  This water will be free of oil but high in dissolved solids. Hence, it should be discharged to the non-oily sewer system.
- Cooling water drains
  If the tubes in the water-cooled heat exchangers in once-through cooling water and/or circulating cooling water develop leaks, then this water is liable to contamination with process fluids. Due to characteristics of the process fluids (light oils or heavy oils) and also cooling water (once-through or circulated) the following four categories should be taken into consideration (light oils refers to pentane and lighter):
  a) Once-through cooling water (light oils): this will be clean water and should be considered as non-oily water.
  b) Once-through cooling water (heavy oils): this will be oily water to acknowledge the possibility of exchanger tube leaks of non-volatile oil.

c) Circulating cooling water blow down (light oils): this will be high solids clean water and should be considered as non-oily water.
d) Circulating cooling water blow down (heavy oils): this will be high solids oily water to acknowledge the possibility of exchanger tube leaks of non-volatile oil. This water can be routed to the oily water sewer if the quality of final waste treated water will not suffer from receiving such an amount of high solids content.

- Process drum drains
  Water that has been withdrawn from process drums containing H_2S or H_2S and NH_3 is designated as "sour water" and if the water is principally condensed steam, it is called "sour condensate." The destination of such drains should be the sour water stripper unit through a pump if required. For non-oily, gravity, and low flow cases the destination can be the non-oily sewer system and/or the oily water sewer system under controlled conditions and not in such amounts that the biological treatment operation suffers.
- Laboratory wastewater
  a) Oily wastes
     Wastes from laboratory oily sinks which are not contaminated with chemicals should be routed to the oily water sewer system.
  b) Chemical contaminated wastes
     All chemical contaminated wastes should be directed to the non-oily sewer system after neutralization in the dedicated neutralization pit adjacent to the laboratory building.
- Flare seal drum blow-down
  Continuous drain from main flare and acid flare seal drums located at bottom of the flare stack(s) which are rich in H_2S should be pumped to the sour water stripper unit for treating. Make-up water to the flare seal drum/pot should be condensate.
- Floating roof drain of tanks
  The roof drain(s) of floating roof tanks should be discharged to the oily water sewer system due to the possibility of hydrocarbon leakage from rubber seals.

6.8 Particular Effluents in Refinery and Petrochemical Plants

Caustic used to scrub pentanes and lighter oils will contain essentially sodium sulfide. Such streams should be neutralized in the chemical neutralization pit and be sent to the non-oily sewer after neutralization.

6.8.1 Caustic Scrubs (Heavy Oils)

Caustic used to scrub gasoline, kerosene, and distillate oils may contain naphthenic acids, phenols, and cresols in addition to spent caustic. These drains should be segregated from the non-oily and chemical sewer systems and should be neutralized before entering the oily water sewer.

6.8.2 Desalter Wastewater

Desalter wastewater effluent should be piped in a pressure line to the dedicated desalter oil–water separator in the wastewater treatment area. It should also have the possibility of

being routed to the main API separator influent under controlled conditions. Effluent water from the desalter water oil-water separator can be directed into the main API separator effluent water pond if the pollutable materials do not exceed allowable figures.

6.8.3 Foul or Sour Water

In petroleum refining, various processing operations produce wastewater solutions; principally, they are condensates containing sulfides, generally as hydrogen sulfide, ammonia, mercaptans, phenolics, and, possibly, small amounts of water-soluble organic acids, nitrogen bases, and cyanides. This wastewater generally is referred to as "foul water" or "sour water." The principal sources of foul water are condensates from accumulators, reflux drums, and knockout pots in catalytic reformers, cracking, hydrocracking, coking, and crude distillation units. Foul water generally is neither highly alkaline nor highly acidic.

Their content of pollutants is relatively low compared to that of spent caustics. However, the high oxygen demand and the odorous or toxic nature of foul water make it desirable to treat it for the reduction of these objectionable characteristics before it undergoes biological treatment or is discharged into the wastewater system.

Foul water should be stripped in the sour water stripper(s), where removal of a single/multiple contaminants is desirable. Stripped water from the sour water stripper unit should be piped in an underground pressure line into the main oily sewer system terminating in the wastewater treating plant.

The stripped water should also have disposal access to the desalter water as make-up and evaporation pond(s)/public water if it is congruent with the local regulations. The characteristics of the stripped water, which are normally determined by the company, should be properly controlled such that disposal of this water does not impede any operation/environmental pollutions in the upset conditions. The waste gases from the stripping operations should be routed to the sulfur recovery unit and/or incinerated.

6.8.4 Spent Caustic Solutions

6.8.4.1 Sources and Characteristics

Typically, uses of caustic solutions are to neutralize and extract:

a) acidic materials that may occur naturally in crude oil and in any of its fractions
b) acidic reaction products that may be produced by various chemical treating processes
c) acidic materials formed during thermal and catalytic cracking such as hydrogen sulfide, phenolics, and organic acids

Spent caustic solutions may therefore contain sulfides, mercaptides, sulfates, sulfonates, phenolates, naphthenates, and other similar organic and inorganic compounds.

6.8.4.2 Disposal Methods

An adequate handling system should be provided for effective disposal of the spent caustic. The system should include tankage and pipelines to segregate, accumulate, and transfer the spent caustic solutions to the disposal site. The following disposal methods should be taken into consideration in each plant:

- direct disposal methods
- chemical methods
- chemical-physical methods
- biological methods.

The soundness of these methods must be determined by the individual refiner, paying due regard to applicable laws and regulations.

6.8.4.2.1 Direct Disposal Methods.

- Dilution
  Controlled disposal of spent caustic solutions into large bodies of water, particularly brackish or salt water, or into rivers capable of adequate dilution may be considered if under any circumstances the maximum concentration of sulfates (as SO_4) does not exceed the value set by environmental regulations. Disposal into freshwater lakes and streams must be given more critical consideration, particularly if the water is used as a source of potable water or for recreation purposes.
- Disposal ponds
  Disposal of spent caustic solutions by means of ponds should be avoided unless otherwise specified for the disposal of small quantities of caustic waste. The following factors should be considered to prevent subsequent air or water pollution where disposal ponds are concerned:
  a) Location
     Odor nuisance within the vicinity will affect site selection. Furthermore, geologic formations at the site must be such that contamination of potable water supplies by seepage will not occur.
  b) Capacity
     To prevent pollution of surface water, the pond must have sufficient capacity to hold the maximum amounts of rainfall, as well as the maximum amounts of waste chemicals to be received and stored. Adequacy of size depends not only on the volume of spent waste to be handled, but also on the anticipated evaporation, seepage, and annual rainfall.
  c) Equipment
     Pressurized pipelines should be provided to transfer the spent caustic solutions from the process units or the central collection system to the pond. Disposal of any spent caustic stream contaminated with oil to the pond should be avoided. If the spent solutions carry entrained oil to the pond, the necessary equipment for oil removal is required for purposes of safety, as well as prevention of pollution and loss of oil.

6.8.4.2.2 Chemical Methods. The following methods for chemical treatment of spent caustic can be considered:

- regeneration
- air oxidation
- neutralization.

- Regeneration
  Caustic used to extract mercaptans from hydrocarbon streams can be regenerated by:
  a) steam stripping the mercaptans from the solution followed by incineration or recovery of the mercaptans

b) oxidation of the mercaptans to disulfides, which can be separated as an oil phase. Oxidation of mercaptans should be accomplished by electrolysis or air blowing. The latter should be conducted under pressure, or with the use of oxidation catalysts, or both.

- Air oxidation
  Spent caustics that contain sulfides or sulfites can be pretreated by air oxidation to reduce their high oxygen demand before they are diluted or further processed by biological treatment.
- Neutralization
  Spent caustics containing hydrogen sulfide, phenolics, or naphthenates (acid oils) can be pretreated by acid or flue gas neutralization followed by separation and recovery or incineration of these constituents.

6.8.4.2.3 Chemical-Physical Methods. Stripping and extraction following neutralization can be used to treat spent caustic solutions. After neutralization, stripping removes residual hydrogen sulfide, mercaptans, and possibly some phenolic compounds. In the neutralization of spent caustics with flue gas, stripping of the volatile components from the solution occurs simultaneously with the neutralization.

6.8.4.2.4 Biological Methods. Biological treatment following pre-treatment can be applied, particularly in areas where the refinery/plant effluent is discharged into brackish or salt water. Due to the high biochemical oxygen demand (BOD) of spent caustic solutions, the solutions should not be amenable to biological treatment unless highly diluted or pre-treated by the chemical or physical methods described previously.

6.8.4.2.5 Caustic Lines Maintaining Temperature. The temperature of the aboveground caustic lines should be maintained at least 22 °C above their freezing points.

6.8.5 MTBE or Leaded Contaminated Streams

- Sources
  Sources of MTBE or leaded contaminated streams will mainly be the following areas already allocated for finished gasoline production facilities:
  finished gasoline tank drainage
  finished gasoline transfer pump area drainage
  finished gasoline loading area drainage
  TEL or MTBE storage and injection facilities drainage.
- Disposal
  Disposal of all MTBE or leaded contaminated streams should be routed to an MTBE or TEL contaminated water pond provided near the spillage area for further transfer to the outside of the plant battery limit by truck for incineration or safe disposal. The pond should be a covered concrete pit equipped with a flame arrester and sample, inspection, and pump-out connections.

6.8.6 Benzene Contaminated Streams

- Sources
  Drains of all hydrocarbons containing more benzene than allowed, such as straight run naphtha, platformate, etc., are sources for such waste liquids. Drainage of all other

hydrocarbon streams containing an allowable amount of benzene component can be handled through ordinary wastewater sewer systems in the plant. However, special attention should be paid to the reduction of benzene content in the sources concerned to the maximum extent possible.

- Disposal
  A segregated drainage system terminating in a dedicated covered pond should be provided to handle all contaminated benzene drains. The recovered waste streams can be routed to the refinery slops tanks.

6.8.7 Spent Sulfuric Acid Products

6.8.7.1 Sources and Characteristics

In general, sulfuric acid is used extensively both as a treating agent and as a catalyst. The principal sources of sulfuric acid sludges are the treatment of lubricating oils, heating and diesel oils, gasoline, and naphthas.

The principal sources of spent catalyst acids are alkylation and the manufacture of alcohol and similar products. The hydrocarbon content in spent acids and sludges varies from a few percent up to as much as 60%. The acidity in titratable sulfuric acid can vary from 20% to 90%.

6.8.7.2 Disposal Methods

Disposal of the sludges or spent catalyst acid in the refinery or plant effluent stream is not permissible and should be avoided. The following disposal methods are listed only as reference applicable methods allowed in principle.

6.8.7.3 Thermal Decomposition

Thermal decomposition is the most important method of recovering sulfuric acid from spent acids and sludges. Thermal decomposition consists of heating or burning the sludge in the presence of a reducing agent. The organic or carbonaceous material in the spent acid or sludges serves as the reducing agent.

6.8.7.4 Manufacture of Ammonium Sulfate

Fertilizer-grade ammonium sulfate is made from spent sulfuric acid products. In these processes, acid recovered by a hydrolysis operation is reacted with ammonia, and the resulting ammonium sulfate is crystallized from the water solution.

6.8.7.5 Burning

Some sludges are low in sulfur content and contain enough combustible material to make them utilizable as fuel, either alone or mixed with fuel oil. Due to air pollution problems, use of this method of disposal should be avoided.

6.8.7.6 Sale or Reuse

In the case of spent caustic solutions, spent sulfuric acid catalysts and sludges may be sold or reused in other operations wherein the remaining acid quality can be utilized.

6.8.7.7 *Offshore Dumping into the Ocean*

This method is not permitted unless otherwise allowed by the environmental protection regulations.

6.8.7.8 *Burying or Dumping on Waste Land*

This method can be used only in rare cases and with permission of local authorities and/or environmental regulations. In this case the sludge must be either a solid or a semisolid, and special precautions must be taken to prevent underground drainage and pollution of surface water.

6.8.8 Nitrogen Base Components

Nitrogen base materials such as pyridine and quinoline may be produced in the thermal processing of high nitrogen content crudes or distillates. They may enter the refinery/plant effluent in wastes from acid-treating operations or in wastewater from cracking operations. Due to the fact that nitrogen bases of high molecular mass are relatively insoluble in water at pH values above 4, neutralization and "springing" should be applied to reduce gross amounts of these compounds. In such cases the streams rich in nitrogen base components should be segregated and routed to the non-oily sewer system after neutralization.

6.8.9 Cyanides

Normally, cyanides are not found in refinery/petrochemical wastewater in significant concentrations. Small amounts may be found in accumulator condensate water from catalytic cracking units when processing high nitrogen containing oils. In such cases, when concentration of cyanides will affect biological treatment operation, the streams concerned should be segregated and treated to convert cyanides to less toxic thiocyanates or ammonia and sodium format.

6.8.10 Aluminum Chloride

- Sources
  Usually, sources are sludge from isomerization or treating processes in which aluminum chloride is the catalyst.
- Disposals and treating
  The sludge should be neutralized quickly and disposed of as silt or by controlled discharge into the non-oily sewer if it does not include oil and to the oily sewer system if it contains oily materials. The aqueous solution from hydrolyzed sludge can be utilized as a flocculating agent.

6.8.11 Polyelectrolyte

Although liquid or dry powder polyelectrolyte is not a hazardous material, its buffered acidic action is, in some instances, irritating when if it comes into contact with the eyes, skin or mucous membranes.

Normal precautions should be employed to prevent the spraying or splashing of liquid polyelectrolyte, particularly if the material is hot. Areas of special concern include the concentrated liquid polyelectrolyte receiving area hose connections, the transfer pumps, and associated valves and piping. All structures, equipment, valves, and piping with surfaces exposed to the polyelectrolyte should be flushed with plant water prior to being handled. Disposal of all drains contaminated to polyelectrolyte should be through the chemical sewer.

6.8.12 Ferric Chloride

Ferric chloride is not toxic for inhalation at ambient temperature. At high temperature (over 70 °C) hydrochloric acid exhalation can form with irritant properties on the skin, upper respiratory tract, and lung tissue. Disposal of all contaminated waste drainages should be through the chemical sewer system.

6.8.13 Phosphoric Acid

Spent phosphoric acid catalyst waste should be neutralized by spreading it in pits filled with limestone, lime, oyster shells, or spent caustic waste. The waste land should be well isolated because these catalysts are deliquescent, and absorbed water will leach the acid from the catalyst.

6.8.14 Hydrofluoric Acid

Hydrofluoric acid tars and gaseous hydrogen fluoride are wastes from alkylation processes in which hydrofluoric acid is the catalyst. The tars and the gas should be disposed by burning/scrubbing.

6.8.15 Other Spent Catalysts

Spent catalysts that contain high-value metals such as nickel, cobalt, molybdenum, platinum, etc. should be reprocessed to recover the metal by the catalyst manufacturer or in recovery plants. Discarding of this type of spent catalyst to the environment should be avoided.

6.8.16 Chemical Cleaning Waste

Spent chemicals from the cleaning of equipment may produce emulsions if discharged directly into the sewer systems. Therefore, spent cleaning solutions should be treated separately to remove iron and solids before being discharged to wastewater sewer systems. In general, such streams should be neutralized and directed to the evaporation pond through the non-oily sewer system.

6.8.17 Sulfur Solidification and Crushing Facilities, and Loading Systems Drainage

The sewer system of this area should collect water drainage (including storm water) and send it to the non-oily sewer system by gravity. The water drainage from sulfur

solidification and crushing facilities, and the loading systems area should be free of sulfur particles.

6.8.18 Water Containing Solids, Emulsifying Agents, etc

Streams impairing gravity separation, such as streams containing solids, emulsifying agents and/or contaminants that tend to flocculate upon dilution, should not be merged with continuously oil contaminated water.

6.8.19 Heavy Viscous Oils Drainage

Drainage of any heavy viscous oil (e.g. asphalt) which may be congealed and lead to clogging along the sewer system should be avoided. Such streams should be routed to the dedicated pits near the sources.

6.8.20 Toxic Metal Contaminated Streams

All drains contaminated with toxic metals such as arsenic, chromium, mercury, cadmium, lead, selenium, etc., which are often found in refinery/petrochemical plants wastewater streams in a concentrations more than allowable, should be segregated. The method of treatment and disposal should be in accordance with environmental regulations.

6.8.21 Solvent Processes Drainage

The local sewer system in a solvent process such as extractive distillation, liquid extraction, physical absorption, chemical absorption, etc. should segregate and reuse, if practical, the unavoidable and inadvertent solvent losses from pump seals, flange leaks, etc.,

The design of a solvent process plant should give very careful consideration to the possible effluent problems. Every effort should be made to limit/exclude the amount of solvents entering the plant effluent system. It should also be abundantly clear that the aqueous effluents to be expected from the solvent processes may contain a very wide range of organic and inorganic chemical pollutants.

Generally, the solvents involved in solvent processes are phenol, mixtures of phenol, glycols, amines, furfural, sulfolane, sulfur dioxide, sulfuric acid, ammoniacal copper acetate, acetonitrile, ketones, urea, and etc.

6.8.22 Treating Processes Drainage

This is a broad category of processes for upgrading various intermediate and final product streams. In many cases, the treating process involves the use of a solvent. All of the treating processes are potential sources of highly undesirable aqueous effluents which should be segregated and treated with similar streams through the refinery/plant.

6.9 Petrochemical Plant Special Effluents

A careful check should be made of processes proposed or used for the manufacture of petrochemicals to decrease the possibility of water-soluble organics entering water supplies.

In general, in order to minimize the wastewater resulting from petrochemical processes, the following methods should be taken into consideration:

a) recycling and reuse of waste streams
b) quenching with oil or chemicals other than water that do not produce waterborne wastes
c) use of alternative processes that do not produce waterborne wastes
d) use of air coolers or of cooling towers in place of once-through cooling water
e) elimination of waste products in the manufacturing operation before they become associated with waste streams
f) processing of waste streams to reduce the amount of chemicals in wastewater leaving the plant.

In the design of petrochemical plant processing units, special attention should be paid to the following design notes:

a) Extensive use of instruments, alarms, and checks by the operators should be provided to prevent loss of chemicals.
b) Adequate facilities should be installed to prevent uncontrolled release of chemicals and wastes to sewers or receiving water.
c) A large storage area capable of holding several days production of wastewater should be provided to allow the water to be checked before being released to final destination.

6.9.1 Summary of Disposal/Treatment Methods

The disposal/treatment methods applied to the reduction/removal of the various compounds that may be found in petrochemical operations should be selected based on the following factors:

a) plant production and/or type of pollutants
b) the final destination of the wastewater effluent
c) the processes ordinarily used for waste disposal
d) economical aspects
e) environmental pollution regulations.

6.9.1.1 Treatment

The following methods can be evaluated for wastewater recovery in petrochemical plants and refineries.

6.9.1.2 Physical Treatment Methods

- Gravity separation
  Gravity separation is the usual method of physical treatment for separation of oil/water. It has limitations that may make it necessary to resort to other methods.
- Stripping
  Steam or flue gas stripping, by which phenolics, mercaptans, hydrogen sulfide, and other compounds can be removed, is the widely used disposal method for petrochemical wastes. Waste gases from stripping should be burned to prevent air pollution.

- Adsorption and extraction
  Many compounds can be removed from water either by adsorption or by extraction, such as extraction applied for removal of phenolics by using isopropyl ether or other suitable solvents.

6.9.1.3 Other Physical Methods

Other physical methods which can be evaluated are:

- sedimentation
- filtration
- flotation
- evaporation.

6.9.1.4 Ultimate Disposal

- Controlled dilution
  This method can be used only on materials that are relatively small in quantity and non-toxic, and then only under certain special conditions. A large volume of dilution water in the receiving stream is usually necessary. This method, as with others, must have adequate controls to ensure that the aquatic life and the quality of the receiving water are not being harmed. In some cases, improved dilution control is obtained by releasing the effluent to the stream through diffusers or jets to obtain better dispersion in the body of the stream.
- Incineration
  This method can be applied only where wastes cannot be successfully disposed of by other methods. In such cases, special incinerator designs should be used to handle the various types of wastes that may be encountered, with careful consideration given to the resulting air pollution problems. Some of the more important variables to be considered in the design and operation of incinerators are time, temperature, percent of excess air, turbulence, and heat release per unit volume of combustion chamber. When disposal by incineration is contemplated, composition of the wastes must be considered insofar as it might cause the emission of irritating or odorous gases, chlorine and fluorine, visible plumes, or particulate matter.

  Incineration of dewatered sludge from wastewater treatment plants reduces the volume of the dry sludge and produces a sterile non-harmful residue that is free from toxic organic chemicals and pathogens. It provides a safe alternative solution when faced with land scarcity for waste disposal and if anaerobic digestion or composting is not an option. Moreover, it also helps to recover some of the energy used in the combustion process, especially in large treatment plants where there is a huge quantity of sludge generation. The disposal of sewage sludge along with the incineration of household rubbish can be integrated both in newly planned plants and retrofitted in older plants (Figure 6.1).

  Furthermore, with the implementation of new technologies, multi-nutrient fertilizer can be produced out of sewage sludge. The thermo-chemical process in Ash Dec removes toxic heavy metals and makes it harmless for the environment. This allows the nutrient cycle to be closed.

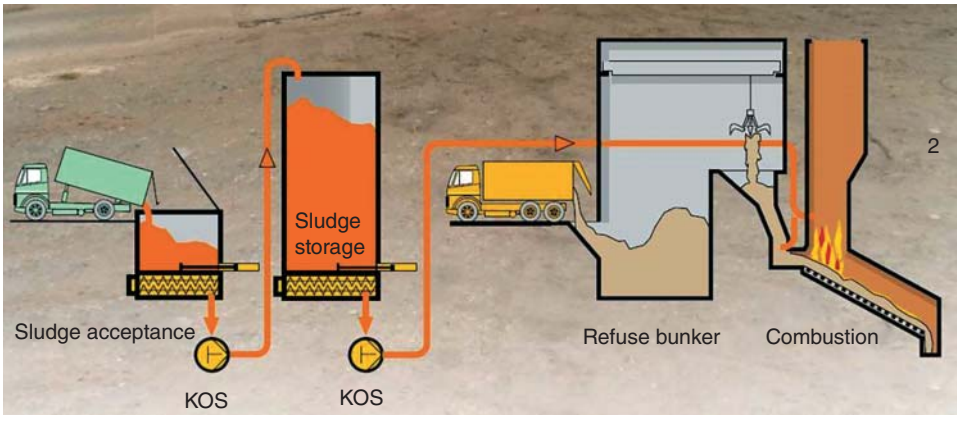


Figure 6.1 *A possible design for integrating sewage sludge incineration into a municipal solid waste incineration plant. Source: Reproduced with permission © Seecon gmbh.*

- Salvage
  Careful consideration should be given to disposal by salvage, particularly if the waste products are not too dilute. Segregated sewer systems should be used to recover losses with a minimum of dilution, permitting reuse of the material in the manufacturing process.
- Deep well injection
  The disposal of waste streams from petrochemical plants into underground strata, which do not contain potable water, may be applied only under certain conditions and if allowed by the local authorities. Very careful pre-treatment or control, or both, of the materials introduced into the strata is necessary to prevent precipitation, which would halt the continuation of the injection. It is also important that the disposal well does not contaminate fresh water sources.
- Other disposal methods
  Application of any other disposal method such as disposal at sea, disposal on waste land surfaces, dumping or burial, or spray irrigation is not allowed unless permitted by the company and environmental regulations.

6.10 NGL, LNG, and LPG Area Effluents

Two specific situations should be considered for effluents from natural gas liquids (NGL), liquefied natural gas (LNG), and liquified petroleum gas (LPG) production, handling, and storage areas:

a) a liquefied gas spill
b) a fire situation.

6.10.1 Liquefied Gas Spill

Accidentally spilled liquefied gas should be drained away as quickly as possible from the equipment to a safe distance where it should be allowed to evaporate in a collecting pit. For

properly supervised areas a maximum spill of 25 m^3 should be assumed. It is assumed that approximately 15 m^3 will evaporate (under dry weather conditions), leaving a balance of minimum 10 m^3, which should be caught in a collecting pit/liquid gas trap. Spilled liquefied gas and water should be separated as much as possible and the liquefied gas should never be allowed to enter any underground flooded drainage system to avoid blocking due to freezing. It is assumed that only one spill or one fire at a time will occur.

6.11 Gas Treatment Facilities Effluents

In view of the low risk of encountering heavy pollution (except during line cleaning) the drainage system in a gas treatment plant can be routed to the storm water sewer system. For line cleaning, the polluted effluent should be discharged into a neutralization pond. The effluent from the neutralization pond should be tested to justify discharge via the non-oily water sewer system for further treatment. Direct discharge from line cleaning into the drainage system is not allowed.

6.12 Effluents from Terminals, Depots, and Product Handling Areas

Effluents from terminals, depots, and product handling areas should be in line with the requirements based on local regulations. Due to economic considerations drainage of terminals, depots, and product handling areas can be integrated with the same drainage type as the refinery or petrochemical plants installed adjacent to the areas concerned. Special attention should be given to the geographical location and elevation of the area.

6.13 General Considerations and Conditions for Release of Waste

With a view to guidelines, standards or criteria, as well as to regulations, programs, measures and discharge permits for release of refinery/plant waste, particular attention should be given to the following factors:

- regional guidelines, standards or criteria, as appropriate, for the quality of wastewater used for specific purposes that is necessary for the protection of human health, living resources, and ecosystems
- regional regulations for waste discharge and/or degree of treatment for all significant types of sources
- stricter local regulations for waste discharge and/or degree of treatment for specific sources based on local pollution problems and desirable water usage considerations
- polluters should be required to obtain a permit to discharge from the competent local authorities (if needed). Such permits should allow for review and modification of discharge conditions reflecting the periodic update of regulations.

6.13.1 Characteristics and Composition of Waste

The following requirements should be considered:

a) type and size of waste source, e.g. industrial process
b) type of waste (origin, average composition)

c) form of waste (solid, liquid, sludge, slurry)
d) total amount (volume discharged, e.g. per year)
e) discharge pattern (continuous, intermittent, seasonally variable, etc.)
f) concentrations with respect to major constituents
g) properties:
   - physical, e.g. solubility and density
   - chemical and biochemical, e.g. oxygen demand, nutrients
   - biological, e.g. presence of viruses, bacteria, yeast, parasites
h) toxicity
i) persistence:
   - physical, chemical, and biological
j) accumulation and biotransformation in biological materials or sediments
k) probability of producing taints or other changes reducing the marketability of resources, e.g. fish, shellfish, etc.
l) susceptibility to physical, chemical, and biochemical changes, and interaction in the aquatic environment with other dissolved organic and inorganic materials.

6.13.2 Characteristics of the Discharge Site and Receiving Environment

The following requirements should be considered:

a) hydrographic, meteorological, geological, biological, and topographical characteristics of the discharge site
b) location and type of discharge (outfall, canal, outlet, etc.) and its relation to other areas, e.g. agricultural, spawning, nursery, and fishing areas
c) rate of disposal per specific period, e.g. quantity per day, per week, and per month
d) initial dilution achieved at the point of discharge into the receiving marine environment, if any
e) methods of packaging and containment, if any
f) dispersion characteristics such as effects of currents, tides, and wind on horizontal transport and vertical mixing (in case of disposal to sea or lake)
g) water characteristics (in case of discharge to sea/river), e.g. temperature, pH, salinity, stratification, oxygen indices of pollution dissolved oxygen (DO), chemical oxygen demand (COD), BOD (nitrogen present in organic and mineral form including ammonia, suspended matter), other nutrients, and productivity
h) existence and effects of other discharges which have been made in the discharge site, e.g. heavy metal background levels and organic carbon content.

6.13.3 Availability of Waste Technologies

The methods of waste reduction and discharge for industrial effluents as well as domestic sewage should be selected taking into account the availability and feasibility of:

a) alternative treatment processes
b) re-use or elimination methods
c) on-land disposal alternative
d) appropriate low-waste technologies.

- General considerations

  Due consideration should be given to the following:

  a) possible effects on amenities, e.g. presence of floating or stranded materials, turbidity, objectionable odor, discoloration, and foaming
  b) effects on human health through pollution impact on edible marine organisms, bathing water, esthetics, etc.
  c) effects on marine ecosystems, in particular living resources, endangered species, and critical habitats
  d) possible effects on other uses of the water (in case of discharging to sea/river), e.g. impairment of water quality for industrial use, underwater corrosion of structures, interference with ship operations from floating materials, interference with fishing or navigation through deposit of waste or solid objects on the sea floor, and protection of areas of special importance for scientific or conservation purposes.

6.14 Effluent Wastewater Characteristics

The quantities and characteristics of the wastewater differ considerably for different processes. In general, the major sources of waste contribution in a petroleum refinery are storage tank drain-offs, crude desalting and distillation, and thermal and catalytic cracking processes, followed by the solvent refining, dewaxing, and drying and sweetening.

6.14.1 Flow

Based on total water usage, crude and vacuum distillation units are the largest water users mainly because of the large volumes required by barometric condensers, desalters, and vacuum ejectors. Catalytic cracking and drying and sweetening are the next largest water users. The extent of water use is significantly affected by the technology level of the processes employed.

6.14.2 Temperature

Crude desalting, especially the electrostatic process, contributes substantial thermal waste loads, as do distillation and cracking. The increased use of cooling towers has played an important role in the reduction in the quantities of water discharged not necessarily by reduction in effluent temperature. Effluent heat loads can have significant adverse effects on the receiving water since the increased temperature causes decreased oxygen solubility and greater oxygen utilization, both of which reduce the ability of the stream to handle waste loads.

6.14.3 pH

pH indicates the hydrogen ion concentration of a wastewater. However, the extreme values often observed do not truly reflect the buffering capacity of a waste or its ultimate effect upon a receiving water course. Most refinery wastewater is alkaline, with the cracking (both thermal and catalytic) and crude desalting processes as the principal problem sources;

some solvent refining processes also contribute substantial alkalinity. Power house boiler treatment produces alkaline wastewater and sludge. Hydrotreating also contributes definite alkaline waste.

Alkylation and polymerization utilize acid processes and have severe acidity problems. In general, petroleum refinery effluents have pH variations, but this is not a major problem from the standpoint of effluent standards. Where pH range is outside the normal limits, equalization of caustic wastes (and sometimes acid wastes) before bleeding into the sewer system is usually sufficient to maintain pH control. In general, large volumes of cooling and wash water dilute out strong acid or caustic discharges, thus pH may become a more significant problem as cooling water volumes decrease.

pH control is also important in regard to the wastewater treatment operation. Very low or very high pH can cause worse emulsification of oils already in the sewer. The pH of the wastewater influent to biological treatment processes is an important consideration for effective treatment.

6.14.4 Oxygen Demand

The measurement of the BOD and/or COD of an effluent will exert on the oxygen resources of a stream. COD and BOD are standard analyses used in this evaluation.

Wastewater from petroleum refineries or petrochemical plants exerts a major, and sometimes severe, oxygen demand. The primary sources are soluble hydrocarbons and sulfides. The small leaks and inadvertent losses that occur almost continuously throughout a complex can become principal pollution sources.

Crude and product storage and the product finishing operations are the major contributors of COD and BOD, mainly because of the many tanks and vessels used, and the number of times a barrel of oil or product is handled in these operations.

The wastewater discharges from these operations are intermittent. The cracking and solvent refining processes are the major BOD contributors on a continuous basis.

6.14.5 Phenol Content

Catalytic cracking, crude oil fractionation, and product treating are the major sources of phenolic compounds. Catalytic cracking produces phenols by the decomposition of multicyclic aromatics, such as anthracene and phenanthrene. Some solvent refining processes use phenol as a solvent, and although it is salvaged by recovery processes, losses are inevitable. Phenols, particularly when chlorinated, cause taste and odor problems in drinking water.

6.14.6 Sulfide Content

Sulfide waste streams generally originate from the crude desalting, crude distillation, and cracking processes. Sulfides are considered to include mercaptans. Sulfides interfere with subsequent refinery operations and are removed by caustic or diethanolamine scrubbing or appear as sour condensate water. Hydrotreating processes which are used to remove sulfides from the feeds or products naturally produce a rich sulfide waste stream, but most of the sulfide is removed as H_2S and is usually recovered or burned.

6.14.7 Oil Content

This is a major pollutant characteristic of refinery/plant wastewater. As free oil, it produces oil slicks and iridescence, and coats boats and shorelines if permitted to discharge to the receiving stream. Oil-coated solids are particularly troublesome since they are usually of neutral relative density (specific gravity), and are not readily removed by conventional gravity separation techniques. Oil or oil-coated solids in the receiving stream also may have a serious detrimental effect on aquatic life.

Oil has limited solubility in water and therefore would be expected to contribute little to effluent BOD or COD. However, crude petroleum and its refined products contain a wide range of soluble hydrocarbons which can ultimately find their way into waste streams through product washes, etc. These product wash streams contribute to effluent BOD and COD.

6.14.8 Light Hydrocarbon Solubility in Water

The solubility of hydrocarbon components in water is of great importance for the environmental sciences. Soluble organics in produced water and refinery effluents are treatment problems for the petroleum industry. Production facilities and refineries have to meet regulatory discharge requirements for dissolved organics. This is expected to become more difficult as environmental regulations become stricter and production from deep water operations increases. However, offshore analysis and remediation of produced water is expensive, and the relatively high polar content of deep-water crude oil also means a higher solubility of organic components in the aqueous phase. In addition, the identities of the water-soluble components are not well known, nor are their concentrations in the produced water brines. Hence, quantitative characterization data are needed as the first step in understanding the dissolution of water-soluble organic compounds in produced water.

Its prediction is usually based on using the pure component solubilities and the mole fraction of the components in the mixture. The solubility of light alkanes (methane and ethane) in pure water has been studied extensively in past decades. However, due to their extremely low solubilities, it is necessary to predict the aqueous solubility of those components using an accurate method. In this section a simple-to-use correlation (developed by Bahadori et al. 2009) is presented for better prediction of the aqueous solubility of light alkanes,

Equation 6.1 presents the new correlation for predicting the aqueous solubility of light alkanes in which four coefficients are used to correlate the mole fraction of individual components and the reduced partial pressure of the component:

$$x_i = 0.001(a + bP_{ri} + cP_{ri}^2 + d\,P_{ri}^3) \tag{6.1}$$

$$a = A_1 + B_1T_{ri} + C_1T_{ri}^2 + D_1T_{ri}^3 \tag{6.2}$$

$$b = A_2 + B_2T_{ri} + C_2T_{ri}^2 + D_2T_{ri}^3 \tag{6.3}$$

$$c = A_3 + B_3T_{ri} + C_3T_{ri}^2 + D_3T_{ri}^3 \tag{6.4}$$

$$d = A_4 + B_4T_{ri} + C_4T_{ri}^2 + D_4T_{ri}^3 \tag{6.5}$$

Table 6.1 *New proposed correlation coefficients to predict the aqueous solubility of light alkanes (Eqs 6.2–6.5).*

Coefficient	Methane	Ethane
A_1	261.159102	1.52452624
B_1	−257.987470	−0.790117139
C_1	0	0
D_1	37.2471507	−0.973352139
A_2	−294.266511	−198.534348
B_2	290.940225	311.386014
C_2	0	0
D_2	−41.6884515	−109.130286
A_3	120.094172	731.199867
B_3	−116.988102	−1132.12025
C_3	0	0
D_3	16.3778867	395.621746
A_4	−18.3989831	−905.085194
B_4	17.7638515*e*	1394.71993
C_4	0	0
D_4	−2.44816293	−486.883551

In above equations, x_i is the mole fraction of solute components (i) in the water phase, P_r and T_r are the reduced partial pressure and temperature of individual components in KPa and K, respectively. The tuned constants are also given in Table 6.1.

Figures 6.2 and 6.3 illustrate the solubility trends of methane and ethane components in water at different temperatures and pressures, applying the new developed method. As can be seen from these figures, the aqueous solubilities of methane and ethane components are almost independent of temperature at high pressures, while at low pressures the solubility decreases with rising temperature.

6.14.9 Predicting the Mutual Solubility of Water–Hydrocarbon Systems

Describing the mutual solubilities of hydrocarbons and water is very important in the energy industry. The presence of water in a hydrocarbon mixture can affect the product quality and damage the operation equipment due to corrosion and formation of gas hydrates. Tracing the concentration of hydrocarbons in aqueous media is also important for technical purposes like preventing oil spills and for ecological concerns such as predicting the fate of these organic pollutants in the environment. This section presents a simple-to-use correlation for an excellent prediction for the mutual solubility of water–hydrocarbon systems in a broad range of temperatures between 0 and 120 °C and heavy hydrocarbons between C_3 and C_{10}.

- Correlation development
  Equation 6.8 presents the new correlation for predicting the water–hydrocarbon mutual solubility in which four coefficients are used to correlate solubility as a function of the τ

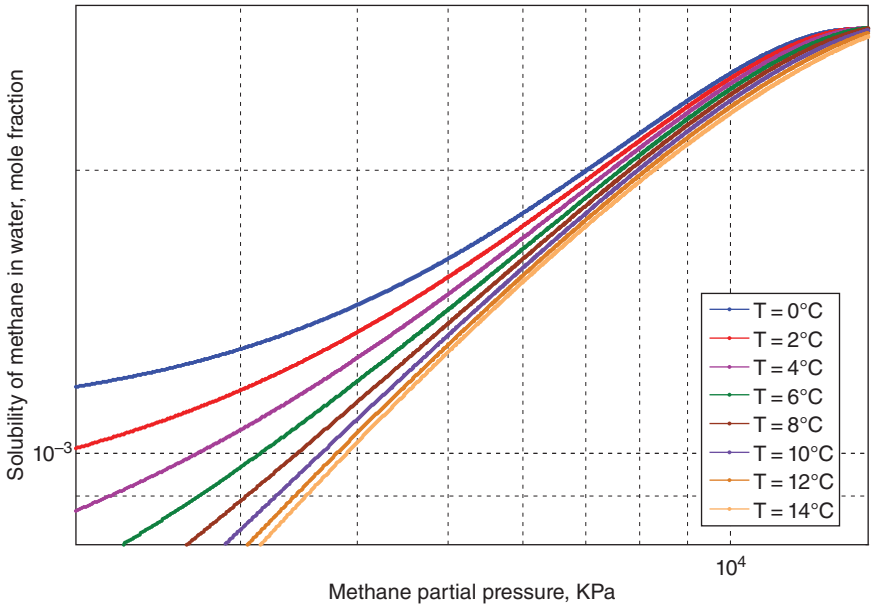


Figure 6.2 *Predicting the aqueous solubility of methane. Source: Reproduced with permission from Bahadori et al. 2009 Energy Sources, Part A: Recovery, Utilization and Environmental Effects 31 (9), pp. 761–766.© Taylor and Francis.*

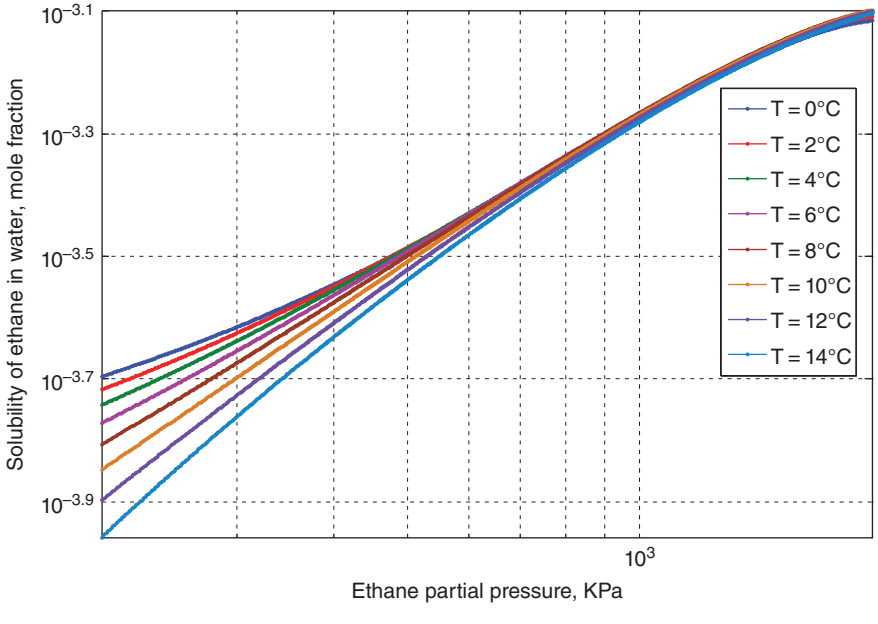


Figure 6.3 *Predicting the aqueous solubility of ethane. Source: Reproduced with permission from Bahadori et al. 2009 Energy Sources, Part A: Recovery, Utilization and Environmental Effects 31 (9), pp. 761–766. © Taylor and Francis.*

and ξ of the component:

$$\tau = \frac{T}{T_{Ci}} \tag{6.6}$$

$$\xi = \frac{T_{NBPi}}{T_{Ci}} \tag{6.7}$$

$$x_i = \alpha(a + b\tau + c\tau^2 + d\,\tau^3) \tag{6.8}$$

$$a = A_1 + B_1\xi + C_1\xi^2 + D_1\xi^3 \tag{6.9}$$

$$b = A_2 + B_2\xi + C_2\xi^2 + D_2\xi^3 \tag{6.10}$$

$$c = A_3 + B_3\xi + C_3\xi^2 + D_3\xi^3 \tag{6.11}$$

$$d = A_4 + B_4\xi + C_4\xi^2 + D_4\xi^3 \tag{6.12}$$

In above equations, x_i is the mole fraction of solute components (i) in the water phase and kg of water dissolved in 100 kg of hydrocarbon. τ and ξ are calculated by Eqs 6.6 and 6.7. The evaluated constants are given in Tables 6.2 and 6.3. α is 0.000001 for calculating hydrocarbon solubility in water and it is equal to 1 for water solubility in hydrocarbons. T_{NBPi} and T_{Ci} are the normal boiling point and critical temperature for component i.

Figures 6.4 and 6.5 illustrate the solubility trends of C_3 to C_{10} components in water at different temperatures. As can be seen, good agreement was observed between the reported data and the obtained results of the new correlation. These graphs also show that light hydrocarbons such as propane are more soluble than heavy hydrocarbons such as decane in water and the solubility of hydrocarbon in water increases in higher temperatures.

Table 6.2 *Evaluated coefficients for predicting hydrocarbon solubility in water (Eqs 6.9–6.12).*

Coefficient	Propane–hexane	Hexane–decane
A_1	$1.53061855208904\times10^{8}$	$-7.80318540290318\times10^{4}$
B_1	$-6.95425772815835\times10^{8}$	$3.69737747273782\times10^{5}$
C_1	$1.05311164420129\times10^{9}$	$-5.77961661971329\times10^{5}$
D_1	$-5.31541395374747\times10^{8}$	$2.98529541379832\times10^{5}$
A_2	$-4.5084296748633\times10^{8}$	$1.3181984347846\times10^{6}$
B_2	$2.04763764916127\times10^{9}$	$-5.78706658568791\times10^{6}$
C_2	$-3.09976139197572\times10^{9}$	$8.46135894896114\times10^{6}$
D_2	$1.56404762898601\times10^{9}$	$-4.12008439650811\times10^{6}$
A_3	$4.47102182743484\times10^{8}$	$-3.85661272900561\times10^{6}$
B_3	$-2.03041426889201\times10^{9}$	$1.66978003215558\times10^{7}$
C_3	$3.073392747304\times10^{9}$	$-2.40930454837587\times10^{7}$
D_3	$-1.5506231578167\times10^{9}$	$1.15845093404961\times10^{7}$
A_4	$-1.51100996876207\times10^{8}$	$3.14620688985382\times10^{6}$
B_4	$6.86533638859106\times10^{8}$	$-1.35459756919058\times10^{7}$
C_4	$-1.03972563665959\times10^{9}$	$1.94391066047826\times10^{7}$
D_4	$5.24852883270059\times10^{8}$	$-9.29742057877851\times10^{6}$

Table 6.3 *Evaluated coefficients for predicting water solubility in hydrocarbons (Eqs 6.9–6.12).*

Coefficient	Propane–hexane	Hexane–decane
A_1	$-0.37543995841323 \times 10^6$	$0.36882777088116 \times 10^6$
B_1	$1.73693356843739 \times 10^6$	$-1.588017272292665 \times 10^6$
C_1	$-2.67896847966559 \times 10^6$	$2.27781165264479 \times 10^6$
D_1	$1.37731071844325 \times 10^6$	$-1.0885375042589 \times 10^6$
A_2	$0.15898975008232 \times 10^6$	$-0.19720127013985 \times 10^6$
B_2	$-0.73780254787291 \times 10^6$	$0.84883989830623 \times 10^6$
C_2	$1.14123199781881 \times 10^6$	$-1.21729901998746 \times 10^6$
D_2	$-0.58830721436155 \times 10^6$	$0.58164606742025 \times 10^6$
A_3	$-0.23187113029754 \times 10^6$	$0.34992894151685 \times 10^6$
B_3	$1.078496564000005 \times 10^6$	$-1.50601457844133 \times 10^6$
C_3	$-1.6717164862978 \times 10^6$	$2.15954437645887 \times 10^6$
D_3	$0.86339618872612 \times 10^6$	$-1.03185031311938 \times 10^6$
A_4	$1.15457781637261 \times 10^5$	$-0.20623421783169 \times 10^6$
B_4	$-5.37774830265444 \times 10^5$	$0.88757317045455 \times 10^6$
C_4	$8.34557228439786 \times 10^5$	$-1.27281419845502 \times 10^6$
D_4	$-4.31441338774772 \times 10^5$	$0.60825470939167 \times 10^6$

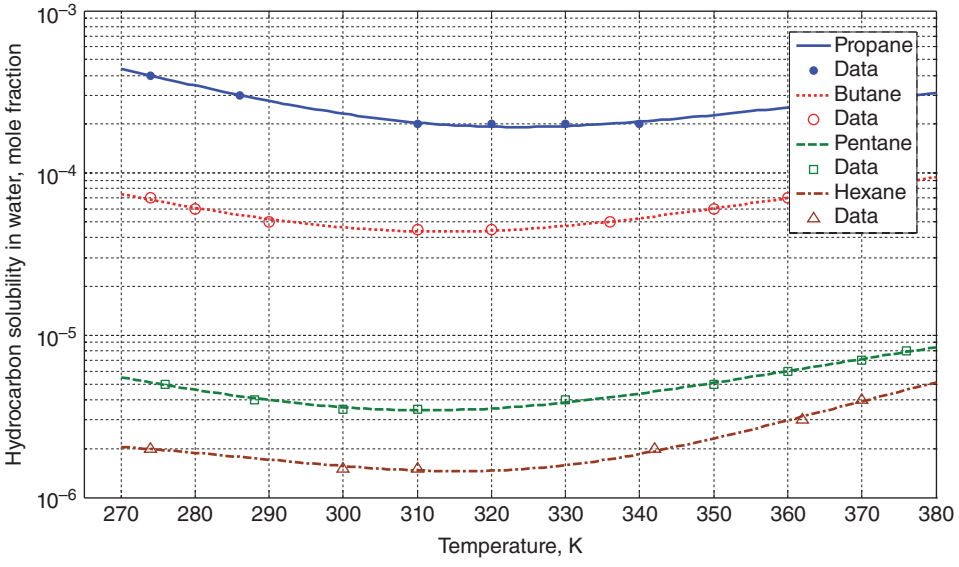


Figure 6.4 *Predicting the aqueous solubility of C_3 to C_6 based on the new developed correlation. Source: Reproduced with permission Bahadori et al. 2008 Chemical Engineering and Technology 31 (12), pp. 1743–1747. © John Wiley & Sons.*

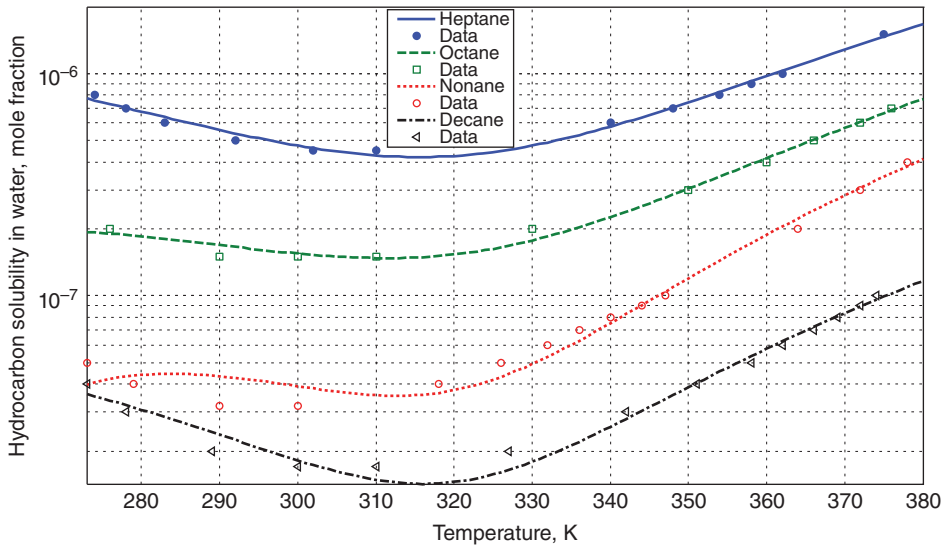


Figure 6.5 *Predicting the aqueous solubility of C_6 to C_{10} based on the new developed correlation. Source: Reproduced with permission Bahadori et al. 2008 Chemical Engineering and Technology 31 (12), pp. 1743–1747. © John Wiley & Sons.*

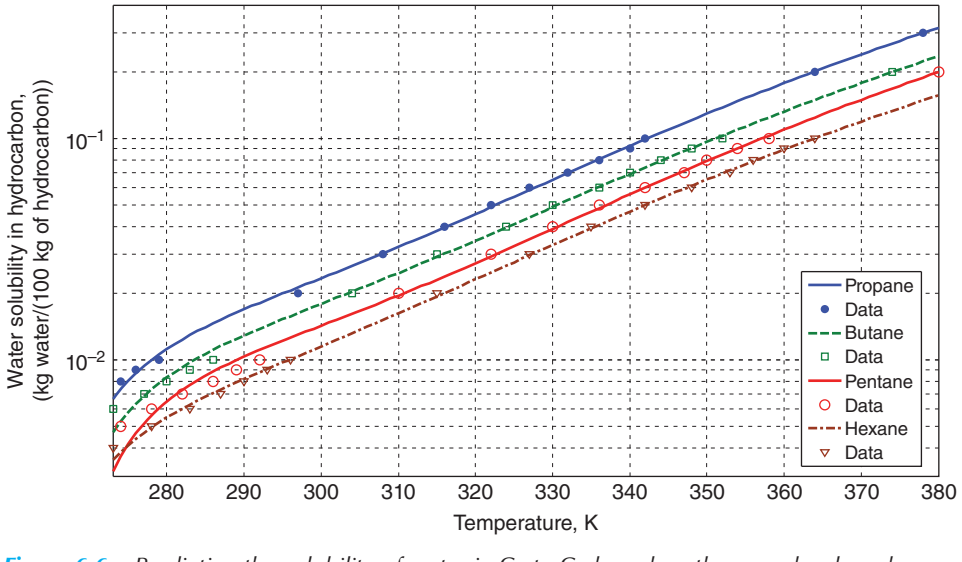


Figure 6.6 *Predicting the solubility of water in C_3 to C_6 based on the new developed correlation. Source: Reproduced with permission Bahadori et al. 2008 Chemical Engineering and Technology 31 (12), pp. 1743–1747. © John Wiley & Sons.*

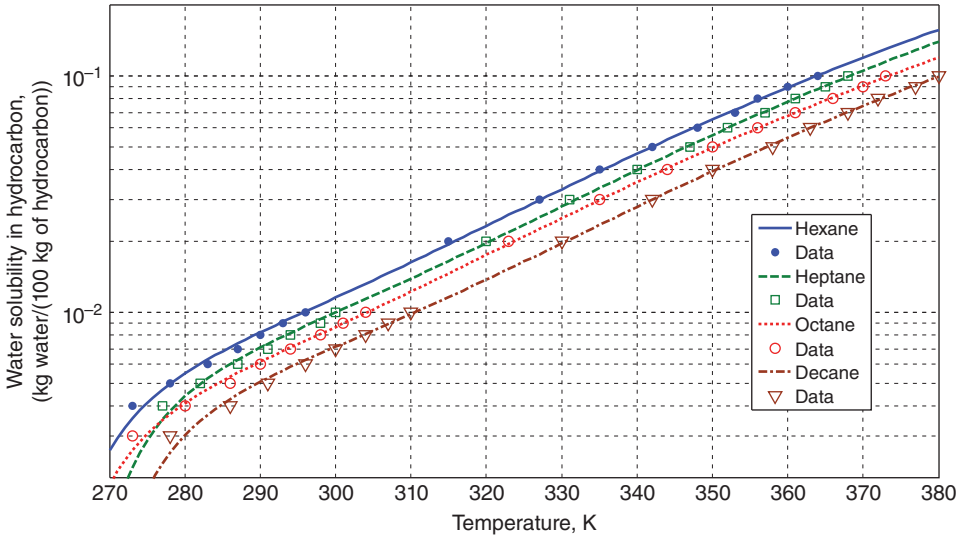


Figure 6.7 *Predicting the solubility of water in C_6 to C_{10} based on the new developed correlation. Source: Reproduced with permission Bahadori et al. 2008 Chemical Engineering and Technology 31 (12), pp. 1743–1747. © John Wiley & Sons.*

Figures 6.6 and 6.7 illustrate the solubility trends of water in different hydrocarbon components over a wide range of temperatures. These graphs illustrate good agreement between the reported data and the obtained results of the new correlation. These graphs also show that water is more soluble in light hydrocarbons comparing with the heavy hydrocarbon components.

6.15 Wastewater Emissions

This section is divided into two parts:

- point source wastewater discharges as released by refinery treatment plants
- diffuse wastewater that arises through stormwater and other miscellaneous runoff from the refinery site that is not captured and treated prior to discharge.

6.15.1 Point Source Discharge

Tables 6.4 and 6.5 can be used to provide default emission data for refinery effluent discharges that are not classified as transfers (transfers include discharging to sewer). The dissolved organic carbon (DOC) content of refinery effluents is usually a known parameter. Hence, the speciation factors for organic compounds in Table 6.4 are based on this parameter. The document from which Table 6.4 was derived indicates a ratio of DOC/COD of 0.267. In the absence of site-specific information regarding DOC, this ratio can be used to determine DOC from measurements of COD.

Table 6.4 *Default speciation factors for organics in refinery effluent.*

Substance	Weight percent of DOC
Toluene	0.00092
Benzene	0.00091
Xylenes	0.0014
Phenol	0.00069
1,2-Dichloroethane	0.00027
Hexachlorobenzene	0.0000044
PAHs	0.0016
Styrene	0.0001
Ethylbenzene	0.00012
1,1,2-Trichloroethane	0.000036
Chloroform	0.0025

PAH, polycyclic aromatic hydrocarbons.
Source: Ontario Ministry of the Environment (1992).

Table 6.5 *Default emission factors for trace elements and inorganics in refinery effluent.*

Substance	Emission factor (kg/m^3 of flow)
Zinc	4.4×10^{-4}
Phosphorous	4.1×10^{-7}
Arsenic	6.7×10^{-6}
Chromium (VI)	7.7×10^{-6}
Selenium	3.1×10^{-6}
Nickel	3.6×10^{-6}
Copper	2.9×10^{-6}
Antimony	5.8×10^{-7}
Cobalt	1.6×10^{-6}
Mercury	1.1×10^{-8}
Cadmium	3.3×10^{-7}
Lead	1.9×10^{-6}
Cyanide	7.6×10^{-9}
Ammonia	1.3×10^{-6}

Source: Ontario Ministry of the Environment (1992).

A similar parameter to DOC was not identified for trace elements and other inorganics in wastewater effluent. Therefore, trace elements and inorganic compound emissions are expressed as default emission factors in Table 6.5.

Tables 6.4 and 6.5 were developed based on experience in industry consultation and a review of available literature on substance levels in refinery wastewater effluents. It is reasonable that default values should be derived in the event that no better data is available. The referred methodology usually involved presenting the organic effluent data on a speciated basis, using the DOC of refinery effluents.

The default speciation numbers presented in Tables 6.4 and 6.5 were determined using test data presented in the Ontario Ministry of the Environment (1992) document. This document provided average effluent concentration levels, as well as the percentage of samples tested that showed substance concentrations below detection limits.

The averages presented were only based on samples with levels exceeding the detection limit, and so account needed to be taken of the samples that showed non-detectable levels. Therefore, using a conservative approach (where it was assumed that samples with non-detectable levels actually contain the compound at half the detection limit), new "average" effluent concentrations were derived. These average effluent concentrations were then divided by the DOC average presented in the same document to derive speciation fractions.

These speciation factors are applied to this effluent parameter in the following manner:

$$WWE_i = DOC \times (WP_i/100) \times \text{flow} \tag{6.13}$$

where

WWE_i = wastewater emission of component i from the treatment plant (kg/h)
DOC = dissolved organic carbon content of the treated effluent discharged by the plant (kg/m^3)
WP_i = weight percent of component i as provided in Table 6.4 above
flow = wastewater flowrate discharged to the receiving body of water (m^3/h).

The emission factors in Table 6.5 are applied in the same way as factors are applied to air emissions, with the exception that they are based on the flow of effluent from the treatment plants (i.e. the emission factors are kg per m^3 of wastewater flow).

6.15.2 Effluent Permissible Concentrations

Maximum permissible concentrations of the contaminants in effluents are presented in Table 6.6 according to typical environmental regulation as a guidance. However, the maximum concentrations of effluent contaminates should be updated during execution of each project in accordance with the latest available information officially issued by the relevant environmental regulation.

The figures indicated in Table 6.6 can be used only for the cases not covered in this book.

When petroleum and chemical wastes are released on the soil surface, hydrocarbons adsorb on the organic mineral matter of the soil, therefore soil pollution with oil and chemical components has become an important problem. The release of chemical and petroleum materials into the soil environment can occur in various ways, including pipeline blow-out. When the spill occurs some kind of soil clean-up is typically necessary. This chapter looks at long-term strategies for cleaning up petroleum and chemical products in unsaturated or saturated zones.

Cleaning up hydrocarbon-based liquids and refined products released from pipelines, oil production units, oil desalter plants, pumping station, tank farms, chemical plants, upstream drilling operations, and other pollutants from oil and petrochemical refineries and above

Table 6.6 *Typical effluent permissible concentrations.*

Contaminants	Discharge to surface runoff (mg/l)	Discharge to groundwater (mg/l)	Irrigation and agriculture usage (mg/l)
Al	5	5	5
Ba	2	1	1
Be	0.1	1	0.1
B	2	1	1
Cd	1	0.01	0.01
Ca	75	—	—
Cr^{6+}	1	1	1
Cr^{3+}	1	1	1
Co	1	1	0.05
Cu	1	1	0.2
Fe	3	0.5	5
Li	2.5	2.5	2.5
Mg	100	100	100
Mn	1	0.5	0.2
Hg	0	0	0
Mo	0.01	0.01	0.01
Ni	1	0.2	0.2
Pb	1	1	1
Se	1	0.01	0.02
Ag	1	0.05	0.01
Zn	2	2	2
Sn	2	2	—
V	0.1	0.1	0.1
AS	0.1	0.1	0.1
Cl^-	Amount of chloride in industrial effluents should not exceed 250 mg/l (ppm) for fresh water	Amount of chloride in industrial effluents should not exceed 250 mg/l (ppm) for fresh water	Amount of chloride in industrial effluents should not exceed 250 mg/l (ppm) for fresh water
F	2.5	2	2
P	1	1	—
CN	0.2	0.02	0.02
C_5H_5OH	1	0	1
CH_2O	1	1	1
NH_4^+	2.5	0.5	—
NO_2-NO_2^-	50	10	—
NO_3-NO_3^-	50	1	—

(*Continued*)

Table 6.6 *(continued)*

Contaminants	Discharge to surface runoff (mg/l)	Discharge to groundwater (mg/l)	Irrigation and agriculture usage (mg/l)
SO_4^{2-}	300	300	500
SO_3^{2-}	1	1	1
TSS	30	30	100
SS	0	0	0
TDS	Total dissolved solids in industrial effluents should not increase the amount of these materials more than 10% in the underground water/river and any other sources within a distance of 200 m from where effluent is dumped	Total dissolved solids in industrial effluents should not increase the amount of these materials more than 10% in the underground water/river and any other sources within a distance of 200 m from where effluent is dumped	Total dissolved solids in industrial effluents should not increase the amount of these materials more than 10% in the underground water/river and any other sources within a distance of 200 m from where effluent is dumped
Oil and grease	10	10	10
BOD	20	20	100
COD	50	50	200
DO	>2	>2	>2
ABS (detergent)	1.5	0.5	0.5
Turbidity	50	50	50
Color	Color of source water should not exceed more than 16 standard units due to industrial effluent, dumped	75 units of color	75 units of color

Table 6.6 *(continued)*

Contaminants	Discharge to surface runoff (mg/l)	Discharge to groundwater (mg/l)	Irrigation and agriculture usage (mg/l)
Temperature	Temperature of industrial effluent should not change the temperature of source water more than ±3 °C up to a distance of 200 m	—	Temperature of industrial effluent should not change the temperature of source water more than ±3 °C up to a distance of 200 m
pH	6.5–8.5	5–9	5–9
Radioactives	0	0	0
Digestable coliform	400/100 ml	400/100 ml	400/100 ml
MPN	1000/100 ml	1000/100 ml	1000/100 ml

ground/underground storage tanks in downstream oil, gas and chemical processing industries typically involves using several corrective actions and strategies. Short-term emergency measures may involve imminent actions to control acute health and safety and such as potential explosions and toxications.

After the imminent danger has been eliminated, longer term corrective actions involve cleaning up pollutants that have entered the surface and subsurface environment. Petroleum products in the subsurface may be trapped between soil particles in the unsaturated zone, floating on the water table or dissolved in groundwater in the saturated zone.

Here we discuss soil pollution control:

a) to inform the authorities concerned how to assess site conditions in the unsaturated zone and where a petroleum product release has occurred, how to obtain the information needed to identify where in the unsaturated zone petroleum product is located, and also how to remove petroleum products from the unsaturated zone at a given site
b) to assess the technologies designed specifically for clean-up of the saturated zone
c) to provide a structural methodology for the evaluation and potential consequences of a leak in a pipeline, the methodology that is intended to assist pipeline operators in assessing the need to install pipeline leak detection facilities, and an overview of available pipeline leak detection techniques.

6.16 Unsaturated Zone

The unsaturated zone is the portion of a porous, usually above the water table in an unconfined aquifer, within which the moisture content is less than saturation, the capillary pressure is less than atmospheric pressure, and the unsaturated zone does not include the capillary fringe. The saturated zone is the zone in which all space between the soil particles is occupied by water, including the capillary zone.

A good understanding of the conditions in the unsaturated zone is essential when selecting an appropriate soil treatment technology. Site assessment will reveal the basic hydrologic, geologic, and chemical data measurements collected at the site of interest. The following points should be considered.

a) What was released? Where? (time since petroleum released)
b) Currently, where in the unsaturated zone is most of the petroleum product likely to be?
c) How much petroleum product is likely to be present in different locations and phases?
d) How mobile are the constituents of the contaminant, where are they likely to travel and at what rate?

6.17 Site Assessment

The data collected should be used to determine the behavior of the contaminant in the subsurface. When dealing with the unsaturated zone, the data are primarily used to determine the mobility of the contaminant and which phase(s) it is likely to be in. The mobility of the petroleum product in the unsaturated zone is related to:

a) the potential for the various phases of contaminant to move through the subsurface
b) the potential for the petroleum product to change from one phase into another.

To choose an effective clean-up technology for soils contaminated by petroleum, it is necessary to collect certain basic information about the released product and the subsurface environment:

1) What contaminants were released? Knowledge of the type of product released, its physical and chemical properties, and its major chemical constituents is required.
2) Where is the petroleum product currently? Distribution of petroleum product within the unsaturated zone, i.e., as a vapor in soil gas, as a residual liquid, or dissolved in pore water.
3) How much petroleum product is in each phase? Immediately after a release (weeks to months) most of the product will exist as a residual liquid, significant fractions will volatilize and dissolved in existing pore water or infiltrating rainwater.
4) Where is the petroleum product going? Mobility affects not only extent of a release, but also the effectiveness of any treatment scheme that depends on mobilizing the contaminants difficult to remove them (e.g. vacuum extraction).

These four questions provide a framework for decision, and more information can often improve the selection process.

6.18 Gathering Release Information

The questions listed in Table 6.7 provide a starting point for finding the mobility and phase distribution of the product in the subsurface. For above-ground spills, the answers to the questions in Table 6.7 are usually easy to obtain.

Petroleum products include a variety of fuel types, each with different physical and chemical properties. In addition, each fuel type is a mixture of many constituent compounds which have properties that can be quite different from those of the mixture. The mobility of different contaminants must be known to determine over spilled fuel ("Will this contaminant spread quickly and reach the water table?"), its partitioning ("Will this contaminant vaporize and pose explosion hazards?") and its degradation potential ("Will this contaminant be biodegraded easily in the unsaturated zone?"). These factors are an important part of the technology selection process.

- How much petroleum product was released?
  The volume of spilled product can help the user to evaluate whether the contaminant has reached the saturated zone and estimate the level of contamination in the unsaturated zone.
- Time since released
  The time since release is important because the composition and properties of the released material changes over time; volatile compounds evaporate, soluble constituents

Table 6.7 *Basic release information assumed to be known.*

Information needed	Why information is important
What contaminants were released?	Physical and chemical properties differ for each contaminant, leading to varying phase partitioning, mobility, and degradation characteristics for each contaminant. Corrective action selection is tied to these characteristics.
How much was released?	The amount released directly affects the phases in which the contaminant may be found.
What was the nature of the release (quick spill/slow leak)?	Phase partitioning and mobility of the released contaminant are both affected by the nature of the release. As a result, selection of appropriate corrective actions may differ for quick spills versus leaks over an extended period of time.
How long since the release?	Contaminants "weather" over time, that is, they change in composition due to processes such as degradation, volatilization, and natural flushing from infiltrating rainfall. This change in composition directly affects the physical and chemical properties of the bulk contaminant.
How was the release detected?	This may provide insight into the above questions and areal extent and distribution of contamination in the subsurface.

dissolve in infiltrating rainwater, and some constituents biodegrade. These biochemical changes that occur over time are called "weathering."

- Gathering site-specific information

  Site-specific information pertains primarily to the hydrologic and geologic characteristics of the site. Geologic characteristics can vary greatly, even over short distances, therefore it is essential to make accurate estimates of soil parameters through numerous field data. Table 6.8 lists the site-specific data that are needed to conduct a site assessment.

  Default values are obtained via tables, figures, and other data for many of the parameters. These default values enable users to make estimates of the critical parameters in a short timescale for a preliminary site assessment.

Table 6.8 *Site-specific parameters to gather.*

Parameter (units)	Important for determining
Soils porosity (%)	Mobility, phase
Particle density (g/cm^3)	Mobility, phase
Bulk density (g/cm^3)	Mobility, phase
Hydraulic conductivity (cm/s)	Mobility, phase
Air conductivity	Mobility, phase
Permeability (cm^2)	Mobility, phase
Soil moisture content (%)	Mobility, phase
Local depth to groundwater (m)	Phase
Soil temperature (°C)	Mobility, phase
Soil pH	Bacterial activity
Rainfall, runoff, and infiltration rate (cm/day)	Mobility, phase composition
Soil surface area (m^2/g)	Mobility, phase
Organic content composition (%)	Mobility, phase
Fractures in rock	Mobility

Table 6.9 *Factors to evaluate the mobility of liquid contaminants.*

Factor	Unit	Increasing mobility (→)		
Release related				
Time since release	Months	Long (>12)	Medium (1–12)	Short (<1)
Site-related				
Hydraulic conductivity	cm/s	Low (<10^{-5})	Medium (10^{-5} to 10^{-3})	High (>10^{-3})
Soil porosity	% soil volume	Low (<10)	Medium (10–30)	High (>30)
Soil surface area	m^2/g	Low (<0.1)	Medium (0.1–1)	High (>1)
Soil temperature	°C	Low (<10)	Medium (10–20)	High (>20)
Rock fractures	–	Absent	–	Present
Moisture content	% volume	Low (<10)	Medium (10–30)	High (>30)
Contaminant-related				
Liquid viscosity	cPoise	Low (<2)	Medium (2–20)	High (>20)
Liquid density	g/cm^3	Low (<1)	Medium (1–2)	High (>2)

Table 6.10 *Factors to evaluate the mobility of contaminant vapors.*

Factor	Units	Increasing mobility (→)		
Site-related				
Air-filled porosity (the total porosity less that fraction filled with water equals the air-filled porosity)	% volume	Low (<10)	Medium (10–30)	High (>30)
Total porosity	% volume	Low (<10)	Medium (10–30)	High (>30)
Water content	% volume	Low (<10)	Medium (10–30)	High (>30)
Depth blow surface	m	Deep (>10)	Medium (2–10)	High (<2)
Contaminant-related				
Vapor density	g/m^3	Low (<50)	Medium (50–500)	High (>500)

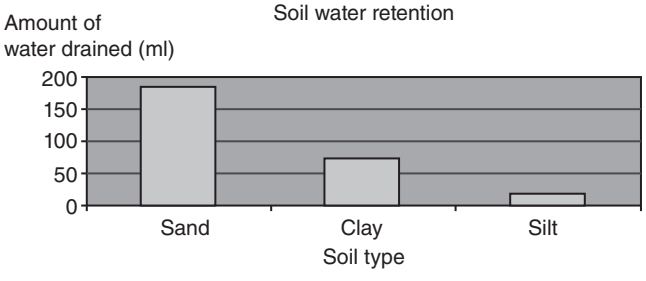


Figure 6.8 *Water-holding properties of various soils on the basis of their texture. Source: Native Revegeation.*

Site-specific data should be obtained whenever possible. If a quick initial assessment is needed it is often necessary to evaluate alternatives without the use of field data or when only incomplete data are available. In these cases, approximations are useful. Tables 6.9 and 6.10 provide typical values for several of the parameters listed in Table 6.8 for various types of soil and rock. These tables can be used to select default values in the absence of measured values. Figure 6.8 shows water-holding properties by soil type. An estimate of the moisture content of a particular soil can be made by using a typical field capacity value from the range of values shown in Figure 3.2.

7

Sewage Treatment

Sewerage is a critical issue because of the grave risk that high demand and incapacity place on the environment and human health with leaks and spills. In addition, aging infrastructure does not hold together well when it is literally weighed down.

Besides the chemical toxins and wastewater found in sewage, dangerous life-threatening micro-life abound in our flows. These pathogens are deadly parasites, bacteria, and viruses that enter our oceans, beaches, and recreational inland bodies of water. A release of highly toxic chemical and biological content into the environment can create health epidemics such as cholera.

- Pathogens
  Some of the lethal health impacts caused by these micro-organisms are diarrhea, stomach cramps, fevers, skin fungi, worms, and hepatitis. Symptoms may be either acute (short term) or chronic (long term).
- High nutrient content
  Untreated raw sewage also contains high levels of nutrients (from pesticides and chemicals) leading to algal blooms, some of which are toxic to humans and can be passed on in the food chain through shellfish consumption or recreational swimming. Symptoms include abdominal pain, vomiting, diarrhea, and liver failure.
- Ecological risks
  Besides the human health impacts, raw sewage leaking into the environmental decimates other life forms, destroying food sources and places for habitation.
- Odors and gases
  Not only does sewage reek, it is dangerous in that passing through the system is not only organically producing decomposition gas, but household and industrial wastewater chemicals. Sewer gases may contain a range of gases, including ammonia, methane, carbon dioxide, and hydrogen sulfide (rotten egg smell), as well as illegal hazardous discharges of fuels and other chemicals, which all contribute to the odors, explosion risks, and health risks. Figure 7.1 shows typical sewage environments.

Waste Management in the Chemical and Petroleum Industries, Second Edition. Alireza Bahadori.
© 2020 John Wiley & Sons Ltd. Published 2020 by John Wiley & Sons Ltd.



Figure 7.1 *Typical sewage situations. Source: Reproduced with permission from © Shutterstock.*

This chapter covers the minimum requirements for the design of small sanitary sewage treatment plants for the oil industry and residential areas. The characteristics and chemistry of sewage and its treatment methods are described. Guidance is given for the disposal of final effluents discharged from sewage treatment works.

7.1 Sewage Effluents

For the protection of the aquatic environment and the maintenance of water quality in lakes, reservoirs, streams, rivers, estuaries, and the sea, sewage treatment works should be designed to reduce the strength of sewage to a level that may be expected to ensure complete avoidance of nuisance in the circumstances in which the sewage is discharged.

7.1.1 Receiving Water

The setting of receiving water standards comes under the jurisdiction of environmental regulations. Hence the maximum concentrations of contaminants in domestic and industrial wastewater included in the latest local environmental authority publications should be respected with the stipulation that no discharge should create conditions that would violate them.

7.1.2 Final Effluents of Domestic Wastewater Plants

Apart from setting maximum permissible concentrations with respect to biochemical oxygen demand (BOD) and suspended solids (SS), which are the most important factors, it should be obvious that oil, grease, and floating solids should be removed from waste before discharge to receiving water.

As regards the five-day BOD (BOD5) and SS, the final effluent, i.e. the end product of sewage treatment plants, is considered satisfactory if it contains not more than 30 parts per million (ppm) of SS and does not absorb more than 20 ppm of dissolved oxygen in five days.

A final effluent of this strength and turbidity when discharged into rivers assumes that the minimum flow of the river will further dilute the effluent by at least eight volumes of river water to one of effluent. Where this degree of dilution in discharging final effluents of base mentioned effluent standards into watercourses is not available, a higher degree of purification may be advisable. On the other hand, where the dilution is great, as in tidal estuaries, less stringent rules might be permitted.

However, in certain instances of inland discharges, the standard of 30 ppm suspended solids and 20 ppm BOD5 might be acceptable without further dilution of at least eight times, as mentioned above, providing there are no water intakes downstream of the effluent outfall within a safe distance of 50 km.

7.2 Methods of Sewage Treatment: General

The primary aim of sewage treatment is to retain the sewage in circumstances in which it is in contact with the air and acted upon by aerobic organisms for a sufficient time to oxidize the organic contents to a sufficient degree for the effluent to be safely passed to natural water without any fear of causing a nuisance. The contaminants in wastewater are removed by physical, chemical, and biological means. The operations involved are classified as physical unit operations, chemical unit processes, and biological unit processes.

7.2.1 Conventional Methods

The conventional methods of treatment, apart from treatment by dilution, fall under three headings: treatment on land through a septic tank, treatment using biological filters, and treatment by activated sludge processes.

7.3 Choice of System: General

The type of sewage treatment plant to be adopted in any particular instance depends on:

a) the system, which will involve the minimum of running costs and annual repayments of cost of construction
b) the extent to which minor nuisance due to flies or sewage works odor matters in the location concerned

c) the area of land available and the suitability of the land for each of the methods of treatment
d) the degree of treatment required
e) the available fall from the incoming sewer at the battery limit of the plant to the point of outfall.

These together form a common-sense economic problem to which there should be only one correct answer in any particular instance. In fact, however, decisions as to the type of works too often depend on the preferences of individual engineers and on what may be considered fashionable at the time.

7.4 Design of Sewage Treatment Plants: General Guidance

Sewage treatment works are designed according to the quantity of sewage to be treated and the strength of the sewage, i.e. the degree of organic pollution. If sewage was generally more constant in consistency than it is, it would be quite possible to design accurately in terms of head of population to be served, but sewage varies considerably according to the amount of water used per head of population, the degree of infiltration of subsoil water, and the quantity and nature of trade waste. In the case of purely or almost purely domestic sewage from a normal town, where water closets are generally installed, the size of the aeration unit of the sewage works (land, percolating filter, or aeration tank) can be, and sometimes is, determined according to the population to be served. In most other cases, however, the aeration unit is sized according to the strength of the sewage as determined by analysis and the average dry weather flow.

In this Engineering Standard general guidance is given on adequate design only. Particular requirements should be determined by local conditions. Hence, the given recommendations can be supplemented as required by skilled engineering advice, if any, based on a knowledge of sewage works practice.

Figure 7.2 shows some typical sewage treatment facilities.

7.5 Design of Small Sewage Treatment Plants

The design guidance and criteria given here deal with the engineering of sewage treatment works suitable for discharge from domestic and industrial communities ranging from single households up to about 1000 population equivalent, and with the storage of sewage by means of a cesspool, the contents of which are periodically removed for disposal or treatment.

7.5.1 Collection of Information

For designing small sewage treatment plants the following main items of basic data should be obtained and considered:

a) Any requirements of the local municipality over and above the permissible effluent standards should be collected from local environment protection authorities.



Figure 7.2 *Sewage treatment plants. Source: Reproduced with permission from © Shutterstock.*

b) Minimum and maximum number of persons (resident and non-resident) to be served.
c) Average 24 hours water consumption and any special conditions affecting the composition of sewage and peak rates of flow; data are obtainable from the local water authorities in many instances.
d) Existence of infiltration water.
e) Particulars of site:
   1) distance from nearest habitable building
   2) prevailing winds
   3) levels
   4) information as to the nature of the ground, including the level and variations of the water table
   5) access for vehicles and plant.
f) Particulars of outfall, e.g. tidal or inland water, rivers, streams, ditches or soakage; also the proximity, highest known flood level, and minimum flow of any stream or other watercourse to which discharge of the effluent is possible.
g) The conditions under which the works will normally operate and be maintained.

h) Possibility of the need for future extensions of the works or of their elimination by a comprehensive scheme.
i) Availability of electric power and mains water.
j) Facilities for eventual disposal of sludge and screenings.

7.6 Preliminary Treatment

Rags and floating debris will inevitably form part of the flow reaching the works. To reduce blockages and fouling of plant, particularly with larger installations, one of the following methods may be adopted:

a) The placing of a small metal screen with 30–75 mm clear spacing between the vertical bars in the inlet channel. Provision should be made for overflow or by-pass of the screen in the event of blockage. Provision should also be made for the regular and safe disposal of screenings.
b) The provision of a macerator in the inlet channel of the pipe to chop up all the debris before it enters the plant.
c) If the sewage has to be pumped at any stage before treatment, a pump incorporating a cutting edge or a separate macerator unit.
d) A grit chamber in which the velocity of waste flow is reduced to a point where the denser sand and other grit will settle out, but the organic solids will remain in suspension (see Figure 7.3). The settled material is buried or used for fill.

7.7 Primary and Secondary Settlement Tanks

Primary settling tanks (or basins) are usually large tanks in which solids settle out of water by gravity (see Figure 7.4) and the settleable solids are pumped away (as sludge), while oils float to the top and are skimmed off. They operate by reducing the velocity of flow to about 0.005 m so that the suspended material (organic settleable solids) will settle out. The usual detention time is 1.5–2.5 hours. Longer periods usually result in depletion of dissolved



Figure 7.3 *Grit chamber. Source: Reproduced with permission from © DDM Imagery.*



Figure 7.4 Primary settling tank. Source: Reproduced with permission from © DDM Imagery.

oxygen and subsequent anaerobic conditions. Removal of suspended solids ranges from 50% to 65%, and a 30% to 40% reduction of the BOD5 can be expected.

Primary settlement tanks are used to settle out solids prior to biological treatment and thus reduce the BOD load on the following units. They should not normally be used for populations of fewer than about 100.

7.7.1 Capacities of Primary Settlement Tanks

The efficiency of a settlement tank is dependent on the velocity of the flow, which is determined by the tank dimensions. In small sewage treatment works in particular, the considerable variations in flow that occur can reduce settlement efficiency.

Settlement tanks may be of the horizontal flow or upward flow type. The latter type is generally more expensive to construct than a horizontal flow tank, but it has distinctive advantages.

Facilities should be provided for the regular removal of sludge, which is crucial to the performance of all settlement tanks. In normal operation, tanks should be desludged at least once each week.

Unless otherwise specified, scum retention boards and removal facilities should be provided for settlement tanks, since small sewage treatment works are more likely to receive a relatively high proportions of oils, fats, and grease than large works.

a) Upward flow tanks

The arrangement of an upward flow settlement tank should be such that the nominal upward flow velocity through it is less than the settling velocity of the material to be removed. A figure of 0.9 m/hour at maximum flow rate is recommended. Where the maximum flow rate is unknown, the surface area of the tank may be calculated from the formula:

$$A = \frac{1}{10} P^{0.85}$$

where:

A = the minimum area (m^2) of the tank at the top of the hopper
P = the design population.

This formula allows for increased variability of flow rates, which occurs as populations decrease. It is based on a dry weather flow of 1801 per head per day but should be

adjusted pro rata for other values of the dry weather flow. The dimensions and capacity of the hopper can be determined from knowledge of its volume and surface area.

b) Primary horizontal flow tanks

The calculation of the capacity of a horizontal flow tank should be based on the number of persons to be served and the dry weather flow. The detention period should not exceed 12 hours at dry weather flow and the following formula is recommended:

$$C = 180P^{0.85}$$

where:

C = the gross capacity of the tank (l)
P = the design population.

This formula allows for the increased variability in flow rates which occurs as populations decrease. It is based on a dry weather flow of 180 l per head per day but should be adjusted pro rata for other values of dry weather flow.

7.8 Sludge Digesters

The sludge which settles in the sedimentation basin is pumped to the sludge digesters (see Figure 7.5) where a temperature of 30–35 °C is maintained. This is the optimum temperature for anaerobic bacteria (bacteria that live in an environment that does not contain oxygen). The usual length of digestion is 20–30 days but it can be much longer during the winter months. Continual adding of raw sludge is necessary and only well-digested sludge should be withdrawn, leaving some ripe sludge in the digester to acclimatize the incoming raw sludge.

7.9 Drying Beds

Digested sludge is placed on drying beds of sand (*see* Figure 7.6) where the liquid may evaporate or drain into the soil. The dried sludge is a porous humus-like cake which can



Figure 7.5 *A sludge digestor. Source: Reproduced with permission from © DDM Imagery.*



Figure 7.6 Drying bed. Source: Reproduced with permission from © DDM Imagery.

be used as a fertilizer base. Liquid effluent from the primary settling tank is passed to the secondary part of the system where aerobic decomposition completes the stabilization. For this purpose, a trickling filter is used.

7.9.1 Secondary Settlement Tanks

With the majority of the suspended material removed from the sewage, the liquid portion flows over a weir at the surface of the secondary settling tank (see Figure 7.7). Chlorination of the effluent from the secondary settling tank takes place in accordance with state and local laws. Depending on the location, most laws require that a free available chlorine (FAC) residual (usually 0.2 mg/l) be maintained after a 30-minute contact period. This contact period is obtained through the use of chlorine contact chambers, which are designed to provide a 30-minute detention time.

From the chlorine contact chamber the treated sewage is normally discharged into a receiving body of water. Secondary settlement tanks, usually known as humus tanks when used in conjunction with biological filters, are essential components of secondary sewage treatment where a 30 : 20 or better quality effluent is required. They are installed immediately following biological treatment, either as independent units or as integral parts of packaged systems.



Figure 7.7 Secondary settling tank. Source: Reproduced with permission from © DDM Imagery.

The design principles for secondary settlement tanks are similar to those for primary tanks. For design, constructional, and operational convenience it may be desirable to make secondary settlement tanks of equal size to primary tanks.

7.9.1.1 Capacities of Secondary Settlement Tanks

a) Upward flow tanks
The surface area should be not less than:

$$A = \frac{3}{40}P^{0.85}$$

where:

A = the minimum area (m^2) of the tank at the top of the hopper
P = the design population.

This formula is based on a dry weather flow of 180 l per head per day and allows for increased variability of flow rates at small populations. It may be adjusted pro rata for other values of dry weather flow.

b) Secondary horizontal flow tanks
The calculation of the capacity of a horizontal flow tank should be based on the number of persons to be served and the dry weather flow. The following formula is recommended:

$$C = 135P^{0.85}$$

where:

C = the gross capacity of the tank (l)
P = the design population.

This formula is based on a dry weather flow of 180 l per head per day and allows for increased variability of flow rates at small populations. It may be adjusted pro rata for other values of dry weather flow. Use of the formula will give gross detention periods of less than nine hours at dry weather flow for all values of dry weather flow and a population in excess of 100.

7.10 Biological Filters

Biological filtration (Figure 7.8) has almost the same structure as a sand filtration facility, so the SS are removed through physical filtration. Furthermore, air is passed through the bottom of the filter to create a film of aerobic microorganisms (biofilm) on the surface of the filter. This allows the biodegradable dissolved organics remaining in the raw water to be adsorbed, dissolved, and removed. In this way, cleaner treated water can be obtained.

In a conventional biological filter, the effluent from a septic tank or a primary settlement tank is brought into contact with a suitable medium, the surface of which becomes coated with a biological film. The film assimilates and oxidizes much of the polluting matter through the agency of microorganisms. The biological filter requires ample ventilation and an efficient system of under drains leading to an outlet.

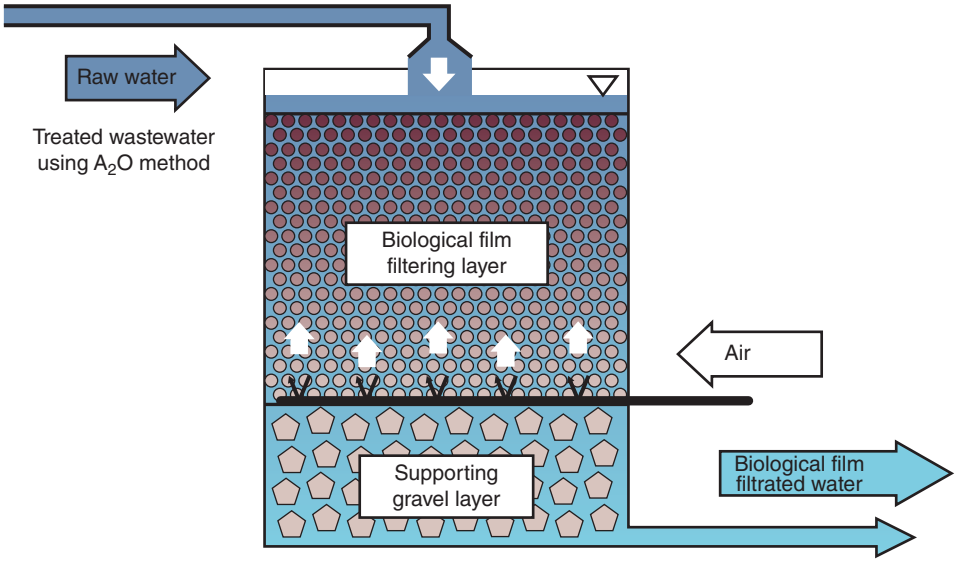


Figure 7.8 *Typical biological filter. Source: Reproduced with permission from © GESUI.*

7.10.1 Distribution

The effluent should be distributed evenly over the surface of the biological filter, through which it percolates to the floor. Biological filters are usually either rectangular or circular in plan, and various methods of distribution may be used. The most suitable for use in small installations is a series of fixed channels or a rotating-arm distributor.

7.10.2 Volume of Filter

It is essential that the volume of filter medium provided is sufficient to allow for surge flows, which occur with small installations, such variations being more pronounced the smaller the number of persons served. The volume of mineral medium required can be calculated by the formula:

$$V = 1.5P^{0.83}$$

where:

V = the volume of medium (m^3)
P = the design population.

In Table 7.1, the volumes of medium required for representative numbers of users are given; intermediate values may be interpolated on a linear basis. The volume of medium per user is also given and it can be seen that surge flows are allowed for.

7.10.3 Mineral Filter Media

Mineral filter media should comply with the requirements of BS 1438 and be chosen with regard to the following considerations:

Table 7.1 Filter medium capacity.

Design population, P	Volume of medium, V (m^3)	V/P
4	4.7	1.18
6	6.66	1.11
8	8.4	1.05
10	10.1	1.01
15	14.2	0.95
20	18	0.90
25	21.7	0.87
30	25.2	0.84
40	32	0.8
50	38.6	0.77
100	69	0.69
200	122	0.61
300	171	0.57
400	217	0.54
500	261	0.52
600	303	0.51
700	345	0.49
800	385	0.48
900	425	0.47
1000	464	0.46

a) The media should be strong enough to resist crushing under its own weight or when walked on.
b) It should be obtained washed and dust-free.
c) It should not contain any toxic substances or other undesirable matter likely to be dissolved into the sewage flow.
d) It should be capable of resisting breakdown due to the flow of the sewage or under frost action.
e) The general shape of the individual pieces should be roughly cubical rather than very elongated or flat.
f) The surface of the pieces should preferably be rough and pitted.
g) Local availability, having regard to suitability.

Several mineral materials are suitable for this purpose, the most usual being hard burnt clinker, blast furnace slag, hard broken stones, and hard crushed gravel. Efficiency is dependent on careful grading; a suitable grading for mineral media is 100–150 mm at the bottom for a depth of about 150 mm, the remainder being 50 mm nominal maximum size which requires, in accordance with BS 1438, the grading limits given in Table 7.2.

7.11 Activated Sludge Units

For the purposes of this Standard, installations operating on activated sludge principles are those providing for the aeration of crude unsettled sewage with activated sludge.

Table 7.2 *Grading limits for 50 mm filter medium.*

Test sieves (mm)	Proportion by mass passing (%)
63	100
50	85–100
37.5	0–30
28	0–5

An important feature of these installations is that a long period of aeration should be provided at some stage in the process in order to bring about oxidation of sludge, thus reducing the rate of production of surplus sludge and the frequency with which this sludge should be removed. In all activated sludge systems there is a need to regularly remove quantities of surplus sludge. For location, general requirements, types of installation, and settlement of activated sludge refer to Clause 13 of BS 6297.

7.12 Tertiary Treatment (Polishing) Processes

Conventional biological treatment can produce an effluent of 30 : 20 standard (SS:BOD), or better, after separation of solids, but for reliable production of higher quality effluents a tertiary or "polishing" stage of treatment is necessary before final disposal. Polishing processes rely mainly on flocculation, sedimentation, or filtration of residual suspended solids directed toward further reduction in ammonia and organic nitrogen, phosphorus, refractory organics, and dissolved solids.

The BOD associated with the solids is removed and some methods also provide further biological purification. Polishing is suitable only for dealing with good quality secondary effluents and, in general, will operate efficiently only at works where biological treatment is adequate. If a suitably chosen polishing process is applied to a good quality secondary effluent it should normally be possible to achieve at least 10 : 10 standard. Several methods are now available. These include slow sand filtration, rapid sand filtration, micro straining, and retention in lagoons. In small sewage treatment works the following methods are more common:

a) treatment over grass plots
b) upward-flow clarifiers (not normally used with activated sludge plants).

7.13 Disposal of Final Effluent

After treatment, the disposal of final effluent should be by one of the following methods:

a) disposal to inland or tidal water
b) disposal to underground strata
c) disposal on land
d) drying and disposal of sludge.

7.14 Advanced Wastewater Treatment

Many of the substances found in wastewater are not affected or are little affected by conventional treatment operations and processes. These substances range from relatively simple inorganic ions, such as calcium, potassium, sulfate, nitrate, and phosphate, to an ever-increasing number of highly complex synthetic organic compounds. As the effects of these substances on the environment become more clearly understood, it is anticipated that treatment requirements will become more stringent in terms of the allowable concentration of many of these substances in the effluent from wastewater treatment plants. In turn, this will require advanced wastewater treatment facilities, which nowadays are not used extensively.

7.14.1 Effects of Chemical Constituents in Wastewater

The typical composition of wastewater is shown in Table 7.3. Most sample wastewater also contains a wide variety of trace compounds and elements, although these are not measured routinely. If industrial wastewater is discharged to domestic sewers, the distribution of the constituents will vary considerably from that reported in Table 7.3.

Some of the substances found in wastewater and the concentrations that may cause problems when discharged to the environment are shown in Table 7.4. This list highlights the fact that a wide variety of substances must be considered and that they will vary with each treatment application.

7.14.2 Advanced Wastewater Treatment Operations and Processes

Unit operations and processes that have been applied to the further treatment of wastewater can be classified as physical, chemical, and biological. Brief descriptions of each of these processes are given in Table 7.5.

7.15 Effluent Disposal and Reuse

Sanitary engineers can design a treatment plant to accomplish as much removal of pollutants as may be required. Ultimate disposal of wastewater effluents will be by dilution in receiving water, by discharge on land or, in some desert areas, by evaporation into the atmosphere as well as seepage into the ground.

Disposal by dilution (after secondary treatment) in larger bodies of water, such as lakes, rivers, estuaries, or oceans, is by far the most common method. The proportion of the self-purification capacity, sometimes called the assimilative capacity, of the receiving water should not be exceeded.

7.15.1 Direct and Indirect Reuse of Wastewater

It is generally impossible to reuse a wastewater completely or indefinitely. The reuse of treated effluent by direct or indirect means is a method of disposal that complements the other disposal methods.

Table 7.3 *Typical composition of untreated domestic wastewater (all values except settleable solids are expressed in mg/l).*

Constituent	Concentration		
	Strong	Medium	Weak
Solids, total	1200	720	350
Dissolved, total	850	500	250
Fixed	525	300	145
Volatile	325	200	105
Suspended, total	350	220	100
Fixed	75	55	20
Volatile	275	165	85
Settleable solids (ml/l)	20	10	10
Biochemical oxygen demand, 5-day 200 °C (BOD5, 20 °C)	400	220	105
Total organic carbon	290	160	80
Chemical oxygen demand	1000	500	250
Nitrogen (total as N)	85	40	20
Organic N	35	15	8
Free ammonia	50	25	17
Nitrites	0	0	0
Nitrates	0	0	0
Phosphorus (total as P)	15	8	4
Organic P	5	3	1
Inorganic P	10	5	3
Chlorides	100	50	30
Alkalinity (as $CaCO_3$)b)	200	100	50
Grease	150	100	50

The amount of effluent that can be reused is affected by the availability and cost of fresh water, transportation and treatment costs, water quality standards, and the reclamation potential of the wastewater. Water reuse may be classified according to use as:

1) municipal
2) industrial
3) agricultural
4) recreational
5) groundwater recharge.

Direct and indirect reuse applications are shown in Table 7.6.

7.15.1.1 Municipal Reuse

Direct reuse of treated wastewater as drinking water after dilution in natural water to the maximum possible extent varies only in degree from the situation existing in many rivers that are used for both water supply and waste disposal.

Advanced methods of wastewater and water treatment, such as demineralization and desalination, are capable of almost complete removal of impurities, and water treated by

Table 7.4 *Typical chemical constituents that may be found in wastewater and their effects.*

Constituent	Effect	Critical concentration (mg/l)
Inorganic ammonia	Increases chlorine demand; toxic to fish; can be converted to nitrates and, in the process, can deplete oxygen resources; with phosphorus, can lead to the development of undesirable aquatic growths	Any amount, variable (depends on pH and temperature)
	Increases hardness and total dissolved solids	
Calcium and magnesium chloride	Imparts salty taste; interferes with agricultural and industrial processes	250
	Toxic to humans and aquatic life	
	Stimulates algal and aquatic growth can cause	75–200
Mercury	Methemoglobinemia in infants (blue babies)	0.00005
Nitrate	Stimulates algal and aquatic growth	0.3 (for quiescent lakes)
	Interferes with coagulation	
	Interferes with lime-soda softening	
		10 (for quiescent lakes)
Phosphate	Cathartic action	0.2–0.4
Sulfate	Toxic to fish and other aquatic life	600–1000
Organic DDT	May be related to the development of cancer; may also cause taste and odor problems in water	0.001
Hexachloride	—	0.02
Petrochemicals	Cause foaming and may interfere with coagulation	0.005–0.1
Phenolic compounds		0.0005–0.001
Surfactants		1.0–3.0

such methods, after chlorination, is safe to drink. These methods are very expensive and where they are found to be necessary due to inadequate water supplies may be economically feasible only if a dual supply system is adopted. In such cases, adequately treated and disinfected wastewater effluents could be reused for flushing toilets, yard watering, and other direct applications.

7.15.1.2 Industrial Reuse

Industry is probably the single greatest user of water in the world, and the largest of the industrial water demands is for process cooling water. However, reuse of final effluents of wastewater treatment plants within petrochemical plants to replace a portion of the industrial water requirement is not recommended.

Table 7.5 *Advanced wastewater treatment operations and processes.*

Description	Type of wastewater treated	Principal use	Waste for ultimate disposal
Physical unit operations			
Air stripping of ammonia	Effluent after secondary treatment	Removal of ammonia nitrogen	None
Filtration, multimedian	Effluent after secondary treatment	Removal of suspended solids	Liquid and sludge
Diatornite bed	Effluent after secondary treatment	Removal of suspended solids	Sludge
Micorstrainer	Effluent from biological treatment	Removal of suspended solids	Sludge
Distillation	Effluent after secondary treatment + filtration	Removal of dissolved solids	Liquid
Electrodialysis	Effluent after secondary treatment + filtration + carbon adsorption	Removal of dissolved solids	Liquid
Flotation	Effluent from primary treatment, effluent after secondary treatment	Removal of suspended solids	Sludge
Foam fractionation	Effluent after secondary treatment	Removal of refractors, organics, surfactants, and metals	Liquid
Freezing	Effluent after secondary treatment + filtration	Removal of dissolved solids	Liquid
Gas phase separation	Effluent after secondary treatment	Removal of ammonia nitrogen	None
Land application	Effluent from primary treatment, effluent after secondary treatment	Nitrification, denitrification, removal of ammonia, nitrogen, and phosphorous	None
Reverse osmosis sorption	Effluent after secondary treatment + filtration + effluent from biological treatment	Removal of dissolved solids	Liquid, liquid and sludge

(*Continued*)

Table 7.5 *(continued)*

Description	Type of wastewater treated	Principal use	Waste for ultimate disposal
Chemical unit processes			
Breakpoint chlorination	Effluent after secondary treatment (filtration)	Removal of ammonia nitrogen	Liquid
Carbon adsorption	Effluent from primary treatment, effluent after secondary treatment (filtration, optional)	Removal of dissolved organics, heavy metals, and chlorine	Liquid
Chemical precipitation	Effluent from biological treatment	Phosphorous precipitation, removal of heavy metals, removal of colloidal solids	Sludge
Chemical precipitation in activated sludge	Effluent from primary treatment	Removal of phosphorous	Sludge
Ion exchange	Effluent after secondary treatment + filtration	Removal of ammonia and nitrate nitrogen	Liquid
Electrochemical treatment	Untreated	Removal of dissolved solids	Liquid and sludge
Oxidation	Effluent after secondary treatment	Removal of refractory organics	None
Biological treatment processes			
Bacterial assimilation	Effluent from primary treatment	Removal of ammonia nitrogen	Sludge
Denitrification	Agricultural return water	Nitrate reduction	None
Harvesting of algae	Effluent from biological treatment	Removal of ammonia nitrogen	Algae
Nitrification	Effluent from primary treatment, effluent from biological treatment	Ammonia oxidation	Sludge
Nitrification – denitrification	Effluent from primary treatment, effluent from biological treatment	Total nitrogen removal	Sludge

Table 7.6 *Potential uses of renovated water.*

Use	Direct	Indirect
Municipal	Park or golf course watering; lawn watering with separate distribution system; potential source for municipal water supply	Groundwater recharge to reduce aquifer, aquifer overdrafts
Industrial	Cooling tower water; boiler feed water; process water	Replenish groundwater supply for industrial use
Agricultural	Irrigation of certain agricultural lands, crops, orchards, pastures, and forests; leaching of soils	Replenish groundwater supply for agricultural overdrafts
Recreational	Forming artificial lakes for boating, swimming, etc.; swimming pools	Develop fish and waterfowl areas
Other	Groundwater recharge to control saltwater intrusion; salt balance control in groundwater; wetting agent, solid waste compaction	Groundwater recharge to control land subsidence problems; soil compaction; oil well repressurizing

7.15.1.3 Agricultural Reuse

The types of crops that can be irrigated with reclaimed wastewater depend on the quality of the effluent, the amount of effluent used, and the health regulations concerning the use of treated and untreated wastewater on crops. Health considerations prohibit the use of untreated wastewater. However, final effluents meeting secondary treatment requirements can be used for irrigation of certain field crops, such as cotton.

7.15.1.4 Recreational Reuse

Golf course and park watering, establishment of ponds for boating and recreation, and maintenance of fish or wildlife ponds are examples of the recreational reuse of water. Today's technology allows the production of an excellent effluent that is well suited for these purposes. The use of treated effluent for park watering has been practiced for many years in western countries.

7.15.1.5 Groundwater Recharge

Groundwater recharge is one of the most common methods for combining water reuse and effluent disposal. Recharge has been used to replenish groundwater supplies in many areas of the United States. Another possible effluent use is in the recharging of oil-bearing strata. Oil companies have conducted much research on flooding techniques to increase the yield of oil-bearing strata.

8

Solid Waste Treatment and Disposal

This chapter covers the minimum requirements for the process design and engineering of plant solid waste treatment and disposal facilities in the oil, gas, and chemical industries.

8.1 Basic Considerations

8.1.1 Classification

Solid wastes include those suspended in liquids and are classified in the following categories in the order of increasing difficulty in disposal:

a) inert dry solids, e.g. trash, silt, spent cracking catalyst
b) combustible dry solids, e.g. trash, waste paper, scrap lumber
c) sludges containing water and solids, e.g. water softener sludges, sanitary sludges
d) sludges containing oil, e.g. spent clays
e) sludges containing oil, water, and solids, e.g. tank bottoms, oil-water separator bottoms.

8.1.2 Methodology

For proper evaluation and selection of solid waste disposal the following information is required:

a) tabulation of sources
b) sludge production rates and quantities
c) physical characteristics such as pumpability, concentration factor, etc.
d) analyses for water, oil and solids contents, volatiles, and ash
e) analyses of the water component for pH, sulfide, acidity or alkalinity, lead, and other constituents having potentially significant effects on water pollution

Waste Management in the Chemical and Petroleum Industries, Second Edition. Alireza Bahadori.
© 2020 John Wiley & Sons Ltd. Published 2020 by John Wiley & Sons Ltd.

f) analyses of the solids component for combustible and non-combustible content and for size distribution of the dry solids
g) heating value of sludge (on dry basis).

8.1.3 Sources

8.1.3.1 Solids in the Crude Oil Supply

All crude oils contain some basic sediment and water (BS&W), which is generally composed of a mixture of water, iron rust, iron sulfides, clay, sand, and so forth produced with the crude oil or picked up in transit. Part of the BS&W is charged to the crude oil unit and may settle out in the desalter, entering the oily water sewer system along with the desalter effluent. The balance will settle out in storage tanks, resulting in eventual tank-cleaning problems.

8.1.3.2 Solids from Surface Water

Process water and all other special drainages throughout the plant/refinery should be isolated from surface runoff. The surface drainage should be collected in a dedicated and separate clean storm water sewer system. Extensive efforts should be made to segregate the surface drainages and avoiding contamination or mixing with the oily water sewers.

8.1.3.3 Solids in the Water Supply

Silt may enter the water supply. Depending on the source of the supplied water to the plant/refinery and its characteristics and impurities, provision of sedimentation before the water is used should be investigated. Special attention should be given to reducing the deposition of solids in cooling tower basins, heat exchangers, and other consumers and, also to preventing these solids from entering oily water sewers.

8.1.3.4 Sanitary Solid Wastes

Sanitary wastes should be segregated from all other types of drainage systems

8.1.3.5 Solids and Sludges in Wastewater Systems

According to the type of plant and the method of plant operation, the sources of solids in a wastewater treatment plant can be determined. The principal sources of solids and sludge and the types generated in a conventional wastewater treatment plant are shown in Table 8.1. Solids may also be formed by interaction of waste streams in the sewer. Figure 8.1 shows a typical source of solids and sludge.

Wastewater contains metal ions, such as iron, aluminum, copper, magnesium, etc., from corrosion of the process equipment, chemicals used in treating cooling water, salts in the water intake, and chemicals used in processing. Insoluble metal hydroxide floc may be formed when alkaline wastes are discharged and raise the pH of wastewater above neutral.

Wastewater containing considerable concentrations of phenols, sulfides, emulsifying agents, and alkalines should be segregated. In general, discharging of any material to

Table 8.1 *Sources of solids and sludge from a conventional wastewater treatment plant.*

Unit operation or process	Type of solids or sludge	Remarks
Screening	Coarse solids	Coarse solids are removed by mechanical and hand cleaned bar screens. In small plants, screenings are often comminuted for removal in subsequent treatment units.
Grit removal	Grit and scum	Scum removal facilities are often omitted in grit removal facilities.
Pre-aeration	Grit and scum	In some plants, scum removal facilities are not provided in pre-aeration tanks. If the pre-aeration tanks are not preceded by grit removal facilities, grit deposition may occur in pre-aeration tanks.
Primary sedimentation	Primary sludge and scum	Quantities of sludge and scum depend upon the nature of the collection system and whether industrial wastes are discharged to the system.
Biological treatment	Suspended solids	Suspended solids are produced by the biological conversion of BOD. Some form of thickening may be required to concentrate the waste sludge stream from biological treatment.
Secondary sedimentation	Secondary sludge and scum	Provision for scum removal from secondary settling tanks is a requirement of the US Environmental Protection Agency (EPA).
Sludge-processing facilities	Sludge, compost, and ashes	The characteristics of the end products depend on the characteristics of the sludge being treated and the operations and processes used. Regulations for the disposal of residuals are becoming increasingly stringent.

the oily sewer system or other drainage systems should be investigated for final waste treatment and disposal targets.

8.1.3.6 Catalytic Processes

Catalysts can appear in the sewer system of plants with catalytic process applications. Means should be provided to minimize catalyst disposal. Hopper trucks or covered portable containers should be provided to prevent catalyst fines from becoming airborne. In some cases spent catalyst is slurred with water and pumped directly to ponds, where the solids settle. Spent solid catalysts which contain vanadium, platinum, or other valuable metals should be returned to the manufacturer for recovery.

8.1.3.7 Solids from Coking Operations

8.1.3.7.1 Coke Fines. Water used to remove coke from coke chambers in delayed coking units should be recirculated through a settling basin to remove entrained coke fines. The basin can be located near the coke storage pile so that storm water will drain through

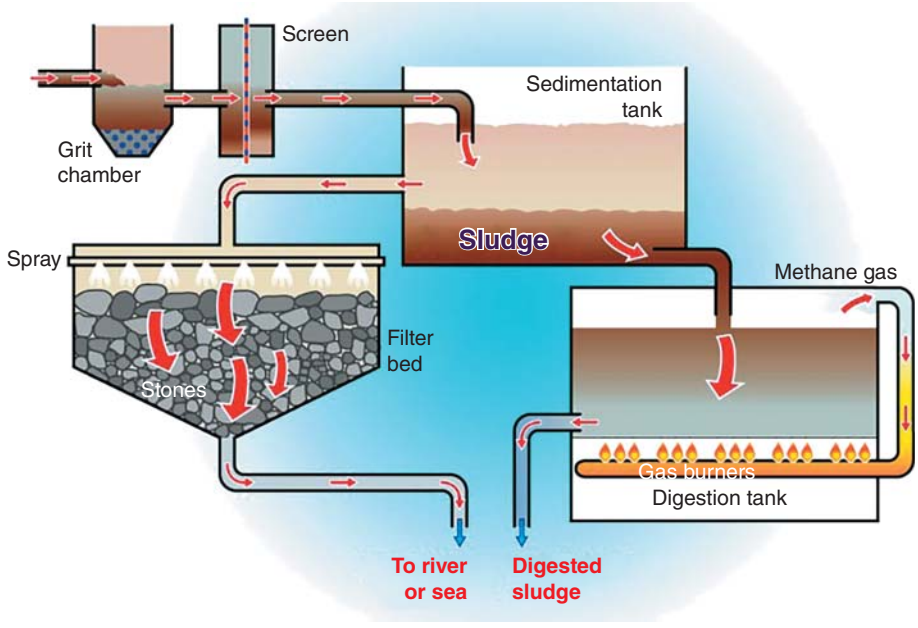


Figure 8.1 *A typical source of solids and sludge.*

the basin to recover coke washed from the storage area. To clean the basin, coke can be transferred directly to the storage pile with appropriate equipment.

8.1.3.7.2 Wax Tailings. Wax tailings from coking processes present a very difficult disposal problem in sewer systems. Wax tailing disposal to the oily sewer system should be avoided. Wax deposits may form to clog the oily water sewer or to reduce the capacity of the oil water separators.

In some cases, the wax tailings will rise and be partially absorbed in the oil layer, causing slop oil treating problems. Investigations should be undertaken to provide facilities to remove wax tailings before discharging to the sewer system. The coker blowdown system may include a scrubber in which a light oil, such as light cycle oil, is recirculated to dissolve wax tailings and remove them from the water. When the American Petroleum Institute (API) gravity of the light oil has reached a certain point, the oil should be returned to the hot-oil system via the fractionator and be replaced by a new charge.

8.1.3.8 Particulate Matter and Fly Ash

Particulate matter from collectors is sometimes commercially valuable either directly or after further treatment. Therefore, special attention should be made to collect the particles for reuse purposes such as:

- addition to concrete in small amounts
- use as a constituent of clay bricks
- use as a soil conditioner.

8.1.3.9 Cleanout Wastes

Solids from cleanout operations normally contain a considerable amount of various metals and should not be sent to the oily water system.

Special precautions and procedures are required for disposal of tank bottoms and other cleanout wastes containing tetra-ethyl lead (TEL).

8.1.3.10 Other Sources

The following sources of solid wastes should also be taken into consideration:

- storage tank drains
- process unit drains
- catalyst contaminated streams
- others.

8.1.4 Characteristics

The characteristics of solid waste vary depending on the origin of the solids and sludge, the amount of aging that has taken place, and the type of processing to which they have been subjected. Some of the physical characteristics of sludges are summarized in Tables 8.2–8.4.

8.1.5 Quantities

The quantity of solids entering the wastewater treatment plant fluctuates over a wide range. To ensure plant capacity can handle these variations, the following factors should be taken into consideration:

a) average and maximum rates of sludge production
b) potential storage capacity of the treatment units within the plant
c) capability to dump short-term peak loads (e.g. by sufficient capacity of equalization basin).

Data on the quantities of sludge produced from various processes and operations, as well as sludge concentrations are shown in Table 8.5.

8.2 Sludge Handling, Treatment, and Reuse

8.2.1 General

In selecting the appropriate methods of sludge processing, reuse, and disposal, special consideration must be given to the regulations controlling the disposal of sludge from wastewater treatment plants. The following main disposal targets should be investigated:

- application of sludge to agricultural and non-agricultural land
- distribution and marketing
- monofilling
- surface disposal
- incineration.

Table 8.2 *Characteristics of solids and sludge produced during wastewater treatment.*

Solid or sludge	Description
Screenings	Screenings include all types of organic and inorganic materials large enough to be removed on bar racks. The organic content varies, depending on the nature of the system and the season of the year.
Grit	Grit is usually made of the heavier inorganic solids that settle with relatively high velocities. Depending on the operating conditions, grit may also contain significant amounts of organic matter, especially fats and grease.
Scum/grease	Scum consists of the floatable materials skimmed from the surface of primary and secondary settling tanks. Scum may contain grease, vegetable and mineral oils, animal fats, waxes, soaps, food wastes, vegetable and fruit skins, hair, paper and cotton, cigarette tips, plastic materials, condoms, grit particles, and similar materials. The relative density (specific gravity) of scum is less than 1.0 and usually around 0.95.
Primary sludge	Sludge from primary settling tanks is usually gray and slimy, and in most cases has an extremely offensive odor. Primary sludge can be readily digested under suitable conditions of operation.
Sludge from chemical precipitation	Sludge from chemical precipitation with metal salts is usually dark in color, though its surface may be red if it contains much iron. Lime sludge is grayish brown. The odor of chemical sludge may be objectionable, but is not as bad as primary sludge. While chemical sludge is somewhat slimy, the hydrate of iron or aluminum in it makes it gelatinous. If the sludge is left in the tank, it undergoes decomposition similar to primary sludge, but at a slower rate. Substantial quantities of gas may be given off and the sludge density increased by long residence times in storage.
Activated sludge	Activated sludge generally has a brownish, flocculant appearance. If the color is dark, the sludge may be approaching a septic condition. If the color is lighter than usual, there may have been under-aeration with a tendency for the solids to settle slowly. Sludge in good condition has an inoffensive “earthy” odor. The sludge tends to become septic rapidly and then has a disagreeable odor of putrefaction. Activated sludge will digest readily alone or when mixed with primary sludge.
Trickling-filter sludge	Humus sludge from trickling filters is brownish, flocculant, and relatively inoffensive when fresh. It generally undergoes decomposition more slowly than other undigested sludges. When trickling-filter sludge contains many worms, it may become inoffensive quickly. Trickling-filter sludge digests readily.
Digested sludge (aerobic)	Aerobically digested sludge is brown to dark brown and has a flocculant appearance. The odor of aerobically digested sludge is not offensive; it is often characterized as musty. Well-digested aerobic sludge dewaters easily on drying beds.

Table 8.2 *(continued)*

Solid or sludge	Description
Digested sludge (anaerobic)	Anaerobically digested sludge is dark brown to black and contains an exceptionally large quantity of gas. When thoroughly digested, it is not offensive, its odor being relatively faint and like that of hot tar, burnt rubber, or sealing wax. When drawn off onto porous beds in thin layers, the solids first are carried to the surface by the entrained gases, leaving a sheet of comparatively clear water. The water drains off rapidly and allows the solids to sink down slowly on to the bed. As the sludge dries, the gases escape, leaving a well-cracked surface with an odor resembling that of garden loam.
Composted sludge	Composted sludge is usually dark brown to black, but the color may vary if bulking agents such as recycled compost or wood chips have been used in the composting process. The odor of well-composted sludge is inoffensive and resembles that of commercial garden-type soil conditioners.
Septage	Sludge from septic tanks is black. Unless the sludge is well digested by long storage, it is offensive because of the hydrogen sulfide and other gases that it gives off. The sludge can be dried on porous beds if spread out in thin layers, but objectionable odors can be expected while it is draining unless it is well-digested

Table 8.3 *Typical chemical composition and properties of untreated and digested sludge.*

Item	Untreated primary sludge		Digested primary sludge		Activated sludge, range
	Range	Typical	Range	Typical	
Total dry solids (% of TS)	2–8	5	6–12	10	0.83–1.16
Volatile solids (% of TS)	60–80	65	30–60	40	59–88
Grease and fats (% of TS), ether soluble	6–30	—	5–20	18	—
Grease and fats (% of TS), ether extract	7–35	—	—	—	5–12
Protein (% of TS)	20–30	25	15–20	18	32–41
Nitrogen (N, % of TS)	1.5–4	2.5	1.6–6	3	2.4–5
Phosphorus (P_2O_5, % of TS)	0.8–2.8	1.6	1.5–4	2.5	2.8–11
Potash (K_2O, % of TS)	0–1	0.4	0–3	1	0.5–0.7
Cellulose (% of TS)	8–15	10	8–15	10	—
Iron (not as sulfide)	2–4	2.5	3–8	4	—
Silica (SiO_2, % of TS)	15–20	—	10–20	—	—
pH	5–8	6	6.5–7.5	7	6.5–8
Alkalinity (mg/l as $CaCO_3$)	500–1 500	600	2 500–3 500	3 000	580–1 100
Organic acids (mg/l)	200–2 000	500	100–600	200	1 100–1 700
Energy content, Btu/b, (Btu/lb × 2.3241 = kJ/kg)	10 000–12 500	11 000	4 000–6 000	5 000	8 000–10 000

Btu, British thermal unit per pound.

Table 8.4 *Typical metal content in wastewater sludge.*

	Dry sludge (mg/kg)	
Metal	Range	Median
Arsenic	1.1–230	10
Cadmium	1–3 410	10
Chromium	10–99 000	500
Cobalt	11.3–2 490	30
Copper	84–17 000	800
Iron	1 000–154 000	17 000
Lead	13–26 000	500
Manganese	32–9 870	260
Mercury	0.6–56	6
Molybdenum	0.1–214	4
Nickel	2–5 300	80
Selenium	1.7–17.2	5
Tin	2.6–329	14
Zinc	101–49 000	1 700

Sludge processing and disposal methods are listed in Table 8.6. Thickening (concentration), conditioning, dewatering, and drying are used primarily to remove moisture from sludge; digestion, composting, incineration, wet air oxidation, and vertical tube reactors are used primarily to treat or stabilize the organic material in the sludge.

8.2.2 Sludge and Scum Pumping

Sludge produced in wastewater treatment plants must be conveyed from one plant point to another in conditions ranging from a watery sludge or scum to a thick sludge.

For each type of sludge and pumping application, a different type of pump may be needed. The application and selection of the various types of sludge pumps are summarized in Table 8.6:

8.2.2.1 Types and Selection of Pumps

8.2.2.1.1 Plunger Pumps. Plunger pumps have been used frequently and, if robust enough, have proved to be quite satisfactory. The advantages of plunger pumps are as follows:

a) The pulsating action of simplex and duplex pumps tends to concentrate the sludge in the hoppers ahead of the pumps and resuspend solids in pipelines when pumping at low velocities.
b) Plunger pumps are suitable for suction lifts up to 3 m and are self-priming.
c) Low pumping rates can be used with large port openings.
d) Positive delivery is provided, unless some object prevents the ball check valves from seating.

Table 8.5 *Typical data for the physical characteristics and quantities of sludge produced from various wastewater treatment operations and processes.*

Treatment operation or process	Relative density (specific gravity) of sludge solids	Relative density (specific gravity) of sludge solids	Dry solids ($kg/10^3m^3$)	
			Range	Typical
Primary sedimentation	1.4	1.02	108.5–168.7	150.6
Activated sludge (waste sludge)	1.25	1.005	72.3–96.4	84.3
Trickling filtration (waste sludge)	1.45	1.025	60.2–96.4	72.3
Extended aeration (waste sludge)	1.30	1.015	84.3–120.5	72.3 (assuming no primary treatment)
Aerated lagoon (waste sludge)	1.30	1.01	84.3–120.5	72.3 (assuming no primary treatment)
Filtration	1.20	1.005	12.1–24.2	18.1
Algae removal	1.2	1.005	12.1–24.2	18.1
Chemical addition to primary sedimentation tanks for phosphorus removal, low lime (350–500 mg/l)	1.9	1.04	241–397.6	301.2 (sludge in addition to that normally removed by primary sedimentation)
Chemical addition to primary sedimentation tanks for phosphorus removal, high lime (800–1600 mg/l)	2.2	1.05	602.4–1325.3	795.2 (sludge in addition to that normally removed by primary sedimentation)
Suspended growth nitrification	—	—	—	Negligible
Suspended growth denitrification	1.20	1.005	12.1–30.1	18.1
Roughing filters	1.28	1.02	—	Included in sludge production from biological secondary treatment processes

Table 8.6 *Sludge processing and disposal methods.*

Unit operation, unit process, or treatment method	Function
Preliminary operations	
Sludge grinding	Size reduction
Sludge degritting	Grit removal
Sludge blending	Blending
Sludge storage	Storage
Thickening	
Gravity thickening	Volume reduction
Flotation thickening	Volume reduction
Centrifugation	Volume reduction
Gravity belt thickening	Volume reduction
Rotary drum thickening	Volume reduction
Stabilization	
Lime stabilization	Stabilization
Heat treatment	Stabilization
Anaerobic digestion	Stabilization, mass reduction
Aerobic digestion	Stabilization, mass reduction
Composting	Stabilization, product recovery
Conditioning	
Chemical conditioning	Sludge conditioning
Heat treatment	Sludge conditioning
Disinfecting	
Pasteurization	Disinfection
Long-term storage	Disinfection
Dewatering	
Vacuum filter	Volume reduction
Centrifuge	Volume reduction
Belt filter press	Volume reduction
Filter press	Volume reduction
Sludge drying beds	Volume reduction
Lagoons	Storage, volume reduction
Heat drying	
Flash dryer	Mass and volume reduction
Spray dryer	Mass and volume reduction
Rotary dryer	Mass and volume reduction
Multiple hearth dryer	Mass and volume reduction
Multiple-effect evaporator	Mass and volume reduction
Thermal reduction	
Multiple-hearth incineration	Volume reduction, resource recover
Fluidized-bed incineration	Volume reduction
Co-incineration with solid wastes	Volume reduction
Wet-air oxidation	Stabilization, volume reduction
Vertical, deep-well reactor	Stabilization, volume reduction
Ultimate disposal	
Land application	Final disposal
Distribution and marketing	Beneficial use
Chemical fixation	Beneficial use, final disposal
Landfill	Final disposal
Lagooning	Volume reduction, final disposal

e) Plunger pumps have constant but adjustable capacity, regardless of large variations in pumping head.
f) High discharge heads may be provided.
g) Heavy solids concentrations may be pumped if the equipment is designed for the load conditions.

The range of plunger pump capacity is from 2.5 to 3.8 l/s per plunger and they are supplied with one, two, or three plungers (called simplex, duplex, or triplex units).

Pump speeds should be between 40 and 50 revs per minute (rpm). The pumps should be designed for a minimum head of 24 m in small plants and 35 m or more in large plants because accumulations of grease in sludge lines cause a progressive increase in head with use.

8.2.2.1.2 Progressive Cavity Pumps. Progressive cavity pumps can be used for all types of sludges. This pump is self-priming at suction lifts up to 8.5 m, but it must not be operated dry because this will burn out the rubber stator. It is available in capacities up to 75 l/s and may be operated at discharge heads of 137 m on sludge. For primary sludges, a grinder normally precedes this type of pump. These pumps are expensive to maintain because of wear on the rotors and the stators, particularly in primary sludge-pumping applications where grit is present. The advantages of these pumps are:

a) easily controlled flowrates
b) minimum pulsation
c) relatively simple operation.

8.2.2.1.3 Centrifugal Pumps. Centrifugal pumps of non-clog design are commonly used. The pumps must have sufficient clearance to pass the solids without clogging and have a small enough capacity to avoid pumping a sludge diluted by large quantities of wastewater overlying the sludge blanket.

Throttling the discharge to reduce the capacity is impractical because of frequent stoppages, hence it is absolutely essential that these pumps be equipped with variable-speed drives. For pumping primary sludge in large plants, centrifugal pumps of special design-torque flow, screw feed, and bladeless should be used. Screw feed and bladeless pumps have not been used very much in recent applications because of the successful use of torque-flow pumps.

Torque-flow pumps have fully recessed impellers and are very effective in conveying sludge. The size of particles that can be handled is limited only by the diameter of the suction or discharge openings. Pumps used in sludge service should have nickel or chrome abrasion-resistant volute and impellers.

The pumps can operate only over a narrow head range at a given speed, so the system operating conditions must be evaluated carefully. Variable speed control should be used where the pumps are expected to operate over a wide range of head conditions. For high pressure applications, multiple pumps may be used and connected together in series. For returning activated sludge to aeration tanks, slow speed centrifugal, mixed flow pumps, and screw pumps are commonly used.

8.2.2.1.4 Diaphragm Pumps. Diaphragm pumps are relatively low capacity and low head; the largest available air-diaphragm pump delivers 14 l/s against 15 m of head.

8.2.2.1.5 High Pressure Piston Pumps. High pressure piston pumps are very expensive and are used in high pressure applications such as pumping sludge long distances. Several types of piston pumps have been developed for high pressure applications and are similar in action to plunger pumps. The advantages of these types of pumps are:

a) they can pump relatively small flowrates at high pressures, up to 13 800 kPa (ga)
b) large solids up to the discharge pipe diameter can be passed
c) a range of solids concentrations can be handled
d) the pumping can be accomplished in a single stage.

8.2.2.1.6 Rotary-lobe Pumps. Rotary-lobe pumps are positive displacement pumps in which two rotating, synchronous lobes push the fluid through the pump. Rotational speed and shearing stresses are low. For sludge pumping, the lobes should be made of hard metal or hard rubber.

One advantage of these pumps is that lobe replacement is less costly than rotor and stator replacement in progressive cavity pumps. Rotary-lobe pumps, like other positive displacement pumps, must be protected against pipeline obstructions.

8.2.2.2 Application of Pumps to Types of Sludge

Types of sludge that are pumped include primary, chemical, and trickling filter sludges, and activated, thickened, and digested sludges. Scum that accumulates at various points at a treatment plant must also be pumped. The application of pumps to types of sludge is summarized in Table 8.7.

8.2.3 Sludge Piping

- In treatment plants, conventional sludge piping should not be smaller than DN 150 (6 in.), although smaller diameter glass-lined pipes have been used successfully.
- Pipe sizes need not be larger than DN 200 (8 in.) unless the velocity exceeds 1.5–1.8 m/s, in which case the pipe should be sized to maintain the velocity. Gravity sludge withdrawal lines should not be less than DN 200 (8 in.) in diameter.
- A number of cleanouts in the form of plugged tees or crosses instead of elbows should be installed so that the lines can be rodded if necessary.
- Pump connections should not be smaller than DN 100 (4 in.) in diameter.
- Pump selection should consider build-up of head due to grease accumulations inside the piping. In some plants provision may also be made for melting the grease by circulating hot water, steam, or digester supernatant through the main sludge lines.
- In the design of long sludge lines, special design features should be considered, including:
  a) providing two pipes unless a single pipe can be shut down for several days without causing problems
  b) providing for external corrosion and pipe loads
  c) adding facilities for applying dilution water for flushing the line

Table 8.7 *Application of pumps to types of sludge.*

Type of sludge or solids	Applicable pump	Comment
Ground screenings	Pumping screenings should be avoided	Pneumatic ejectors may be used.
Grit	Torque-flow centrifugal	The abrasive character of grit and the presence of rags make grit difficult to handle. Hardened casings and impellers should be used for torque-flow pumps. Pneumatic ejectors may also be used.
Scum	Plunger; progressive cavity; diaphragm; centrifugal	Scum is often pumped by the sludge pumps; valves are manipulated in the scum and sludge limes to permit this. In larger plants, separate scum pumps are used. Scum mixers are often used to ensure homogeneity prior to pumping. Pneumatic ejectors may also be used.
Primary sludge	Plunger; torque-flow centrifugal; diaphragm; progressive cavity; rotary-lobe	In most cases, it is desirable to obtain as concentrated a sludge as practicable from primary sedimentation tanks, usually by collecting the sludge in hoppers and pumping intermittently, allowing the sludge to collect and consolidate between pumping periods. The character of untreated primary sludge will vary considerably, depending on the characteristics of the solids in the wastewater and the types of treatment units and their efficiency. Where biological treatment follows, the quantity of solids from: 1. waste activated sludge 2. humus sludge from settling tanks following trickling filters 3. overflow liquors from digestion tanks 4. centrate or filtrate return from dewatering operations will also affect the sludge characteristics. In many cases, the character of the sludge is not suitable for use in conventional non-clog centrifugal pumps.
Chemical precipitation	Same as for primary sludge	Same as for primary sludge
Digested sludge	Plunger; torque-flow centrifugal; progressive cavity; diaphragm; high-pressure piston; rotary-lobe	Well-digested sludge is homogeneous, containing 5–8% solids and a quantity of gas bubbles, but may contain up to 12% solids.

(*Continued*)

Table 8.7 *(continued)*

Type of sludge or solids	Applicable pump	Comment
		Poorly digested sludge may be difficult to handle. If good screening and grit removal is provided, non-clogy centrifugal pumps may be considered.
Trickling-filter humus sludge	Non-clog and torque-flow centrifugal; progressive cavity; plunger; diaphragm	Sludge is usually of homogeneous character and can be easily pumped.
Return or waste-activated sludge	Non-clog and torque-flow centrifugal; progressive cavity; diaphragm	Sludge is dilute and contains only fine solids so that non-clog pumps may commonly be used. For non-clog pumps, slow speeds are recommended to minimize the break-up of flocculant particles.
Thickened or concentrated sludge	Plunger; progressive cavity; diaphragm; high-pressure piston; rotary-lobe	Positive displacement pumps are most applicable for concentrated sludge because of their ability to generate movement of the sludge mass. Torque-flow pumps may be used but may require the addition of flushing or dilution facilities.

d) providing the means to insert a pipe cleaner at the treatment plant
e) including provisions for steam injections
f) providing air relief and blow-off valves for the high and low points, respectively
g) considering the potential effects of waterhammer.

8.2.4 Preliminary Operation Facilities

Sludge grinding, degritting, blending, and storage are necessary to provide a relatively constant, homogeneous feed to sludge processing facilities. Blending and storage can be accomplished either in a single unit designed to do both or separately in other plant components.

8.2.4.1 Sludge Grinding

Some of the processes that must be preceded by sludge grinders for the purpose of preventing clogging are:

a) pumping with progressive cavity pumps
b) solid bowl centrifuges
c) belt filter press
d) heat treatment
e) chlorine oxidation (for enhancing chlorine contact with sludge particles).

Slow speed, more durable, and reliable grinders should be applied. The design should include improved bearings and seals, hardened steel cutters, overload sensors, and mechanisms that reverse the cutter rotation to clear obstructions or shutdown the unit if the obstruction cannot be cleared.

8.2.4.2 Sludge Degritting

In some plants where separate grit removal facilities are not used ahead of the primary sedimentation tanks or where the grit removal facilities are not adequate to handle peak flows and peak grit loads, grit removal facilities should be provided before further processing of the sludge. Where further thickening of the primary sludge is desired, a practical consideration is sludge degritting. The most effective method of degritting is through the application of centrifugal forces in a flowing system to achieve separation of grit particles from the organic sludge. Such separation is achieved through the use of cyclone degritters, which have no moving parts. The efficiency of the cyclone degritter is affected by pressure and by the concentration of the organic in the sludge. To obtain effective grit separation, the sludge must be relatively dilute. As the sludge concentration increases, the particle size that can be removed decreases.

8.2.4.3 Sludge Blending

Sludge is blended (if required) to produce a uniform mixture to downstream operations and processes. Uniform mixtures are most important in short detention time systems, such as sludge dewatering, heat treatment, and incineration. Special attention should be given to segregation of oily and non-oily sludges.

Sludge from the various sources can be blended in several ways.

a) *In primary settling tanks*. The same type (oily or non-oily) of sludges from secondary or advanced wastewater treatment sludges can be returned to the primary settling tanks, where they will settle and mix with the primary sludge.
b) *In pipes*. This procedure requires careful control of sludge sources and feed rates to ensure the proper blend.
c) *In sludge processing facilities with long detention times*. Aerobic and anaerobic digesters (complete-mix type) can blend the feed sludges uniformly.
d) *In a separate blending tank*. This practice provides the best opportunity to control the quality of the blended sludges.

In treatment plants of less than 140 m^3/hour capacity, blending is usually accomplished in the primary settling tanks. In large facilities, optimum efficiency is achieved by separately thickening sludges before blending. Blending tanks should be equipped with mechanical mixers and baffles to ensure good mixing.

8.2.4.4 Sludge Storage

Sludge storage must be provided to smooth out fluctuations in the rate of sludge production and to allow sludge to accumulate during periods when subsequent sludge processing facilities are not operating. Sludge storage should be provided ahead of the following processes to establish a uniform feed rate:

a) lime stabilization
b) heat treatment
c) mechanical dewatering
d) drying
e) thermal reduction.

Sludge tanks may be sized to retain the sludge for a period of several hours to a few days. If sludge is stored longer than two or three days, it will deteriorate and be more difficult to dewater. Sludge is often aerated to prevent septicity and to promote mixing. Means should be provided to reduce and control the odors from sludge storage.

8.2.5 Thickening (Concentration)

Thickening should be used to increase the solids content of sludge by removing a portion of the liquid fraction before land disposal of the sludge or other applications as required. Representative values of percent total solids from various treatment operations or processes are shown in Table 8.8.

Sludge thickening methods are described in Table 8.9.

8.2.5.1 Application

On large projects where sludge must be transported a significant distance, such as to a separate plant for processing, a reduction in sludge volume will result in a reduction in pipe size and pumping costs. Volume reduction is very desirable when liquid sludge is transported by tank trucks for direct application to land as a soil conditioner. In treatment plants with less than 140 m^3/hour capacity, separate sludge thickening may not be required. In small plants, gravity thickening is accomplished in the primary settling tank or in the sludge digestion units, or both.

8.2.5.2 Methods of Application

The following thickening methods can be used depending on the type of sludge (see Table 8.9):

- gravity
- dissolved air flotation
- imperforate basket centrifuge
- solid bowl centrifuge
- gravity belt thickener
- rotary drum thickener.

For gravity thickening, a circular tank should be used. Provisions for dilution water and occasional chlorine addition should be included to improve process performance.

For flotation, only dissolved air flotation should be used. Higher loadings can be used with flotation thickeners than are permissible with gravity thickeners because of the rapid separation of solids from the wastewater.

Table 8.8 *Expected sludge concentrations from various treatment operations and processes.*

Operation or process application	Sludge solids concentration, % dry solids	
	Range	Typical
Primary settling tank		
Primary sludge	4.0–10.0	5.0
Primary sludge to a cyclone	0.5–3.0	1.5
Primary and waste-activated sludge	3.0–8.0	4.0
Primary sludge and trickling-filter humus	4.0–10.0	5.0
Primary sludge with iron addition for phosphorus removal	0.5–3.0	2.0
Primary sludge with low lime addition for phosphorus removal	2.0–8.0	4.0
Primary sludge with high lime addition for phosphorus removal	4.0–16.0	10.0
Scum	3.0–10.0	5.0
Secondary settling tank		
Waste-activated sludge with primary settling	0.5–1.5	0.8
Waste-activated sludge without primary settling	0.8–2.5	1.3
High-purity oxygen-activated sludge with primary settling	1.3–3	2
High-purity oxygen-activated sludge without primary settling	1.4–4	2.5
Trickling-filter humus sludge	1–3	1.5
Rotating biological contractor waste sludge	1–3	1.5
Gravity thickener		
Primary sludge only	5–10	8
Primary and waste-activated sludge	2–8	4
Primary sludge and trickling-filter humus	4–9	5
Dissolved-air flotation thickener (waste-activated sludge only)	4–6	5
Dissolved-air flotation thickener (with chemical addition)	3–5	4
Centrifuge thickener (waste-activated sludge only)	4–8	5
Gravity belt thickener (waste-activated sludge only with chemical addition)	3–6	5
Anaerobic digester		
Primary sludge only	5–10	7
Primary and waste-activated sludge	2.5–7	3.5
Primary sludge and trickling-filter humus	3–8	4
Aerobic digester		
Primary sludge only	2.5–7	3.5
Primary and waste-activated sludge	1.5–4	2.5
Waste-activated sludge only	0.8–2.5	1.3

Table 8.9 *Occurrence of thickening methods in sludge processing.*

Method	Type of sludge	Frequency of use and relative success
Gravity	Untreated primary	Commonly used with excellent results. Sometimes used with hydroclone degritting of sludge.
Gravity	Untreated primary and waste activated sludge	Often used. For small plants, generally satisfactory results with sludge concentrations in the range of 4–6%. For large plants, results are marginal.
Gravity	Waste-activated sludge	Seldom used; poor solids concentration (2–3%).
Dissolved-air flotation	Untreated primary and waste-activated sludge	Some limited use; results similar to gravity thickeners.
Dissolved-air flotation	Waste-activated sludge	Commonly used; good results (3.5–5% solids concentration).
Imperforate basket centrifuge	Waste-activated sludge	Limited use; excellent results (8–10% solids concentration).
Solid bowl centrifuge	Waste-activated sludge	Increasing; good results (4–6% solids concentration).
Gravity belt thickener	Waste-activated sludge	Increasing; good results (3–6% solids concentration).
Rotary drum thickener	Waste-activated sludge	Limited use; good results (5–9% solids concentration).

8.2.5.3 Design Considerations

- In designing thickening facilities, it is important to provide adequate capacity to meet peak demands and prevent septicity, with its attendant odor problems, during the thickening process.
- To maintain aerobic conditions in gravity thickeners, provisions should be made for adding 24–30 m^3/m^2/day of final effluent to the thickening tank.
- Minimum solids loadings should be used to design thickeners.
- The use of polymers as flotation aids is effective in increasing the solids recovery in the floated sludge and in reducing the recycle loads.

8.3 Stabilization

Sludges are stabilized to reduce pathogens, eliminate offensive odors, and inhibit, reduce, or eliminate the potential for putrefaction. The means to eliminate the nuisance conditions through stabilization such as the following facilities should be taken into consideration.

a) the biological reduction of volatile content
b) the chemical oxidation of volatile matter
c) the addition of chemicals to the sludge to render it unsuitable for the survival of microorganisms
d) the application of heat to disinfect or sterilize the sludge.

8.3.1 Design Considerations

When designing a sludge stabilization process, the following factors have to be taken into consideration:

a) the quality of the sludge to be treated
b) the integration of the stabilization process with the other treatment units
c) the objectives of the stabilization process.

The following sludge stabilization processes should be considered and the technology that best conforms with the appropriate environmental regulations should be selected:

a) lime stabilization
b) heat treatment
c) anaerobic sludge digestion
d) aerobic sludge digestion
e) composting.

8.3.2 Lime Stabilization

- Sufficient lime should be added to untreated sludge to raise the pH to 12 or higher. The methods used should be evaluated for proper placement of lime injection.
- The minimum criteria for lime stabilization in the lime pre-treatment method is to maintain the pH above 12 for about two hours so as to ensure pathogen destruction and to provide enough residual alkalinity so that the pH does not drop below 11 for several days.
- Testing should be performed for specific applications to determine the actual dosage requirements.
- Because lime stabilization does not destroy the organic necessary for bacteria growth, the sludge must be treated with an excess of lime or disposed of before the pH drops significantly. An excess dosage of lime may range up to 1.5 times the amount needed to maintain the initial pH of 12.
- Post-lime stabilization has several significant advantages when compared to pre-lime stabilization:
  a) dry lime can be used, therefore no additional water is added to the dewatered sludge
  b) there are no special requirements for dewatering
  c) scaling problems and associated maintenance problems of lime sludge dewatering equipment are eliminated.

Adequate mixing should be provided for a post-lime stabilization system so as to avoid pockets of putrescible material.

8.3.3 Heat Treatment

Heat treatment, which is classified also as conditioning process, should be designed for continuous processing and should consider heating of the sludge in a pressure vessel to temperatures up to 260 °C at pressures up to 2760 kPa (gauge) for short periods of time

(approximately 30 minutes). The heat treatment process is most applicable to biological sludges that may be difficult to stabilize or condition by other means.

The advantages of heat treatment are:

a) the solids content of the dewatered sludge can range from 30% to 50%, depending on the degree of oxidation achieved
b) the processed sludge does not normally require chemical conditioning
c) the process stabilizes sludge and will destroy most pathogenic organisms
d) the processed sludge will have a heating value of 28–30 kJ/g of volatile solids
e) the process is relatively insensitive to changes in sludge composition.

The major disadvantages are:

a) high capital cost
b) close supervision, skilled operators, and a strong preventative maintenance program are required
c) the process produces sidestreams with high concentrations of organic, ammonia nitrogen, and color
d) significant odorous gases are produced that require extensive containment, treatment, and/or destruction
e) scale formation in the heat exchangers, pipes, and reactor requires acid washing or high pressure water jets.

8.3.4 Anaerobic Sludge Digestion

The following processes can be investigated for proper process selection based on the sludge concentration, rate, and characteristics:

a) Standard-rate digestion
b) single-stage high-rate digestion
c) two-stage digestion
d) separate sludge digestion.

The design should be based on:

a) the concept of mean cell residence time
b) the use of volumetric loading factors
c) observed volume reduction
d) loading factors based on population.

Anaerobic digester design data are given in Table 8.10.

The advantages of aerobic digestion are:

- simplicity of operation and maintenance
- lower capital costs
- lower biochemical oxygen demand (BOD) and total phosphorous in the supernatant
- few effects from loading, pH, and toxic interference
- insignificant odors
- non-explosive
- reduces grease and hexane solubles

Table 8.10 *Anaerobic digester design data.*

Parameter	Value
Number of tanks	Multiple desired
Solids retention time – mesophilic	20–60 d
Solids retention time – thermophilic	10–20 d
Temperature – mesophilic	10–35 °C
Temperature – thermophilic	38–60 °C
Volume allowance	0.001–0.01 m^3/capita/day
Volatile suspended solids loading	0.64–6.4 kg/m^3/day
pH range	6.6–7.6
Digested sludge solids concentration	4–6%

- better sludge fertilizer
- shorter retention periods
- excellent small plant alternative.

The disadvantages of aerobic digestion are:

- higher operating costs
- highly sensitive to ambient temperature
- no useful by-products
- variable dewaterability
- lower volatile solids reduction
- questionable economics for larger plants.

Aerobic digester design data are given in Table 8.11.

Table 8.11 *Aerobic digester design data.*

Parameter	Value
Number of tanks	Multiple desired
Solids retention time at 20 °C – primary sludge	15–20 day
Solids retention time at 20 °C – primary and activated sludge or trickling filter sludge	15–20 day
Solids retention time at 20 °C – waste-activated sludge only	10–15 day
Solids retention time at 20 °C – waste-activated sludge without primary settling	12–18 day
Volume allowance	0.8–0.11 m^3/capacity/day
Volatile suspended solids loading	0.32–2.24 kg/m^3/day
Minimum dissolved oxygen	1–2 mg/l
Oxygen requirements – destroy cell tissue	2 : 1
Oxygen requirements – reduce primary sludge	1.6 : 1–1.9 : 1
Diffusion aeration – waste-activated sludge only	20–30 m^3/min/1000 m^3
Diffusion aeration – mixed or other sludges	Over 60 m^3/min/1000 m^3
Mechanical aeration	20–40 kW/1000 m^3

8.3.5 Composting

The composting process involves the complex destruction of organic material coupled with the production of humic acid to produce a stabilized end product.

The main types of composting systems used are the aerated static pile, window, and in-vessel (enclosed mechanical) systems. Aerated static pile is preferred.

The compost mix should be at least 40% dry solids to ensure adequate composting.

The following important factors should be determined/clarified in the design of a composting system:

- type of sludge
- amendments and bulking agents
- carbon:nitrogen ratio
- volatile solids
- air requirements
- moisture content
- pH
- temperature
- mixing and turning
- heavy metals and trace organic
- site constraints.

8.4 Conditioning

Sludge should be conditioned to improve its dewatering characteristics if required. Based on the economical and technical evaluation of the conditions, a suitable conditioning method such as addition of chemicals, heat treatment, irradiation, or solvent extraction should be used. The heat treatment process is most applicable to biological sludges that may be difficult to stabilize or condition by other means.

Intimate admixing of sludge and coagulant should be made in the chemical conditioning process for proper conditioning.

The mixing must not break the floc after it has formed, and the detention should be kept to a minimum so that sludge reaches the dewatering unit as soon after conditioning as possible.

8.5 Disinfection

The following methods may be used to achieve pathogen reduction beyond that attained by stabilization:

a) pasteurization
b) other thermal processes such as heat conditioning, heat drying, incineration, pyrolysis, or starved air combustion
c) high pH treatment, typically with lime, at a pH higher than 12.0 for three hours
d) long-term storage of liquid digested sludge

e) complete composting at temperatures above 55 °C and curing in a stockpile for at least 30 days
f) addition of chlorine to stabilize and disinfect sludge
g) disinfection with other chemicals
h) disinfection by high-energy irradiation.

Storage should be taken into consideration in land application systems to retain sludge during periods when it cannot be applied because of weather or crop considerations. Because of the potential contamination effects of the stored sludge, special attention must be devoted to the design of these lagoons with respect to limiting percolation and the development of odors.

8.6 Dewatering

Dewatering is a mechanical (physical) unit operation used to reduce the moisture content of sludge for one or more of the following reasons:

a) The costs of trucking sludge to the ultimate disposal site become substantially lower when sludge volume is reduced by dewatering.
b) Dewatered sludge is generally easier to handle than thickened or liquid sludge. In most cases, dewatered sludge may be shoveled, moved about with tractors fitted with buckets and blades, and transported by belt conveyors.
c) Dewatering is required normally prior to the incineration of the sludge to increase the energy content by removal of excess moisture.
d) Dewatering is required before composting to reduce the requirements for supplemental bulking agents or amendments.
e) In some cases, removal of the excess moisture may be required to render the sludge odorless and non-putrescible.
f) Sludge dewatering is required prior to landfilling in monofills to reduce leachate production at the landfill site.

8.6.1 Sludge Dewatering Methods

Dewatering methods and their advantages and disadvantages are presented in Table 8.12.

The dewatering device should be determined by the type of sludge to be dewatered, the characteristics of the dewatered product, and the space available. Some sludges, particularly aerobically digested sludges, are not amenable to mechanical dewatering. Selection of the optimum dewatering device should be made by conducting bench scale or pilot studies.

8.6.2 Vacuum Filtration

The solids content of the feed should be 6–8%. Higher solids contents make the sludge difficult to distribute and condition for dewatering; lower solids contents require the use of larger than necessary vacuum filters.

Table 8.12 *Comparison of alternative sludge-dewatering methods.*

Dewatering method	Advantages	Disadvantages
Vacuum filter	• Skilled personnel not required • Maintenance requirements are low for continuously operating equipment	• Highest energy consumer per unit of sludge dewatered • Continuous operator attention required • Vacuum pumps are noisy • Filtrate may have high suspended solids content, depending on filter medium
Solid bowl centrifuge	• Clean appearance, minimal odor problems • Fast startup and shutdown capabilities • Easy to install, produces relatively dry sludge cake • Low capital cost-to-capacity ratio	• Scroll wear potentially a significant maintenance problem • Requires grit removal and possibly a sludge grinder in the feed stream • Skilled maintenance personnel required • Moderately high suspended-solids content in centrate
Imperforate basket centrifuge	• Same machines can be used for both thickening and dewatering • Chemical conditioning may not be required • Clean appearance, minimal odor problems • Fast startup and shutdown capabilities • Very flexible in meeting process requirements • Not affected by grit • Excellent results for difficult sludges	• Limited size capacity • Except for vacuum filters, consumes more energy per unit of sludge dewatered • Skimming stream may produce significant recycle load for easily dewatered sludges • Has highest capital cost-to-capacity ratio
Belt filter press	• Low energy requirements • Relatively low capital and operating costs • Less complex mechanically and easier to maintain • High-pressure machines are capable of producing very dry cake • Minimal effort required for system shutdown	• Hydraulically limited in throughput • Requires sludge grinder in feed stream • Very sensitive to incoming sludge feed characteristics • Short media life as compared to other devices using cloth media • Automatic operation generally not advised

Table 8.12 (continued)

Dewatering method	Advantages	Disadvantages
Recessed plate filter press	• Highest cake solids concentration • Low suspended solids in filtrate	• Batch operation • High equipment cost, high labor cost • Special support structure requirements • Large floor area required for equipment • Skilled maintenance personnel required • Additional solids due to large chemical addition require disposal
Sludge drying beds	• Lowest capital cost method where land is readily available • Small amount of operator attention and skill required • Low energy consumption • Low to no chemical consumption • Less sensitive to sludge variability • Higher solids content than mechanical methods	• Requires large area of land • Requires stabilized sludge • Design requires consideration of climatic effects • Sludge removal is labor intensive
Sludge lagoons	• Low energy consumption • No chemical consumption • Organic matter is further stabilized • Low capital cost where land is available • Least amount of skill required for operation	• Potential for odor and vector problems • Potential for groundwater pollution • More land intensive than mechanical methods • Appearance may be unsightly • Design requires consideration of climatic effects

In addition to the disadvantages listed in Table 8.6 the following factors should also be taken into consideration for selection of this type of dewatering equipment:

a) system complexity
b) the need for conditioning chemicals
c) high operating and maintenance costs.

8.6.3 Centrifugation

The centrifugation process is widely used in the wastewater industry for separating liquids of different density, thickening slurries, or removing solids.

Disposal of centrate to wastewater influent should be avoided. Before final design decision making, pilot plant tests should be run. Special consideration must be given to providing sturdy foundations and sound-proofing because of the vibration and noise that result from centrifuge operation.

8.6.4 Belt Filter Press

Belt filter presses are continuous-feed sludge dewatering devices that involve the application of chemical conditioning, gravity drainage, and mechanically applied pressure to dewater sludge. Belt filter presses can be applied to all types of wastewater sludge.

Sludge blending facilities should be included in the system design where the sludge characteristics are likely to vary widely.

Safety considerations in design should include adequate ventilation to remove hydrogen sulfide or other gases and equipment guards to prevent loose clothing from being caught between the rollers.

8.6.4.1 Filter Presses

In a filter press, dewatering is achieved by forcing the water from the sludge under high pressure. The advantages of this dewatering equipment include:

a) high concentrations of cake solids
b) filtrate clarity
c) high solids capture.

Disadvantages include:

d) mechanical complexity
e) high chemical costs
f) high labor costs
g) limitations on filter cloth life.

The following filter press types are preferred:

a) fixed-volume, recessed plate filter press
b) variable-volume, recessed plate filter press (diaphragm press).

The following features should be considered in the design of a filter press facility:

a) adequate ventilation in the dewatering room
b) high-pressure washing system
c) an acid wash circulating system to remove calcium scale when lime is used
d) a sludge grinder ahead of the conditioning tank
e) cake breakers or shredders following the filter press (particularly if the dewatered sludge is incinerated)
f) equipment to facilitate removal and maintenance of the plates.

8.6.5 Sludge Drying Beds

Sludge drying beds are typically used to dewater digested sludge. After drying, the sludge is removed and either disposed of in a landfill or used as a soil conditioner.

The principal advantages of drying beds are low cost, infrequent attention required, and high solids content in the dried product.

The following types of drying beds may be used:

a) conventional sand
b) paved (drainage or decanting)
c) artificial media
d) vacuum assisted.

Conventional sand drying beds are preferred.

Open beds may be used where an adequate area is available and is sufficiently isolated to avoid complaints caused by occasional odors. Open sludge beds should be located at least 100 m from dwellings to avoid odor nuisance. Covered beds with greenhouse types of enclosures should be used where it is necessary to dewater sludge continuously throughout the year regardless of the weather and where sufficient isolation does not exist for the installation of open beds.

In cold climates, the effects of freezing and thawing should be considered to improve the dewatering characteristics of sludge.

8.6.6 Lagoons

Drying lagoons may be used as a substitute for drying beds for the dewatering of digested sludge, if permitted by company. Lagoons should not be used for dewatering untreated sludges, limed sludges, or sludges with a high-strength supernatant because of their odor and nuisance potential.

Environmental and groundwater regulations should be considered in the application of lagoons. If a groundwater aquifer used for a potable water supply underlies the lagoon site, it will be necessary to line the lagoon.

Sludge should be discharged to the lagoon in a manner suitable to accomplish an even distribution of sludge. Facilities for decanting of supernatant should be provided, and the liquid should be recycled to the treatment facility.

A minimum of two cells should be provided, even in very small plants, to ensure availability of storage space during cleaning, maintenance, or emergency conditions.

8.7 Heat Drying

Sludge drying is a unit operation that involves reducing water content by vaporization of water to the air. Drying is necessary in fertilizer manufacturing to permit the grinding of the sludge, to reduce its mass, and to prevent continued biological action. The moisture content of the dried sludge should be less than 10%.

The following mechanical processes may be used for drying sludge:

a) flash dryers
b) spray dryers
c) rotary dryers
d) multiple-hearth dryers
e) multiple-effect evaporation.

Sludge dryers are normally preceded by dewatering. Flash dryers are preferred for use in wastewater treatment plants.

The heat recovered from the dried sludge should be used (if possible) to supply the energy requirements of the process.

Fly ash and odor control should be considered in heat drying of sludge.

8.8 Thermal Reduction

Thermal reduction of sludge involves the total or partial conversion of organic solids to oxidized end products, primarily carbon dioxide and water, by incineration or wet-air oxidation or the partial oxidation and volatilization of organic solids by pyrolysis or starved-air combustion to end products with energy content. Thermal reduction processes are used by medium to large sized plants with limited ultimate disposal options.

The major advantages of thermal reduction are:

- maximum volume reduction, thereby lessening the disposal requirements
- destruction of pathogens and toxic compounds
- energy recovery potential.

The major disadvantages are:

- high capital and operating cost
- highly skilled operating and maintenance staff are required
- the residuals produced (air emissions and ash) may have adverse environmental effects
- disposal of residuals, which may be classified as hazardous wastes, may be uncertain and expensive.

8.8.1 Thermal Reduction Process Applications

8.8.1.1 Multiple-hearth incineration

Multiple-hearth incineration is used to convert dewatered sludge cake to an inert ash. This process is normally used only in large plants or in small plants where land for disposal of sludge is limited, and in chemical treatment plants for the recalcining of lime sludges.

Feed sludge must contain more than 15% solids because of limitations on the maximum evaporating capacity of the furnace. Auxiliary fuel should be provided.

In addition to dewatering, the required ancillary processes should include ash-handling systems.

8.8.1.2 Fluidized-bed incineration

The fluidized bed incinerator commonly used for sludge incineration is a vertical, cylindrically shaped refractory. It has a lined steel shell that contains a sand bed and fluidized air orifices to produce and sustain combustion. The applications of fluidized-bed process are similar to those of multiple-hearth incineration.

8.8.1.3 Co-incineration

The major objective of co-incineration is to reduce the combined costs of incinerating sludge and solid wastes. The process has the advantages of producing the heat energy

necessary to evaporate water from sludges, supporting the combustion of solid wastes and sludge, and providing an excess of heat for steam generation, if desired, without the use of auxiliary fossil fuels.

8.8.1.4 Wet-air oxidation

This process involves wet oxidation untreated sludge at an elevated temperature and pressure. A major disadvantage associated with this process is the high-strength recycle liquor produced. The liquors represent a considerable organic load on the treatment system.

8.8.1.5 Wet oxidation in a vertical deep-well reactor

This process consists of discharging liquid sludge in the pressure- and temperature-controlled environment of a tube-and-shell reactor suspended within a deep well. The advantages of this process are:

a) small space requirements
b) high removal of suspended solids and organic matter
c) few odors or objectionable air emissions
d) low energy requirements because the process is exothermic.

The principal disadvantages are that it does not have a long history of operation and maintenance, and skilled operators are required for process control.

8.9 Land Application of Sludge

The following steps should be evaluated for development of a sludge land application system:

a) characterization of sludge quantity and quality
b) review of pertinent federal, state, and local regulations
c) evaluation and selection of site and disposal option
d) determination of process design parameters such as loading rates, land area requirements, application methods, and scheduling.

The following factors should be considered in evaluation of the sludge characteristics:

- organic content (usually measured as volatile solids)
- nutrients
- pathogens
- metals
- toxic organic.

If regulations require, detailed sampling and analysis of sludge should be made to identify and characterize the sludge constituents to determine if the sludge is suitable for land application. Maximum annual loading rates should be prescribed as well as permissible cumulative loading rates, depending on whether the land is used for agricultural or non-agricultural purposes.

Sludge applied to the land surface or incorporated into the soil must be treated by a process to significantly reduce pathogens (PSRP). Sludge applied to land where crops for human consumption are grown must be treated by a process to further reduce pathogens

(PFRP). Examples of a PSRP stabilization process are aerobic digestion, air drying, anaerobic digestion, composting, and lime stabilization. Examples of a PFRP stabilization processes are composting, heat drying, and thermophilic aerobic digestion.

For site selection and evaluation the following factors should be taken into consideration:

- land application option(s) such as application to agricultural lands, forest lands, etc.
- topography
- soil permeability
- site drainage
- depth to groundwater
- subsurface geology
- proximity to critical areas
- accessibility
- maximum sludge loading rates based on the pollutant limits set forth in regulatory guidelines or by the nutrient loading rates necessary to meet vegetation requirements.

Application of sludge in the liquid state is attractive and dewatering processes are not required in this case. Liquid sludge may be applied to land by vehicle or by irrigation methods.

Liquid sludge can be injected below the soil surface by using tank wagons or tank trucks with injection shanks, or it can be incorporated immediately after the surface application by using plows or discs equipped with sludge distribution manifolds and covering spoons.

Special attention should be given to minimization of potential odors and vector attraction, minimization of ammonia loss due to volatilization, elimination of surface runoff, and minimum visibility leading to better public acceptance.

8.10 Chemical Fixation

The chemical fixation/solidification process is applied to the treatment of industrial sludge and hazardous wastes to immobilize undesirable constituents. Stabilized sludge may also be disposed of in landfills.

The chemical fixation process consists of mixing untreated or treated liquid or dewatered sludge with stabilizing agents such as cement, sodium silicate, pozzolan (fine-grained silicate), and lime so as to chemically react with or encapsulate the sludge. The process may generate a product with a high pH, which inactivates the pathogenic bacteria and viruses.

8.11 Gathering Contaminant-Specific Information

In addition to release-related and site-related information, a site assessment should include knowing the physical and chemical properties of the contaminants released. To a large extent, contaminant properties govern partitioning in the subsurface, what phase(s) it is likely to reside in, how it is likely to move away from the site, and whether it is likely to degrade significantly over time.

Table 8.13 lists contaminant-specific data that are needed to conduct a site assessment. To illustrate, assume the liquid density of gasoline is needed. The user can locate the liquid

Table 8.13 *Factors to evaluate the mobility of contaminants in pore water.*

Factor	Units	Increasing mobility (→)		
		Site-related		
Hydraulic conductivity	cm/s	Low ($<10^{-5}$)	Medium (10^{-5}–10^{-3})	High ($>10^{-3}$)
Moisture content	% volume	Low (<10)	Medium (10–30)	High (>30)
Rainfall infiltration rate	cm/day	Low (<0.05)	Medium (0.05–0.1)	High (>0.1)
Soil porosity	% volume	Low (<10)	Medium (10–30)	High (>30)
Rock fractures	—	Absent	—	Present
Depth blow surface	m	Shallow (<2)	Medium (2–10)	Deep (>10)
		Contaminant-related		
Water solubility	mg/l	Low (<100)	Medium (100–1000)	High (>1000)

Table 8.14 *Fluid properties.*

Fluid	Approximate density (kg/m^3) at 15 °C and 1 bar	Approximate vapor pressure (bar [abs]) at 0 °C
Crude oil, heavy	875–1000	0.3
Fuel oil	920–1000	0.01
Gas oil/diesel	850	0.01
Crude oil, light	700–875	0.55
Kerosene/naphtha/gasoline	700–790	0.01–1.2
NGL (condensate)	600–700	0.1–1
LPG	500–600	0.2–1.5
LNG	420	4–6
Ethylene	1.6	
Natural gas	1.1	
Sour natural gas (>0.5% H_2S)	1.1	

LPG, liquified petroleum gas; LNG, liquified natural gas.

density in Table 8.13 and find the default source in Table 8.14. Moving to Table 8.14, the typical value for automotive gasoline in the liquid density column is 0.73 g/cm^3.

The hydraulic conductivity of soil directly affects a contaminant's mobility or ability to move away from the release site in the non-aqueous phase liquid (NAPL) and dissolved phases.

A high rainfall infiltration rate can cause contamination to move from one phase to another. Some hydrocarbons will dissolve in the infiltrating rainwater, reducing the residual liquid portion of the contamination while increasing the amount of contaminant dissolved in pore water.

Soil temperature should also affect contaminant mobility and vapor pressure, and therefore the ease with which contaminants move into air spaces in soil increases with increasing temperature.

8.12 Evaluating Contaminant Mobility

The mobility of the contaminants in a site assessment focuses on unsaturated zone and also between phases. Many in situ corrective actions depend on mobilizing contaminants.

The factors that control the mobility of contaminants differ for each phase are:

a) Residual liquid contaminant: The movement of bulk liquids in the unsaturated zone is dominated by three factors:
   1) Gravity: Where exerts a direct downward force, the magnitude of which depends only on the density of the contaminant.
   2) Pressure gradients: Where generally result from infiltrating liquid (precipitation and contaminants), and most often act in the same direction as gravity.
   3) Capillary suction: Where depends on the soil characteristics and the forces it generates act in all direction, although not equally.

   In addition to these three major forces, other physical, chemical, and environmental factors can influence a liquid's mobility in the unsaturated zone.
b) Contaminant vapors: Vapors are generally mobile in the unsaturated zone. The degree of mobility greatly depends on the air-filled porosity of the soil. Several other factors also influence vapor transport in the unsaturated zone as listed in. Contaminant vapors may be mobilized by several natural or induced processes or forces:
   1) bulk transport due to pressure gradients
   2) bulk transport due to vapor density gradients
   3) in situ generation of gases or vapors
   4) molecular diffusion due to concentration gradients.

   Vapor density differences are important only when liquid contaminant of sufficient volatility is present. For example, the density of air saturated with gasoline vapors (i.e. in contact with liquid gasoline) is about 1950 g/m^3 at 20 °C and moist air has a density of about 1200 g/m^3 at 20 °C. In the absence of other driving forces, heavier (contaminant containing) vapors should tend to migrate downward in the unsaturated zone. The driving force (density difference) will diminish as the vapors become more diluted.
c) Contaminant dissolved in pore water: Table 8.13 lists factors that can help to determine the relative mobility of contaminants dissolved in pore water in the unsaturated zone. As with Table 3.3, the site-related factors in Table 8.5 may vary with depth. If information about the soil profile is available, this can be completed for each distinct soil group. Otherwise, a best estimate of actual conditions must be made to complete the preliminary assessment.

8.13 Technology Selection

Five technologies are used to determine UST sites:

a) soil venting
b) biorestoration
c) soil flushing

d) hydraulic barriers
e) excavation.

8.13.1 Soil Venting

Soil venting is a general term that refers to any technique that removes contaminated vapors from the unsaturated zone. Venting may be passive or active. Passive venting is usually used for removal of methane gas.

Active venting uses an induced pressure gradient to move vapor through the soil and is more effective than passive venting.

8.13.2 Biorestoration

In situ biorestoration of the unsaturated zone is a process where oxygen and nutrients are added to contaminated soil to promote the breakdown of contaminants (see Figure 8.2). In some cases, specially acclimated, commercially available bacteria may also be introduced to the subsurface, but this is not a common procedure. Bacteria capable of biodegrading petroleum hydrocarbons are commonly found in subsurface soils. Natural breakdown of petroleum hydrocarbons is likely to occur whenever they are introduced to the subsurface, but without the addition of nutrients and oxygen biodegradation occurs very slowly.

8.13.3 Soil Flushing

Soil flushing refers to the in situ process where the zone of contamination is flooded with water or a water/surfactant mixture in order to dissolve the contaminants into the water or otherwise mobilize the residual contaminant to the water table.

The contaminants are then brought to the surface for treatment by strategically placed extraction wells. The wells must be located such that the groundwater is completely controlled hydraulically to ensure that the leached or mobilized contaminants do not escape once they reach the groundwater. Figure 8.3 shows a schematic diagram of a soil flushing system.

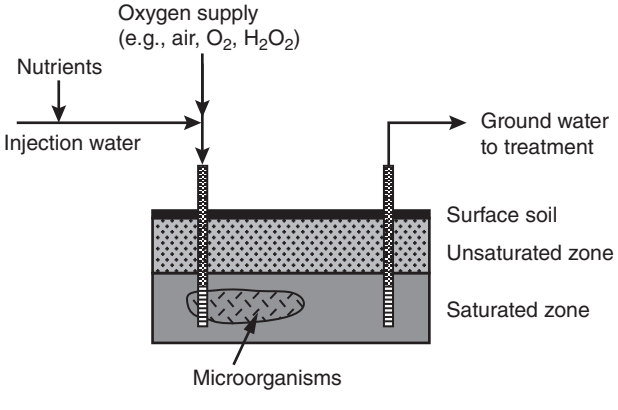


Figure 8.2 *A bioremediation system.*

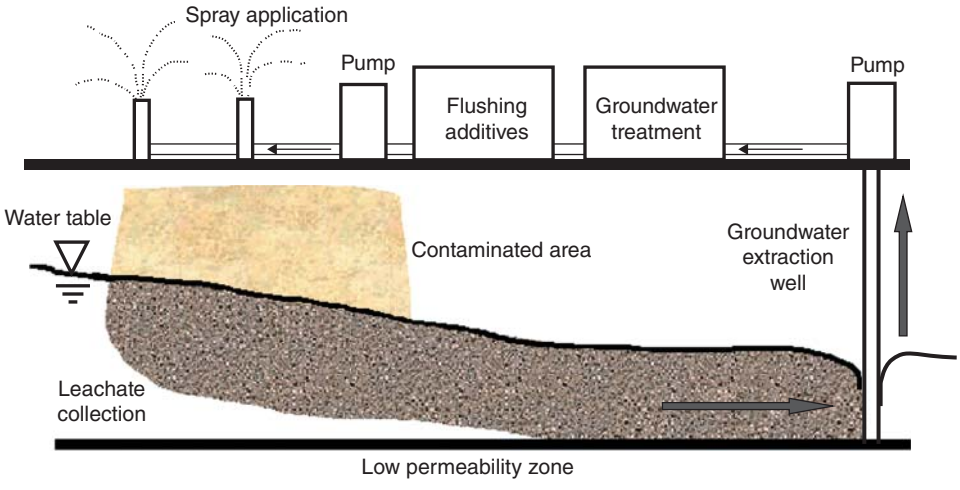


Figure 8.3 *A soil flushing system. Source: FRTR.*

One soil flushing method removes contaminants by using water to dissolve the liquid, sorbed, or vapor contaminants. These processes are controlled by the contaminant solubilities and Henry's law constants.

A second soil flushing method mobilizes contaminants existing as free product in the soil pores and adsorbed to the soil. Contaminants found in these phases can be mobilized by the pressure gradient of the infiltrating flushing water.

The viscosity and density of contaminants control the extent to which a compound may be mobilized as free product. This type of soil flushing is expected to remove a greater portion of gasoline than heating oil or #6 fuel oil because gasoline is less viscous than either of the other two petroleum products. Many of the constituents of gasoline are also more soluble than those of #6 fuel oil or heating oil and would be more readily mobilized in the dissolved phase as well.

8.13.4 Hydraulic Methods

Typically a trench is dug into the contaminated soil and residual liquid will began to seep into the trench. An impervious layer can be placed at the base of the trench to prevent re-infiltration of the product. As the product accumulates, it can be pumped out or removed manually, maintaining a gradient which facilitates further seepage into the trench.

8.13.5 Excavation

Excavation is an alternative to in situ treatment methods. Excavation soil may be treated off site or disposed of (land field) without treatment. Treated soil is sometimes placed back in the excavation at the site. At present, excavating contaminated soil is more common than in situ treatment. Excavation, however, has many drawbacks not faced by in situ methods as follows:

a) Excavating contaminated soils allows uncontrolled release of contaminant vapors to the atmosphere, increasing exposure risks.
b) Above- and below-ground structures, buried utility lines, sewers, and water mains, and buildings can pose real problems if contamination extends near or below the structures.
c) Above-ground treatment methods tend to be more expensive than in situ methods.
d) Disposal of contaminated soil is becoming increasingly difficult, and in some regulatory regions the soil is considered a hazardous waste.
e) A source of backfill is required to fill the excavation.

Excavation is a well-known technique and it has the ability to remove most or all of the contamination from the site.

8.14 Saturated Zone

The saturated zone is defined as the zone below the ground surface in which all pore spaces are filled with water. Petroleum products reaching the saturated zone are subject to greatly increased mobility of the contaminant, particularly in the horizontal direction. Mobilization of the contaminants increases the magnitude of clean-up efforts and the opportunity for liability.

8.15 Site Assessment

After emergency measures have been accomplished at a site, the first step in a remediation plan should be to gain a general view of conditions at the site. A preliminary investigation should always be carried out before any sampling or analysis is specified. The aim of a preliminary investigation should be:

a) to check the likelihood of contamination, which may affect the suitability of the site for a specific use or any proposed future use
b) to identify whether any special procedures and precautions may need to be taken during operations
c) to provide the information from which an effective investigation of the site can be made.

8.15.1 Gathering Contaminant-Specific Information

Petroleum products are a mixture of many compounds. In general, remediation efforts are usually tied to one or more individual constituents, which should be targeted:

a) when the phase of contamination being evaluated is other than the original NAPL
b) if the mixture has weathered considerably
c) assessment on a compound that is thought to present the greatest potential threat
d) to design a treatment system.

The properties of the NAPL mixture should be targeted:

a) when the phase of contamination being evaluated is the original NAPL
b) to evaluate the physical movement of NAPL through the subsurface.

8.15.2 Evaluating the Contaminant Phase in the Saturated Zone

Petroleum products reaching the saturated zone will primarily be found in one of three phases:

1) NAPL
2) dissolved in groundwater
3) sorbed to soil particles.

If the release is large, almost all of the petroleum product will exist as NAPL, but over time a portion of the NAPL will transfer to the dissolved and sorbed phases.

If the release is small, all the NAPL may be trapped in the unsaturated zone.

8.15.2.1 Volume of Floating NAPL

Volume determinations of floating hydrocarbons are typically obtained by the following equation:

$$V_N = A_N T_N n \tag{8.1}$$

where

A_N = areal extent of the NAPL plume
T_N = average thickness of the NAPL plume
n = effective porosity of the soil formation.

NAPL thickness is fairly difficult to estimate accurately because the apparent thickness of the plume, as measured in a monitoring well, is typically greater than the true thickness. NAPL thickness will also vary throughout the plume, particularly if pumping wells are installed to contain the plume. Measuring plume thickness at several locations allows a better estimate of the average thickness.

A light non-aqueous phase liquid (LNAPL) is a groundwater contaminant that is not soluble and has a lower density than water

A dense non-aqueous phase liquid (DNAPL) is a liquid that is both denser than water and immiscible in or does not dissolve in water.

The term DNAPL is used primarily by environmental engineers and hydrogeologists to describe contaminants in groundwater, surface water, and sediments. DNAPL tends to sink below the water table when spilled in significant quantities and only stop when they reach impermeable bedrock. Their penetration into an aquifer makes them difficult to locate and remediate.

Examples of materials that are DNAPL when spilled include:

- chlorinated solvents, such as trichloroethylene, tetrachloroethene, 1,1,1-trichloroethane and carbon tetrachloride
- coal tar
- creosote
- polychlorinated biphenyls (PCBs)
- mercury
- extra heavy crude oil, with an API gravity of less than 10.

When spilled into the environment, chlorinated solvents are frequently present as DNAPL and the DNAPs can provide a long-term secondary source of the chlorinated solvent to dissolved groundwater plumes. Chlorinated solvents are typically immiscible in water, having low solubility in water by definition, yet still have a solubility above the concentrations allowed by drinking water protections.

Therefore, DNAPL which is a chlorinated solvent can act as an ongoing pathway for constituents to dissolve into groundwater. Common use of chlorinated solvents in manufacturing operations began during World War II, with the rate of usage for most solvents increasing into the 1970s.

By the early 1980s, chemical analyses became available that documented the widespread contamination of groundwater with chlorinated solvents. Since that time, a considerable effort has been extended to improve our ability to locate and remediate DNAPL present as chlorinated solvents.

DNAPL that is not viscous, such as chlorinated solvents, tends to sink into aquifer materials below the water table and becomes much more difficult to locate and remediate than LNAPL, which tends to float at the water table when spilled into natural soils.

Once LNAPL infiltrates through the soil, it will stop at the height of the water table since the LNAPL is less dense than water. The effort to locate and remove LNAPL is relatively cheaper and easier than for DNAPL because LNAPL will float on top of the water in the underground water table.

Figure 8.4 illustrates the problem posed by the presence of LNAPL. It shows a monitoring well with a screen segment perforated (or slotted) to allow entry to the groundwater.

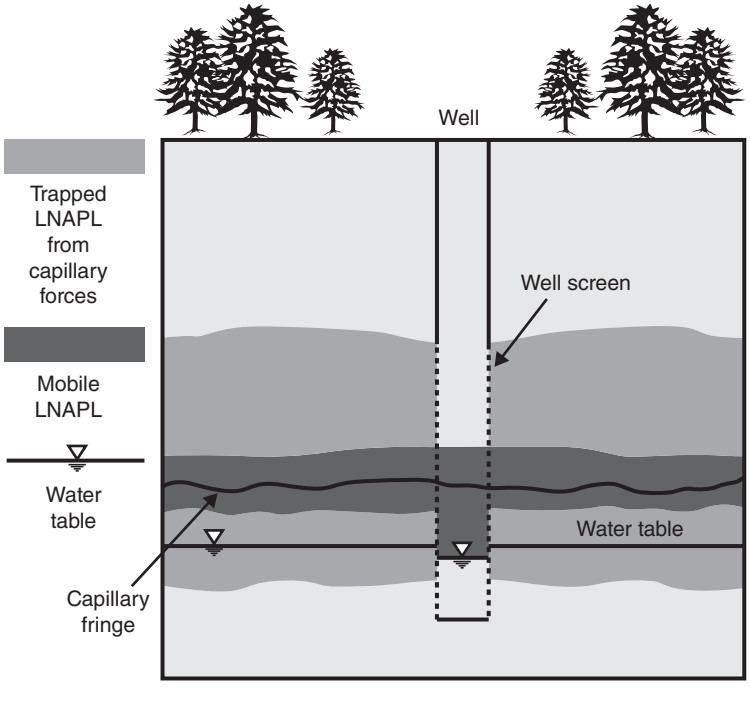


Figure 8.4 *The problem of the presence of LNAPL.*

The horizontal thick black line indicates the water table: If there were no LNAPL in the area, the water face inside the well would coincide with this line. However, the actual water face inside the well is depressed by the weight of the LNAPL that enters the well.

The next solid black line up is not horizontal. This is the capillary fringe. Without any LNAPL, this is the level in the soil to which the clear water would rise. The LNAPL resides on and presses down on the water in the capillary fringe. The dark-gray area is where enough LNAPL has accumulated to have mobility in the soil. The light-gray area is where LNAPL resides and is tied to the soil by capillarity. In this zone the LNAPL is not mobile.

The thickness of LNAPL in a monitoring well typically exceeds the thickness of the mobile LNAPL in the subsurface by a factor estimated to range between 2 and 10.

Due to this difference, the LNAPL thickness measured in a monitoring well is commonly referred to as the apparent thickness and is not an accurate measurement of the LNAPL thickness in the subsurface.

The monitoring well acts as a low point into which LNAPL drains. When LNAPL accumulates in the well, its weight depresses the water table in the well, resulting in additional LNAPL drainage into the well.

The difference between the actual and apparent LNAPL thickness increases with the increase in the capillary fringe, and the capillary fringe increases as the grain size of the formation gets smaller: the capillary fringe in silt is 1000 mm while in coarse grain sand it is only 125 mm.

The result is that in a silty formation, for example a 20-in. thick layer of petroleum inside a well, may represent a mere 2-in. layer of mobile petroleum in the formation, while in a coarse sand formation these same 20 in. inside the well may represent 10 in. in the formation.

Many studies have been performed to correlate LNAPL thickness in a monitoring well to actual LNAPL thickness. These studies have produced correlations that can be used to estimate the actual LNAPL thickness from apparent LNAPL thickness. However, these correlations may not be accurate under a variety of field conditions and typically produce only order-of-magnitude estimates.

It should be recognized that if LNAPL is detected in a monitoring well, it is unlikely to be as bad as it looks and that estimates of release volumes derived from measurements in wells should take this LNAPL relationship into consideration.

8.16 Evaluating Contaminant Mobility

Implementing an effective remedial technology for a saturated zone requires an understanding of how for the contaminants have traveled (vertically as well as horizontally) and the direction and velocity of plume movement.

8.16.1 Mass of Dissolved and Sorbed Contaminants in Groundwater

To estimate the mass of dissolved contaminants, the dissolved plume volume and average concentration must be known. This requires numerous samples from wells throughout the plume, both horizontally and vertically. Sorption of dissolved contaminants slows the center of mass of the plume relative to groundwater movement. This does not

mean that the dissolved contaminant velocity is less than that of groundwater. Rather, the dissolved concentrations at the front of the plume are lessened due to adsorption, causing the plume center of mass to move slower than groundwater flow. The liquid and dissolved contaminant phases are highly mobile while sorbed contaminants are relatively immobile.

8.16.2 Extent of Contaminant Plume

Since the NAPL and dissolved contaminant can move at different rates and in different directions in the subsurface, the two phases may need to be delineated separately. Delineation of the down-gradient and lateral extent of the plume is generally more important than of the up-gradient extent because movement in the up-gradient direction is generally limited.

Most petroleum products are less dense than water and will float on the water table in the bulk liquid phase. However, if denser than water, the contaminant will sink through the aquifer until it reaches an impermeable barrier. The areal extent of a denser than water contaminant plume is more difficult to estimate. Figure 8.5 shows a typical leaking underground tank with contaminant plume.

Floating product will move in the same general direction as groundwater, but movement of dense contaminants at the bottom of the aquifer is controlled by the grade of the impermeable barrier and may be different to groundwater movement. The flow direction of the denser than water bulk liquid is opposite to that of the groundwater, but the dissolved component travels with the groundwater.

If all the monitoring wells at a site are screened at or near the water table, they might not intercept a dissolved plume flowing deeper in the aquifer. Also, the entire dissolved plume may not be contained if the pumping rate is not adequate or recovery wells are not

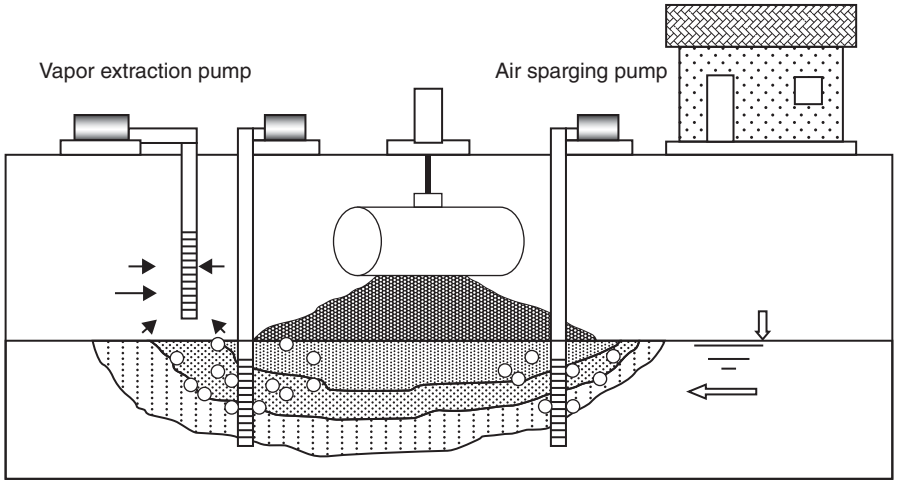


Figure 8.5 *A typical leaking underground tank with contaminant plume. Source: Reprinted with permission © Elsevier, F. Nadim* et al.*,* Journal of Petroleum Science and Engineering *26 (2000) 169–178.*

installed deep enough. A dissolved plume may exist relatively deep in the aquifer if the vertical component of groundwater flow is large. This is most prevalent at sites where the water table is relatively flat and the recharge rate is high. Infiltrating rainwater acts to "push" the plume down below the water table.

8.16.3 Mobility of Contamination in the Saturated Zone

The important factors that influence NAPL and dissolved products to move through the subsurface are:

a) subsurface stratigraphy, aquifer saturated thickness
b) local topography, location of nearby water bodies
c) location, depth, and pumping rates of nearby wells
d) regional and local groundwater flow direction(s), water table gradients (potentiometric head differences)
e) hydraulic conductivity of formation(s)
f) density and viscosity of the bulk product or its constituents.

The above data can be used to estimate how quickly and in what directions contaminant plumes will travel. Groundwater flow direction is important in predicting where a contaminant is likely to migrate, and with seasonal changes the water levels can affect flow patterns.

8.17 Setting Remediation Goals

An effective remediation plan should call for all phases of a clean-up. If the goal of remediation is to return the site to pre-release conditions, there are several typical clean-up phases that are likely to be implemented:

a) emergency responses are a first priority to ensure that no immediate health or safety threat exists
b) containment of the dissolved and NAPL contaminants limits the extent of contamination and facilitates restoration efforts
c) removal and/or treatment of subsurface contamination must be accomplished
d) a site monitoring program should be set up to detect any changes of incompletment restoration.

8.18 Technology Selection

There are a variety of ways to direct effort to a release of petroleum product into the environment. No immediate action is necessary for a full-scale remediation effort to restore the environment to pre-release conditions. A typical remediation plan that has restoration to pre-release conditions has three main components:

a) Containment of NAPL and/or dissolved product: Migration of contaminants can be prevented through trench excavation, which is effective only for containment of NAPL, and pumping wells which contain both NAPL and dissolved product.

b) NAPL removal: NAPL recovery is often accomplished in conjunction with either trench excavation or pumping well installation.
c) Dissolved product removal: Groundwater treatment methods can be either above ground or in situ. The above-ground methods are air stripping and carbon adsorption. In situ treatment is where contaminants are treated or removed without disturbing the subsurface or bringing groundwater above ground.

8.19 Dissolved Contaminants

Two methods are described here for preventing further migration of subsurface contaminants:

a) trench excavation
b) pumping well installation.

8.19.1 Trench Excavation

A very simple way to prevent migration of floating NAPL is to dig a trench down-gradient of the plume. As the NAPL reaches the trench, it can be intercepted, removed, and disposed of, thereby preventing migration beyond the trench.

At a minimum, implementing a trench excavation containment system requires the following information:

a) the direction of the plume
b) the depth to the water table
c) the down-gradient and lateral extent of the NAPL plume.

8.19.2 Pumping Well Installation

Pumping wells are an effective and commonly used method for containing a contaminant in the saturated zone. Unlike trenches, pumping wells are effective in containing dissolved contaminants and denser than water NAPL as well as floating NAPL. This method artificially lowers the water table at the site, drawing local groundwater and contaminants to the well.

The two most important considerations in this method are well location and pumping rate. To determine location and pumping rate, the site hydrogeology and vertical and areal extent of contamination must be known. Each pumping well has a zone of contribution (ZOC), within which local groundwater will flow toward the well. To prevent contaminant migration, the well configuration and pumping rate must be such that the contaminant plume is completely contained within the well's ZOC. If the contaminant plume is very large or soil conditions prevent adequate pumping rates, several wells may be required to fully contain the plume. Hydraulic conductivity due to complex stratigraphy varies for different types of formations and estimating the average hydraulic conductivity of such a site is difficult. The extent of the ZOC will therefore not be equal in all directions and could result in poor location of wells.

8.19.3 Recovery of Floating NAPL

Recovery of NAPL floating on the water table is a common part of site remediation when a release of petroleum products reaches the saturated zone. There are several methods used to recover floating NAPL. The most common of these uses is a pumping oil/water separation scheme, depending on the containment method implemented at the site and vacuum extraction. Some of these methods are described here.

- NAPL recovery with trench excavation: The two most common types of equipment used to recover NAPL from trenches are skimmers and filter separators. Skimmers float over the water surface and automatically pump NAPL off the water surface. Filter separators work much like skimmers except that the filter allows only petroleum product to pass through it.
- NAPL recovery with pumping well installation: The two main types of recovery systems involving pumping wells are single pump and dual pump systems. In a single pump system, one pump is used to both contain the plume and recover NAPL. For dual systems, one pump is used to create a depression in the water table and another to remove NAPL floating on water table.
- Vacuum extraction of floating NAPL: Vacuum extraction is more commonly associated with treatment of the unsaturated zone. As the NAPL floats on the water table some of the contaminant will transfer from the liquid phase to the vapor phase. The rate of natural volatilization depends primarily on the vapor pressure of the contaminants and the volume of air spaces in the soils above the NAPL plume. Vacuum extraction enhances natural volatilization by removing the vapors from the soil and bringing them to the surface. This creates a disequilibrium between the liquid and vapor phases, and allows volatilization to continue at a greater rate.

8.19.4 Treatment of Contaminants Dissolved in Groundwater

Above-ground treatment of groundwater is generally accomplished by installing extraction or recovery wells that bring the groundwater to the surface, where it can be treated (i.e. pump and treat). The two most commonly used above-ground treatment technologies are:

a) air stripping
b) carbon adsorption.

8.19.4.1 Air stripping

Air stripping is the generic term used to describe several similar above-ground methods for treating contaminated groundwater. This method is cost-effective, with a straightforward design and well understood concepts.

There are four common air-stripping methods:

a) Diffused aeration: The contaminated groundwater is channeled through a large holding tank or pond with one or more diffuser pipes along the bottom. Air is pumped through the diffuser pipes and bubbles up through the tank, providing a medium into which the dissolved contaminant can volatilize.

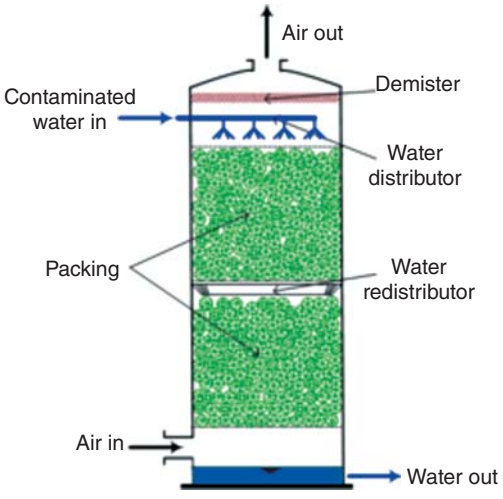


Figure 8.6 *Typical packed tower air stripper.*

b) Tray aeration: This method is not as efficient in removing volatile organic as the other air-stripping methods, but because of its simplicity and low maintenance it is sometimes used as a pre-treatment for other methods.
c) Spray aeration: Contaminated groundwater is sprayed through nozzles over a pond or basin, greatly increasing the surface area of the water. As the water falls back to the pond, volatile organic compounds (VOCs) are transferred to the atmosphere.
d) Packed tower: Packed towers are the best system for removing VOCs from groundwater and they are often the most cost-effective method as well. This is therefore the most widely used air-stripping method. A typical packed tower is shown in Figure 8.6. Contaminated groundwater is pumped to the top of the column and allowed to flow by gravity down through the packing material while uncontaminated air is pumped up through the column.

8.19.4.2 Activated Carbon Adsorption

Like air stripping, activated carbon is commonly used to remove VOCs from contaminated groundwater. The effectiveness of carbon as a treatment process is due to its ability to function as an adsorbent for molecules dissolved in water. This ability is largely due to carbon's large internal surface area.

Two forms of carbon are used to treat water:

a) Powdered activated carbon (PAC): This is dispersed freely into the water and subsequently filtered out. It is used mostly as a drinking water treatment and rarely for treatment of contaminated groundwater because it is not easily reused.
b) Granular activated carbon (GAC): GAC is coarser than powdered carbon and is typically contained in a cylindrical unit. Contaminated water is passed through the unit until the adsorption capacity of the carbon is spent. The granular carbon can then be regenerated

for future use. The design of a GAC system is not as straightforward as for air stripping because of the complex interaction of the factors influencing removal efficiency.

8.20 Methodology for Pipeline Leak Consequence Evaluation

The methodology given in this book only evaluates the potential safety and environmental consequences of a leak and not the direct economic consequences related to repair and deferred production/transportation. The latter consequences are in general not reduced by the presence of a leak detection system and may be evaluated objectively whereas the safety and environmental consequences are assessed, when necessary, on a more subjective basis.

The potential consequences of a leak are a function of various parameters related to the pipeline, its location, and the type of fluid that is transported. By comparing the outcome of the safety and environmental consequence evaluation with a leak consequence classification the pipeline operator is able to determine the pipeline leak detection facilities required for the pipeline. The reduction in leak consequences as a result of a decreased time for leak detection and system shutdown can be demonstrated with the methodology given in this book.

This methodology will not provide an absolute quantitative assessment of the consequences of a potential leak, but intends to rank pipelines on the basis of potential leak consequences.

A pipeline is not expected to leak if it is properly designed, constructed, operated, and maintained. Experience has shown, however, that despite all preventive measures taken pipelines do occasionally leak. Therefore, even when authorities have no requirements for pipeline leak detection systems, the pipeline asset holder should formulate his own requirements based on a structured, quantified approach.

Proper pipeline management should ensure the technical integrity of a pipeline in order to prevent failures and fluid releases. If a release does occur regardless of the measures taken to safeguard the pipeline integrity and the inspections to verify their effectiveness, e.g. by damage due to third party activity, a leak detection system should make the operator aware of this.

A leak detection system in itself has no effect whatsoever on the leak expectancy of a pipeline and will only make the operator aware of the occurrence of a leak, enabling him to take remedial actions in order to limit the consequences of the release.

Installation of a leak detection system should not be given the first priority when a pipeline has a high leak expectancy; measures should be taken to reduce the probability of a leak to as low as reasonably practicable (ALARP principle).

The need for a leak detection system should not be related to the risk level itself but should be evaluated by assessing the potential reduction in failure risk due to reduced safety and environmental consequences in case a leak occurs.

8.20.1 Evaluation of Leak

The leak consequence evaluation in this book is a simplified version of the leak. The leak consequences are assessed by combining:

- factual input data, such as fluid pressure, density, etc.
- assumed input data, such as most likely leak to hole size, time to detect a leak and shut-down operation, etc.
- factors such as fluid hazard factor, population density factor, etc.
- calculated parameters, such as fluid release rate, fluid release amount, etc.

The factors used in the assessment are based on expert operation.

The safety consequences are assessed based on the potential leak rate, the possibility of ignition, the population density and the hazardous characteristics of the fluid, and are expressed as a safety consequence factor (SCF). The environmental consequences are assessed on the basis of the potential leak volume, the persistence and/or seepage of the fluid into the environment, and the clean-up cost and other costs associated with the environmental consequences of a leak. The persistence and/or seepage of the fluid is adjusted by a climate correction factor. The environmental consequences are expressed as an environmental consequence factor (ECF).

Since the conditions will normally vary along the length of the pipeline, the pipeline is divided into sections and the safety and environmental consequences of a potential leak are evaluated for each section. For example, on offshore pipelines the leak detection requirements are highest close to the platform with regard to limiting safety consequences, whilst for environmental consequences the requirements are often the highest in the shore approach area. Special leak detection techniques focusing on these different criteria should be used in the respective locations.

Other parameters will also vary along the pipeline, such as internal pressure, most likely hole size, time to detect a leak, water depth, etc. The worst conditions within a particular section are assumed to be valid over the whole section length.

The safety and environmental consequences of a leak are assumed to be pipeline section length dependent, since the potential number of leaks is length dependent.

The requirements for a leak detection system should be to classify the SCFs and ECFs as “low,” “medium,” or “high.”

The threshold levels between the “low” and “medium,” and the “medium” and “high” categories have been initially defined but not verified and confirmed.

The need to install a leak detection system on pipelines is evaluated primarily on the basis of the safety and environmental consequences of a leak. The leak expectancy (Le) is applied in this evaluation as a secondary parameter (see Table 8.15).

Table 8.15 *Leak expectancy factor.*

Leak expectancy		
Input	Meaning	Leak expectancy factor (*Le*)
HH	Very high	$\sqrt{3}$
H	High	$\sqrt{2}$
N	Neutral	1
L	Low	$1/\sqrt{2}$
LL	Very low	$1/\sqrt{3}$

8.20.2 Potential Leak Rate and Leak Mass

The actual amount of fluid released in the case of a leak might range from very small to very large, depending on the leak rate, the presence of a leak detection system, the time to shut down pumps or compressors, and the presence and mode of operation of valves.

In the methodology the leak size, i.e. the size of the hole in the pipeline wall, is a variable input parameter. The user can select the most likely hole size on the basis of potential failure modes, for example a hole of 50 mm caused by the impact of a tooth of a backhole excavator. The leak rate is then calculated as the fluid mass flow through the hole.

As part of the leak consequence evaluation, the potential leak mass is calculated using a number of assumptions. The calculated leak rate is assumed to continue until the leak is detected and the first remedial actions have been taken, such as closing block valves or shutting down pumps or compressors. The reducing leak rate during the remedial actions after valve closure or pump or compressor shutdown is not incorporated in this methodology since this would complicate the assessment to a level which would be outside the scope of this leak consequence evaluation methodology.

(Note: The effect of this assumption is not as large as it seems, since for both gas and liquid lines the consequences of a leak mainly refer to the time period between the onset of the leak and the system shutdown.)

The safety consequences of a fluid release are governed by the leak rate, whereas the environmental consequences are related to the leak volume.

For onshore pipelines the population density around the pipeline is evaluated on the basis of location classes as defined in ANSI/ASME B31.8:

Location Class 1. Areas such as waste land, deserts, mountains, grazing land, farmland, and sparsely populated areas.

Location Class 2. Fringe areas around cities and towns, industrial areas, ranches or country estates.

Location Class 3. Suburban housing developments, shopping centers, residential areas, industrial areas, and other populated areas not meeting Location Class 4 criteria.

Location Class 4. Areas where multistorey buildings are prevalent, and where traffic is heavy or dense and where there may be numerous other utilities underground.

For more detailed information about definition of these location classes, refer to ANSI/ASME B31.8.

For the safety consequences assessment for offshore pipelines, a distinction is drawn between the following pipeline locations:

- open sea
- shore approach
- risers and pipeline sections on a platform and in the safety zone around a platform for an unmanned platform or complex
- similar to the above but for a manned platform or complex.

Table 8.16 gives a list of fluid types, with fluid hazard factors (S1) assigned to each fluid type. Table 8.17 lists the pipeline location classes and gives the population density factors

Table 8.16 *Fluid hazard factors (S_1).*

Fluid	Approximate density (kg/m^3) at 15 °C and 1 bar	Approximate vapor pressure (bar [abs]) at 0 °C	Fluid hazard factor, S_1
Crude oil, heavy	875–1000	0.3	0.5
Fuel oil	920–1000	0.01	1
Gas oil/diesel	850	0.01	1
Crude oil, light	700–875	0.55	1
Kerosene/naphtha/gasoline	700–790	0.01–1.2	5
NGL (condensate)	600–700	0.1–1	8
LPG	500–600	0.2–1.5	10
LNG	420	4–6	10
Ethylene	1.6		10
Natural gas	1.1		6
Sour natural gas (>0.5% H_2S)	1.1		10

Table 8.17 *Population density factor (S_2).*

Area classification	Population density factor, S_2
Onshore location class (as per ANSI/ASME B31.8)	
Class 1	1
Class 2	4
Class 3	8
Class 4	10
Offshore	
Open sea	1
Shore approach	5
Risers and safety zone (unmanned platforms)	6
Risers and safety zone (manned platforms)	10

(S2) assigned to the various locations. The SCF of a leak is calculated by:

$$SCF = L_R \times L_e \times l_g \times S_1 \times S_2 \times \left(\frac{L_s}{100}\right) \tag{8.2}$$

where:

L_R = potential leak rate
l_g = ignition factor
S_1 = fluid hazard factor
S_2 = population density factor
$L+$ = section length (m).

(Note: The value 100 merely reduces the result to a number between 1 and 1000.)

8.20.3 Environmental Consequence Factor

The ECF depends on the following parameters:

- potential leak mass (L_m)
- persistence/seepage factor (E_1)
- climate correction factor (E_2)
- clean-up and/or other associated costs (E_3).

The ECF is only applicable to pipelines transporting liquids, i.e. air pollution and potential fire damage are not included in the evaluation.

The environmental consequences of a pipeline leak are expressed and quantified for practical reasons in terms of associated consequential money costs (US$) related to clean-up, compensation, etc. These depend on the volume of fluid released, the type of fluid, the environment category, and the type of contingency plans.

The amount of liquid released is adjusted by a factor which reflects the persistence of the liquid in the environment. This factor depends on the fluid type, the climate, and whether the leak is offshore or onshore. It is assumed that the environmental damage is related to the liquid fluid components that remain in the environment after evaporation of the lighter fractions.

For onshore leaks the damage to the environment caused by the persistence of the fluid is affected by the type of crude oil. Light crude will seep into the ground more easily than heavy crude, and it is therefore more harmful and more difficult and costly to remove.

The assessment of clean-up costs is based on costs for light crude. The cost for another fluid is calculated by multiplying the persistence factor for offshore leaks (which depend on the fluid density) or other persistence/seepage factor for onshore leaks.

It is assumed that in an offshore leak of light condensate with a density of 600 kg/m^3, or of any other hydrocarbon with a lower density, the total amount of fluid will evaporate under atmospheric conditions, and thus for those offshore leaks the persistence factor is zero.

For denser fluids, the offshore persistence factor E_1 may be calculated from the formula:

$$E_1 = 0.004 \times \text{density}\,(15^\circ\text{C}, 1\ \text{bar})\text{-}2.4 \tag{8.3}$$

The onshore persistence/seepage factor E_1 may be calculated from the formulae:

For density less than 850 kg/m^3:

$$E_1 = 0.0022 \times \text{density}\,(15^\circ\text{C}, 1\ \text{bar})\text{-}0.88 \tag{8.4}$$

For density greater than 850 kg/m^3:

$$E_1 = 0.0013 \times \text{density}\,(15^\circ\text{C}, 1\ \text{bar}) + 2.1 \tag{8.5}$$

The factors for onshore leaks are estimated from expert option. These relationships are shown in Figure 8.7.

The climate correction factor, E_2 in Table 8.18, allows for the relationship between liquid evaporation and the ambient temperature.

The clean-up cost and other associated costs for a liquid spill are expressed per unit volume in Table 8.19. The environment categories identified and associated clean-up cost and/or other consequential costs for light crude are given in US$/m^3.

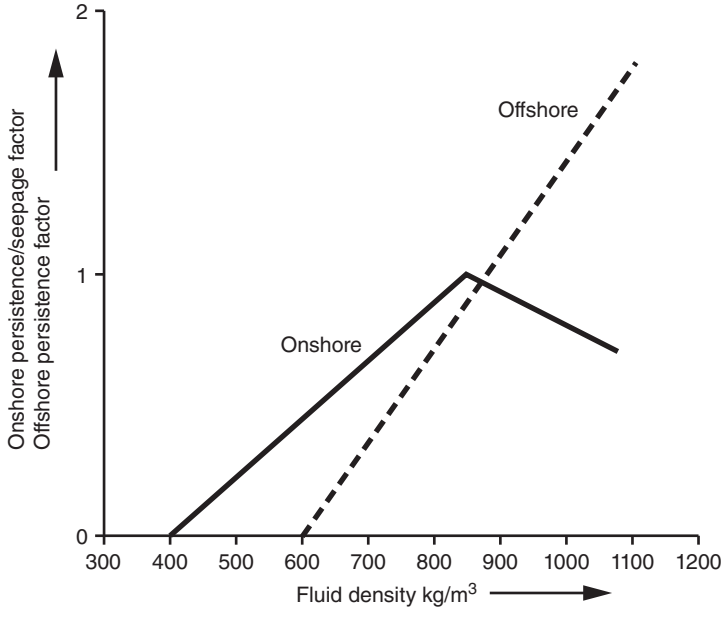


Figure 8.7 *Persistence factor (offshore) and persistence/seepage factor (onshore).*

Table 8.18 *Climate correction factor for persistence/seepage factor (E_2).*

Climate	Average annual temperature (°C)	Correction factor, E_2
Warm	>20	0.75
Moderate	5> and <20	1
Cold	>5	1.25

Table 8.19 *Clean-up and/or other associated costs.*

Environment	Clean-up costs; E_3 (US$/m^3)	Remarks
>40 km from shore	13	Based on surveillance of the released fluid only, whilst allowing self-degradation
5–40 km from shore	110 or 240	Value depend on remedial actions: chemical dispersant treatment (dispersant and application) is 110 USD/m^3 Containment and recovery (equipment, deployment, recovery, transport, and disposal) is 240 USD/m^3
<5 km from shore	3500	Including coastal clean-up, fishing and tourism compensation and amenity impact
Standard terrain	630	
Water course areas	2200	
Designated environmentally sensitive areas	2500	

The costs, quoted in 1993 money terms, have been estimated by experts using North Sea experience. They are assumed to be applicable worldwide.

Possible fines and other intangible costs related to the possible damage to the environment, e.g. loss of goodwill and credibility, are not included in the above costs. These should either be evaluated as a separate cost in an economic consequence evaluation or incorporated into the methodology by increasing the clean-up and/or other associated costs (E_3) values. Actual costs are not included since they will be principal dependent.

The ECF of a leak is calculated from the formula:

$$ECF = (L_m \times 1000/R_o) \times L_e \times L_s \times E_1 \times E_2 \times \left(\frac{E_3}{100000}\right) \tag{8.6}$$

8.21 Leak Detection Techniques

Leak detection techniques are based on either continuous or intermittent measurements of specific parameters. Intermittent leak detection methods are often able to detect smaller leak rates compared with continuous leak detection techniques.

Some continuous techniques can only detect transient pipeline conditions during the onset of a leak and will not be able to identify the presence of a leak at a later time.

For some intermittent techniques fluid transportation through the pipeline needs to be interrupted. Using intermittent techniques, the detection time of a leak will be completely dependent on the frequency of inspection.

Techniques for detection of leaks in liquid lines offer better performance than those for gas pipelines, which in turn are better than those for two-phase pipelines.

The conflicting balance of sensitivity to leaks and false alarms will determine the sensitivity setting of the leak detection system. Large leaks can normally be detected more rapidly than small ones. To maintain the user's confidence in the system, avoiding false alarms should have a higher priority than attempting to shorten the leak detection time or reducing the minimum detectable leak rate.

The performance of pipeline leak detection techniques is dependent on fluid type, operating pressure including fluctuations, batch or continuous operation, pipeline length and size, metering accuracy, etc.

The decision about which technique to adopt depends on a detailed case by case evaluation. If the consequences of a leak are considered significant then the more sophisticated techniques of leak detection are required. It may be necessary to deploy more than one leak detection technique in order to achieve the overall leak detection performance that is required.

Leak detection systems are categorized into the following groups according to their inherent principle of leak detection:

a) balancing of pipeline mass input versus output
b) pressure and/or flow analysis
c) monitoring of characteristic signals generated by a leak
d) off-line leak detection.

A summary of the capabilities and application of the various leak detection techniques is given in Table 8.20. The leak rate categories used in Table 8.20 are:

full bore rupture: 100% of flow
major leak: 50–100% of flow
large leak: 25–50% of flow
medium leak: 5–25% of flow
small leak: 1–5% of flow.

8.21.1 Balancing Mass Input Versus Output

This category of leak detection system relies on the fact that in a leak-free pipeline the fluid mass flow into the pipeline equals the flow out. Using this mass balance principle the flow-in and flow-out measurements are continuously monitored for any variations over a time interval. Volume flow readings should either be corrected for density or pressure and temperature variations to reference mass flows. To eliminate the effect of flow variations during normal operation, the flow readings should be averaged (totalized) over discrete time periods.

The uncorrected mass balance method can be applied only under steady state operations as it does not allow for changes in the pipeline inventory, i.e. line pack variation. Its accuracy depends largely on the accuracy of the flow meters and on the steadiness of operations.

In addition to the inlet and outlet flow measurements, the corrected mass balance method uses a correction factor for any changes in the pipeline inventory. Pressure and, if necessary, temperature measurements at intervals along the pipeline are used for calculating the correction factor. The capability for detecting small leaks depends upon the number and accuracy of measurements along the length of the pipeline.

An alternative method is dynamic simulation, which is a model-assisted balance method. A real-time computer model calculates the inventory of the pipeline and the line pack variations of the pipeline under steady state and transient operating conditions. It will correct not only for pressure and temperature effects but also for changes in fluid properties, such as where different batches of fluids are present in the pipeline at the same time. A difference between the mass balance predicted by the model and that actually measured indicates the presence of a leak. Also, unexpected flow and/or pressure trends are used as indicators of the occurrence of a leak.

The dynamic simulation method is similar to the corrected mass balance system. The main difference is that the dynamic simulation method calculates the pipeline inventory whereas the corrected mass balance method interpolates between the measurements along the pipeline. The latter is usually considered to be less accurate because of the inherent accumulation of measurement errors.

The sensitivity of these methods is generally good. Their disadvantage is that they have limited capabilities for locating the leak.

The development of a statistical pipeline leak detection (SPLD) system does not need complicated modeling of the pipeline inventory as the system continuously calculates the

Table 8.20 *Summary of the capabilities and application of leak detection techniques.*

Leak detection method	Leak type	Mode of operation	Response time	Leak location capability	Remarks
Low pressure	Gas: full bore ruptures Liquid: major leaks	Any	Seconds to minutes	Offshore: none Onshore: between block valves if pressure readings available	Commonly used, high thresholds to avoid false alarms
Pressure decrease/flow increase	Gas: major leak Liquid: large leaks	Steady state	Seconds to minutes	Offshore: none Onshore: between block valves if pressure readings available	—
Pressure gradient along the pipeline	Gas: major leaks Liquid: large leaks	Steady state	Minutes	Between block valves if pressure readings available	Onshore only
Negative pressure wave	Gas: large leaks Liquid: medium leaks	Steady state	Seconds to minutes	Within 1 km	Detects only the onset of a leak
Wave alert	Gas: medium to large leaks Liquid: small to medium leaks	Steady and transient state	Seconds to minutes	Within 1 km depending on transducer spacing	Detects only the onset of a leak
Mass balance	Medium to large leaks	Steady state	Minutes to hours	None	—
Corrected mass balance	Small to medium leaks	Steady and transient state	Minutes to hours	Offshore: none Onshore: between block valves	—

Dynamic simulation	Small leaks	Steady and transient state	Minutes to hours	At best within 10% of pipeline length	—
Statistical leak detection	Small leaks	Steady and transient state	Minutes to hours	Indication only	Low probability of false alarm
Ultrasonic leak detection pig	Liquids: small leaks (typical 50 l/h)	Intermittent	Depends on pigging frequency	Within 100 m	Hard liquids only
Acoustic reflectometry	Liquids: large leaks (on-line), small to medium leaks (shut-down)	Steady state	Depends on monitoring frequency	Within 1 km	Hard liquids only
Differential static pressure test	Small leaks (hard liquids), medium leaks (soft liquids), large leaks for gas	During shut down	Hours to days	None, between block valves	Capabilities depends on length and temperature effects
Sniffer tube, hydrocarbon sensing-cables	All fluids, including multiphase: small leaks	Any	Hours	Within 100 m	Short lines only

statistical probabilities of a leak based on fluid flow and pressure measured at the inlet and outlet of a pipeline. Depending on the control and operation of a pipeline, the statistical technique is used to identify changes in the relationship between the pipeline pressure and flow which always occur when there is a leak.

The SPLD system works as a statistical filter, which is applied to a pipeline input/output balance and decides between a leak-free and a leak-present hypothesis. The major advantages of this system are its simplicity and robustness compared with other software-based techniques. The SPLD system can run on a PC and is capable of discriminating between fluctuations due to operational variations of the pipeline and the actual occurrence of a leak; it is thus very reliable for leak detection. The SPLD system has been commercialized since October 1991. The statistical filter of the SPLD system can also be combined with a commercially available dynamic simulation method, which makes the latter even more reliable. This combined statistical and dynamic simulation leak detection system is at present the most sophisticated leak detection system available.

8.21.2 Pressure and/or Flow Analysis

The operation of a pipeline can be characterized by the flow of the fluid and the pressure gradient along the pipeline. Pressure drop and flow along a pipeline are related to the flow resistance of the pipeline. A leak will alter the pressure drop profile of a pipeline and therefore affect the "normal" pressure and flow relationships. Detection of such alterations can be used to indicate the occurrence of a leak.

If a large leak occurs, particularly in the upstream part of a pipeline, the inlet pressure will drop. Observation of a lower than expected inlet pressure indicates the presence of a leak. Detection of low pressure is usually connected to an automatic shut-down system. To avoid false alarms the system is usually set such that only major leaks can be detected.

A leak will result in an increase in flow upstream and a decrease in flow downstream of the leak. As a result of this the pressure gradient will increase upstream and decrease downstream of the leak. The occurrence of a discontinuity in the pressure gradient, which is calculated from the pressure readings along the pipeline, is an indication of a large leak. The rate of change of pressure and flow readings can also be monitored and used to detect sudden changes which indicate the occurrence of a leak.

The combined pressure decrease/flow increase method uses the fact that a leak in an operational pipeline will cause an increase in the flow and a decrease in the pressure upstream of the leak. The simultaneous occurrence of both is an indication of a leak.

8.21.3 Monitoring of Characteristic Signals Generated by a Leak

A suddenly occurring leak will cause a sudden pressure drop at the leak location in the pipeline. This sudden pressure drop will create a pressure wave traveling at sonic velocity both upstream and downstream from the leak. Detection of this pressure wave is an indication of the occurrence of a leak. The response time of this negative pressure wave technique is very short because it responds to waves that travel at sonic velocities (in crude oil, approximately 1000 m/s). When the wave is detected both upstream and downstream of the leak, the location of the leak may be calculated from the time difference of detection by the nearest sensors on either side of the leak location. The system will only respond to an instantaneously occurring leak of measurable size. In practice the sensitivity can be poor

because the alarm thresholds are often set high to avoid false alarms triggered by pressure transients generated by upstream or downstream processing plant or other noise-producing installation, such as pump or compressor stations.

A system which is less sensitive to pipeline noise than the negative pressure wave system uses dual transducers which filter out noise signals. The system is made directional, i.e. it detects signals originating from either the upstream or the downstream direction of the pipeline. This is achieved by installing the two transducers at an appropriate distance from each other and using an electronic signal subtracting system.

Leak detection based on negative pressure wave techniques will only detect the initiation of a leak and not its presence. If the pressure wave created at the moment of leak initiation is not detected, the leak will not be noticed.

Liquid escaping under pressure through a small opening produces supersonic noise. An ultrasonic leak detection pig, which is equipped with hydrophones and data recording, can detect and locate the presence of a leak. A very small leak, down to 10 l/h, can be detected and fairly accurately located with this technique. Being intermittently operated, the response time will depend on the frequency of running the ultrasonic leak detection pig.

A hydrocarbon-permeable tube (sniffer tube) can be laid in close proximity along the pipeline. Small leaks of hydrocarbons from the pipeline which have permeated into the tube will be detected when the tube is periodically purged into a gas analyzer.

Hydrocarbon-sensing cables can be laid along the pipeline. Electrical properties of the cable change when hydrocarbons come into contact with the cable. Contact with water does not affect the properties of the cable.

A prototype system for the measurement of methane in sea water has been developed. The device extracts dissolved gas from a continuous flow of water and determines the methane content using infrared absorption techniques.

Remote sensing of hydrocarbon emissions, e.g. using an infrared technique from an aircraft, is becoming commercially available. Particularly for gas and multi-phase pipelines, this offers a powerful alternative to ground-based patrolling techniques.

8.21.4 Off-Line Leak Detection

Intelligent pigs have been developed for detection and location of leaks in a pipeline using flow direction recognition in a blocked-in pressurized pipeline. This bi-directional pig has an opening through the body with a sensitive flow meter and a transmitter. By locating the pig at various points along the line and using above-ground interpretation of the flow measurements through the pig, the leak can eventually be located. Locating the leak, however, is time consuming and the line should be equipped with pumping or pressurizing facilities at both ends. This system is of interest for pipelines larger than 8 in. in diameter when a small leak has been detected but its location is unknown.

An alternative to the above technique for pipelines smaller than 8 in. is a bi-directional pig equipped with a differential pressure transducer and a transmitter. When located in the pipeline the pig measures the pressure drop on either side. The leak will be on the side at which the pressure drops more rapidly.

The pressure in a blocked-in pressurized pipeline will drop when there is a leak. For a static pressure leak test the pipeline, or a section of it, is pressurized with the transported hydrocarbon fluid. If pressurizing to a higher level is required the leak test should be done with water for safety and environmental reasons. After pressurizing, the block valves

are closed and the pressure and temperature are monitored for a specified period of time (24 hour minimum). A differential static pressure test can be carried out if block valves are equipped with differential pressure transducers.

A difference in the rate of pressure drop in two adjacent sections that cannot be explained by temperature effects, inaccuracy of readings or valve leakage is an indication that there are uncertainties about the advantages and disadvantages of pressure testing existing pipelines for condition monitoring purposes at pressure higher than the maximum allowable operating pressure (MAOP).

The advantage of pressure testing at high pressures for leak detection is that an existing leak is detected more easily. Also, long defects which have almost broken the surface can be opened, resulting in a leak which is also detected. The disadvantage is the risk that existing defects might be enlarged and/or activated to grow, possibly leading to failures during normal pipeline operations following the pressure test.

(Note: Pressure testing above the MAOP is primarily done for strength testing in order to avoid a pipeline rupture (DEP 31.40.40.38-Gen).)

Sound which is generated when liquid is forced through a small opening during pressure testing can be detected by acoustic monitoring. For pipelines transporting hard liquids, leak detection by an acoustic reflectometry method is feasible. The technique is based on the phenomenon that a pressure wave traveling through a pipeline is reflected at the position of a leak due to a local change of acoustic properties for lines which are used intermittently. This technique can be used during downtime when the level of disturbing noise is low.

8.22 Leakproof Control of Pipeline Gas Piping, Tanks, and Technological Installations Using Radioactive Tracers

A tracer can be added to the pressurizing fluid for detection of small leaks. The leak is detected by patrolling the pipeline with a detector which is sensitive to the tracer or by visual observation of a visible tracer.

The method of isotopic tracers can be used as a complementary technique to hydraulic and pneumatic pressure tests, and has many advantages. It is sensitive and easy to apply, and the test and preliminary works are not time-consuming. In addition, the isotopic test can be carried out at low pressure (0.2–0.4 MPa) without excessive effort of construction materials. It should be mentioned that hydraulic tests cannot be applied to some objects despite the fact that such tests are necessary.

The isotopic tracers method is based on the phenomenon of migration of the isotopic tracer in the direction of the leak, its penetration to the surrounding medium, adsorption of the tracer in this medium, and measurement of gamma radiation emitted by the tracer. Methyl bromide labeled with radioisotopic ^{82}Br is the best tracer.

The chemical reaction is carried out in a special generator constructed for this purpose. Depending on the type of generator, activities up to 10 Ci (370 G Bq) can be handled. To transport the gaseous radioactive tracer to the dispensing point special containers are used. The radiotracer is sucked off from the generator to the container. The containers vary in size depending on the activity of the tracer to be transported.

The detection and localization of leaks is carried out by recording changes of radiation intensity (resulting from adsorption of the radioactive tracer in the insulating material) with the aid of portable radiometers with scintillation detectors.

The measurement of the dose rate on the surface of the generator container and the determination of the boundaries of the controlled area is carried out with the aid of Geiger-Muller counters. When simultaneous measurements are carried out at many points highly sensitive multichannel radiometers are used.

8.22.1 Leak Detection in Liquid Pipelines

In methyl bromide (and in the case of water, potassium bromide) labeled with radioactive ^{82}Br should be introduced to the liquid in the pipeline and detected with the aid of a special gamma-ray detector placed in a pressure-proof pig (Figure 8.8) moving with the medium through the pipeline. The detector is introduced to the pipeline after the tracer has passed. It continuously measures the natural radiation in the pipeline and also the peaks of gamma radiation of ^{82}Br (if present). The minimum activity which must be present in the leak in order to be detected is 1–10 μCi (37–370 kBq).

The signals recorded on the tape are called the general localization of the leak and supply information as to the position of the leak with an accuracy of several to several tens of meters depending on the distance between the distance markers (^{60}Co sources placed on the outer walls of the pipeline) and the rate of tape winding of the recorder. Exact localization of the leak is carried out by searching the radiation of the ground above the pipeline in the area delineated as described above. In the case of pipelines of very small diameters, to which radiometers cannot be introduced, only accurate localization is carried out.

In such cases the detection is based on the measurement of tracer radiation, which penetrated through the leak to upper layers of the ground, by means of a detector moved just above the surface of the ground. In this method it is necessary to stop the operation of the pipeline for some time in order to follow the movement of the added tracer. The total applied activity should be 20 Ci (740 G Bq). The minimum leak detected should be in the range of 30–1000 cm^3/h. With the detectors introduced into the pipeline it is possible to examine pipelines with diameters 200–800 mm.

8.22.2 Leak Detection in Gas Pipelines

The choice of examination methods depends on the size of the leak, the length of the section of the gas pipeline to be examined, and the pipe diameter. These factors affect the rate of movement of the tracer on the way from the point of its introduction to upper layers of the soil in the leak zone, where the tracer is detected by means of a gamma-ray detector.

Leak testing with the aid of radioactive tracers can be carried out before, during, and after the pressure tests for strength. The choice of the variant of the method depends on the pressure decrease in the conventional pressure test.

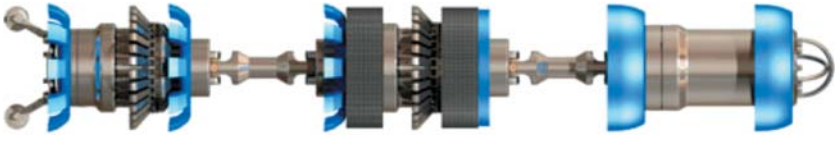


Figure 8.8 Pipeline pig.

8.22.2.1 Labeling the Total Volume of the Gas Pipeline

This method can be applied to short pipelines and small leaks. The medium and the tracer should be pumped into the pipeline at one or more points in such a way as to evenly distribute the tracer in the whole volume of the line.

For detection, apply high test pressure as much as possible. When a definite pressure is attained the pumping is interrupted. After several hours (this time is necessary to allow the labeled gas to pass through the smallest leaks to the upper layers of the ground) the radiation of the tracer in the leak is recorded. In this method it is possible to simultaneously detect all leaks without the necessity of following the movement of the tracer, i.e. without digging up the pipeline when locating leaks.

8.22.2.2 Single Injection of Tracer

This method is used for testing short sections. First, the gas is pumped up to a definite pressure. The pumping is then interrupted and the radioactive tracer introduced into the middle section of the gas piping.

Introduction of the tracer into the middle section of the gas piping permits the time of localization of the leaks to be reduced. Radiometers located on the pipe on both sides of the point of injection of the tracer allow the direction of movement of the tracer, i.e. the part in which the leak occurs, to be determined.

8.22.2.3 Injection of the Tracer at Several Points

This method is used in the case of examination of long sections of gas pipeline. The leak is localized by following the movement of the radioisotope with the aid of radiometers located on both sides of the injection point. In this method very small portions of the tracer are used (the radioactivity of each is about 1 mCi). The last portion of the tracer injected in close proximity to the leak is sufficiently high to be measured above the leak zone.

8.22.2.4 Tracer Injection Under Constant Pressure of the Inspection Medium

This method can be applied to gas pipelines of any length with large leaks. It should be noted that the single pumping may not be sufficient to transport the tracer to the leak zone the gas is continuously pumped under a constant pressure. Continuous pumping of the gas has advantages in the case of small leaks since it allows the time of their localization to be reduced. It is necessary to continuously maintain a definite supply of the gas in order to compensate for the losses through the leaks. The localization can be carried out at any place and the minimum detectable leakage rate is less than 30 cm^3/h.

8.23 Final Sludge and Solids Conveyance, Storage, and Disposal

The solids removed as sludge from preliminary and biological treatment processes should be concentrated and stabilized by biological and thermal means, and reduced in volume in preparation for final disposal if required.

Environmental regulations and subsurface water pollution limitations should be considered for final selection of disposal method.

8.23.1 Conveyance Methods

Sludge may be transported long distances by pipeline, truck, barge, rail, or a combination of these modes. To minimize the danger of spills, odors, and dissemination of pathogens to the air, liquid sludges should be transported in closed vessels such as tank trucks, railroad tank cars, or covered tank barges.

Stabilized, dewatered sludges may be transferred in open vessels, such as dump trucks if permitted by the company and allowed by the regulations. However, if the sludge is hauled long distances, the vessels should be covered.

8.23.1.1 Pipeline

In general, the energy requirements for long distance transportation of untreated sludges with a solids concentration of more than 6% are prohibitive. Adequate flowrates in large diameter pipes should be maintained to reduce the possibility of grit accumulation, grease build up in unlined pipes, and other problems resulting from low flow conditions.

8.23.1.2 Truck

Trucking is the most flexible and most widely used method for transporting sludge. Either liquid or dewatered sludge may be hauled by truck to diverse destinations. Trucking dewatered sludge is usually the most economical method for small to medium sized treatment facilities.

8.23.1.3 Barge

Barge transport is generally economical only for large facilities treating wastewater flows in excess of 15 800 m^3/h or in locations where one barge can serve several plants. Barges can also be used for carrying dewatered sludge in containers. Barging sludge for ocean disposal is prohibited.

8.23.1.4 Rail

Rail transportation may be used for sludges of any consistency, but those with high solids content are transported most economically by rail. The use of rail transportation for small quantities of sludges or for short distances is not justifiable economically.

8.23.2 Environmental Considerations in Sludge Transportation

Environmental features such as air pollutant load, traffic, noise, etc. should be taken into consideration in sludge transportation. On a mass basis, the transportation mode that contributes the lowest pollutant load is piping. Next in sequence are barging and unit train rail transportation. The highest pollutant load is from trucking.

8.23.3 Sludge Storage

Sludge that has been digested aerobically before it is disposed of or used beneficially should be stored.

Storage of liquid sludge can be accomplished in sludge storage basins, and storage of dewatered sludge can be done on storage pads.

8.23.3.1 Sludge Storage and Basins

If the basins are not loaded too heavily, provision of an aerobic surface layer through the growth of algae and by atmospheric reaeration should be considered. Alternatively, surface aerators can be used to maintain aerobic conditions in the upper layers.

The number of basins used should be sufficient to allow each basin to be out of service for a period of about six months. The depth of the sludge storage basin should be 3–5 m.

8.23.3.2 Sludge Storage Pads

- Where dewatered sludge has to be stored prior to land application, a sufficient storage area should be provided based on the number of consecutive days that sludge hauling could occur without applying sludge to land. Allowances also have to be made for paved access and for an area to maneuver the sludge-hauling trucks, loaders, and application vehicles.
- The storage pads should be constructed of concrete or bituminous concrete and designed to withstand truck loadings and sludge piles.
- Provisions for leachate and stormwater collection and disposal should be considered.

8.23.4 Final Disposal

Final disposal for the sludge and solids that are not beneficially used usually involves some form of land disposal. Ocean disposal of sludge is prohibited.

As in the case of land application of sludge, the regulations for other methods of sludge disposal require close attention and should be reviewed when planning and designing sludge disposal facilities.

8.23.4.1 Landfilling

If a suitable site is convenient, landfill can be used for disposal of sludge, grease, grit, and other solids. Stabilization may be required depending on state or local regulations.

Dewatering of sludge is required to reduce the volume to be transported and to control the generation of leachate from the landfill.

In a true sanitary landfill, the wastes should be deposited in a designated area, compacted in place with a tractor or roller, and covered with a 30 cm layer of clean soil.

Special attention should be given to minimization of nuisance conditions such as odors and flies.

In selecting a land disposal site, consideration must be given to:

a) environmentally sensitive areas such as wetlands, flood plains, recharge zones for aquifers, and habitats for endangered species
b) runoff control to surface water

c) groundwater protection
d) air pollution from dust, particles, and odors
e) disease vectors
r) safety as related to toxic materials, fires, and access.

Trucks carrying wet sludge and grit should be able to reach the site without passing through heavily populated areas or business districts.

8.23.4.2 Lagooning

Lagooning is economical if the treatment plant is in a remote location.

Excess liquid from the lagoon, if there is any, should be returned to the plant for treatment.

Lagoons should be located away from the roads, highways, and dwellings to minimize possible nuisance conditions and should be fenced to keep out unauthorized persons.

Subsurface drainage and percolation should be investigated to determine if the underlying groundwater will be affected.

The lagoon should be lined if excessive percolation is a problem or if regulations require leachate control.

8.23.5 Incineration

Incinerators are generally limited to situations where adequate land for disposal of raw wastes is limited, or where land disposal or other procedures are impractical.

The chief advantage of incineration is reduction of waste containing organic matter to a relatively small volume of inert material. The chief disadvantage is the high initial cost and operating cost.

Steam generation should be considered if feasible and economically justified.

Air pollution regulations for smoke, fly ash, or hydrocarbon content of stack gases must be considered in the design stage.

Incinerator feeds should be limited to solid or semisolid paste-like materials of low moisture content. Slurry type sludges, such as oil-water separator sludge and tank bottoms, can be dewatered and deoiled by centrifugation or filtration to produce a solids cake suitable for incineration.

Cake can be transported by belt, screw, or ribbon conveyors to a skip hoist which will elevate the cake to a charge hopper, Other solids, including relatively dry spent clay, trash, rubbish, and garbage in trucks, can be charged directly to the feed hopper from a truck ramp or indirectly using clam shell equipment. Liquid wastes can be burned with appropriate burners in the firebox.

Special attention should be made to provide water scrubbers or cyclone separators if required by air pollution regulations.

A smoke monitor and alarm should be provided.

Stacks should be sufficiently elevated to disperse the gases and avoid concentrations of contaminants, such as sulfur dioxide, at high ground levels.

The incinerators can be equipped with multiple hearths or a single hearth.

8.23.6 Ash Handling and Disposal

The ash may or may not be wetted by a water spray as it is removed. The ash can be dropped into a pit and removed by an elevating device to a hopper which is emptied into a truck when required. Ash may be used for road, fire bank, and tank foundation construction.

8.24 Disposal of Solid Waste

This section describes the solid waste disposal procedure, covering types, hazard, non-hazard, siting, sources, segregation, reduction, resource recovery, treatment sludge concentration, and sampling equipment. It does not provide all of the detailed information that is needed for the design and operation of a solid waste system.

8.24.1 Types of Waste

There are two types of waste: hazardous and non-hazardous.

8.24.1.1 Hazardous Waste

Hazardous waste includes the following:

- refinery waste
- petrochemical industry waste
- fertilizer industry waste
- chemical industry waste
- desalting plant and production unit waste.

8.24.1.1.1 Refinery Waste. The following general refinery wastes are considered hazardous:

a) leaded tank bottoms
b) neutralization hydrofluoric alkylation sludge
c) dissolved air floatation (DAF) unit sludge
d) kerosine filter cake
e) lube oil filtration clays
f) slop oil emulsion solids
g) exchanger bundle cleaning solvent
h) API separator sludge.

8.24.1.1.2 Petrochemical Industry Waste. Sources of solid wastes in the petrochemical industry are:

- plastic and rubber
- waste catalysts
- activated carbon, Japanese acid clay, and zeolite
- alkali waste (soda, amine) and waste acid
- vinyl chloride tar
- oil sludge
- tar, resin, pitch, and sludge.

Table 8.21 *Composition of BPG.*

Constituents	Percentage dry weight
$CaSO_4$, $2H_2O$	90–95
Water of crystallization	19–20
Total phosphate (PO_4)	0.8–1.6
Total fluoride (F)	0.5–1.9
Sodium + potassium ($Na_2O + K_2O$)	0.5–1.0
Silica (SiO_2) and other insolubles	2–3
Organic matter	0.4–0.8
Toxic constituents, mg/kg dry weight except radioactivity	
Cadmium (Cd)	1.25–3.22
Chromium (Cr)	1.47–1.72
Copper (Cu)	4.00–4.76
Lead (Pb)	6.37–6.47
Manganese (Mn)	5.48–10.39
Radioactivity	29 pCi/g dry weight

8.24.1.1.3 Fertilizer Industry Waste. Phosphatic fertilizer industry solid waste by-product phospho-gypsum (BPG) generate in fertilizer industry. Only 20% of total BPG is used for producing ammonium sulfate, the reminder being released to land-fill or lagooning in slurry form. The general characteristics of BPG and toxic metal constituents are given in Table 8.21.

8.24.1.1.4 Solid Waste from Chemical Industry Pesticides. Dichloro diphenyl trichloroethane (DDT) and benzene hexachloride (BHC) are commonly used pesticides, along with organophosphorous and carbonate compounds. In the process, wastewater releases highly corrosive substances (pH 1–1.7) containing DDT, sulfuric acid, and suspended solid. The wastewater is neutralized with lime and the settled effluent still contains DDT.

In production of BHC about 30 m^3 of wastewater per ton of BHC containing 0.4 BHC is released, which is highly corrosive and toxic (pH 2.6–3.0).

Lime neutralization and sludge drying in sand beds can be used. About 90% of BHC in wastewater goes into the sludge.

Concentrated, unused pesticides should be stored, returned, or disposed off as toxic waste.

8.24.2 Siting of Hazardous Waste Facilities

8.24.2.1 Permit requirements

Every facility that treats, stores, or disposes of hazardous wastes must obtain a permit from the local environmental protection organization to approve the site selected for operation of the facilities mentioned. Details of all aspects of design, operation, and maintenance must be described in the permit and show compliance with the applicable requirements.

Table 8.22 *Examples of possible environmental impacts.*

Groundwater contamination
Surface-water contamination
Air pollution
Leaks, spills, accidents
Destruction of wildlife habitat, natural areas, wetlands
Loss of any unique site features (e.g. archeological)
Permanent contamination of site
Contamination of nearby crops, fisheries
Traffic congestion
Odors
Noise
Visual ugliness
Effects on character of community: magnet for other heavy industry, image as dumping ground

8.24.2.2 Environmental impacts

Environmental impacts include potential effects on ecological processes, human health, and the esthetics of the natural and cultural landscape. For any given facility, these impacts will depend on the volumes and types of wastes to be managed and on the design and operation of the facility.

Table 8.22 lists examples of potential environmental impacts that should be considered, taking into account both expected and possible accidental effects from each element of the facility's operation (e.g. transport, storage, treatment, incineration). Environmental impacts in the absence of a facility should also be adhered if the facility will in fact help to remedy disposal practices currently in use that are more hazardous. That point should be made and factually supported. Safeguards to prevent or mitigate such impacts should also be kept in mind.

8.24.3 Non-Hazardous Waste

8.24.3.1 Drilling Fluid (Mud)

Function of drilling fluids:

a) remove drilled solid (cuttings) from the bottom at the hole and carry them to the surface, where they are removed
b) lubricate and cool the drill bit and string
c) control downhole pressure
d) deposit an impermeable wall cake on the well bore wall to seal the formations being drilled so contaminants do not enter the mud and the fluid phase of the mud does not enter the formation.

8.24.3.2 Nature of Drilling Discharge

The solid concentration discharge ranges from 60% to 90% by weight when drilling a very shallow onshore well. The total volume of mud discharged may be 119 m^3 (1000 barrels) or less. Very deep onshore wells drilled over long period of time may generate up to 3570 m^3 (30 000 barrels) of mud. For offshore wells the volume of mud discharged ranges from 119 to 595 m^3 (1000 to 5000 barrels) for a typical well.

8.24.3.3 Environment Effect

The environment effects of drilling discharge onshore include the following:

a) Excess soluble salts and high exchangeable sodium percentages, which are the major inhibiting effects of drilling muds to plants and soils.
b) Most drilling muds cause soil dispersion, resulting in surface crusting. Proper treatment can minimize or eliminate these effects.

8.24.4 Sources, Segregation, Quantities, and Characteristics of Solid Waste in Refineries

There are numerous sources and types of refinery solid waste. Most wastes can be segregated at source for more efficient handling before reclamation or disposal.

Because of varied refinery configurations, each refinery will have problems specific to its location, process, and local regulations. Even considering the individuality of refineries, there are basic waste materials produced which are common to most refining processes and therefore can be handled similarly for resource recovery or disposal. Besides these basic wastes, there are other wastes with characteristics and quantities that are not easily defined. A list of waste sources and classification of wastes is presented in Table 8.23. Obviously such a list cannot be all inclusive.

8.24.4.1 Sources and Classification

Some of the more easily defined waste materials are given in Table 8.3 listed by refinery unit source and classified into combustibles, noncombustibles, and biodegradables.

8.24.4.2 Segregation of Wastes

By studying Table 8.23 and relating it to a particular operation, prudent segregation practices that can reduce the cost and effort of handling become apparent. The following categories for segregation should be considered:

1) oily process sludges
2) non-oily wastes
3) biological sludges
4) miscellaneous
5) sanitary wastes.

8.24.4.2.1 Oily Process Sludges. Oily sludge is the most difficult waste to handle. Oil sludges are obtained as sediments from storage tanks, crude desalters, sewer cleaning,

Table 8.23 *Sources and characteristics of refinery solid wastes.*

Source	Classification Combustible	non-combustible[a]	Biodegradable
	Refining processes		
Crude oil storage	Wax bottoms	Sand, rust, slit	—
Product storage		Sludge, sand rust, silt	
Crude processing		Sand, rust, silt, salt, slop oil emulsions	
Thermal cracking	Separator coke		
Catalytic cracking		Spent catalyst	
Catalytic reforming		Spent catalyst	
Polymerization		Spent catalyst	
Alkylation		Corrosion products (sludge, tar)	
HF alkylation		Calcium fluoride sludge	
Asphalt manufacture	Asphalt drips	Asphalt emulsions	Emulsions, light solvent
Cooling	Coke fines, wax tailings		
Product treating	Acid sludge Adsorbents	Lead sludge Adsorbents	
Lubes and grease	Soaps	Clay	
Wax	Slops, drips	—	
	Non-refining operations		
Utilities: steam generation	—	Boiler blowdown sludge	
Utilities: feedwater treatment	—	Lime sludge	
Utilities: cooling towers	—	Suspended solids	
	Wastewater pollution control		
API separators	Oily sludges, heavy hydrocarbon	Sand, silt	Oily coated inert solids
Air flotation	Oily froth		
Clarifiers	Biological flocculation	Flocs	Biological flocculation
Flocculation	Floc.	Clay	
Filters		Filter cake	
Biological oxidation	Biological flocculation		Biological sludge
	Air pollution control		
Bag filters		Catalyst dust	
Electrostatic precipitators		Catalyst dust	

[a]In many cases the non-combustibles are associated with combustibles and the whole mass must be processed to remove the combustible before disposal of the inert residue.

vessel cleaning, oil-water separators, dissolved air flotation, lube oil processing, and alkylation. A thorough study is required to determine which wastes are compatible for mixing prior to recovery.

8.24.4.2.2 Non-oily Wastes. Non-oily wastes are much easier to handle. These wastes come from storm sewer cleanings, grit chambers, tank cleaning, cooling tower cleanings, water treating, and catalyst replacement. Used catalyst is the most likely material for resource recovery.

8.24.4.2.3 Biological Sludges. Biological sludges are those obtained from biological wastewater treatment plants. These sludges are concentrated by various methods, and when the quality allows may be used as soil conditioners.

8.24.4.2.4 Miscellaneous Waste. Miscellaneous solid waste materials not related to oil processing can generally be disposed of in municipal landfills.

8.24.4.2.5 Sanitary Wastes. The sanitary sewage collection and disposal system should be segregated from the process wastewater system to eliminate the requirement to chlorinate the treated water effluent. Where refineries do operate sanitary waste treatment systems, adequate information is available in the literature to answer solids disposal questions.

8.24.4.3 Typical Quantities and Characteristics

The major sources of metallic constituents in a refinery are API separator bottoms, dissolved air flotation units, waste biological sludge, storm slit, and waste fluid catalytic cracking (FCC) catalyst. The metallic content of wastes varies widely between refineries. The metals in solid waste are zinc, vanadium, selenium nickel, mercury, lead, copper, chromium, arsenic, and cadmium.

8.24.5 Source Reduction Methods

For source reduction, modification of process and operating procedures should be considered. This is done to reduce the quantity of waste solid and to alter their characteristics. Some source reduction techniques are described here.

8.24.5.1 Tank Cleaning

Variable angle mixers installed in storage tanks can be used in conjunction with selected solvents (such as, crude, light cycle oil, and water) to reduce the time, manpower, and cost of removing residual solids from storage tanks.

The selected solvent is added to the tank to be cleaned and the mixers are operated for 5–15 days in various positions typically ranging 30° from either side of the center line. This sweeps all parts of the tank floor and lifts the solids so that solvent and oily solids are in intimate contact. The resulting deoiling of the solids recovers valuable hydrocarbon for reuse. It also reduces the oil content of the residual solids, making them less difficult to dispose of ultimately and reduces the quantity of residual solids by removing the oil and wax content of the solids. An additional advantage of this technique is the greater safety afforded by conducting the major portion of the cleaning activity from outside the tank.

8.24.5.2 Biosludge from Water Treatment

Several techniques are available to reduce the quantity of waste biosludge resulting from wastewater treatment.

8.24.5.2.1 Sludge Age. The sludge age in the biological treatment system can be increased. To accomplish this without creating sludge settling problems usually requires careful pretreatment to remove colloidal material in the wastewater entering the biounit. Removal may be accomplished by use of a well-operated air flotation or sand filter system. The sludge age can usually be increased sufficiently to reduce sludge wastage to very low levels.

8.24.5.2.2 Aerobic Digestion. Aerobic digestion of the waste biosludge will result in a significant reduction in the quantity of sludge. It is also a necessary pretreatment step for landfarming of biological sludge to prevent odor problems.

8.24.5.2.3 Hydrolysis. Other methods of reducing waste biological sludge include chemical treatment, such as acid treatment, to break down the biological cell wall. Thus, organics can be oxidized and the resultant biological sludge is more easily dewatered for ultimate disposal.

8.24.5.2.4 Air Floatation Float Recycle. Air floatation units are usually operated with chemical additives to improve their efficiency. Alum, ferric chloride, lime, and polyelectrolytes are typical chemical agents used. If possible, the chemical usage should be limited to polyelectrolytes since alum, lime, and ferric chloride type treatment creates a significant volume of oily solids for disposal. The use of polyelectrolytes alone opens up the possibility of recycling the float, which is now primarily oil, to the front of the system, thus reducing the quantity of solid material for disposal.

8.24.5.2.5 Beneficial Combination. Some wastes may be combined to advantage. For instance, lime from boiler feed water treatment can be used for pH control on landfarm operations.

8.24.5.2.6 Shutdown Planning. The environmental department should be involved in the planning for all types of shutdowns so that the quantities and characteristics of wastes to be generated by the shutdown are anticipated. The shutdown planning should ensure that all possible steps are taken to keep quantities to a minimum, to control the characteristics of the waste to simplify its disposal, and to plan the disposal techniques to be used.

8.24.6 Resource Recovery and Waste Minimization

8.24.6.1 Resource Recovery

The main items which are recoverable and reusable include oil, catalyst, acids, caustics, digested biological sludges, filter clays, and, in some cases, chromate inhibitors used in cooling tower treatment. Almost every refinery can identify recoverable items from waste generated by processes which are individual to that refinery.

8.24.6.1.1 Oil Reclamation. All refineries practice the recovery of waste oils to some degree. The recovered oils may be reintroduced into various process feed streams or sold directly for fuel or other uses. The techniques for recovery include simple gravity separation, emulsion breaking with chemicals and heat, and the use of lighter oils and solvents to aid in emulsion breaking and thinning of heavier oil fractions. After the oil is recovered, the residual waste is amenable to landfarming as the ultimate method of disposal. If a sludge is to be landfarmed, oil should be recovered until the oil content is no more than 15%. Since oil concentration is a limiting factor for the quantity of waste to be applied to a plot of land, the less oil a waste contains the smaller the land area required for landfarming.

8.24.6.1.2 Catalyst Reuse. The metal content of many catalysts is frequently of sufficient quantity to allow the catalysts to be reprocessed for resale or metal recovery. Most spent catalysts are stable enough that ultimate disposal can be accomplished by landfilling. It is good practice not to mix spent catalyst with other wastes in a landfill. In many cases, landfills become acceptable means for disposal if they are dedicated completely to a particular waste material.

8.24.6.1.3 Acids and Caustics. Waste materials should be neutralized prior to disposal. Reacting waste chemicals in this manner reduces the amount of fresh chemical required for neutralization and can be defined as a reuse process. Neutralized acid and caustic solutions can be discharged into the wastewater treatment system whenever the total dissolved solids limit is not exceeded. Spent alkylation acid can be returned to sulfuric acid manufacturers for reprocessing.

8.24.6.1.4 Biological Sludges. Biological sludge should not be used for growing food products but waste sludge may be spread in tank farm areas.

8.24.6.1.5 Filter Clays. Filter clays used for oil and wax purification can be regenerated in multiple hearth furnaces for reuse. A particular clay will withstand several regeneration cycles before particle size and reaction surface deteriorate. Waste filter clay is non-reactive and is amenable to landfill as an ultimate disposal method.

8.24.6.1.6 Chromate Inhibitor Reuse. Chromate continues to be one of the most effective corrosion inhibitors for cooling systems. Because of restrictions, the reduction of chromium content in wastewater has become imperative. Chromate can be recovered from cooling tower blowdown for reuse in the make-up water. This is accomplished by the ion exchange process. Stringent wastewater regulations have made this reuse process more attractive.

The refinery engineer must always consider reuse waste materials in the design and development of refining processes. Maximum resource recovery might be the difference between success or failure for a particular project.

8.24.6.2 Minimization of Waste Generation

Waste minimization is very often economically beneficial for an industry and also results in improved environmental quality. The following requirements for design and operating features for waste minimization should be considered:

8.24.6.2.1.1 Integrated Units. Separated components of crude oil can pass from one unit to the next with little or no intermediate tankage. This reduces the amount of sludge generated from intermediate storage capacity.

8.24.6.2.1.2 In-line Blending. 95% of all prime fuels can be blended into a pipeline as opposed to blending into tankage. Sludge generated from finished product tankage is then minimal.

8.24.6.2.1.3 Crude Tank Mixers. The crude oil tanks at the refinery should be equipped with mixers. The use of mixers prevents the deposit of settleable solids and thereby reduces the frequency for cleaning.

8.24.6.2.1.4 Air Cooler Maximization. Over 70% of the cooling in the refinery should be through air fans as opposed to water-cooled heat exchangers. This reduces potential contamination of cooling water with process fluid. It reduces the volume of cooling water make-up and cooling water in circulation. In addition, it minimizes the generation of heat exchanger tube bundle cleaning sludge by substituting air coolers for heat exchangers.

8.24.6.2.1.5 Use of Demineralized Clarified River Water. This technique reduces the cooling blowdown stream, thereby minimizing the generation of cooling tower treatment sludge.

8.24.6.2.1.6 Closed Cooling Water System. This concept uses a cooling tower system to recirculate the same volume of water for cooling purposes. This further minimizes the volume of water that could be contaminated with process fluids, and the blowdown of significant quantities of cooling water treatment chemicals, e.g. Cr and Zn.

8.24.6.2.1.7 Amine Degradation Prevention. In refinery which uses di-ethanol amine (DEA) to absorb H_2S and CO_2 acid gases from sour gas streams, DEA forms certain non-regenerable compounds requiring occasional disposal of amine and consequent replacement with fresh amine. To reduce amine disposal, the refinery should use continuous slip-stream filtration in addition to carbon filtration to remove degradation products. In addition to filtration, additives should also be injected into the amine to inhibit deterioration.

8.24.6.2.1.8 Separate Sewer Systems. In refinery sewer design, segregation of all sources is recommended. All non-oily aqueous wastes can be transported via separate sewer systems. The oily aqueous wastes should be transported to the API separator. The segregated sewer design reduces the load on the API separator, thereby increasing its efficiency and minimizing potential formation of API separator sludge from solids of non-hazardous origin.

8.24.6.2.1.9 Forebay Skimming of the API Separator. A slot skimmer should be installed at the head of the API separator to recover as much oil as possible from the separator influent for direct recycle to the refinery. This technique is an oil recovery/recycle

process that reduces the oil loading on the separator and reduces the amount of oily sludge generation.

8.24.6.2.1.10 Pressurized Air Operation of the DAF Unit. DAF unit sludge generation is minimized by using the pressurized air method of operation which concentrates the DAF sludge and minimizes the quantity generated and handled.

8.24.6.2.1.11 Independent Parallel Bay Separator Design. The refinery's API separator should be in a three-bay parallel design with flexibility and capacity so that individual bays can be taken out of service for maintenance without affecting separator efficiency.

8.24.6.2.1.12 Coke Fines Recovery/Reuse. The delayed coking unit produces anode-grade coke as a product. Coke fines are generated by the process on an intermittent basis. Instead of segregating the fines as a waste product, the refinery recovers this material and recycles it for sale along with the marketable product. This minimizes a waste-stream generation. In addition, the coke fines handling equipment design prevents coke solids introduction into the oily water sewer system and its eventual deposition at the bottom of the API separator as a sludge.

8.24.6.2.1.13 Process Catalyst Reuse, Reclamation, and Recovery. The refinery utilizes catalyst wherever possible that can be reclaimed, recovered, or reused in the various processing operations.

8.24.6.2.1.14 Spent Naphthenic Caustic Reuse. A unit should be installed to process spent naphthenic caustics into naphthenic acids for sale as a by-product.

8.24.6.2.1.15 Slop Oil Recovery/Reuse. All slop oils generated should be collected and directed to the crude unit and coker for recovery and production of fuels and petroleum products. This minimizes the sewering of oily materials and production of API separator sludge and slop oil emulsion solids.

Paving of process areas minimizes solids (mostly dirt) entering the refinery oily water sewer system. These solids would otherwise be removed from the API separator as hazardous waste.

Contract filtration services should be used to dewater/deoil wastewater treatment sludges prior to land treatment. By reducing the volume and oil content of these sludges, further land treatment operation can be conducted in a smaller area and at lower oil loading rates, and the oil can be recovered/reused in the refinery.

Installation of an air-operated skimmer at the head of the API separator complements the existing mechanical skimmer and further enhances oil recovery from the separator inflow. This results in further reducing the oil loading on the separator and subsequent formation and disposition of oily sludges that would be removed as hazardous waste.

8.24.6.2.1.15.1 Replacement of sludge storage impoundments with above-ground tankage. The tank system includes a mixing tank plus two storage tanks. The system will use heat and chemical addition to remove oil and water from the sludges as an initial step in reducing the volume and oil content of the wastes. These tanks will also eliminate

water accumulation in the sludges from rainfall and volatile hydrocarbon air emissions from the sludges.

8.24.6.2.1.15.2 A filtration service dewaters biological solids generated by the secondary treatment system. The waste biosludge has a very high water content and is dewatered prior to disposal on the land treatment area. Instead of acting as a hydraulic gradient to promote contaminant migration through the treatment zone, the dry bio-sludge serves to augment the existing land farm microorganisms in waste assimilation and fixation.

Refineries should try to sell spent FCC catalyst for use in the manufacture of Portland cement, in lieu of landfill disposal.

An effort should be made to keep surfactant materials out of the sewers to minimize formation of oil-in-water emulsions that create oily sludges (e.g. API separator bottoms, slop oil emulsion cuff, and DAF float).

Secondary containment should be provided for all intermediate and final product transfer tankage pumps. This measure prevents potential soil contamination in case of a leak or spillage.

A dredge barge in the biological clarifier improves biosludge recycling and minimizes sludge accumulation in the final polishing pond.

An oil skimming system should be installed in the oily stormwater-retention pond. This pond serves as a surge pond for the API separator. The skimming system performs a recovery/recycle function by skimming oil for reprocessing. In addition, the system also reduces the oil loading on the separator and subsequent generation of API separator sludge (hazardous waste) and slop oil emulsion solids (hazardous waste).

A vacuum truck should collect catalyst fines which deposit around the process units during loading and unloading operations. This minimizes the amount of solids introduced to the sewer system. This in turn reduces the overall amount of hazardous (oily) wastewater solids generated at the API separator.

Rerouting desalter water from the API separator to intermediate tankage and then back to separator. This allows for oil skimming at the tank, which minimizes emulsion carry-over to the separator, decreasing the generation of slop oil emulsion solids (hazardous waste).

Use of a solvent still to reclaim spent paint solvents (hazardous waste).

Periodic clean out of the oily water sewer system to reduce overall generation of hazardous waste at API separator.

Use of covers for all oily water sewer openings in the process area to minimize the amount of solids introduced into the sewer system. This reduces the overall amount of hazardous (oily) wastewater solids generated at the API separator.

8.24.7 Hazardous Waste Reduction

The framework of reduction for control of hazardous waste covers:

a) generators
b) transportation
c) treatment
d) storage
e) disposal.

8.24.7.1 Generators

The waste generator or handler must determine whether or not the waste is hazardous. Waste classified as solid hazardous waste must meet two criteria. The first criterion applied is whether the material is a solid waste and the second step determines whether or not the solid waste is hazardous. Four characteristics of hazardous waste are shown in Table 8.24. These four characteristics are defined in 40 CFR 261 Resource Conservation and Recovery Act, US Regularly Act (RCRA) 1974 and (HSW 4) Hazardous and Solid Waste 1984. Reference can be made to these sources.

Generator owners are responsible for establishing standard operating procedures (SOPs) that, when followed, satisfy regulation. Furthermore, they must ensure that employees follow the SOPs as a condition of employment.

For each hazardous waste a multi-copy form called a manifest accompanies the waste on leaving the facility and continues with it to its ultimate disposal.

The tracking system for the manifest includes the name and address of the transporter, treater, storer, or disposer; and a description of the wastes, including type, quantities, and official classifications. The manifest should contain certification that the generator minimizes the hazardous waste as much as economically practical and that the chosen method of disposal minimizes risk to human health and the environment.

8.24.7.2 Transportation

The transporter of hazardous waste should take every precaution to ensure that spill will not occur and must report any spill as soon as possible.

8.24.7.3 Treatment, Storage, and Disposal

8.24.7.3.1 Treatment. Any method, technique, or process, including neutralization, designed to change the physical, chemical, or biological character composition of any hazardous waste so as to neutralize it or render it non-hazardous or less hazardous or to recover it make it safer to transport, store, or dispose of or amenable for recovery, storage, or volume reduction will reduce the quantity of waste.

8.24.7.3.2 Storage. The holding of hazardous waste for a temporary period and at the expiring time the hazardous waste is treated, disposed of or stored elsewhere are the second steps to reduce the waste.

8.24.7.3.3 Disposal. The discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid/waste or hazardous waste into any land or water so that any constituent thereof may enter the environment or be emitted into the air or discharged into any water,

Table 8.24 *Characteristics of hazardous waste.*

Ignitability	RCRA	40 CFR	261.21
Corrosivity	RCRA	40 CFR	261.22
Reactivity	RCRA	40 CFR	261.23
Toxicity	RCRA	40 CFR	261.24

including ground-water are factors to be considered for prevention and minimizing of environmental pollution.

These procedures can be divided into two categories: standard of performance and permit requirements. Performance standards should be per RCRA ACT 40 CFR part 264/265 subparts A through E. The permit requirement should be per RCRA ACT 40 CFR 265.

The general provisions that apply to all treatment, storage, and disposal facilities (TSDFs) are as follows:

a) Waste analysis to ensure accurate information concerning the properties of the waste for adequate treatment, storage, or disposal.
b) Security measures to prevent unauthorized entry with resulting injury or environmental damage. Inspection to assess the facility and its potential problems.
c) Training of facility personnel to reduce mistakes that could threaten human health, safety, and the environment.
d) Compliance with government standards, including flood plain, earthquake, and hydrological considerations.

Land disposal facilities should be designed to prevent groundwater pollution. New landfills should include double liners and leakage collection systems. Groundwater quality should be monitored to ensure that protective systems are effective, and operators must take corrective action when the systems fail.

8.24.8 Treatment Prior to Ultimate Disposal

8.24.8.1 Concentration

Concentrating solids is easily understood when considering that doubling of solids concentration results in halving the volume for ultimate disposal. Increasing concentration from 1% to 2%, or from 2% to 4%, is especially important because of the large reduction in volume.

Because of new effluent regulations, wastewater treatment sludges have become the single largest source of sludge. These sludges are difficult to process because they are often gelatinous or oily. Furthermore, the physical properties of wastewater sludge may change frequently because of turnarounds or changes in refinery operations.

Selection of the concentration process depends on the characteristics of the sludge and the ultimate disposal methods available at the specific location.

8.24.8.2 Sludge Concentration by Gravity Differential Method

8.24.8.2.1 Air Floating Unit. After removal of the majority of free oil in an API separator, the remaining 50–100 ppm free oil together with colloidal emulsions and suspended solids may be further reduced in a dissolved or induced air floatation unit (DAF or IAF). These units typically concentrate sludge to 4–5 wt%.

The basic principle of either DAF or IAF is that air bubbles attach to the suspended oil or solids causing the particles to float to the surface, where they can be skimmed. For air floating unit specifications refer to the API *Manual on Disposal of Refinery Waste* (1980).

8.24.8.2.2 Chemical Flocculation. Chemical flocculation is another pre-treatment for removing oil and solids. For further specification refer to the API *Manual on Disposal of Refinery Waste* (1980).

8.24.8.3 Sludge Concentration by Mechanical Dewatering

8.24.8.3.1 Centrifugation. Three types of centrifuges are used for processing high solids content sludges: scroll, imperforate basket, and disc. Scroll centrifuges are frequently called solid bowl centrifuges, which is confusing since imperforate basket centrifuges also have a solid bowl.

Oily wastes containing a wide range of solids, oil, and water can be processed by centrifugation. Units have also been designed to process emulsions and oily sludges with high solids content, such as separator and tank bottoms. For further information on the three types of centrifuges refer to the API *Manual on Disposal of Refinery Waste* (1980).

8.24.8.3.2 Filtration. Two types of mechanical filters are generally used to concentrate sludges that have been settled or floated by gravity: pressure filters and vacuum filters.

- *Pressure filters*
  A pressure filter should consist of metal plates covered by a fabric filtering medium. The covered plates should be hung in a frame equipped with both a fixed and a movable head. The plates should be forced together with a chamber left between the cloth surfaces. Sludge will be pumped through a central opening in the plates to the cloth-lined chamber. Sludge is retained on the fabric and liquid is forced through the fabric to the plate surface, where it drains away. At the end of the filtration cycle, the plates are separated and the sludge cake is discharged from the unit. Feed pressures ranging between 5.5 and 15.5 bar (80 and 225 psi) gage are common.

  Pressure filters of the plate and frame type should not be used for filtration of oily sludges or oily slurries because the filter media plugs rapidly. This severely limits the filtration rate. If spent inert solids, such as lime sludge, are available they can be mixed with the waste to provide porosity and improve the ease of removal of the cake from the filter media.
- *Vacuum filters*
  The typical filter installation consists of a horizontal compartmented drum that supports the filter media on its outer surface. The drum is rotated, partially submerged, in a tank containing the waste sludge. As each section of the drum passes through the tank, vacuum pulls the liquid inward and the solids are retained as a thin cake in the filter media covering the outer drum surface. For more detail refer to the API *Manual on Disposal of Refinery Waste* (1980).

8.24.8.4 Sludge Concentration by Incineration

Incineration is the ultimate in volume reduction. It results in an ash which must be landfilled. Gases are passed out of the stack where particulates and acid vapors (CO_2, SO_2, and HCl), if present, are removed. Hydrocarbons present in the sludge reduce the amount of

auxiliary feed required. The chief disadvantages are the high capital and operating costs. These costs, per ton of waste incinerated, are especially high for small incinerators and for large incinerators if not used to their full capacity. Evaluation of the need and economics for incineration therefore requires three basic steps. First, make an accurate estimate of the amount and characteristics of the waste to be incinerated. Second, evaluate alternative disposal methods and types of incinerators. Finally, make an economic and environmental comparison of the alternatives.

- **Types of incinerator**
  For a brief description of the main types of incinerator and applications refer to the API *Manual on Disposal of Refinery Waste* (1980), Sections 6.4.1 and 6.4.8.
- **Incinerator design considerations**
  Incinerator design requires close cooperation with the incinerator vendor after the characteristics and amount of sludge are known. Specific design considerations depend on the type of incinerator being considered. General factors include:
  1) The quality of the feed, including variations in composition, production rate, and combustion characteristics. For example, when the feed to a fluid bed incinerator forms a low-melting eutectic which will bog a fluid bed or will corrosive fumes attack metal rabble arms.
  2) Control of incineration temperature to ensure complete and safe combustion with minimum maintenance and operating costs. The need for auxiliary fuel, the control of excess air, turbulence, or mixing heat transfer and residence time in the combustion zone must be considered.
  3) Control of air pollution due to incomplete combustion.
- **Pyrolysis**
  Pyrolysis is heating of waste in the presence of less air than would be required for complete combustion. By doing this some of the hydrocarbon is utilized and some may be partially oxidized. These materials, along with complete products of combustion, are burned in an afterburner for heat recovery or some material may be collected by condensation as a liquid for subsequent use as a heat or hydrocarbon source. Regeneration of activated carbon is also a pyrolysis process, with the limited oxygen being used to prevent complete destruction of the carbon.

8.24.8.5 Land Treatment

Land treatment is a waste treatment and disposal process whereby waste is mixed with or incorporate into the surface soil and degraded, transformed, or immobilized. Land treatment technology, site and waste evaluation, design and operation criteria provide the potential environmental effects of land treatment.

8.24.8.5.1 Technology.

Waste characteristics

Biodegradable waste is suitable for land treatment. The chemical structure, molecular weight, water solubility, and vapor pressure are characteristics that determine the ease of biodegradation.

Soil characteristics

The principle soil characteristics affecting land treatment are pH, salinity, cation-exchange capacity, redox behavior, texture, aeration, moisture-holding capacity, internal drainage, and soil temperature.

Waste degradation

The factors affecting waste degradation may be adjusted in the design and operation of a land treatment facility, as described here:

a) The optimum soil pH for bacterial growth is near 7. This pH is generally maintained by liming to promote microbial activity and to immobilize heavy metals in the waste.
b) Soil moisture content should be maintained above a certain minimum, usually between 30% and 90% of the water-holding capacity of the soil.
c) Soil temperature should be maintained above 10 °C.
d) Nutrients, additional nitrogen must be supplied when highly carbonaceous waste is applied.

8.24.8.5.2 Site Characteristics. Sites for land treatment should include regional and site geology, hydrology, topography, soil, climate, and land use.

Land treatment facilities should not be located in an aquifer recharge zone or within 60 m of a fault that has had displacement since the Holocene. Current standards require the treatment zone to be less than 137 cm deep and at least 90 cm above the seasonal water table. Although topography can be modified to some extent by grading, the site should not be so flat as to avoid pounding nor so steep as to cause excessive erosion and runoff. The site should not be subject to flooding or washout.

As a treatment medium, the soil should be evaluated in terms of its assimilative capacity (retention and degradation), and the potential for erosion and leaching of hazardous waste constituents. In general, land treatment facilities should not be established on deep, sandy soil because of the potential for groundwater contamination. Silty soils with crusting problems are undesirable because of the potential for excessive runoff. Generally, soils suitable for land treatment are loam, sandy clay loam, silty clay loam, clay loam, and silty clay. Soil properties that should be evaluated include soil depth, texture, drainage, pH, organic matter, soluble salts, cation-exchange capacity, moisture-holding capacity, and microbial counts.

Wind, temperature, and rainfall are three variables of climate that are generally considered in site selection. Careful design and well-planned can overcome most climatic constraints.

Existing and future land use for the site of the land treatment facility should be evaluated in the planning stages. Zoning restrictions, potential effects on environmentally sensitive areas, proximity to existing or planned developments, and effects on the local economy should all be considered.

8.24.8.5.3 Advantages and Disadvantages of Land Treatment. The advantages of land treatment are summarized as follows:

- The waste is degraded, transformed, or immobilized, thus the long-term liability is lower than for other land disposal options.

- The treatment area is continually monitored, thus remedial action can be taken immediately when there are signs of waste migration from the treatment zone.
- The cost for land treatment is lower than for landfills and incineration.

The disadvantage of land treatment is:

- There is potential for adverse environmental impacts if the facility is not properly designed and managed.

8.24.8.5.4 Design Considerations.

- **Area and facility layout**
  Land treatment generally requires a large parcel of land to accommodate the treatment area, buffer zone, roads, waste storage, equipment storage, retention pond, and on-site structures. For this reason, the area available plays a significant role in the layout and in many design and operating features of the facility. Some salient features are shown in Table 8.25.
  a) Equipment.
  b) Water management.
  c) Soil erosion.
  d) Waste application.
  e) Facility inspection and record keeping.
  f) Site monitoring.
- **Potential environmental impacts**
  Soil, a natural acceptor of wastes, has been viewed as a physical, chemical, and biological filter that can effectively deactivate, decompose, or assimilate a wide range of waste materials. The factors affecting this assimilative capacity must be considered in order to develop robust systems for land treatment. Without a detailed analysis of land treatment components and a good design and management plan, adverse environmental effects can result.
- **Water quality**
  Operators of land treatment facilities must adequately protect the surface and subsurface water from contamination with hazardous-waste constituents or by-products from waste degradation. Waste constituents that are not degraded by microorganisms, transformed, or immobilized in soil may leach to the groundwater. Runoff resulting from excess waste

Table 8.25 *Design and operational considerations.*

Land requirement	pH adjustment and nutrient supply
Facility layout	Frequency and rate of waste application
Access road	Application and mixing methods
Equipment selection	Contingency plan
Runon and runoff control	Vegetation
Erosion control	Site security and inspection
Odor and air-emission control	Site monitoring
Waste storage	Record keeping
Land preparation	Closure and postclosure care

application or heavy rains may carry the constituents and contaminated sediments to nearby streams and lakes.

Incorporation of wastes into the surface soil may result in soluble constituents moving downward by leaching. Thus, it would be a race between mobility and degradability of organic waste constituents. Under regulations, the seasonal groundwater table beneath a land treatment facility can be as shallow as 2.40 m below grade, or about 90 cm below the treatment zone. In some cases, an impermeable layer with a leachate-collection system placed a meter or so below the treatment zone can prevent waste constituents or their metabolites from contaminating the groundwater.

Surface water contamination resulting from improper water or damaged diversion structures and retention ponds is probably a major environmental concern. In a land treatment operation, wastes are concentrated in the soil surface; the concentration of waste constituents in the runoff water may be sufficiently high to have deleterious effects on certain trophic levels in the aquatic ecosystem. Waste constituents may be transported as particulate, dissolved, or bound on eroded soil particles.

- **Air quality**
  Air quality at a land treatment site can be impaired by odors, dust, volatile substances, and aerosols emitted from waste spreading and incorporating processes. Many industrial hazardous wastes contain heavy metals and organic substances that are highly toxic in particulate or volatile form. The level of volatile compounds present in the air is not necessarily related to the severity of the odor problems. Insufficient data has adverse effects of land treatment practices on air quality. For air monitoring at waste management facilities and for worker protection refer to ASTM-D4844-88.

8.24.8.5.5 Landfill of Hazardous Waste. Landfill contains isolate wastes that are not recoverable to present long-term environmental protection. Disposal to landfill sites of oily wastes such as sludges obtained from the bottom of separator systems needs selection of a suitable location.

Approval of the relevant authorities is necessary before selection of a site for oily waste disposal. Oil may leach from the site into groundwater and if the rock strata are porous, or fissured, this would lead to contamination of drinking water supplies. In addition, the site has to be selected such that the surface water runoff is either contained or intercepted. The oil must be further stabilized to minimize its mobility. This can be achieved in a number of ways, including co-disposal. For co-disposal there should be at least 4 m of mature domestic refuse between the oily waste level and the base of the landfill. Maturing of the waste takes three to four years, by which time most of the putrescible and solid organic matter has degraded. In an emergency the oily waste should be dumped on the oldest available refuse.

For high-level wastes, e.g. oil or emulsions containing 25% oil and 75% water, the mixing rate should not exceed 5% of the domestic refuse volume. For low-level waste, i.e. leached material with an oil content less than 5% by volume, the loading rate should be less than 30% of the underlying domestic waste volume. Ditches or strips for high-level wastes should not exceed 300 mm in thickness (preferably 100 mm), and for low-level wastes 500 mm is the maximum thickness. Layers of refuse of around 2 m should cover any oily waste layers.

The addition of fly ash or quicklime (CaO) can also be used to render oily sludge inert, and this can be accomplished prior to disposal at a landfill site. Fly ash, the residual ash

powder from coal-fired power stations, has a very high surface area and stabilizes the oil by adsorption. The fly ash and sludge may be mixed on site using impellers or screw mixers. The fly ash is added as a polymer-stabilized slurry and the resulting sludge/fly ash mix must be dewatered before dumping. An alternative and less expensive method is to mix the sludge and fly ash at the disposal site using conventional bulldozers and diggers available on site. Quicklime can be used in a similar way to produce a friable, inert material which on compaction can be used as a base infill for low-grade roads. Sludges with oil contents of 5–10% require some 15% quicklime addition, while higher oil contents can be accommodated simply by adding more quicklime. Waste oils can be used for spraying on dirt roads to hold down the dust.

8.24.9 Disposal of Waste Generated in Drilling Wells

8.24.9.1 Onshore Drilling

Preserve pit (sump) is used to store drilling mud and cuttings to serve as the means for final disposal. The walls of the reserve pit must be high enough to provide 1–1.5 m at native topsoils on top of the mud and cuttings after back filling. There are three major methods of disposal.

1) Dewatering the pit wastes with subsequent back filling using the pit walls.
2) Land farming the wastes into the surrounding soils.
3) Transfer by vacuum truck removal to an approved disposal site.

8.24.9.1.1 Back Filling. Back filling a reserved pit is common method employed. Before the back-filling operation begins, it is first necessary to remove the top aqueous layer. After the oil is skimmed, the aqueous layer can be divided by mixing the pit area with organic flocculants such as polyacrylamide or inorganic flocculants such as gypsum. The flocculation should be as complete as possible. When this process is over, the aqueous layer should be removed. Sometimes the aqueous layer is allowed to evaporate, which can take considerable time. In some cases the wall of the pit dike is cut and the fluid is drives out. Analysis should be conducted to ensure that the release of water meets environmental protection guidelines and requirements.

The aqueous layer can also be removed by vacuum truck and:

1) injected into the well that was drilled (if it is plugged and abandoned)
2) injected into the drilled well's annulus (if it is completed as a producing well)
3) transported to a nearby injection well.

After the aqueous layer has been removed, back filling at the reserve pit can be performed.

8.24.9.1.2 Land Farming. The second major disposal method utilizes land farming techniques. Land farming essentially consists of spreading the contents of the reserve pit evenly over the drilling location with subsequent incorporation into the soil using basic soil tilting equipment. Land farming is particularly useful for wells that produce hydrocarbons.

8.24.9.1.3 Vacuum Truck Removal. In this method both the aqueous and solid phases of the reserve pit are pumped to trucks while dirt-moving equipment "squeezes" the pit dikes together.

8.24.9.2 Offshore Drilling

In offshore drilling the amount of oil discharged is usually restricted. There are a number of different disposal techniques:

Feasible options

Shunting: The drilling mud and cutting through a pipe extending below the surface of the water (usually near to the sea floor) should be released. Shunting minimizes the physical transport of the waste and environmental control.

Impractical options

a) Transport to an ocean dump site.
b) Transport to a land disposal area.
c) Piped to another area.

8.24.10 General Sampling Considerations

Sampling equipment must be selected that is chemically compatible with the type of waste and type of analyses.

Generally, plastic sampling equipment is not suitable for waste containing or to be analyzed for organic parameter. Stainless steel, glass, and plastic are acceptable for most samples being analyzed for inorganics. It is up to the user to ensure that the equipment will not contaminate or bias the analyses.

The sampling equipment must be capable of extracting a sample from the desired location, depth, or point and at the same time provide protection from cross-contamination during sampling. For instance, one very common problem is extracting a sludge sample from beneath a top layer of wastewater or sludge without contaminating the sample with the overlying wastewater or sludge. This situation, as well as many others, requires special equipment. The collector is therefore faced in many instances with having to manufacture the necessary equipment.

Recommended sampling procedures are for collection of samples from the edge of ponds or lagoons or from pier or catwalks. Sampling from boats is not recommended and should be attempted only if the collector knows the waste poses no health risks and every possible safety measure has been taken.

Tanks and drums containing unknown substances also pose potential health risks for the collector due to the possibility of fire, explosion, or the release of deadly gases on opening. In these situations, only spark-proof, remote opening devices should be used and only fully trained and experienced personnel should attempt to do this.

Samples which have not been properly mixed or have been mixed in such a way that constituents such as VOCs are destroyed or driven off are not truly representative. Some of the most difficult types of samples to composite are cohesive fine textured solids and sludges. Lime-neutralized metal-finishing wastes are an example of these wastes. Because of the

sticky cohesive nature of these wastes, mixing is very difficult in the field. It may be best to have the laboratory mix the sample. Depending on the type of analyses required, it may be possible to slurry and mix the sample by the addition of water without affecting the analyses. Laboratory personnel should be consulted before attempting this. If the composite has not been appropriately mixed prior to shipment, this should be clearly indicated on the sample.

The volume of sample needed depends on the type of analyses to be carried out and the testing equipment and procedure to be followed. There are two rules of thumb that can be applied:

- If low chemical concentrations of the parameter to be tested are expected, take a large volume of sample.
- If high chemical concentrations of the parameter to be tested are expected, smaller volumes will suffice.

When possible, it is recommended that sampling proceeds from the least contaminated to the most contaminated areas to reduce the potential for cross-contamination.

8.24.10.1 General Planning of Waste Sampling

The analysis and testing of solid waste requires collection of adequately sized, representative samples. Wastes are found in various locations and physical states.

Each sampling routine must be tailored to fit the waste and situation. Wastes often occur as non-homogeneous mixtures in stratified layers or as poorly mixed to form a mass. For example, wastes are commonly stored or disposed of in surface impoundments with stratified or layered sludges covered by ponded wastewater. In these situations, the collector may be faced with sampling the wastewater, the sludge, and some depth of soil beneath the sludge. Collecting representative samples in these situations requires a carefully assessed, well-planned, and well-executed sampling routine.

8.24.10.1.1 Significance and Use. The procedures covered in this guide are general and provide the user with information helpful for writing sampling plans, safety plans, labeling and shipping procedures, chain-of-custody procedures, general sampling procedures, general cleaning procedures, and general preservation procedures.

8.24.10.1.2 Sampling Plans. A sampling plan is a scheme or design to locate sampling points so that suitable representative samples for the waste body can be obtained. Development of sampling plans requires the following:

- Review of background information about the waste and site.
- Knowledge of the waste location and situation.
- Decisions as to the types of samples needed.
- Decisions as to the sampling design required.
- Background data on the waste (this is extremely helpful in preassessment of the waste's composition, hazards, and extent).
  (Note: The background information is needed to determine necessary safety equipment, safety procedures, sampling equipment and sampling design, and the procedures to be used. For more details see ASTM D4687.)

- Waste location and site conditions (these greatly influence a sampling plan).
  The most common waste locations include lagoons, landfills, pipes, point discharges, piles, drums, bins, tanks, and trucks. The site conditions include the physical condition of the waste (solid, liquid, or gas) and describe the conditions when it was disposed of.

Based on these considerations, the collector must be able to sample.

The samples collected may be either composite or single. The sample collector must sort the samples and provide representative ones.

A composite sample is a well-mixed collection of subsamples of the same waste taken from different points. A composite sample can be used in determining an average measure of a parameter. Composite samples are taken when differences in the waste exist.

A single sample is a well-mixed sample taken from a single point. It is used to measure a particular parameter or parameter set at a given point or within a unique homogeneous layer or throughout the strata at one or several locations.

Sampling plans or schemes should be prepared well in advance of sampling. The most common sampling schemes involve the selection of sampling points by a coordinate system or a grid system.

8.24.10.1.3 Coordinate Sampling System. This system uses one or two coordinates and involves collecting samples at random points from the origin of the coordinates. Random numbers can be generated using the random number tables available in most statistic texts. The origin of the coordinate system is normally located at one corner of the site and the sampling area marked off in steps, centimeters, meters, etc. This system can be used for sampling landfills, waste piles, and lagoons. For storage areas containing barrels, the number of barrels from the origin is often used as the intervals along the coordinate. For sampling from a flowing stream the origin may be taken as time-zero (start), and samples collected at random time intervals over the period of interest.

8.24.10.1.4 Grid System. This system also involves taking samples at regular intervals, grid points, along an imaginary grid system laid out over the site. The number of sampling points will vary with the size of the grid. Such sampling schemes are used when a statistically sound sampling program is required. They should be used only when the waste body is known to be homogeneous or when the strata have been defined. If the waste is stratified, a separate grid system may be required for each stratum.

8.24.10.2 Sampling Equipment

- **Composite liquid waste sample (coliwasa)**
  A coliwasa is a device employed to sample free-flowing liquids and slurries contained in drums, shallow tank, pits, and similar containers. It consists of a glass, plastic, or metal tube and should be equipped with an end closure that can be opened and closed while the tube is submerged in the material to be sampled (Figure 8.9).
- **Weighted bottle**
  This sampler (Figure 8.10) consists of a glass or plastic bottle, sinker, stopper, and a line that is used to lower, raise, and open the bottle. Weighted bottles are used to sample liquids and free-flowing slurries. A weighted bottle with lime is built to the specifications in ASTM Methods D270 and E300.

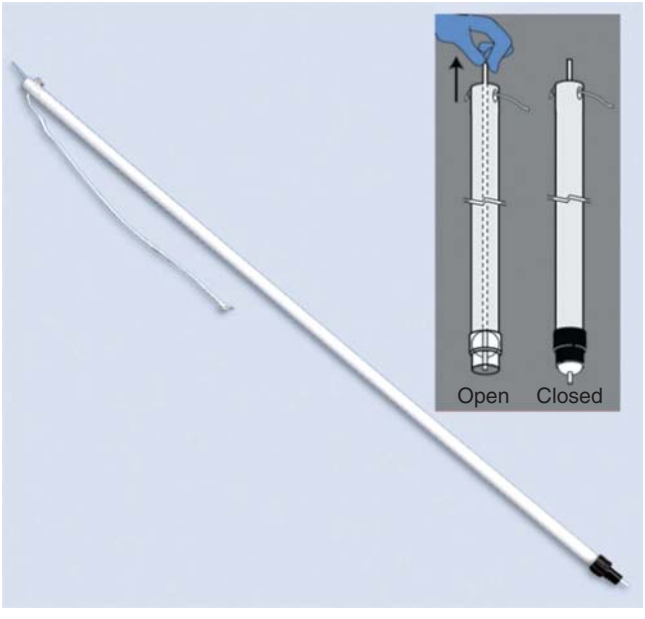


Figure 8.9 *Composite liquid-waste sampler. Source: Reproduced with permission © Enasco.*



Figure 8.10 *Weighted-bottle sampler. Source: Reproduced with permission © Clarkson Lab.*



Figure 8.11 A dipper. Source: Reproduced with permission © Caulfield Industrial.

- **Dipper**
  A dipper (Figure 8.11) consists of a glass, metallic, or plastic beaker clamped to the end of a two- or three-piece telescoping aluminum or fiberglass pole that serves as the handle. Dippers are used to sample liquids and free-flowing slurries. Dippers are not available commercially and must be fabricated.
- **Thief sampler**
  A thief sampler (Figure 8.12) consists of two slotted concentric tubes usually made of stainless steel or brass. The outer tube has a conical pointed tip that permits the sampler to penetrate the material being sampled. The inner tube is rotated to open and close the sampler. A thief is used to sample dry granules or powdered wastes whose particle diameter is less than one-third the width of the slots. Thief samplers are available from laboratory supply stores.
- **Trier sampler**
  A trier sampler (Figure 8.13) consists of a tube cut in half lengthwise with a sharpened tip that allows the sampler to cut into sticky solids and loosen soil. Trier samplers are used to sample moist or sticky solids with a particle diameter less than one-half the diameter of the trier. Trier samplers 61–100 cm long and 1.27–2.54 cm in diameter are available at laboratory supply stores. Larger trier samplers can be fabricated.

  The sampler in Figure 8.13, made from 304 stainless steel, is tapered for extracting a plug of material from solids (soil, clay) or semi-solids (grease, sludge). Its length is 18 cm.



Figure 8.12 *A thief sampler. Source: Reproduced with permission © QAQC LAB.*



Figure 8.13 *A trier sampler. Source: Reproduced with permission © Krackeler Scientific, Inc.*

8.24.11 Air Monitoring of Waste for Employee Protection

This section describes routine operations at an active treatment, storage, or disposal site and the extraordinary conditions that can be encountered in opening and cleaning up a remedial action site.

The user must predict all the difficulties that could develop at waste facility due to hazardous airborne transmissions. Although the air contaminant measurements obtained may indicate that acceptable tolerable levels of toxic agents are present, care must still be exercised before concluding that all atmospheric contaminants at the site are under control.

8.24.11.1 Significance and Use

The techniques of air monitoring are many and varied. This guide is intended to describe the standard approaches that are used in designing and air monitoring programs to protect waste management site workers.

When entering a remedial action site to initiate an investigation or a clean-up operation, operating personnel may be faced with the extreme hazards of fire, explosion, and acute or chronic health hazards. A thorough safety and health program, including a site-specific safety and health plan, must be in place to direct worker activity. Details for such plans can be found in the OSHA Interim Final Rule for Hazardous Waste Operations and Emergency Response. Air monitoring is an integral part of such a program.

Upon obtaining readings at the site, a decision must be made as to whether conditions are under control or not. That decision will depend on the nature of the contaminants (toxicity, reactivity, volatility, etc.), the extent of the problem (area affected, number of workers, etc.), and the level of worker protection available. Since all such parameters will be site specific, the necessary decision-making is beyond the range of this Standard.

This section does not include monitoring sites containing radioactive materials, nor does it cover general safety aspects, such as access to emergency equipment or medical support of emergency needs. These items should be covered in a safety and health plan.

8.24.11.2 Establishing a Test Protocol

Various combinations of equipment and sampling techniques are used in workplace air monitoring. The best monitoring program is one that combines accuracy with a timely response in a cost-effective manner.

The particular test protocol that is selected for an industrial hygiene study depends on the nature of the contaminants and the end purpose of the monitoring effort (i.e. routine monitoring, searching for worst case exposure, looking for contaminant leaks in a process).

8.24.11.3 Selecting Specific Methods

The choice of sampling method is most often tied in with the analytical method. There may be no difference in the analytical work whether it is for a 15-minute ceiling sample or a 7-hour full-day sample. If the analytical method has poor sensitivity, however, it may be necessary to increase the pump flow rate for the short duration sample to make certain that sufficient sample is collected. Such fine adjustments must be worked out between the sampling personnel and the laboratory personnel.

A number of sources of information are available to describe the general methodology. Recommended Practice ASTM D1605 lists some of the classic methods that have been used when sampling for gases or vapors. The American Conference of Governmental Industrial Hygienists offers a publication that provides a review of newer equipment and methodology. The final combination of equipment and procedures is predicted on the precision, accuracy, and sensitivity needed to support the test protocol.

Once the goals and protocol for the sampling program have been set, the specific sampling/analytical method must be selected. Within the Annual Book of ASTM Standards, Volume 11.05 is dedicated to atmospheric analysis and to occupational health and safety issues. Other sources of health and safety support include the NIOSH Manual of Analytical Methods and the OSHA Analytical Methods Manual. The specific equipment and sampling media for a particular set of airborne contaminants are selected from sources such as these.

8.24.12 Procedures

8.24.12.1 Operating Site

The procedures described in this section apply to air-monitoring activities at an operational waste treatment storage or disposal site. At an operating site, controls (work practices, engineering controls, and personal protective equipment) would be in place to minimize the exposure of workers to hazardous conditions. These are defined in the health and safety plan.

8.24.12.1.1 Knowledge of Materials. Knowledge of the materials arriving at or present at an operating site is critical to the design of a sampling plan. If hazardous wastes are arriving they must be listed on the manifest. The results of waste sample analyses will also help to identify the contaminants of greatest concern in an incoming shipment. It is also likely that specific users of the disposal site will tend to be consistent in the types of wastes they send to the site based on the generating process and history of shipment. For example, paint manufacturers will most likely send mixtures of solvents, resins, and pigments, whereas plating firms will generally send alkaline sludge of heavy metal waste, and so on. Deviation from established patterns, however, is possible and should not be discounted in the sampling plan design.

8.24.12.1.2 Worker Sampling. Of all the different techniques for workplace air monitoring, personal sampling of the worker's breathing zone is paramount. While some workers may be quite sedentary in an operations trailer at a control panel, others may be out covering all areas of the work site. For this reason, the assessment must be capable of following the activity of the worker.

The first order of personal monitoring is long duration time weighted average (TWA) sampling. For an 8-hour work shift, TWA samples must be a minimum of 7 hours duration either as a single sample or a series of two or more samples. For any other work hours situation, the procedure is to sample for the duration of the shift less than 1 hour.

For workers handling organic wastes (e.g. vapor degreaser solvent waste) the program should call for charcoal tube sampling with analysis for one or two of the chlorinated solvents most likely to be present in the waste. Such TWA monitoring, as well as the

following information, should be repeated periodically to ensure that worker exposure is not increasing.

Another form of personal monitoring that should be carried out is for peak exposures. For example, 15-minute ceiling samples might be taken while a set of containers is being opened to inspect or remove the contents. The same type of sampling might be done while pumping the contents of a truck into a holding tank. At these times, personal protective equipment (e.g. respiratory protection) is often used to minimize worker exposure to vapors. Ceiling samples will help ensure that workers are using respirators with a high enough protection factor.

Ceiling samples might be the only form of monitoring for certain toxic agents. If waste acid pickling solution were to come in from a steel mill for neutralization, it might be appropriate to sample for hydrogen chloride. In that instance, only 15-minute samples would be of interest because that is how exposure to HCl is controlled by health/regulatory agencies.

New equipment has come into use to cover both TWA and peak sampling. Some personal dosimeters, worn by employees, give an overall average exposure and also record the instantaneous exposure of the worker during the day. These units, which are read out on a portable computer, are generally good for only one particular contaminant, although all the different types are read using the same computer. These might be very useful in monitoring a heavy equipment operator for carbon monoxide or a waste treatment plant attendant for sulfur dioxide.

Another concept to be considered in monitoring, and safety and health plans is the additive effect of certain substances. Another section presents the concept of screening for only one or two solvents. When this is done, the eventual comparison with permissible exposure limits must be made using a safety factor. This safety factor is intended to take account of the possible effects of other similar compounds which are likely to be present but are not measured routinely.

8.24.12.1.3 Area Monitoring. A good complement to personal monitoring is fixed location area monitoring. This can be done with sample collecting-type equipment, direct reading instruments, or specialized fixed-parameter monitors such as those described in Another section. Area monitoring offers the advantage of potentially providing an early warning. A combustible vapor meter in a solvent storage area can give warning before an employee walks in to find a leak.

A carbon monoxide monitoring system around a pyrolyzer or incinerator can warn both the operator in the control room and workers in the loading area of a system upset.

An oxygen meter permanently mounted in a below-ground pit can warn an employee of an oxygen-deficient atmosphere before he enters the confined space.

Direct-reading colorimetric tubes offer a convenient means for obtaining a quick reading. Besides their suitability for qualitative checks, they also provide reasonable quantitative estimates. For more details see ASTM D4844-88.

8.24.13 Hazards

Proper safety precautions must always be observed when sampling wastes. Persons collecting samples must be aware that the waste can be a strong sensitizer and can be corrosive, flammable, explosive, toxic, and capable of releasing extremely poisonous

gases. The background information obtained about the waste should be helpful in deciding the extent of safety precautions to be observed and in choosing the protective equipment to be used.

Personnel should wear protective equipment when response activities involve known or suspected atmospheric contamination, when vapors, gases, or airborne particulates may be generated, or when direct contact with skin-affecting substances may occur. Respirators can protect the lungs, gastrointestinal tract, and eyes against air toxicants. Chemical-resistant clothing can protect the skin from contact with skin-destructive and -absorbable chemicals. Good personal hygiene limits or prevents ingestion of material.

8.24.14 Quality Assurance Considerations

Quality assurance for solid waste sampling should include adherence to the sampling plan and safety plan, and, in some cases, the use of quality control samples.

Four types of quality control samples relate to the quality assurance of field sampling:

1) field blanks
2) split samples
3) field rinsates
4) field spikes.

The selection of the type of quality control samples to be used should be made prior to the sampling event and be included in the sampling plan. The nature of the sampling, the intended uses of the data, and the material being sampled all impact on the selection of quality control samples.

8.25 Emissions to Land

To characterize emissions to land are discussed here:

- groundwater monitoring
- spills.

8.25.1 Groundwater Monitoring

Some facilities conduct monitoring of groundwater to characterize releases from the facility. Where available, this monitoring data may be used to assist in the characterization of releases. This involves determining upstream and downstream concentrations, and using this information, in conjunction with groundwater flow information, to determine the contribution of the facility to pollutant levels in the groundwater.

This approach is reasonable in situations where there is no loss of substances (e.g. due to evaporation) prior to the substance entering the groundwater, and where the time between the release occurring and the substance entering the groundwater is minimal. Therefore, for those facilities where groundwater monitoring captures all releases to land, such monitoring can be used as a reasonable measure of emissions to the environment. If this is not the

case (e.g. where the rate of transmission through the soil/clay is low, or where there are other routes whereby substances to land are carried offsite (such as evaporation or surface runoff), it will be necessary to characterize such releases using the other EETs presented in this section.

8.25.2 Spills

For many facilities, the primary source of releases will be through spills (this may also include intentional spillage due to vessel washdown). Accidental spills can contribute to releases to land (directly), to water (through runoff), and to air.

As discussed above, unless the spilled material is routed to a secure containment facility, the quantity of material spilled, less the quantity collected (or cleaned up), is required to be reported. In practical terms, a log of spillages could be maintained detailing the quantities spilled, and the composition of the spill (in particular, the quantities of NPI substances spilled).

This log could then form part of the information required to meet NPI reporting requirements.

The quantity spilled can be partitioned into air emissions and releases to land by assuming that all of the light end fraction is volatilized and the remaining fraction is released into the ground. The time, quantity of spill, temperature, and porosity of the soil all play an important part in the estimation of release. The evaporation rate of compounds into the atmosphere is given by the following equation:

$$E_i = 1.2 \times 10^{-10} \times (M \times poi/T) \times u^{0.78} \times y^{0.89} \tag{8.7}$$

where:

E_i = evaporation rate of substance i (g/s)
u = wind speed over the surface of the spill (cm/s)
y = crosswind dimension (cm)
M = molecular weight of the substance
poi = vapor pressure of substance i at spill temperature T (dyne/cm^2 = 0.0001 kPa)
T = temperature (K).

Once losses to the atmosphere have been quantified, releases to land can be estimated using the following equation:

$$ER_{\mathrm{LAND},i} = QttySPILL - (t \times (E_i)) \tag{8.8}$$

where:

$ER_{\mathrm{LAND},i}$ = emission to the land of compound i
$QttySPILL$ = quantity of compound in the liquid spilled
E_i = loss through evaporation of substance i as estimated using the evaporation equation above
t = time period between when the liquid was initially spilled and eventual clean up.

8.26 Evaluation of Soil Infiltration Problems

Sodium (Na) is one of the most problematic ions present in excessive concentrations causes specific toxicity. An indirect effect of high sodium content is the deterioration of the physical condition of soil, such as formation of crusts, water logging, and reduced soil permeability. If the infiltration rate is greatly reduced, it may be impossible to supply the crop or landscape plant with sufficient water for good growth. In this section, a simple predictive tool which is easier than existing approaches, being less complicated with fewer computations, is formulated to accurately predict the sodium adsorption ratio (SAR) as a function of the concentration of Na^+, magnesium (Mg^{2+}), calcium (Ca^{2+}), the salinity of applied water, and the ratio of bicarbonate (HCO_3^-) over Ca^{2+} for interpretations of water quality for irrigation.

The proposed method showed consistently accurate results for salinity of applied water up to 8 dS/m and ratio of HCO_3^- over Ca^{2+} up to 20. Predictions showed an excellent agreement with the reported data, with an average absolute deviation of less than 3%.

8.26.1 Predictive Tool

The water infiltration problem occurs within the top few centimeters of the soil and is mainly related to the structural stability of the surface soil. To predict a potential infiltration problem, the SAR is often used:

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \tag{8.9}$$

where the cation concentrations are expressed in meq/l. The adjusted SAR (R_{Na}) is a modification of Eq. (8.9) that takes into account changes in calcium solubility in the soil water. Use of the R_{Na} value is preferred in irrigation applications with reclaimed water because it reflects the changes in calcium in the soil water more accurately. At a given SAR, the infiltration rate increases as salinity increases or decreases as salinity decreases:

$$\text{adj } R_{Na} = \frac{Na^+}{\sqrt{\frac{Ca_x^{2+} + Mg^{2+}}{2}}} \tag{8.10}$$

where Na^+ and Mg^{2+} concentrations are expressed in meq/l and the value of Ca_x^{2+}, also expressed in meq/l, is obtained through the novel predictive tool presented in this work. R_{Na} and the electrical conductivity (EC_w) of the irrigation water should be used in combination to evaluate the potential permeability.

Reclaimed water is normally high in calcium and there is little concern for the water dissolving and leaching too much calcium from the surface soil. However, reclaimed water is sometimes high in sodium; the resulting high SAR is a major concern in planning an irrigation project with reclaimed water.

Table 8.26 *Tuned coefficients used in Eqs (8.12)–(8.15) for estimating absorption efficiency according to reliable data (Metcalf and Eddy 2003).*

Coefficient	Tuned coefficients for $\frac{HCO_3^-}{Ca^{2+}}$ ratio less than 1	Tuned coefficients for $\frac{HCO_3^-}{Ca^{2+}}$ more than 1
A_1	$2.611\,975\,700\,671 \times 10^{-1}$	$-1.261\,315\,558\,414\,8$
B_1	$1.532\,373\,403\,574\,4 \times 10^{-1}$	$-2.655\,970\,585\,552 \times 10^{-1}$
C_1	$-2.530\,151\,232\,964\,7 \times 10^{-2}$	$5.828\,360\,829\,045\,2 \times 10^{-2}$
D_1	$1.571\,168\,859\,802\,3 \times 10^{-3}$	$-3.556\,269\,185\,664\,2 \times 10^{-3}$
A_2	$4.431\,237\,130\,478\,5 \times 10^{-1}$	$7.237\,129\,012\,651$
B_2	$-1.338\,787\,312\,612\,08 \times 10^{-4}$	$1.083\,718\,411\,946\,3 \times 10^{-1}$
C_2	$1.331\,463\,290\,992\,54 \times 10^{-4}$	$-3.453\,721\,069\,700\,1 \times 10^{-2}$
D_2	$-1.492\,096\,496\,081\,5 \times 10^{-5}$	$2.418\,481\,843\,997\,3 \times 10^{-3}$
A_3	$-3.579\,296\,229\,024\,05 \times 10^{-2}$	$-9.624\,785\,380\,063\,9$
B_3	$1.542\,938\,560\,298\,8 \times 10^{-5}$	$-2.348\,109\,969\,710\,9 \times 10^{-1}$
C_3	$-1.484\,126\,577\,012\,2 \times 10^{-5}$	$7.434\,356\,014\,711\,3 \times 10^{-2}$
D_3	$1.651\,786\,981\,818\,1 \times 10^{-6}$	$-5.187\,846\,098\,313\,1 \times 10^{-3}$
A_4	$9.727\,316\,573\,282\,2 \times 10^{-4}$	$4.636\,747\,565\,375$
B_4	$-5.593\,676\,932\,437\,7 \times 10^{-7}$	$1.418\,500\,534\,036\,8 \times 10^{-1}$
C_4	$4.706\,258\,505\,524\,1 \times 10^{-7}$	$-4.469\,049\,976\,561\,4 \times 10^{-2}$
D_4	$-5.124\,896\,840\,135\,8 \times 10^{-8}$	$3.110\,495\,960\,142\,2 \times 10^{-3}$

The required data to develop this method includes reliable data (Metcalf and Eddy 2003) to predict the Ca_x^{2+} parameter in Eq. (8.10) to reflect the changes in calcium in the soil water more accurately, as a function of salinity of applied water (E_c) and ratio of HCO_3^-/Ca^{2+}, R, in meq/l. In this work, the Ca_x^{2+} parameter is predicted by a simple tool.

Eq. (8.11) represents the proposed governing equation in which four coefficients are used to correlate the Ca_x^{2+} parameter values as a function of the ratio HCO_3^-/Ca^{2+} (R) for different salinities of applied water (E_c) where the relevant coefficients are reported in Table 8.26:

$$\ln(Ca_x^{2+}) = a + \frac{b}{R} + \frac{c}{R^2} + \frac{d}{R^3} \tag{8.11}$$

where:

$$a = A_1 + B_1E_c + C_1E_c^2 + D_1E_c^3 \tag{8.12}$$

$$b = A_2 + B_2E_c + C_2E_c^2 + D_2E_c^3 \tag{8.13}$$

$$c = A_3 + B_3E_c + C_3E_c^2 + D_3E_c^3 \tag{8.14}$$

$$d = A_4 + B_4E_c + C_4E_c^2 + D_4E_c^3 \tag{8.15}$$

Below is a summary of the list of symbols in the equations presented above:

A = tuned coefficient

B = tuned coefficient
C = tuned coefficient
D = tuned coefficient
Ca^{2+} = Ca concentration (meq/l)
Na^{+} = Na concentration (meq/l)
Mg^{2+} = Mg concentration (meq/l)
E_c = salinity of applied water (dS/m)
R = ratio of HCO_3^-/Ca^{2+}
R_{Na} = adjusted SAR
SAR = sodium adsorption ratio.

The optimum tuned coefficients (A, B, C, and D) help to cover the Ca_x^{2+} parameter values data reported in the literature (Metcalf and Eddy 2003).

The predictive tool is recommended for salinity of applied water (E_c) up to 8 dS/m and a ratio of HCO_3^-/Ca^{2+} up to 20.

Entering guidelines for interpretations of water quality for the irrigation table reported in Metcalf and Eddy (2003). The coefficients presented in Table 8.26 can be retuned quickly according to the proposed approach if new data become available in the future just by readjusting the tuned coefficients.

Figures 8.14 and 8.15 show the results from the proposed predictive tool in comparison with the reported data (Metcalf and Eddy 2003; Pettygrove and Asano 1985) to predict the Ca_x^{2+} parameter in Eq. (8.11) to reflect the changes in calcium in the soil water more

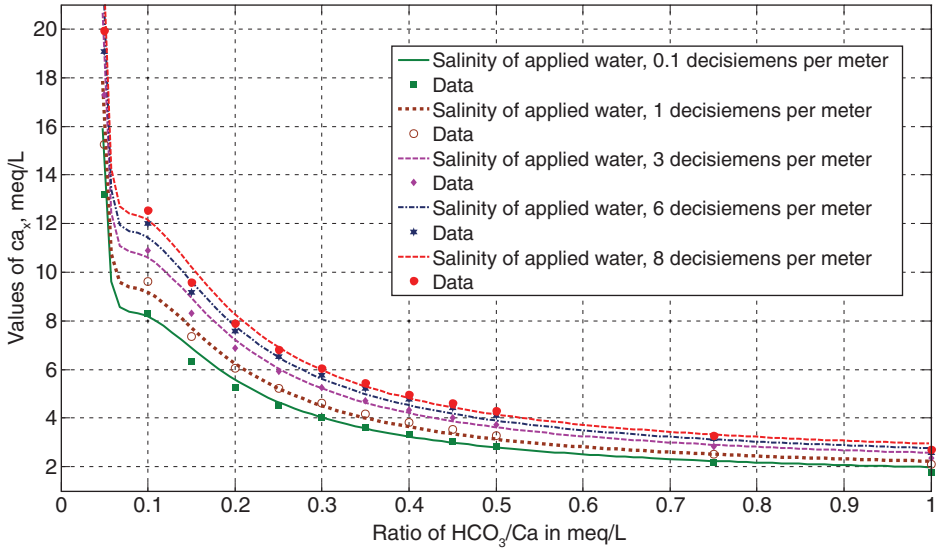


Figure 8.14 *Prediction of* Ca_x^{2+} *in comparison with reported data (Metcalf and Eddy (2003)) for ratio of* HCO_3^-/Ca^{2+} *less than 1. Source: Reprinted with permission. A. Bahadori, M. Al-Haddabi and H.B. Vuthaluru (2012)* Communications in Soil Science and Plant Analysis*, 43 (19), pp. 2492–2503.*

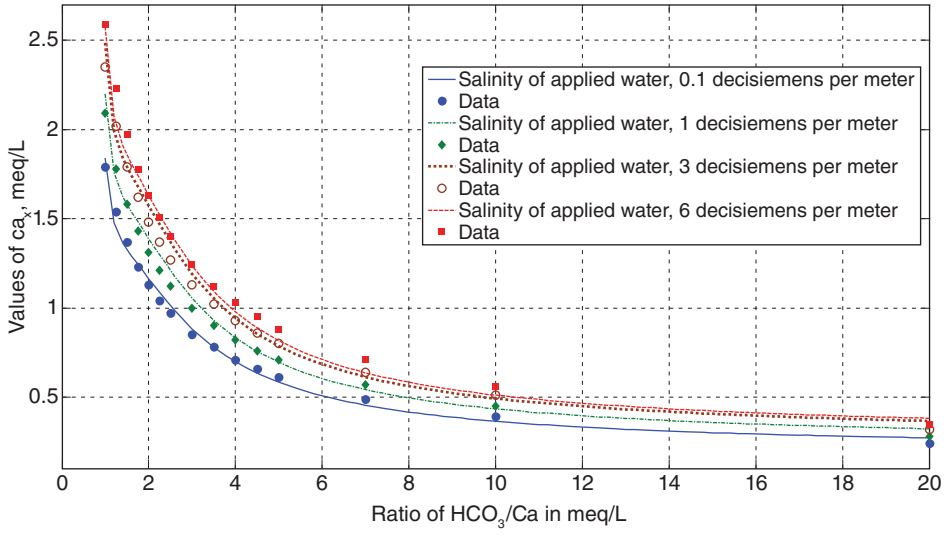


Figure 8.15 *Prediction of* Ca_x^{2+} *in comparison with reported data (Metcalf and Eddy 2003) for ratio of* HCO_3^-/Ca^{2+} *greater than 1. Source: Reprinted with permission. A. Bahadori, M. Al-Haddabi and H.B. Vuthaluru (2012)* Communications in Soil Science and Plant Analysis*, 43 (19), pp. 2492–2503.*

accurately, as a function of salinity of applied water (E_c) and ratio of HCO_3^-/Ca^{2+} (R) in meq/l. It is clear that the proposed method yields results with good accuracy.

A typical example is given below to illustrate the simplicity of the use of the proposed correlation for rapid estimating Ca_x^{2+} to calculate the adsorbed sodium ratio.

8.26.2 Sample Calculations for Practice Engineers

The water quality analyses in Table 8.27 were reported for an aerated lagoon effluent used for irrigating agriculture land. Using the reported water quality data: (i) calculate R_{Na} and (ii) determine whether an infiltration problem may develop by using this effluent for irrigation.

8.26.2.1 Solution

First, convert the concentrations of the related water quality parameters to meq/l:

$Ca^{2+} = 37/20.04 = 1.85$ meq/l
$Mg^{2+} = 46/12.15 = 3.79$ meq/l
$Na^{+} = 410/23 = 17.83$ meq/l
$HCO_3^- = 295/61 = 4.84$ meq/l

Determine the value of Ca_x^{2+} using the given water quality data:

Salinity of applied water, $E_c = 2.4$ dS/m
Ratio of $HCO_3^-/Ca^{2+} = 4.84/1.85 = 2.62$

Table 8.27 Given data in example.

Water quality parameter	Concentration (mg/l)
BOD	39
TSS	160
Total N	4.4
Total P	5.5
pH	7.7
Ca^{2+}	37
Mg^{2+}	46
Na^{+}	410
K^{+}	27
HCO_3^-	295
SO_4^{2-}	66
Cl^-	526
Boron	1.2
Electrical conductivity (dS/m)	2.4
TDS	1536
Alkalinity	242
Hardness	281

Because the ratio of HCO_3^-/Ca^{2+} is more than 1, we use the second column coefficients:

$a = -1.362\,119\,57$	From Eq. (9)
$b = 7.276\,462\,851$	From Eq. (10)
$c = -9.710\,091\,705$	From Eq. (11)
$d = 4.688\,317\,993\,9$	From Eq. (12)
$Ca_x^{2+} = 1.298\,59$	From Eq. (8)

Calculate the R_{Na} using Eq. (2):

$$\text{adj } R_{Na} = \frac{Na^+}{\sqrt{\frac{Ca_x^{2+} + Mg^{2+}}{2}}} = \frac{17.83}{\sqrt{\frac{1.29 + 3.79}{2}}} = 11.19 \tag{8.16}$$

The calculated R_{Na} (11.19) is in good agreement with the reported R_{Na} (11.29), with a deviation of is less than 1%.

In order to determine whether an infiltration problem will develop or not:

According to guidelines for interpretations of water quality for irrigation With R_{Na} (11.19) and salinity of applied water (2.4 dS/m), no restrictions are indicated for use of this reclaimed water.

Definitions and Terminology

Abandonment Discontinued use of a system component or components by removing them or rendering them inaccessible and inoperable.

Absorption Process of incorporation or assimilation by which one substance is physically taken into and included with another substance, for example bacteria assimilating nutrients from effluent.

Activated sludge A flocculent microbial/mass, produced when sewage is continuously aerated. Sludge that has undergone flocculation to form a bacterial culture, typically carried out in tanks. Can be extended with aeration.

Activated sludge process Wastewater treatment process that uses activated sludge to biologically convert non-settleable (suspended, dissolved, and colloidal) organic materials to a settleable product using aerobic and facultative microorganisms. Typically followed by clarification and sludge return.

Acute A stimulus severe enough to rapidly induce an effect. In aquatic toxicity tests, an effect observed in 96 hours or less is typically considered acute. When referring to aquatic toxicology or human health, an acute effect is not always measured in terms of lethality.

Additive Product added to a sewage treatment system marketed to improve performance.

Adsorption Adhesion of a substance to the surface of solid bodies or liquids with which it is in contact.

Advanced primary treatment The use of special additives in raw wastewater to cause flocculation or clumping to help settling before the primary treatment such as screening.

Advanced wastewater treatment Any advanced process used above and beyond the *de facto* typical minimum primary and secondary wastewater treatment.

Aeration The process of bringing about intimate contact between air and a liquid.

Aeration, active Introduction of air via either mechanical means or diffused aeration.

Aeration chamber Chamber or tank in which wastewater is brought into contact with air to facilitate biological degradation such as in (but not limited to) the activated sludge process.

Waste Management in the Chemical and Petroleum Industries, Second Edition. Alireza Bahadori.
© 2020 John Wiley & Sons Ltd. Published 2020 by John Wiley & Sons Ltd.

Aeration, diffused Process of introducing air bubbles under pressure into a treatment unit using a compressor or blower and a diffuser.

Aeration liquor Mixed liquor. The contents of the aeration tank, including living organisms and material carried into the tank by either untreated wastewater or primary effluent.

Aeration, mechanical Process of introducing air into a treatment component by physical agitation using a device such as a paddle, paddle wheel, spray nozzle or turbine.

Aeration, passive Process of introducing air into a treatment component without mechanical means.

Aeration system Piping, diffusers, air source, vents, and all other necessary devices for an active aeration process.

Aeration tank A chamber for injecting air into water. The tank where raw or settled wastewater is mixed with return sludge and aerated. The same as "aeration bay," "aerator," or "reactor."

Aerobic Wastewater treatment depending on oxygen for bacterial breakdown of waste.

Aerobic bacteria Bacteria that require free (elementary) oxygen for growth.

Aerobic decomposition Decomposition and decay of organic material in the presence of "free" or dissolved oxygen.

Aerobic digestion The breakdown of wastes by microorganisms in the presence of dissolved oxygen. This digestion process may be used to treat only waste-activated sludge, or trickling filter sludge and primary (raw) sludge, or waste sludge from activated sludge treatment plants designed without primary settling. The sludge to be treated is placed in a large aerated tank where aerobic microorganisms decompose the organic matter in the sludge. This is an extension of the activated sludge process.

Aerobic process A waste treatment process conducted under aerobic (in the presence of "free" or dissolved oxygen) conditions.

Aerobic treatment unit (ATU) (i) Treatment component that utilizes oxygen to degrade or decompose wastewater, with or without mechanical means. (ii) Term traditionally used to describe proprietary devices that use direct introduction of air into wastewater by mechanical means to maintain aerobic conditions within the pretreatment component.

Aerobic wastewater treatment Oxygen-dependent wastewater treatment requiring the presence of oxygen for aerobic bacterial breakdown of waste.

Agglomeration The grouping or coming together of dispersed suspended matter into larger particles, called "iloc," which settle more rapidly.

Aggregate (i) Primary soil particles that cohere to each other more strongly than other surrounding particles. (ii) Naturally occurring inorganic material (crushed rock or gravel) screened into sizes for various uses.

Air scour The use of air either alone or in combination with backwash to enhance filter cleaning.

Algae Microscopic plants which contain chlorophyll and live floating or suspended in water. They also may be attached to structures, rocks or other similar substances. Algae produce oxygen during sunlight hours and use oxygen during the night hours. Their biological activities appreciably affect the pH and dissolved oxygen of the water.

Alkaline The condition of water or soil that contains a sufficient amount of alkali substances to raise the pH above 7.0.

Alkalinity A measure of a substance's ability to neutralize acid. Water containing carbonates, bicarbonates, hydroxides, and occasionally borates, silicates, and phosphates can be alkaline. Alkaline substances have a pH value over 7.

Ammonia (NH_3) A chemical combination of hydrogen (H) and nitrogen (N) found extensively in nature. An indicator of fresh pollution.

Anaerobic Wastewater treatment in which bacteria break down waste without using oxygen.

Anaerobic bacteria Bacteria that grow in the absence of free oxygen and derive oxygen from breaking down complex substances.

Anaerobic wastewater treatment Wastewater treatment in the absence of oxygen, anaerobic bacteria break down waste.

Anoxic Condition in which all constituents are in their reduced form (no oxidants present). Conditions in a septic tank are generally anaerobic, but not anoxic.

Antidegradation Policies which ensure protection of water quality for a particular water body where the water quality exceeds the level necessary to protect fish and wildlife propagation, and recreation on and in the water. This also includes special protection of waters designated as outstanding natural resource waters. Antidegradation plans are adopted by each state to minimize adverse effects on water.

Aquifer A geologic formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit water.

Areal fill Above-grade soil treatment area designed and installed such that the entire infiltrative surface is located above the original ground elevation using suitable imported soil material for fill. Utilizes gravity, pressure-dosed gravity or low-pressure distribution. A final cover of suitable soil stabilizes the completed installation and supports vegetative growth.

Attached-growth process Configuration in which the microorganisms responsible for treatment colonize a fixed medium.

Average monthly discharge limitations The highest allowable average of daily discharges over a calendar month, calculated as the sum of all daily discharges measured during that month divided by the number of days on which monitoring was performed (except in the case of fecal coliform).

Average weekly discharge limitation The highest allowable average of daily discharges over a calendar week, calculated as the sum of all daily discharges measured during a calendar week divided by the number of daily discharges measured during that week.

Backfill (i) Material placed in an excavation. (ii) To place material in an excavation. (iii) Portion of an excavation above the haunch zone. For straight-walled tanks or structures, that portion of an excavation above the bedding.

Backfill, initial Portion of an excavation above the haunch zone or bedding with a depth of 6–12 in. (15–30 cm) above the piping, conduit tank, or structure.

Backfill, final Portion of an excavation extending from above the initial backfill to the final grade.

Backflow Reverse direction of flow, with liquid returning to the source.

Backflow prevention device Any device, method, or configuration used to prevent a reversal of flow.

Backflush To reverse the direction of flow to clean laterals or filter media.

Backwash To clean a granular media bed by means of an upward flow of clean water.

Bacteria Single cell microscopic living organisms lacking chlorophyll, which digest many organic and inorganic substances. An essential part of the ecosystem, including within human beings.

Bacteria, aerobic Bacteria that can metabolize only in the presence of molecular oxygen.

Bacteria, anaerobic Bacteria that can metabolize in the absence of molecular oxygen.

Bacteria, facultative Bacteria that can metabolize with or without molecular oxygen present in the environment.

Bacteria, mesophilic Bacteria which grow best at temperatures between 20 and 50 °C (68 and 122 °F) with optimum growth between 25 and 40 °C (77 and 104 °F).

Bacteria, psychrophilic Bacteria which grow best at temperatures between 10 and 30 °C (50 and 86 °F) with optimum growth between 12 and 18 °C (54 and 64 °F).

Bacteria, thermophilic Bacteria which grow best at temperatures between 35 and 75 °C (95 and 167 °F) with optimum growth between 55 and 65 °C (131 and 149 F).

Baffle Physical barrier placed in a component to dissipate energy, direct flow, retain solids and FOG, and/or draw water from a specific depth.

Best available technology economically achievable (BAT) Technology-based standard established by the Clean Water Act as the most appropriate means available on a national basis for controlling the direct discharge of toxic and non=conventional pollutants to navigable waters. BAT effluent limitation guidelines, in general, represent the best existing performance of treatment technologies that are economically achievable within an industrial point source category or subcategory.

Bioassay A test used to evaluate the relative potency of a chemical or a mixture of chemicals by comparing its effect on a living organism with the effect of a standard preparation on the same type of organism.

Biochemical oxygen demand (BOD) The rate at which organisms use the oxygen in water or wastewater while stabilizing decomposable organic matter under aerobic conditions. In decomposition, organic matter serves as food for the bacteria and energy results from its oxidation. BOD measurements are used as a measure of the organic strength of wastes in water.

Biodegradation The breakdown of organic matter by bacteria to more stable forms which will not create a nuisance or give off foul odors.

Bioengineering A low-tech construction method using living plants as a functioning, self-sustaining part of the system. Examples include control of erosion of stream banks, water quality treatment, and flood control and habitat restoration.

Biofilm Thin coating of microbial growth, organic matter, and microbial secretions on a solid substrate particle.

Biofilter Media filter in which the media used is biological in origin (i.e. peat or coir).

Biological filter A bed of relatively inert material (such as slay, molded plastics, clinker, etc.) to promote or assist natural aerobic degradation of sewage.

Biological nutrient removal (BNR) Use of microbiological activity for removal of nitrogen and phosphorus in a wastewater treatment system.

Biological oxidation The process by which bacteria and other types of microorganisms consume dissolved oxygen and organic substances in wastewater, using the energy released to convert organic carbon into carbon dioxide and cellular material.

Biomass A mass or clump of organic material consisting of living organisms feeding on the wastes in wastewater, dead organisms, and other debris.

Bio-solids Rich organic material leftover from aerobic wastewater treatment, essentially dewatered sludge that can be reused.

Blackwater Portion of the wastewater stream that originates from toilet fixtures, dishwashers, and food preparation sinks.

Bleed To drain a liquid or gas, as in bleeding accumulated air from a water line or bleeding (draining) a trap of accumulated water.

BOD5 The five-day biochemical oxygen demand. The total amount of oxygen used by microorganisms decomposing organic matter increases each day until the ultimate BOD is reached, usually in 50 to 70 days. BOD usually refers to the five-day BOD.

Branches Branches are collection from various drain funnels, catch basins, and area drains and tie into sublaterals. They are called T, Y, T-Y, double Y, and V branches according to their respective shapes.

Bubble, coarse Bubble of 3–8 mm diameter generated by an air diffuser.

Bubble, fine Bubble of 0.2–3 mm diameter generated by an air diffuser.

Bubble, micro Bubble of less than 0.2 mm diameter generated by an air diffuser.

Building sewer Piping that conveys wastewater to the first system component or the sewer main.

Bulking Inability of sludge solids to separate from the liquid under quiescent conditions. Under aerobic conditions bulking may be associated with the growth of filamentous organisms, low dissolved oxygen, or high sludge loading rates. Under anaerobic conditions bulking may be associated with attachment of gas bubbles to solids.

Buoyancy Tendency of a body to float in water or other liquid. The upward force that a fluid exerts on an object that is less dense than itself.

Bypass The intentional diversion of waste streams from any portion of a treatment (or pretreatment) facility.

Catch basins Catch basins are used to collect surface drainage and process wastes in individual drainage areas and to trap sediment at the point nearest the source.

Catchment area An area defined by a number of effluent streams which have a common discharge directed into a surface water drainage system or water course.

Cesspool A covered watertight tank used for receiving and storing sewage from premises which cannot be connected to a public sewer and where ground conditions prevent the use of a small sewage treatment works, including a septic tank. A further stage of treating sewage.

Chamber Pre-formed manufactured distribution medium with an open-bottom configuration commonly used in soil treatment areas.

Chemical oxygen demand (COD) The equivalent amount of oxygen consumed under specified conditions in the chemical oxidation of the organic and oxidizable inorganic matter contained in wastewater, corrected for the influence of chlorides. In American practice, unless otherwise specified, the chemical oxidizing agent is hot acid dichromate.

Chlorination The application of chlorine to water, sewage, or industrial wastes, generally for the purpose of disinfection, but frequently for accomplishing other biological or chemical wastewater treatment results.

Chlorine Term commonly used to describe a chlorine source such as sodium hypochlorite, a highly reactive chemical used as a disinfectant and oxidizing agent.

Chlorine, combined available Chlorine that has combined with ammonia in wastewater to form chloramines. Although they are slow-reacting, chloramines also serve as disinfectants.

Chlorine, residual Total amount of chlorine (free and combined available forms) remaining in water, sewage, or industrial wastes at the end of a specified contact period after the chlorination process.

Clarification Any process or combination of processes the main purpose of which is to reduce the concentration of suspended matter in a liquid.

Clarifier A large circular or rectangular tank or basin in which water is held for a period of time during which the heavier suspended solids settle to the bottom. Clarifiers are also called settling basins and sedimentation basins. May also be a tank or basin in which wastewater is held for a period of time during which the heavier solids settle to the bottom and the lighter materials float to the water surface.

Cleanout Device designed to provide access for removal of deposited or accumulated materials, generally from a pipe.

Clear water Fraction of the wastewater stream including, but not limited to, surface water, groundwater, condensate, ice machine drainage, and/or discharge from swimming pools, hot tubs, and water-treatment devices.

Coagulant A chemical that causes very fine particles to clump (floc) together into larger particles. This makes it easier to separate the solids from the liquids by settling, skimming, draining, or filtering.

Coagulant aids Materials added to enhance the action of coagulants, generally by affecting the electrical balance of the particles.

Coagulation The clumping together of very fine particles into larger particles (floc) caused by the use of chemicals (coagulants). The chemicals neutralize the electrical charges of the fine particles, allowing them to come closer and form larger clumps. This clumping together makes it easier to separate the solids from the water by settling, skimming, draining or filtering.

Cold climate limitations Cold temperatures, ice cover, plant dormancy, equipment performance, ice build-up, and reduced microbial action create design challenges for cold weather wastewater treatment.

Colloids Very small solids (particulate or insoluble material) in a finely divided form that remain dispersed in a liquid for a long time due to their small size and electrical charge.

Combined sewer Carries both sanitary sewage and storm water runoff. Sewer systems in which the storm water and sanitary waste are combined. A benefit is that non-point pollution flushed from the watershed during moderate rain is treated, but the system can be overwhelmed during severe storms, resulting in untreated waste being flushed into the receiving waters as a combined sewer overflow.

Combined wastewater A mixture of storm or surface runoff and other wastewater such as domestic or industrial wastewater.

Comminution A mechanical treatment process which cuts large pieces of waste into smaller pieces so they won't plug pipes or damage equipment (shredding).

Comminutor A device used to reduce the size of the solid chunks in wastewater by shredding (comminuting). The shredding action is like many scissors cutting or chopping to shreds all the large solids material in the wastewater.

Constructed wetland A wetland constructed for the purpose of pollution control and waste management. The flow rate, residence time, and other factors are controlled to enhance the removal of BOD, SS, and N. A waterproof barrier is usually placed below the substrate to isolate the wastewater from the groundwater. Plants such as cattails, bulrushes, and reeds provide a dense cover and an oxygenating substrate for bacteria in the root zone.

Conventional pollutants Pollutants typical of municipal sewage, for which municipal secondary treatment plants are typically designed. Defined by Federal Regulation [40 CFR 401.16] as BOD, TSS, fecal coliform bacteria, oil, and grease.

Conventional septic system A wastewater treatment system consisting of a septic tank and a typical trench or bed subsurface wastewater infiltration system.

Corrosion The gradual decomposition or destruction of a material by chemical action, often due to an electrochemical reaction. Corrosion may be caused by (i) stray current electrolysis, (ii) galvanic corrosion caused by dissimilar metals, or (iii) differential-concentration cells. Corrosion starts at the surface of a material and moves inward.

Corrosion inhibitors Substances that slow the rate of corrosion.

Corrosive A chemical that can cause burns to the skin, eyes or respiratory system.

Corrosive gases In water, dissolved oxygen reacts readily with metals at the anode of a corrosion cell, accelerating the rate of corrosion until a film of oxidation products such as rust forms. At the cathode, where hydrogen gas may form a coating on the cathode and slow the corrosion rate, oxygen reacts rapidly with hydrogen gas forming water, and again increases the rate of corrosion.

Daily discharge The discharge of a pollutant measured during any 24-hour period that reasonably represents a calendar day for the purposes of sampling. For pollutants with limitations expressed in units of mass, the daily discharge is calculated as the total mass of the pollutant discharged during the day. For pollutants with limitations expressed in other units of measurement (e.g. concentration) the daily discharge is calculated as the average measurement of the pollutant throughout the day.

Dechlorination Removal of the free and combined chlorine residual to reduce the potentially toxic effects of chlorinated effluents.

Degradation The conversion or breakdown of a substance to simpler compounds, for example the degradation of organic matter to carbon dioxide and water.

Denitrification An anoxic process that occurs when nitrite or nitrate ions are reduced to nitrogen gas and nitrogen bubbles are formed as a result of this process. The bubbles attach to the biological floc in the activated sludge process and float the floc to the surface of the secondary clarifiers. This condition is often the cause of rising sludge observed in secondary clarifiers or gravity thickeners.

Design population The minimum and maximum number of persons (resident and non-resident) to be served.

Detention time (retention time, residence time) The average period of time wastewater stays in a treatment system. Detention times vary for different types of wastewater treatment systems and can range from hours to weeks.

Dewatered sludge Sludge after it has been dewatered. Also known as sludge cake.

Dewatered sludge cake Sludge after dewatering, which is cake-like, compressed. The lower the water content the better for wastewater treatment purposes.

Dewatering Removing water from sludge or other solids.

Diffuser Part or device that injects air under pressure into wastewater (e.g. submerged porous plate, perforated pipe, or orifice).

Digestion The breaking down of sludge and other waste biologically by microorganisms. Results in by-products such as methane gas, carbon dioxide, sludge solids, and water. Aerobic digestion requires oxygen, anaerobic digestion the absence of oxygen.

Discarded material Used or spent material that is not reused in any way and is committed to final disposition.

Disinfection The use of chemicals to kill any disease-causing organisms in the polished wastewater. UV light can also be used.

Dispersion (i) Scattering and mixing. (ii) Repellant action of an electric potential on fine particles in suspension in water, as in a stream carrying clay.

Disposal The discharge, deposit, injection, dumping, spilling, leaking, or placing of any solid waste or hazardous waste into or on any land or water so that such solid waste or hazardous waste or any constituent thereof may enter the environment, be emitted into the air, or be discharged into any waters, including groundwater. Thus, waste deposited in a landfill, land farmed wastewater discharged to a basin or surface impoundment, or stormwater runoff diverted to a percolation or settling pond is disposal.

Disposal well A deep well used for the disposal of liquid wastes.

Dissolved oxygen (DO) The oxygen dissolved in sewage, water, or other liquid, usually expressed in milligrams per liter or percent of saturation. It is the test used in BOD determination.

Dissolved solids Solids physically suspended in sewage that cannot be removed by proper laboratory filtering.

Dosing, demand Configuration in which a specific volume of effluent is delivered to a component based upon patterns of wastewater generation from the source.

Drain Small sewer connections discharging through a sealed connection to the nearest catch basin from points such as pump bases, equipment drips, low points of floors, funnels, etc.

Drain, interceptor Subsurface drain used to intercept and divert laterally moving groundwater or perched water away from the soil treatment area or other system component to an effective outlet.

Drainage Network of natural or artificial groundwater or surface water features, including agricultural drain tiles, cut banks, and ditches, which intercept and divert surface water and/or lower groundwater.

Drawdown Drop in the liquid level of a tank as a result of some phase of operation.

Drawdown test Measurement of the drop in liquid level in a dosing tank measured over time to calculate dosing/delivery rate. May be expressed as the pump delivery rate or siphon delivery rate.

Drip system A separate drain system for recovery of oil from contaminated fluids.

Ecological engineering The design, management or reconstruction of sustainable ecosystems that serve human needs such as providing clean water and food while requiring low energy inputs. Ecological engineering has enhanced our understanding of environmental problems such as wastewater treatment, wetlands damage and mitigation, the effect of non-point pollution on ecosystems, and ecosystem restoration.

Effluent Liquid which flows out of a containing space and/or sewage, water or other liquid, partially or completely treated, or in its natural state, as may flow out of a reservoir, basin, or treatment plant, or part thereof.

Effluent limitation Any restriction (including schedules of compliance) established by a governmental authority on quantities, rates, and concentrations of chemical, physical, biological, and other constituents which are discharged from point sources into navigable waters, the waters of the contiguous zone, or the ocean.

Effluent quality Physical, biological, and chemical characteristics of a liquid flowing from a component or device.

Effluent screen Removable, cleanable (or disposable) device installed on the outlet piping of a septic tank for the purpose of retaining solids larger than a specific size and/or modulating effluent flow rate.

Emerging contaminants Newly identified compounds or substances that have the potential to adversely affect public health or the environment and for which there is no currently published health standard.

Emulsification Suspension of solids as a result of decreased surface tension due to the presence of an emulsifying agent or some substance that alters or prohibits normal microbial activity.

Emulsifying agent Agent capable of modifying the surface tension of emulsion droplets to prevent coalescence. Examples are soap and other surface-active agents, certain proteins and gums, water-soluble cellulose derivatives, and polyhydric alcohol esters and ethers.

Emulsion A mixture of two or more liquids which cannot be combined, therefore one liquid is "suspended" in the other.

Endogenous respiration Auto-oxidation by organisms in biological processes.

Environmental sensitivity Relative susceptibility of the natural environment to adverse impacts from an outside constituent.

Extended aeration An aeration system that adds aerobic sludge digestion to the activated sludge process.

Extension Alteration of a wastewater treatment system resulting in an increase in capacity, lengthening, or expansion of the existing collection, treatment or dispersal component.

Facultative pond A wastewater treatment pond that includes surface aeration and algal photosynthesis for oxygen replenishment.

Filter Device that removes constituents through processes such as sieving, stagnation, adsorption, or absorption. A filter has both area and depth with respect to flow.

Filter, activated carbon Device filled with a porous form of carbon that is used to decolorize liquids, recover solvents, and remove toxins and odors from water and air.

Filter, bottomless media Media filter that does not incorporate a liner or other physical barrier between the media and the existing soil on which it has been placed. Used as a final treatment and dispersal component.

Filter, coir Media filter that uses organic fibric material (coir) from the outer husk of coconuts.

Filter, disc Device consisting of concentrically grooved discs stacked one upon the other and used for removal of particles larger than a specific size. Typically used in drip distribution systems.

Filter, media Device that uses materials designed to treat effluent by reducing BOD and/or removing suspended solids in an unsaturated environment. Biological treatment is facilitated via microbial growth on the surface of the media.

Filter medium The material of which the biological filter is formed and on which a biological film containing bacteria and fungi develops.

Filter, peat Media filter that uses appropriate organic fibric material (peat) as the media. Typically packaged as prefabricated modular units with the media in a container. A type of biofilter.

Filter, sand Media filter which uses sand of particular specifications as the media.

Filter, screen Filter consisting of a mesh material configured as a cylinder and used to remove particles larger than a specific size in pressurized systems.

Filter, trickling Type of media filter which uses a variety of media such as rigid plastics of varying shapes, stone, or tire chips. Includes a clarifier in its configuration and may include a recirculation mode.

Filter, upflow Media filter through which wastewater flows from a lower to a higher elevation. Usually characterized by an anaerobic environment.

Filter run The time of filter operation between backwashes.

Filtration Removal of suspended materials using processes such as sieving, stagnation, adsorption, absorption, and possibly biochemical degradation.

Final effluent The effluent discharged from a sewage treatment plant.

Final treatment and dispersal Last treatment component (or combination of components) through which effluent is returned to the hydrologic cycle via a soil treatment area or a discharging outfall.

Floc The agglomeration of smaller particles in a gelatinous mass that can be more easily removed from the liquid than the individual small particles.

Flocculant Same as flocculating agent, the catalyst substance that causes the chemical reaction with TSS to form flocculent, often encapsulating the solids.

Flocculating agent The flocculant or chemical used to cause flocculation.

Flocculation The provision of retention time with gentle agitation to allow the floc particles or precipitate associated with the impurities to increase in size by agglomeration.

Flocculent The "floc" or wooly mass of clusters that is formed in flocculation. Often used interchangeably with flocculant, but really refers to the floc mass and not the catalyst flocculating agent.

Flow, instantaneous Highest recorded flow occurring within a short specific period of time (expressed in gallons per minute).

Flow, peak Highest flow occurring within a specified time (minutes, hours, days, etc.). May be further expressed as peak hourly flow, peak daily flow, peak monthly flow, peak seasonal flow, etc.

Flow, surge Flow of effluent that occurs in a short enough period of time that it upsets the function of one or more components of the treatment train.

Flow equalization System configuration that includes sufficient effluent storage capacity to allow for uniform flow to a subsequent component despite variable flow from the source.

Free water surface (FWS) wetland A lined basin or channel with porous plant substrate and wetland vegetation in which the shallow water is exposed to the air.

Fungi Small, non-chlorophyll-bearing plants, without roots, stems or leaves, which tend to overpower bacteria at low pH and dissolved oxygen concentrations. They generally have a filamentous-type structure and are therefore not welcome in a secondary process clarifier.

Grab sample A sample which is taken from a waste stream on a one-time basis without consideration of the flow rate of the waste stream and without consideration of time.

Granular media The material used to effect filtration.

Graywater Water captured from non-food preparation sinks, showers, baths, spa baths, clothes washing machines, and laundry tubs.

Grease Fats, soaps, oils, waxes, etc. in wastewater.

Grit Heavy, inorganic matter, such as sand or pebbles.

Grit chamber Usually in municipal wastewater treatment, a chamber or tank in which primary influent is slowed down so heavy typically inorganic solids can drop out, such as metals and plastics.

Groundwater Subsurface water in the saturation zone from which wells and springs are fed. In a strict sense the term applies only to water below the water table. Also called "phreatic water" and "plerotic water."

Hazardous waste Hazardous waste is solid waste which poses specified health and environmental hazards.

Headworks The beginning of the treatment plant where the influent begins treatment.

Heavy metals Metals which can be precipitated by hydrogen sulfide in an acid solution, including lead, silver, gold, mercury, bismuth, and copper.

Hydraulic seals Seals that are used to isolate various parts of a sewer system, preventing vapor travel and spread of fire or explosion.

Hydrogen ion concentration [H+] The weight of hydrogen ion in moles per liter of solution. Commonly expressed as the pH value, which is the logarithm of the reciprocal of the hydrogen ion concentration.

Hydrogen sulfide gas (H_2S) Hydrogen sulfide is a gas with a rotten egg odor that is produced under anaerobic conditions. Hydrogen sulfide gas is particularly dangerous because it dulls the sense of smell so that you don't notice it after you have been around it for a while. In high concentrations, hydrogen sulfide gas is only noticeable for a very short time before it dulls the sense of smell. The gas is very poisonous to the respiratory system, explosive, flammable, colorless, and heavier than air.

Hydrolysis Conversion of organic nitrogen to ammonia by enzymes secreted by bacteria, plants, and animals in a reaction that adds water.

Immediate oxygen demand (IOD) The amount of oxygen that is utilized by the components of a wastewater within 15 minutes (unless otherwise specified) after being introduced into water that contains dissolved oxygen.

Impermeable Not permitting the passage of fluid through pores. In practical terms, some small level of hydraulic conductivity may occur, but at so low a level (e.g. $1 \times 10–7$ cm/s) that it is considered to be negligible.

Industrial ecology Industrial ecology focuses on combining perpetually desirable outcomes in the environment, economy, and technology sustainably. The primary tenet is that all systems mimic nature and are thus closed loop, continuous, and circular. In wastewater treatment industrial ecology means that all so-called "waste" is re-input into the same or other process. For example, biosolids as fertilizer can be considered a use of

sludge consistent with industrial ecology. Recycling wastewater into the treatment plant, manufacturing or other process is another example.

Industrial sources Non-municipal or industrial sources often generate wastewater that is discharged to surface waters. The types of wastewaters generated at a facility depend on the specific activities undertaken at a particular site, and may include manufacturing or process wastewaters, cooling waters, sanitary wastewater, and stormwater runoff.

Industrial wastes The solid and liquid wastes originating from industrial processes.

Industrial wastewater treatment Wastewater treatment for industries such as manufacturing, food processing, corrugators, printing, and so on. Paper and pulp mill treatment of wastewater is an example of industrial wastewater treatment. Municipal wastewater treatment is an example not considered to be industrial.

Infiltration The seepage of groundwater into a sewer system, including service connections. Seepage frequently occurs through defective or cracked pipes, pipe joints and connections, interceptor access risers and covers, or manhole walls.

Infiltration/inflow The total quantity of water from both infiltration and inflow without distinguishing the source.

Inflow Water discharged into a sewer system and service connections from such sources as, but not limited to, roof leaders, cellars, yard and area drains, foundation drains, cooling water discharges, drains from springs and swampy areas, around manhole covers or through holes in the covers, cross-connections from storm and combined sewer systems, catch basins, storm waters, surface runoff, street wash waters or drainage. Inflow differs from infiltration in that it is a direct discharge into the sewer rather than a leak in the sewer itself.

Influent Water, wastewater, or other liquid – raw (untreated) or partially treated – flowing into an interceptor, reservoir, basin, treatment process, or treatment plant. The untreated wastewater or raw sewage coming into a wastewater treatment plant.

Influent screens Screens used to remove large inorganic solids from the waste stream.

Inhibitory substances Materials that kill or restrict the ability of organisms to treat wastes.

Injection well Well by which effluent is transmitted to an underground formation. In most cases these are regulated and require a permit from a regulatory authority.

Inorganic Material such as sand, salt, iron, calcium salts, and other mineral materials. Inorganic substances are of mineral origin, whereas organic substances are usually of animal or plant origin. See also "organic."

Inorganic material Material that will not respond to biological action (sand, cinders, stone). Non-volatile fraction of solids.

Inorganic waste Waste material such as sand, salt, iron, calcium, and other mineral materials that is only slightly affected by the action of organisms. Inorganic wastes are chemical substances of mineral origin, whereas organic wastes are chemical substances of an animal or plant origin.

Innovative and alternative (I&A) A term defined by the EPA to describe non-conventional technologies. Alternative systems are fully proven systems that reclaim or reuse wastewater, productively recycle wastewater components, recover energy, or eliminate the discharge of pollutants. A variety of wastewater treatment systems have been included in the definition, including land treatment, aquaculture, containment ponds, and on-site treatment using small diameter or vacuum sewers.

Innovative and alternative (I&A) An EPA term for wastewater treatment systems that reuse all or part of the wastewater.

Lagoon Constructed basin lined with either soils with very low permeability or a synthetic material, surrounded with berms and which contains at least 3 ft. of wastewater which utilizes sunlight, wind or mechanical aeration, and natural bacteria to break down waste via physical, chemical, and biological processes.

Lagoon, evaporation Lagoon where wastewater is stored and the water is allowed to evaporate over time.

Lagoon, storage Lagoon where some form of wastewater is stored before it is either conveyed to another component for further processing or is reused.

Lagoon sludge Lagoon sludge is a relatively shallow basin or natural depression used for the storage or digestion of sludge, sometimes for its ultimate detention or dewatering.

Laterals Sewers collecting the effluent from two or more sublaterals discharging to the mains.

Lime Any of several compounds consisting of calcium hydroxide ($Ca(OH)_2$) or calcium oxide (CaO).

Liquefaction Liquefaction as applied to sludge digestion means the transformation of large solid particles of sludge into either a soluble or a finely dispersed state.

Liquid/solids separation The process of separating the liquids and solids in a given wastewater. Liquid/solids separation comes in one of three processes: (i) if the solids sink (specific gravity greater than 1) use a clarifier, (ii) if the solids float (specific gravity less than 1) use a floatation unit (DAF), (iii) if they neither sink nor float (specific gravity is 1) try using a screen (rotary or parabolic).

Loading Quantity of material applied to a device at one time.

Loading rate, areal Quantity of effluent applied to the footprint of the soil treatment area (or the absorption area of an above-grade soil treatment area) expressed as volume per area per unit time, e.g. gallons per day per square foot (gpd/sq. ft.).

Loading rate, biochemical Quantity of BOD5 delivered to a treatment component expressed as mass per time (e.g. pounds of BOD5 per day).

Loading rate, biological Quantity of organic matter delivered to a treatment component expressed mass per time (e.g. pounds per day).

Loading rate, mass Sum of organic and inorganic effluent constituents delivered to a treatment component in a time interval, expressed as mass per time.

Loading rate, nutrient Sum of organic and inorganic nutrients (primarily nitrogen and phosphorus) delivered to a treatment component in a specified time interval expressed as mass per time.

Loading rate, organic Biodegradable fraction of chemical oxygen demand (biochemical oxygen demand and volatile solids) delivered to a treatment component in a specified time interval expressed as mass per time or area, e.g. pounds per day or pounds per cubic foot per day (pretreatment), pounds per square foot per day (infiltrative surface or pretreatment). Typical residential system designs assume biochemical loading equals organic loading;

Local limits Conditional discharge limits imposed by municipalities upon industrial or commercial facilities that discharge to the municipal sewage treatment system.

Main sewer A sewer line that receives wastewater from many tributary branches and sewer lines, and serves as an outlet for a large territory or is used to feed an intercepting sewer.

Make-up water Water supplied to replenish the water of a system.

Malfunction Condition in which a component is not performing as designed/installed.

Manholes Manholes are used in sewer mains as junction points and sediment traps, and to provide access for maintenance and inspection.

Media The material in a trickling filter on which slime accumulates and organisms grow. As settled wastewater trickles over the media, organisms in the slime remove certain types of wastes thereby partially treating the wastewater. Also the material in a rotating biological contactor or in a gravity or pressure filter.

Microorganisms Very small organisms that can be seen only through a microscope. Some microorganisms use the wastes in wastewater for food and thus remove or alter much of the undesirable matter.

Mixed liquor The combination of primary effluent and active biological solids (return sludge) in the activated sludge process that is fed into the aeration tank.

Mixed liquor suspended solids (MLSS) Suspended solids in the mixed liquor of an aeration tank.

Mixed liquor volatile suspended solids (MLVSS) The organic or volatile suspended solids in the mixed liquor of an aeration tank. The volatile portion is used as a measure or indication of the microorganisms present.

Mixed media gravity filter A filter using more than one filtering media (such as coal and sand).

Mixing zone An area where an effluent discharge undergoes initial dilution and is extended to cover the secondary mixing in the ambient water body. A mixing zone is an allocated impact zone where water quality criteria can be exceeded as long as acutely toxic conditions are prevented.

Natural systems Ecologically based biological wastewater treatment systems such as constructed wetlands having minimal dependence on mechanical elements.

Neutralization Addition of an acid or alkali (base) to a liquid to cause the pH of the liquid to move toward a neutral pH of 7.0.

Nitrification An aerobic process in which bacteria change the ammonia and organic nitrogen in wastewater into oxidized nitrogen (usually nitrate). The second-stage BOD is sometimes referred to as the nitrification stage (first-stage BOD is called the carbonaceous stage).

Nitrification stage A stage of decomposition that occurs in biological treatment processes when aerobic bacteria, using dissolved oxygen, change nitrogen compounds (ammonia and organic nitrogen) into oxidized nitrogen (usually nitrate). The second-stage BOD is sometimes referred to as the nitrification stage (first-stage BOD is called the carbonaceous stage).

Nitrifying bacteria Bacteria that change the ammonia and organic nitrogen in wastewater into oxidized nitrogen (usually nitrate).

Nitrobacteria Principal genera of autotrophic bacteria responsible for the second step of biological nitrification: conversion (oxidation) of nitrite to nitrate.

Nitrogen (N) This nutrient is present in various forms in wastewater, principally ammonia and nitrate.

Nitrogen fixation The conversion of nitrogen gas to organic nitrogen, ammonia or nitrate. Nitrogen fixation can occur biologically (i.e. conversion of nitrogen gas to organic nitrogen by certain photosynthetic blue-green algae), by natural physical processes (i.e. conversion of nitrogen gas to nitrate by lightning), or by industrial processes (manufacture of fertilizers and explosives).

Nitrogenous A term used to describe chemical compounds (usually organic) containing nitrogen in combined forms. Proteins and nitrates are nitrogenous compounds.

Nutrient Any substance that is assimilated (taken in) by organisms and promotes growth. Nitrogen and phosphorus are nutrients which promote the growth of algae. There are other essential and trace elements which are also considered nutrients.

Nutrient cycle The transformation or change of a nutrient from one form to another until the nutrient has returned to the original form, thus completing the cycle.

Odor Quality of gases, liquids, or particulates that stimulates the olfactory organ.

Oil interceptor A device designed to remove small oil globules by gravity from the water by limiting the flow velocity and the overflow rate.

Onsite Local wastewater treatment for a single house or small community.

Open dump A facility that does not meet the criteria for a sanitary landfill and is not a facility for disposal of hazardous waste.

Organic Substances that come from animal or plant sources. Organic substances always contain carbon. (Inorganic materials are chemical substances of mineral origin.)

Organic loading The pounds of BOD per day applied to a unit process.

Organic waste Waste material which comes mainly from animal or plant sources. Organic waste generally can be consumed by bacteria and other microscopic organisms. Inorganic waste is chemical substances of mineral origin.

Organics (i) A term used to refer to chemical compounds made from carbon molecules. These compounds may be natural materials (such as animal or plant sources) or manmade materials (such as synthetic organics). See also "inorganic." (ii) Any form of animal or plant life.

Overland flow land treatment Partially treated wastewater is applied to relatively impermeable soils at the top of a grass-covered gradient. The waste is cleaned by the vegetation and microbial action, and excess water is captured at the bottom of the slope.

Oxidation The conversion of organic material to a more stable form using bacteria, chemicals, or oxygen.

Oxidation direct Oxidation direct is oxidation of substances in sewage without the benefit of living organisms by the direct application of air or oxidizing agents such as chlorine.

Oxidation ponds Oxidation ponds are basins in which wastewater undergoes a biological oxidation treatment by action of algae and bacteria.

Oxidation sewage Oxidation sewage is the process whereby, through the agency of living organisms in the presence of oxygen, the organic matter that is contained in sewage is converted into a more stable or a mineral form.

Oxygen consumed The quantity of oxygen taken up from potassium permanganate in solution by a liquid containing organic matter. Commonly regarded as an index of the carbonaceous matter present. Time and temperature must be specified.

Parts per million (ppm) Parts by mass in sewage analysis equal to milligrams per liter divided by the relative density (specific gravity). In water analysis ppm is always

understood to imply mass/mass ratio (mg/kg), even though in practice a volume may be measured instead of a mass.

Pathogenic Something which causes disease or is otherwise harmful to humans.

Pathogenic organisms Organisms, including bacteria, viruses or cysts, capable of causing diseases (giardiasis, cryptosporidiosis, typhoid, cholera, dysentery) in a host (such as a person). There are many types of organisms which do not cause disease. These organisms are called non-pathogenic.

Peak demand The maximum momentary load placed on a water treatment plant, pumping station, or distribution system. This demand is usually the maximum average load in 1 hour or less, but may be specified as the instantaneous load or the load during some other short time period.

Peaking factor Ratio of maximum flow to the average flow, such as maximum hourly flow or maximum daily flow to the average daily flow.

Percent saturation The amount of a substance that is dissolved in a solution compared with the amount that could be dissolved in solution, expressed as a percentage.

Percolation The flow of liquid through a filtering medium.

Permeability The ability of a porous medium such as soil to transmit fluids (liquids or gases).

pH A measure of the acidity or alkalinity of water, or any given substance. The scale is 1 to 14, with 7 being neutral. Over 7 is alkaline or caustic, under 7 is acid or base.

Phosphorus (P) This nutrient, which is present in wastewater, acts as a fertilizer for algae in surface waters.

Phosphorus, inorganic Forms of phosphorus from mineral sources, such as orthophosphate, pyrophosphate ($P2O_7^{4-}$), and tripolyphosphate ($P3O_{10}^{5-}$).

Phosphorus, organic Phosphorus formed primarily by biological processes. Sources of organic phosphorus in sewage include bodily wastes, food residues, and the conversion of orthophosphates in biological treatment processes.

Physical waste treatment process Physical waste treatment processes include the use of racks, screens, comminutors, clarifiers (sedimentation and flotation), and filtration. Chemical or biological reactions are important treatment processes, but not part of a physical treatment process.

Pollutant Any substance which causes impairment (reduction) of water quality to a degree that has an adverse effect on any beneficial use of the water.

Pollutant, conservative Pollutants that do not readily degrade in the environment and which are mitigated primarily by natural stream dilution after entering receiving bodies of waters. Included are pollutants such as metals.

Pollutant, non-conservative Pollutants that are mitigated by natural biodegradation or other environmental decay or removal processes in the receiving stream after in-stream mixing and dilution have occurred.

Pollution The impairment (reduction) of water quality by agricultural, domestic or industrial wastes (including thermal and radioactive wastes) to a degree that the natural water quality is changed to hinder any beneficial use of the water or render it offensive to the senses of sight, taste, or smell or when sufficient amounts of wastes create or pose a potential threat to human health or the environment.

Population equivalent The equivalent, in terms of a fixed population, of a varying or transient population of a hospital or restaurant based upon a figure of 0.06 kg BOD per head per 120 l per head per day.

Porosity (i) Open space or interstices in rock, other earth materials or synthetic media. (ii) Ratio of the open space to the total volume, often described as a percentage.

Post-denitrification Biological wastewater treatment process for nitrogen removal that utilizes an anoxic zone located at the effluent end of an aeration tank. Due to lack of organic carbon, methanol addition is typically required.

Post-chlorination The addition of chlorine to the plant effluent, following plant treatment, for disinfection purposes.

Potable water Water that does not contain objectionable pollution, contamination, minerals, or infective agents and is considered satisfactory for drinking.

Pre-aeration The addition of air at the initial stages of treatment to freshen the wastewater, removes gases, add oxygen, promote flotation of grease, and aid coagulation.

Pre-chlorination (wastewater) The addition of chlorine in the collection system serving the plant or at the headworks of the plant prior to other treatment processes mainly for odor and corrosion control. Also applied to aid disinfection, to reduce plant BOD load, to aid in settling, to control foaming in Imhoff units, and to help remove oil.

Precipitation When a substance dissolved in a liquid passes out of solution and into solid form.

Precursor, trihalomethanes Natural organic compounds found in all surface and groundwater. These compounds may react with halogens (such as chlorine) to form trihalomethanes. They must be present in order for THMs to form.

Pre-denitrification Biological wastewater treatment process for nitrogen removal that utilizes an anoxic zone located at the influent end of an aeration tank. Organic matter present in the wastewater serves as a carbon source for denitrifying bacteria.

Preliminary treatment The removal of metal, rocks, rags, sand, eggshells, and similar materials which may hinder the operation of a wastewater treatment plant. Preliminary treatment is accomplished by using equipment such as racks, bar screens, comminutors, and grit removal systems.

Pretreatment Any component or combination of components that provides treatment of wastewater prior to conveyance to a final treatment and dispersal component or reuse. This treatment is often designed to meet primary, secondary, tertiary, and/or disinfection treatment standards.

Pretreatment facility Industrial wastewater treatment plant consisting of one or more treatment devices designed to remove sufficient pollutants from wastewaters to allow an industry to comply with effluent limits established by the US EPA General and Categorical Pretreatment Regulations or locally derived prohibited discharge requirements and local effluent limits. Compliance with effluent limits allows for a legal discharge to a publicly owned treatment works.

Preventive maintenance Regularly scheduled servicing of machinery or other equipment using appropriate tools, tests, and lubricants. This type of maintenance can prolong the useful life of equipment and machinery, and increase its efficiency by detecting and correcting problems before they cause a breakdown of the equipment.

Primary clarifier A wastewater treatment device which consists of a rectangular or circular tank that allows those substances in wastewater that readily settle or float to be separated from the wastewater being treated.

Primary settlement tank A tank in which the majority of settable solids are removed from the crude sewage flowing through it.

Primary treatment Water purification based on the difference in density of the polluting substance and the medium, the former being removed either by rising or settling. This process can include screening, grit removal, sedimentation, and sludge dig. A wastewater treatment process that takes place in a rectangular or circular tank and allows those substances in wastewater that readily settle or float to be separated from the water being treated.

Primary wastewater treatment Removal of sand, grit, and larger solids from wastewater by screens, settling tanks, and/or skimming devices, estion, and sludge disposal.

Priority pollutants The EPA has proposed a list of 126 priority toxic pollutants. These substances are an environmental hazard and may be present in water. Because of the known or suspected hazards of these pollutants, industrial users of the substances are subject to regulation. The toxicity to humans may be substantiated by human epidemiological studies or based on effects on laboratory animals related to carcinogenicity, mutagenicity, teratogenicity, or reproduction. Toxicity to fish and wildlife may be related to either acute or chronic effects on the organisms themselves or to humans by bioaccumulation in food fish. Persistence (including mobility and degradability) and treatability are also important factors.

Process variable A physical or chemical quantity that is usually measured and controlled in the operation of a wastewater treatment plant or an industrial plant.

Propeller fan Fan in which the air enters and leaves the impeller in a direction substantially parallel to its axis.

Protozoa A group of motile microscopic animals (usually single-celled and aerobic) that cluster in colonies and often consume bacteria as an energy source.

Prussian blue A paste or liquid used to show a contact area.

Primary waste treatment Mechanical separation of solids, grease, and scum from wastewater. With the aid of flocculating agents, primary treatment can eliminate 50–65% of the suspended solids. Solids removed by primary treatment may comprise as much as 30–40% of the original BOD of the water.

Psychrophilic bacteria A group of bacteria that grow and thrive in temperatures below 68 °F (20 °C).

Purification The removal, by natural or other methods, of pollution from a given medium.

Putrefaction Biological decomposition of organic matter resulting in the production of foul-smelling products associated with anaerobic conditions.

Raw sewage Untreated sanitary wastewater.

Raw wastewater Plant influent or wastewater before any treatment.

Reagent A substance which takes part in a chemical reaction and is used to detect and measure another substance.

Recalcination A lime-recovery process in which the calcium carbonate in sludge is converted to lime by heating to 1800 °F (980 °C).

Recarbonation A process in which carbon dioxide is bubbled into the water being treated to lower the pH.

Receiving body A stream, lake or other waterway into which treated or untreated waste is discharged.

Receiving water A stream, river, lake, ocean, or other surface or groundwater into which treated or untreated wastewater is discharged. Rivers, lakes, or other water sources that receive treated or untreated wastewaters.

Reclaimed water Reusable wastewater from wastewater treatment such as tertiary treatment of wastewater in biological and other systems.

Reducing agent Any substance, such as base metal (iron) or the sulfide ion, that will readily donate (give up) electrons. The opposite is an oxidizing agent.

Reduction The addition of hydrogen, removal of oxygen, or addition of electrons to an element or compound. Under anaerobic conditions (no dissolved oxygen present), sulfur compounds are reduced to odor-producing hydrogen sulfide (H_2S) and other compounds.

Refractory A material having the ability to retain its shape and chemical composition when subjected to high temperatures, or the area of an incinerator or similar equipment which contains the high temperatures.

Remediation Act or process of correcting a fault or deficiency without changing system structure or form.

Residual chlorine The amount of free and/or available chlorine remaining after a given contact time under specified conditions.

Residuals The solids generated and/or retained during the treatment of wastewater. They include trash, rags, grit, sediment, sludge, biosolids, septage, scum, grease, as well as those portions of treatment systems that have served their useful life and require disposal, such as the sand or peat from a filter. Because of their different characteristics, management requirements can differ as stipulated by the appropriate regulations.

Respiration The process in which an organism uses oxygen for its life processes and gives off carbon dioxide.

Respirator A device designed to protect the wearer from a hazardous atmosphere.

Retention time The time water, sludge or solids are retained or held in a clarifier or sedimentation tank.

Return air Air entering a space from air-conditioning, heating, or ventilating apparatus.

Return sludge The recycled sludge in a publicly owned treatment works that is pumped from a secondary clarifier sludge hopper to the aeration tank.

Return sludge ratio (*R*/*Q*) The ratio of the return sludge flow to the wastewater flow.

Reuse The use of water or wastewater after it has been discharged and then withdrawn by another user.

Rising sludge Rising sludge occurs in the secondary clarifiers of activated sludge plants when the sludge settles to the bottom of the clarifier, is compacted, and then starts to rise to the surface, usually as a result of denitrification.

Runoff That part of rainfall which flows off the surface to reach a sewer or river.

Runoff reduction The process whereby practices are implemented to minimize the quantity of stormwater runoff generated, and/or attenuate runoff near its source using storage, infiltration, and/or uptake by vegetation.

Runoff volume Amount of precipitation (and/or irrigation) minus surface storage, infiltration, evapotranspiration, and interception that exits a defined area.

Sand Soil particles between 0.05 and 2.0 mm in diameter.

Sanitary collection system The pipe system for collecting and carrying liquid and liquid-carried wastes from domestic sources to a wastewater treatment plant.

Sanitary sewer A pipe or conduit (sewer) intended to carry wastewater or waterborne wastes from homes, businesses, and industries to the publicly owned treatment works. Storm water runoff or unpolluted water should be collected and transported in a separate system of pipes or conduits (storm sewers) to natural watercourses.

Sanitary wastewater (domestic) Wastewater, including toilet, sink, shower and kitchen flows, originating from human domestic activities.

Scale A combination of mineral salts and bacterial accumulation that sticks to the inside of a collection pipe under certain conditions. Scale, in extreme growth circumstances, creates additional friction loss to the flow of water. Scale may also accumulate on surfaces other than pipes.

Screen (i) Porous material or mesh configured as a plate or cylinder that allows the passage of particles smaller than particular size (e.g. an effluent screen) according to a specific flow/pressure relationship. A screen has area but no depth with respect to flow. (ii) Use of a porous material or mesh to separate particles by size.

Scum A layer or film of foreign matter (such as grease or oil) that has risen to the surface of water or wastewater. A residue deposited on the ledge of a sewer, channel, or wet well at the water surface. A mass of solid matter that floats on the surface. Usually fatty material in wastewater that floats.

Secondary clarifier A wastewater treatment device which consists of a rectangular or circular tank that allows those substances not removed by previous treatment processes that settle or float to be separated from the wastewater being treated.

Secondary settlement tank A tank in which settable solids or humus is separated from the effluent flowing through it from biological filters or an activated sludge plant.

Secondary treatment A wastewater treatment process used to convert dissolved or suspended materials into a form more readily separated from the water being treated. Usually the process follows primary treatment by sedimentation. The process commonly is a type of biological treatment process followed by secondary clarifiers that allow the solids to settle out from the water being treated.

Secondary waste treatment Processing by various types of systems that employ aeration and biological oxidation stages to decompose dissolved and colloidal organic contaminants (inorganic plant nutrients may also be partially removed).

Secondary wastewater treatment Biological removal of organics and solids from wastewater. Secondary wastewater effluent limits are generally 30 mg/l BOD5 and 30 mg/l of TSS.

Sediment Soil that has washed or eroded from a land surface.

Sedimentation Settling of solid material out of a liquid, typically accomplished by reducing the velocity of the liquid below the point at which it can transport the suspended material. May be enhanced by coagulation and flocculation.

Sedimentation basin (clarifier, settling tank) A tank or basin in which wastewater is held for a period of time during which the heavier solids settle to the bottom and the lighter materials float to the water surface.

Sedimentation tanks Provide a period of quiescence during which suspended waste material settles to the bottom of the tank, is scraped into a hopper, and then is pumped

out for disposal. During this period, floatable solids (fats, oils) rise to the surface of the tank and are skimmed off into scum pipes for disposal.

Sedimentation, wastewater The process of settling and depositing of suspended matter carried by wastewater. Sedimentation usually occurs by gravity when the velocity of the wastewater is reduced below the point at which it can transport the suspended material.

Seed sludge In wastewater treatment, seed, seed culture or seed sludge refers to a mass of sludge which contains populations of microorganisms. When a seed sludge is mixed with wastewater or sludge being treated, the process of biological decomposition takes place more rapidly.

Septic tank A system sometimes used where wastewater collection systems and treatment plants are not available. The system is a settling tank in which settled sludge and floatable scum are in intimate contact with the wastewater flowing through the tank and the organic solids are decomposed by anaerobic bacterial action. Used to treat wastewater and produce an effluent that flows into a subsurface leaching (filtering and disposal) system where additional treatment takes place. Also referred to as an "interceptor;" but the preferred term is "septic tank."

Septic tank effluent pump system A facility where effluent is pumped from a septic tank into a pressurized collection system which may flow into a gravity sewer, treatment plant, or subsurface leaching system.

Septic wastewater A condition produced by anaerobic bacteria. If severe, the wastewater produces hydrogen sulfide, turns black, gives off foul odors, contains little or no dissolved oxygen, and has a high oxygen demand.

Septicity The condition in which organic matter decomposes to form foul-smelling products associated with the absence of free oxygen. If severe, the wastewater produces hydrogen sulfide, turns black, gives off foul odors, contains little or no dissolved oxygen, and the wastewater has a high oxygen demand.

Series operation Wastewater being treated flows through one treatment unit and then flows through another similar treatment unit.

Settling Process of subsidence and deposition of suspended matter carried by a liquid. Typically accomplished by reducing the velocity of the liquid below the point at which it can transport the suspended material.

Settling time Time during which suspended, aggregated, precipitated, or colloidal substances settle by gravity.

Sewage The fluid discharged from medical, domestic, and industrial sanitary appliances. The waterborne wastes of a community. The used water and added waste of a community which is carried away by drains and sewers. The used household water and water-carried solids that flow in sewers to a wastewater treatment plant. The preferred term is "wastewater."

Sewage system Any of several drainage systems for carrying surface water and sewage for disposal.

Sewer An underground pipe or open channel in a sewage system for carrying water or sewage to a disposal area. A pipe or conduit that carries wastewater or drainage water. The term "collection line" is often also used.

Sewerage A system of sewers and ancillary works to convey sewage from its point of origin to a treatment works or other place of disposal.

Sludge The accumulated suspended solids of sewage deposited in tanks or basins. A mixture of solids and water produced during the treatment of wastewater. Biosolids remaining after secondary or tertiary treatment. Sludge may be applied to agricultural fields as a soil amendment, composted or palletized. The settleable solids separated from liquids during processing or the deposits of foreign materials on the bottoms of streams or other bodies of water.

Sludge dewatering Removing the remaining water from sludge for reuse and to lighten the sludge for reuse or disposal.

Sludge digestion The process of changing organic matter in sludge into a gas or a liquid or a more stable solid form. These changes take place as microorganisms feed on sludge in anaerobic (more common) or aerobic digesters.

Sludge gasification A process in which soluble and particulate organic matter are converted into gas by anaerobic decomposition. The resulting gas bubbles can become attached to the settled sludge and cause large clumps of sludge to rise and float on the water surface.

Sludge return Process that sends the material (sludge) settled in a clarifier back to a septic or processing tank for further treatment or to maintain adequate microbial populations for treatment.

Sludge volume index (SVI) A calculation used to indicate the tendency of activated sludge solids (aerated solids) in the secondary clarifier to thicken or to become concentrated during the sedimentation/thickening process. To determine the SVI, a mixed liquor sample from the aeration basin is allowed to settle for 30 minutes. The suspended solids concentration for a sample of the same mixed liquor is also determined. The SVI is calculated by dividing the measured (or observed) wet volume (ml/l) of the settled sludge by the dry weight concentration of MLSS in g/l. When mixed liquor has an SVI well above 100 ml/g of solids, it tends to form a thin slurry or billowing sludge blanket or to form bulky sludge.

Soil (i) Unconsolidated mineral and/or organic material on the immediate surface of the earth that serves as a medium for the growth of plants. (ii) Unconsolidated mineral or organic matter on the surface of the earth that has been subjected to and shows effects of pedogenic and environmental factors of climate (including water and temperature effects), and macro- and microorganisms, conditioned by relief, acting on parent material over a period of time.

Solid waste Any garbage, refuse, or sludge from a waste treatment plant, water supply treatment plant, or air pollution control facility, or other discarded material, including solids, liquids, semisolids, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations and from community activities. In addition, solid waste does not include radioactive sources, special nuclear, and/or their by-product material.

Solids, settleable Suspended solids that settle out of suspension within a specified period of time, expressed in milliliters per liter (ml/l).

Solids, suspended That portion of total solids that is retained on a filter of 2.0 µm (or smaller) nominal pore sized under specified conditions.

Solids, total (TS) Material residue left in a vessel after evaporation of a sample subsequent to drying to a constant weight in an oven at 217–221 °F (103 to 105 °C). Includes

total suspended solids (TSS) and total dissolved solids (TDS). Typically expressed in mg/l.

Solids, total dissolved (TDS) Material that passes through a filter of 2.0 μm (or smaller) nominal pore size, evaporated to dryness in a weighed dish, and subsequently dried to constant weight at 180 °C. Typically expressed in mg/l.

Solids, total suspended (TSS) Measure of all suspended solids in a liquid, typically expressed in mg/l. To measure TSS, a well-mixed sample is filtered through a standard glass fiber filter and the residue retained on the filter is dried to a constant weight at 217–221 °F (103–105 °C). The increase in the weight of the filter represents the amount of TSS.

Sorption Removal of an ion or molecule from solution by adsorption and/or absorption. A term often used when the exact nature of the mechanism of removal is not known.

Springing The separation of acid oils, either phenolic or naphthenic, by neutralization of spent caustic solutions. The acid oils are known as "sprung acids."

Storm drain A pipeline or channel system that carries surface water and/or runoff to public waters, but does not feed into the sewer system.

Storm water Storm water is rainwater discharged from a catchment area as a result of a storm.

Storm water runoff (SRO) The pulse of surface water following a rainstorm. The water carries sediment, gas, oil, animal feces, glass, and other waste from the watershed to receiving waters, creating a difficult urban/suburban wastewater problem.

Sublaterals Sublaterals are sewer branches [min. 150 mm (6 in.) diameter nominal size] that collect effluent from catch basins and convey it to the laterals.

Subsurface flow wetland (SF) A type of constructed wetland in which primarily treated waste flows through deep gravel or other porous substrate planted with wetland vegetation. The water is not exposed to the air, avoiding problems with odor and direct contact.

Surface loading One of the guidelines for the design of settling tanks and clarifiers in treatment plants. Used by operators to determine if tanks and clarifiers are hydraulically (flow) over- or under-loaded. Also called overflow rate.

Surface runoff The precipitation that cannot be absorbed by the soil and flows across the surface by gravity. The water that reaches a stream by traveling over the soil surface or falls directly into the stream channels, including not only large permanent streams but also tiny rills and rivulets. Water that remains after infiltration, interception, and surface storage has been deducted from total precipitation.

Surface water Surface water is natural rainwater from the ground surface, paved areas, and roofs plus occasional courtyard and car-washing wastewaters and incidental fire-fighting water.

Surfactant Abbreviation for surface-active agent. The active agent in detergents that possesses a high cleaning ability.

Susceptibility to separation (STS) number The oil contents in parts per million of the suspend water after the specified settling period.

Suspended growth processes Wastewater treatment processes in which the microorganisms and bacteria treating the wastes are suspended in the wastewater being treated. The wastes flow around and through the suspended growths. The various modes of the activated sludge process make use of suspended growth reactors. These reactors can be used for BOD removal, nitrification, and denitrification.

Suspended solids Solids physically suspended in sewage that can be removed by proper laboratory filtering.

Suspended solids (SS) in sewage Solid in suspension in sewage liquors as measured by filtration either through a glass fiber filter paper followed by washing and drying at 105 °C or by centrifuging flowed by washing and removal of the supernatant liquid.

Suspended solids (i) Solids that either float on the surface or are suspended in water, wastewater, or other liquids, and which are largely removable by laboratory filtering. (ii) The quantity of material removed from water in a laboratory test, as prescribed in Standard Methods for the Examination of Water and Wastewater, and referred to as total suspended solids dried at 103–105 °C.

Suspension A solution having small particles dispersed throughout.

Tank An artificial container in which liquids are held or detained.

Tank, dosing Tank or compartment which provides storage of effluent and contains a device (pump or siphon) and associated appurtenances used to convey effluent to another pretreatment process or a final treatment and dispersal component.

Tank, flow equalization Dosing tank that provides storage of effluent and uses timed dosing to allow for uniform delivery to a subsequent component over time, usually a day or more. Also known as a surge tank.

Tank, processing Term applied to a septic tank when it is configured to receive a combination of raw sewage and recirculated effluent in order to enhance nitrogen removal.

Tank, pump Dosing tank which provides storage of effluent and houses a pump and associated appurtenances used to convey effluent to another pretreatment process or a final treatment and dispersal component.

Tank, recirculation Dosing tank that mixes effluent from two or more components within the treatment train and allows a portion of partially treated effluent to pass through one or more treatment components again.

Tank, septic Water-tight, covered receptacle for treatment of sewage. Receives the discharge of sewage from a building, separates settleable and floating solids from the liquid, digests organic matter by anaerobic bacterial action, stores digested solids through a period of detention, allows clarified liquids to discharge for additional treatment and final dispersal, and attenuates flows.

Tank, siphon Dosing tank or compartment which provides storage of effluent and contains a siphon to convey effluent from the tank to another pretreatment process or to a final treatment and dispersal component.

Temperature controller Device which responds directly or indirectly to deviation from a desired temperature by actuating a control or initiating a control sequence.

Temperature sensor A device that opens and closes a switch in response to changes in the temperature. This device might be a metal contact, or a thermocouple that generates minute electric current proportional to the difference in heat, or a variable resistor whose value changes in response to changes in temperature.

Tertiary treatment Any process of water renovation that upgrades treated wastewater to meet specific reuse requirements. May include general clean-up of water or removal of specific parts of wastes insufficiently removed by conventional treatment processes. Typical processes include chemical treatment and pressure filtration. Also called advanced waste treatment.

Tertiary treatment, effluent polishing A further stage of treating sewage by removing suspended solids. Consequential removal of residual BOD may occur. The use of filtration to remove microscopic particles from wastewater that has already been treated to a secondary level.

Tertiary waste treatment Following secondary treatment, the clarified effluent may require additional aeration and/or other chemical treatment to destroy bacteria remaining from the secondary treating stage and to increase the content of dissolved oxygen needed for oxidation of the residual BOD. Tertiary treatment can also be used to remove nitrogen and phosphorus.

Tertiary wastewater treatment (advanced) Biological or chemical polishing of wastewater to remove organics, solids, and nutrients. Tertiary wastewater effluent limits are generally 10 mg/l BOD5 and 10 mg/l TSS.

Thickening Treatment to remove water from the sludge mass to reduce the volume that must be handled.

Toe walls Toe walls are raised curbs which control spillage and drainage of storm, process, and fire water.

Top water level (TWL) The maximum water level in a settlement tank, an aeration tank or a sludge storage tank.

Total dissolved solids The combined total of all dissolved solids in wastewater, both organic and inorganic, and very fine, such as colloidal minerals. Generally particles must be smaller than 2 µm to be considered a dissolved solid. For example, salt dissolved in water is a dissolved solid. Therefore TDS will "survive" screening or other coarse filtration.

Total maximum daily load (TMDL) The sum of the allowable loads of a single pollutant from all contributing point and non-point sources. A calculation of the maximum amount of a pollutant that a water body can receive on a daily basis and still meet water quality standards and an allocation of that amount to the pollutant's sources.

Total organic carbon (TOC) A measure of the amount of carbon in a sample originating from organic matter only. It is measured by burning the sample and measuring the CO_2 produced.

Total solids The total amount of solids in solution and suspension.

Total suspended solids (TSS) As the name implies, the total solid particles that are suspended (as opposed to dissolved) in the wastewater. TSS must be filtered out, flocculated, digested, and so on for removal in the treatment of wastewater. Though not necessarily pollutants, TSS is considered to be a measure of pollutants in water by the EPA in the USA.

Toxic pollutant Pollutants or combinations of pollutants, including disease-causing agents, which after discharge and upon exposure, ingestion, inhalation or assimilation into any organism, either directly from the environment or indirectly by ingestion through food chains, will, on the basis of information available to the US EPA, cause death, disease, behavioral abnormalities, cancer, genetic mutations, physiological malfunctions (including malfunctions in reproduction) or physical deformations in such organisms or their offspring. Toxic pollutants also include those pollutants listed under CWA Section 307(a)(1) or any pollutant listed under Section 405(d), which relates to sludge management.

Toxicity test A procedure to determine the toxicity of a chemical or an effluent using living organisms. A toxicity test measures the degree of effect on exposed test organisms of a specific chemical or effluent.

Treatability How treatable a water sample is with a given substance.

Treatment Method, technique, or process designed to remove solids and/or pollutants from wastewater.

Treatment, advanced secondary Level of treatment that achieves 95% reduction in BOD and TSS, generally to levels below 10 mg/l.

Treatment, aerobic Digestion of organic matter in an environment containing molecular (or dissolved) oxygen (O_2).

Treatment, anaerobic Digestion of organic matter in an environment without molecular (or dissolved) oxygen (O_2).

Treatment, biological Process involving the metabolic activities of bacteria and other microorganisms in the breakdown of complex organic materials into simpler, more stable substances.

Treatment, chemical Process involving the addition of chemicals to obtain a desired result, such as precipitation, coagulation, flocculation, pH adjustment, disinfection, or sludge conditioning.

Treatment, physical Treatment which involves only physical means of solid/liquid separation, such as filtration, flotation, and sedimentation. Chemical and biological reactions do not play an important role in physical treatment.

Treatment, primary Physical treatment processes involving removal of particles, typically by settling and flotation with or without the use of coagulants (e.g. a grease interceptor or a septic tank provides primary treatment).

Treatment, secondary Biological and chemical treatment processes designed to remove organic matter. A typical standard for secondary effluent is BOD and TSS less than or equal to 20 mg/l each on a 30-day average basis.

Treatment, tertiary Advanced treatment of wastewater for enhanced organic matter removal, pathogen reduction, and nutrient removal. Typical standards for tertiary effluent vary according to regulatory requirements.

Trickling filter An aerobic biological wastewater treatment process used as secondary treatment of sewage. Effluent from the primary clarifier is distributed over a bed of rocks. As the liquid trickles over the rocks, a biological growth on the rocks breaks down the organic matter in the sewage. The effluent is then taken to a clarifier to remove biological matter coming from the filter.

Turbidity The cloudy appearance of water caused by the presence of suspended and colloidal matter. In the Handbook on Wastewater Management waterworks field, a turbidity measurement is used to indicate the clarity of water. Technically, turbidity is an optical property of the water based on the amount of light reflected by suspended particles. Turbidity cannot be directly equated to suspended solids because white particles reflect more light than dark-colored particles and many small particles will reflect more light than an equivalent large particle. Any finely divided, insoluble impurities that mar the clarity of the water. A measure of the clarity of water. Typically, turbidity is measured by determining light transmission through the water.

Turbidity meter An instrument for measuring and comparing the turbidity of liquids by passing light through them and determining how much light is reflected by the particles

in the liquid. The normal measuring range is 0–100 and is expressed as nephelometric turbidity units (NTUs).

Turbidity units (TU) Turbidity units are a measure of the cloudiness of water. If measured by a nephelometric (deflected light) instrumental procedure, turbidity units are expressed in nephelometric turbidity units (NTU) or simply TU. Those turbidity units obtained by visual methods are expressed in Jackson turbidity units (JTU), which are a measure of the cloudiness of water and are used to indicate the clarity of water. There is no real connection between NTUs and JTUs. The Jackson turbidimeter is a visual method and the nephelometer is an instrumental method based on deflected light.

Ultrafiltration A membrane filter process used for the removal of some organic compounds in an aqueous (watery) solution.

Ultraviolet (UV) disinfection A disinfection method in which final wastewater effluent is exposed to UV light to kill pathogens and microorganisms.

Unit A unit is one process, offsite and/or utility unit or facility that forms part of a complete operable refinery and/or complex.

Unit operations, physical Treatment methods in which the application of physical forces predominates as a means for removal of wastewater constituents. Includes flocculation, sedimentation, flotation, filtration, screening, mixing, and gas transfer.

Unit processes, biological Treatment methods in which the removal or conversion of constituents is brought about by biological activity. Primarily used to remove the biodegradable organic constituents through conversion to cell tissue or gases. Also used to remove nutrients (nitrogen and phosphorus).

Unit processes, chemical Treatment methods in which the removal or conversion of constituents is brought about through the addition of chemicals or by other chemical reactions. Includes precipitation, adsorption, and disinfection.

Upset An exceptional incident in which there is unintentional and temporary non-compliance with the permit limit because of factors beyond the reasonable control of the permittee. An upset does not include non-compliance to the extent caused by operational error, improperly designed treatment facilities, inadequate treatment facilities, lack of preventive maintenance, or careless or improper operation.

Volatile A volatile substance is one that is capable of being evaporated or changed to a vapor at relatively low temperatures. Volatile substances also can be partially removed by air stripping. In terms of solids analysis, volatile refers to materials lost (including most organic matter) upon ignition in a muffle furnace for 60 minutes at 550 °C. Natural volatile materials are chemical substances usually of animal or plant origin. Manufactured or synthetic volatile materials such as ether, acetone, and carbon tetrachloride are highly volatile and not of plant or animal origin.

Volatile acids Fatty acids produced during digestion that are soluble in water and that can be steam-distilled at atmospheric pressure. Also called organic acids. Volatile acids are commonly reported as equivalent to acetic acid.

Volatile solids Those solids in water, wastewater, or other liquids that are lost on ignition of the dry solids at 550 °C for 60 minutes.

Volume, dose (i) Amount of effluent delivered to the distribution system during a dosing event, including the drainback volume, pipe fill volume, and the delivered dose volume. (ii) Amount of effluent delivered as determined by the pump-on and pump-off levels in a demand dosed system.

Vulnerability assessment (water) An evaluation of drinking water source quality and its vulnerability to contamination by pathogens and toxic chemicals.

Waste-activated sludge (mg/l) The excess growth of microorganisms which must be removed from the process to keep the biological system in balance. That portion of sludge from the secondary clarifier in the activated sludge process that is wasted to avoid a build-up of solids in the system.

Wastewater A community's used water and water-carried solids (including used water from industrial processes) that flow to a treatment plant. Storm water, surface water, and groundwater infiltration also may be included in the wastewater that enters a wastewater treatment plant. The term "sewage" usually refers to household wastes, but this word is being replaced by the term "wastewater." The liquid-borne waste products of domestic, industrial, agricultural and manufacturing activities. In a community, an average of 50–100 gallons of wastewater is generated per person per day.

Wastewater, industrial Water or liquid-carried waste from an industrial process resulting from industry, manufacture, trade, automotive repair, vehicle wash, business or medical activity. This wastewater may contain toxic or hazardous constituents.

Wastewater, raw Any wastewater leaving a source.

Wastewater, residential strength Effluent from a septic tank or other treatment device with a BOD5 less than or equal to 170 mg/l, TSS less than or equal to 60 mg/l, and fats, oils, and grease less than or equal to 25 mg/l.

Wastewater facilities The pipes, conduits, structures, equipment, and processes required to collect, convey, and treat domestic and industrial wastes, and dispose of the effluent and sludge.

Wastewater ordinance The basic document granting authority to administer a pretreatment inspection program. This ordinance must contain certain basic elements to provide a legal framework for effective enforcement.

Wastewater reclamation Treatment or processing of wastewater to produce water of a quality appropriate for another use, including recycling or reuse.

Wastewater recycling Reclamation process of collection and treatment of wastewater on-site for return and use back into the same site, for example collection and reclamation of gray water from an establishment for subsequent toilet flushing in that same establishment.

Wastewater reuse Reclamation process of collection and treatment of wastewater for the deliberate application of that treated wastewater for a beneficial purpose such as turf irrigation.

Wastewater stabilization pond Constructed basin lined with either soil with very low permeability or a synthetic material, surrounded with berms and containing at least 3 ft. of wastewater, which utilizes sunlight, wind or mechanical aeration, and natural bacteria to break down waste via physical, chemical, and biological processes to stabilize wastewater. Typically consists of two or more basins with operational controls allowing or facilitating flow through the basins.

Wastewater treatment plant An arrangement of pipes, equipment, devices, tanks, and structures for treating wastewater and industrial wastes. A water pollution control plant.

Wastewater treatment system Assembly of components for collection, treatment, and dispersal of sewage or effluent.

Wastewater treatment system, cluster Wastewater treatment systems designed to serve two or more sewage-generating dwellings or facilities with multiple owners. Typically includes a comprehensive, sequential land-use planning component and private ownership.

Wastewater treatment system, collector Wastewater treatment system that conveys sewage or effluent from multiple sources to a location where treatment and dispersal occur.

Wastewater treatment system, community Publicly owned wastewater treatment system for collection, treatment, and dispersal of wastewater from two or more lots, or two or more equivalent dwelling units.

Wastewater treatment system, decentralized Wastewater treatment system for collection, treatment, and dispersal/reuse of wastewater from individual homes, clusters of homes, isolated communities, industries, or institutional facilities, at or near the point of waste generation.

Wastewater treatment system, individual Wastewater treatment system designed to serve one sewage-generating dwelling or facility.

Wastewater treatment system, onsite Wastewater treatment system relying on natural processes and/or mechanical components to collect and treat sewage from one or more dwellings, buildings, or structures and disperse the resulting effluent on property owned by the individual or entity.

Water pollution A general term signifying the introduction into water of microorganisms, chemicals, wastes, or sewage which renders the water unfit for its intended use.

Water quality standard A law or regulation that consists of the beneficial use or uses of a waterbody, the numeric and narrative water quality criteria that are necessary to protect the use or uses of that particular waterbody, and an antidegradation statement.

Water quality-based effluent limit A value determined by selecting the most stringent of the effluent limits calculated using all applicable water quality criteria (e.g. aquatic life, human health, and wildlife) for a specific point source to a specific receiving water for a given pollutant.

Water softening Reduction in the number of and/or removal of polyvalent cations, which are the principal cause of hardness in water.

Water table Upper surface of groundwater or that level in the ground where the water is at atmospheric pressure.

Water treatment discharge By-product from a water treatment device, such as regeneration water from an ion-exchange unit, reject water from a reverse-osmosis unit, or the backwash from an iron filter.

Weir Device designed to measure or control flow. Consists of a wall or obstruction of known geometric shape placed perpendicular to the direction of flow.

Well Hole bored or drilled into the ground.

Well, monitoring Well constructed for the purpose of determining groundwater level or constituents.

Well, water Well constructed for the purpose of extracting potable water.

Well-sorted Material of uniform size with maximum void space.

Whole effluent toxicity The total toxic effect of an effluent measured directly with a toxicity test.

Zone Portion of a component that is separately managed as a single unit.

Zone of dispersal Layers of soil or rock material surrounding the zone of treatment through which the effluent moves away from the final treatment and dispersal component.

Zone of saturation Layer in the ground in which interstitial voids (cracks, crevices, holes, etc.) are filled with water. The level at the top of this zone is the water table.

Zone of treatment Soil or fill material which removes pollutants from pretreated effluent by processes which include physical filtration of bacteria and other constituents, adsorption of viruses and bacteria by clay and organic matter, biological destruction of pathogens by soil microorganisms, sorption or precipitation of phosphorus, biochemical transformations of nitrogen compounds, and biological assimilation of phosphorus and nitrogen.

Bibliography

Abdel-Gawad, S. and Abdel-Shafy, M. (2002). Pollution control of industrial wastewater from soap and oil industries: a case study. *Water Science and Technology* 46 (4–5): 77–82.

Abed, K.A., El Morsi, A.K., Sayed, M.M. Shaib, A.A.E. Gad, M.S. (2018). Effect of waste cooking-oil biodiesel on performance and exhaust emissions of a diesel engine. *Egyptian Journal of Petroleum* 27 (4): 985–989.

Abilov, F.A., Orudjev, A.G., and Lange, R. (1999). Optimization of oil-containing wastewater treatment processes. *Desalination* 124 (1–3): 225–229.

de Abreu Domingos, R. and da Fonseca, F.V. (2018). Evaluation of adsorbent and ion exchange resins for removal of organic matter from petroleum refinery wastewaters aiming to increase water reuse. *Journal of Environmental Management* 214: 362–369.

de Abreu, R.C. and Fourrier, J.E. (2019). Landfilling of oil and gas exploration and production wastes: geotechnical and environmental considerations. *Environmental Science and Engineering*: 178–185.

Adams, M., Campbell, I., and Robertson, P.K.J. (2008). Novel photocatalytic reactor development for removal of hydrocarbons from water. *International Journal of Photoenergy* 1–7 (Article ID 674537).

Agarwal, P., Gupta, A., Dasgupta, S., Rao, E., Khot, P. (2018) Waste water treatment by chemical coagulation method – increasing output and reducing environmental impact.*SPE International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility 2018*.

Akhbarizadeh, R., Moore, F., Mowla, D., and Keshavarzi, B. (2018). Improved waste-sourced biocomposite for simultaneous removal of crude oil and heavy metals from synthetic and real oilfield-produced water. *Environmental Science and Pollution Research* 25 (31): 31407–31420.

Al Mujaini, M., Joshi, S.J., Sivakumar, N., Al-Bahry, S.N. (2018). Potential application of crude oil degrading bacteria in oil spill and waste management. *SPE International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility 2018*.

Waste Management in the Chemical and Petroleum Industries, Second Edition. Alireza Bahadori.

© 2020 John Wiley & Sons Ltd. Published 2020 by John Wiley & Sons Ltd.

Allen, E. (2008). Process water treatment in Canada's oil sands industry: II. A review of emerging technologies. *Journal of Environmental Engineering and Science* 7: 499–524.

Allen, E. (2008). Process water treatment in Canada's oil sands industry. I. Target pollutants and treatment objectives. *Journal of Environmental Engineering and Science*: 123–138.

Allison, E. (2016). United States experience regulating unconventional oil and gas development. *SPE/AAPG Africa Energy and Technology Conference 2016*, pp. 501–505.

Al-saba, M.T., Amadi, K.W., Al-Hadramy, K.O., Al-Hameedi, A., Alkinani, H. (2018). Experimental investigation of bio-degradable environmental friendly drilling fluid additives generated from waste. *SPE International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility 2018*.

Altaş, L. and Büyükgüngör, H. (2008). Sulfide removal in petroleum refinery wastewater by chemical precipitation. *Journal of Hazardous Materials* 153 (1–2): 462–469.

AltelaRain™ System ARS-4000 (2007). New Patented Technology for Cleaning Produced Water On-Site. Altela Information, 26 January.

American Petroleum Institute (1969). *Manual on Disposal of Refinery Wastes, Liquid Wastes*, 1e, vol. 1. American Petroleum Institute.

American Petroleum Institute, *API Manual on Waste Disposal of Refinery* (1980).

American Society for Testing and Materials, ASTM D-1888 (1978). *Test Methods for Particulate and Dissolved Matter, Solids, or Residue in Water*, 2e. ASTM.

American Standard for Testing of Materials, ASTM D 270, ASTM D 4687 "General Planning of waste Sampling", ASTM D 4844 "Air Monitoring at Waste Management Facilities for Worker", ASTM E 300.

API Publication 420 (1990). *Monographs on Refinery Environmental Control, Management of Water Discharges, The Chemistry and Chemicals of Coagulation and Flocculation*, 1e (ed. American Petroleum Institute).

API Publication 421 (1990). *Monographs on Refinery Environmental Control, Management of Water Discharges, Design and Operation of Water Separators*, 1e. American Petroleum Institute.

API Publication 4296 (1978). *Analysis of Refinery Waste Waters for the EPA Priority Pollutants*, 1e. American Petroleum Institute.

API Publication 4346 (1981). *Refinery Waste Water Priority Pollutant Study-Sample Analysis and Evaluation of Data*, 1e. American Petroleum Institute.

API Publication 4388 (1988). *Land Treatment-Safe and Efficient Disposal of Petroleum Waste*, 1e. American Petroleum Institute.

API Standard 650 (1988). *Welded Steel Tanks for Oil Storage*, 8e. American Petroleum Institute.

Arensdorf, J.J., Miner, K., Ertmoed, R. et al. (2009). Mitigation of reservoir souring by nitrate in a produced water re-injection system in Alberta. In: *Proceedings – SPE International Symposium on Oilfield Chemistry*, vol. 2, 999–1006.

Asia, I.O., Enweani, I.B., and Eguavoen, I.O. (2006). Characterization and treatment of sludge from the petroleum industry. *African Journal of Biotechnology* 5 (5): 461–466.

Avellan, A., Stegemeier, J.P., Gai, K. et al. (2018). Speciation of mercury in selected areas of the petroleum value chain. *Environmental Science and Technology* 52 (3): 1655–1664.

AWWA (1998). *Water Treatment Plant Design*, 3e, 221–280. McGraw-Hill.

Azad, A.K., Rasul, M.G., Islam, R., and Ahmed, S.F. (2018). A study on energy and environmental management techniques used in petroleum process industries. *Green Energy and Technology*: 219–230.

Azetsu-Scott, K., Yeats, P., Wohlgeschaffen, G. et al. (2007). Precipitation of heavy metals in produced water: influence on contaminant transport and toxicity. *Marine Environmental Research* 63: 146–167.

Bahadori, A., Vuthaluru, H.B., Tadé, M.O., and Mokhatab, S. (2008). Predicting water–hydrocarbon systems mutual solubility. *Chemical Engineering and Technology* 31 (12): 1743–1747.

Bahadori, A., Vuthaluru, H.B., and Mokhatab, S. (2009). Simple correlation accurately predicts aqueous solubility of light alkanes. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* 31 (9): 761–766.

Bahadori, A., Al-Haddabi, M., and Vuthaluru, H.B. (2012). *Communications in Soil Science and Plant Analysis* 43 (19): 2492–2503.

Bahadori, A., Clark, M.W., and Boyd, B. (2013a). *Essentials of Water Systems Design in the Oil, Gas and Chemical Processing Industries*. New York: Springer.

Bahadori, A., Zahedi, G., Zendehboudi, S., and Bahadori, M. (2013b). Estimation of air concentration in dissolved air flotation (DAF) systems using a simple predictive tool. *Chemical Engineering Research and Design* 91 (1): 184–190.

Baker, J.R., Milke, M.W., and Mihelcic, J.R. (1999). Relationship between chemical and theoretical oxygen demand for specif classes of organic chemicals. *Water Research* 33 (2): 327–334.

Bakhshian, S., Dashtian, H., Abuzar Mirzai, P., and AlAnazi, B.D. (2009). A review on impacts of drilling mud disposal on environment and underground water resources in south of Iran. In: *Proceedings of the SPE/IADC Middle East Drilling Technology Conference and Exhibition*, 447–454.

Ball HL. (1994). Nitrogen reduction in an on-site trickling filter/upflow filters wastewater treatment system. *Proceedings of the 7th International Symposium on Individual and Small Community Sewage Systems. Atlanta, GA, 1994*. American Society of Agricultural Engineers.

Belkin, S., Brenner, A., and Abeliovich, A. (1992). Effect of inorganic constituents on chemical oxygen demand I. Bromides are unneutralized by mercuric sulfate complexation. *Water Research* 26 (12): 1577–1581.

Benge, G., Miller, D., Miller, S., Goodman, R. (2018). New API standards for shale development Society of Petroleum Engineers. *SPE Hydraulic Fracturing Technology Conference and Exhibition 2018*.

Bessa, E., Sant'Anna, G.L., and Dezotti, M. (2001). Photocatalytic/H_2O_2 treatment of oil field produced waters. *Applied Catalysis B: Environment* 29: 125–134.

Bhurgri, S., Talpur, F.N., Nizamani, S.M., Shah, M.R., Bong, C.W. (2018). Isolation of *Bacillus cereus* from botanical soil and subsequent biodegradation of waste engine oil. *International Journal of Environmental Science and Technology* 15 (7): 1453–1466.

Bilstad, T. and Espedal, E. (1996). Membrane separation of produced water. *Water Science and Technology* 34: 239–246.

Bong, C.P.-C., Goh, R.K.Y., Lim, J.-S., Ramli, A.R., Takeshi, F. (2017). Towards low carbon society in Iskandar Malaysia: implementation and feasibility of community organic waste composting. *Journal of Environmental Management* 203: 679–687.

Boysen, J. (2007). The freeze–thaw/evaporation (FTE) process for produced water treatment, disposal and beneficial uses. In: *14th Annual International Petroleum Environmental Conference*, 5–9. Houston.

Boysen, J.E., Harju, J.A., Shaw, B. et al. (1999). The current status of commercial deployment of the freeze thaw evaporation treatment of produced water. In: *SPE/EPA Exploration and Production Environmental Conference*, 1–3. Austin: SPE 52700.

BS 1438: (1971). (1983) "Media for Biological Percolating Filters". British Standards Institution.

BS 6297: (1983). "Design and Installation of Small Sewage Treatment Works and Cesspools". British Standards Institution.

Buller AT, Johnsen S, Frost K, (2003). Offshore produced water management – knowledge, tools and procedures for assessing environmental risk and selecting remedial measures. Memoir 3. Statoil Research and Technology Offshore.

Çakmakce, M., Kayaalp, N., and Koyuncu, I. (2008). Desalination of produced water from oil production fields by membrane processes. *Desalination* 222: 176–186.

Campos, J.C., Borges, R.M.H., Oliveira Filho, A.M., Nobrega, R., Sant'Anna Jr., G.L. (2002). Oilfield wastewater treatment by combined microfiltration and biological processes. *Water Research* 36 (1): 95–104.

Canadian Association of Petroleum Producers (2008). Environmental Challenges and Progress in Canada's Oil Sands. 16 pp.

Chan, L.-H., Starinsky, A., and Katz, A. (2002). The behavior of lithium and its isotopes in oilfield brines: evidence from the Heletz–Kokhav field, Israel. *Geochimica et Cosmochimica Acta* 66: 615–623.

Chaubal, S. (2006). The wastewater challenge. *Hydrocarbon Engineering* 11 (11): 87–88.

Chen, R.-X. and Wang, W.-C. (2019). The production of renewable aviation fuel from waste cooking oil. Part I: Bio-alkane conversion through hydro-processing of oil. *Renewable Energy*: 819–835.

Chen, C., Guo, J., He, X., Zeng, Q. (2011). Analyzing and treatment of waste water from petroleum industry. *5th International Conference on Bioinformatics and Biomedical Engineering*, art. no. 5781163.

Chen, P., Willingham, T., Sowaidi, A.A., Stojkovic, D., Brown, J. (2018a). Solids loading assessment for produced water reinjection in a carbonate reservoir. *Society of Petroleum Engineers – Abu Dhabi International Petroleum Exhibition and Conference 2018, ADIPEC 2018*.

Chen, W.-T., Zhang, Y., Lee, T.H., Sharma, B.K. (2018b). Renewable diesel blendstocks produced by hydrothermal liquefaction of wet biowaste. *Nature Sustainability* 1 (11): 702–710.

Chiang, H.-L., Choa, C.-G., Chen, S.-Y., and Tsai, M.-C. (2003). The reuse of biosludge as an adsorbent from a petrochemical wastewater treatment plant. *Journal of the Air and Waste Management Association* 53 (9): 1042–1051.

Chittick, E.A. and Srebotnjak, T. (2017). An analysis of chemicals and other constituents found in produced water from hydraulically fractured wells in California and the challenges for wastewater management. *Journal of Environmental Management* 204: 502–509.

Coelho, A., Castro, A.V., Dezotti, M., and Sant'Anna, G.L. Jr. (2006). Treatment of petroleum refinery sourwater by advanced oxidation processes. *Journal of Hazardous Materials* 137 (1): 178–184.

Colorado School of Mines (2009). Technical assessment of produced water treatment technologies. In: *An Integrated Framework for Treatment and Management of Produced Water*, 8–128. Colorado: RPSEA Project 07122-12.

Daniels, R., Davies, J., Gravell, A., and Rowland, P. (2000). Movement of petroleum hydrocarbons in sandy coastal soils. *Journal of Environmental Monitoring* 2 (6): 645–650.

Darwish, M.A., Al Asfour, F., and Al-Najem, N. (2003). Energy consumption in equivalent work by different desalting methods: case study for Kuwait. *Desalination* 152: 83–92.

Das, P. and Tiwari, P. (2018). The effect of slow pyrolysis on the conversion of packaging waste plastics (PE and PP) into fuel. *Waste Management* 79: 61.

Davarpanah, A. (2018). Feasible analysis of reusing flowback produced water in the operational performances of oil reservoirs. *Environmental Science and Pollution Research* 25 (35): 35387–35395.

Diban, P. and Foo, D.C.Y. (2018). Targeting and design of heating utility system for offshore platform. *Energy* 146: 98–111.

DIN 997 "*Tracing Dimensions for Bars and Rolled Steel Sections*", (1970).

Diya'Uddeen, B.H., Daud, W.M.A.W., and Abdul Aziz, A.R. (2011). Treatment technologies for petroleum refinery effluents: a review. *Process Safety and Environmental Protection* 89 (2): 95–105.

do Amaral Sobrinho, N.M.B., Ceddia, M.B., Zonta, E., de Freitas, F.C., Lima, E.S.A. (2018). Spatial variability and solubility of barium in a petroleum well-drilling waste disposal area. *Environmental Monitoring and Assessment* 190 (4): 228.

Doran, G. and Leong, L.Y.C. (2000). *Developing a Cost Effective Solution for Produced Water and Creating a 'New' Water Resource*. United States Department of Energy DOE/MT/95008-4.

Eckenfelder, W.W., Bowers, A.R., Roth, J.A. et al. (1997). *Chemical Oxidation: Technologies for the Nineties*, vol. 6 (eds. W.W. Eckenfelder, A.R. Bowers and J.A. Roth), 1–12. Technomic Publishing Co. Inc.

El-Naas, M.H., Al-Zuhair, S., Al-Lobaney, A., and Makhlouf, S. (2009). Assessment of electrocoagulation for the treatment of petroleum refinery wastewater. *Journal of Environmental Management* 91 (1): 180–185.

Ely, J.W., Horn, A., Cathey, R. et al. (2011). Game changing technology for treating and recycling frac water. In: *Proceedings – SPE Annual Technical Conference and Exhibition*, vol. 1, 506–517.

EPA (1980). *Onsite Wastewater Treatment and Disposal Systems Design Manual*. US EPA.

Ettouney, H.M., El-Dessouky, H.T., Gowin, P.J. et al. (2002). Evaluating the economics of desalination. *Chemical Engineering Progress* 98: 32–39.

Faibish, R.S. and Cohen, Y. (2001a). Fouling-resistant ceramic-supported polymer membranes for ultrafiltration of oil-in-water microemulsions. *Journal of Membrane Science* 185: 129–143.

Faibish, R.S. and Cohen, Y. (2001b). Fouling and rejection behavior of ceramic and polymer-modified ceramic membranes for ultrafiltration of oil-in-water emulsions and microemulsions. *Colloids and Surface A: Physicochemical and Engineering Aspects* 191: 27–40.

Fakhru'l-Razi, A., Pendashteh, A., Abdullah, L.C. et al. (2009). Review of technologies for oil and gas produced water treatment. *Journal of Hazardous Materials* 170: 530–551.

Fang, H.-Y., Chou, M.-S., and Huang, C.-W. (1993). Nitrification of ammonia-nitrogen in refinery wastewater. *Water Research* 27 (12): 1761–1765.

Galil, N. and Rebhun, M. (1992). Multiple technological barriers combined with recycling of water and oil in wastewater treatment of a coastal petrochemical complex. *Water Science and Technology* 25 (12): 277–282.

Galil, N. and Rebhun, M. (1993). Combined aerated ponds and chemical clarification in the treatment of petrochemical wastewater. *Water Science and Technology* 27 (7–8): 79–88.

Gao, W., Smith, D.W., and Habib, M. (2008). Petroleum refinery secondary effluent polishing using freezing processes – toxicity and organic contaminant removal. *Water Environment Research* 80 (6): 517–523.

Gaya, U.I. and Abdullah, A.H. (2008). Heterogeneous photocatalytic degradation of organic contaminants over titanium dioxide: a review of fundamentals, progress and problems. *Journal of Photochemistry Photobiology C: Photochemistry Reviews* 9: 1–12.

Gheorghe, C.G., Pantea, O., Matei, V. et al. (2011). The efficiency of flocculants in biological treatment with activated sludge. *Revista de Chimie* 62 (10): 1023–1026.

Ghobashy, M.M., Younis, S.A., Elhady, M.A., and Serp, P. (2018). Radiation induced in-situ cationic polymerization of polystyrene organogel for selective absorption of cholorophenols from petrochemical wastewater. *Journal of Environmental Management* 210: 307–315.

Gloyna, E.F. and Tischler, L.F. (1979). Design of waste stabilization pond systems. *Progress in Water Technology* 11 (4–5): 47–70.

Grini PG, Hjelsvold M, Johnsen S, 2002, Choosing produced water treatment technologies based on environmental impact reduction. HSE Conference. *Kuala Lumpur, Malaysia, 20–22 March*, SPE paper 74002.

Gu, Q., Peng, C., Li, F. et al. (2005). Treatment of oil-contaminated wastewater through bed coalescence using a new filter medium. *Environmental Engineering Science* 22 (4): 472–478.

Guan, W.-S., Lei, Z.-X., and Zhu, J.-H. (2000). Petro-chemical wastewater treatment by biological process. *Journal of Environmental Sciences* 12 (2): 220–224.

Guida, M.Y. (2017). Bio-oil and bio-char feedstocks from pyrolysis of olive mill wastes, such as olive mill solid waste and olive mill wastewater. *Indian Journal of Environmental Protection* 37 (8): 632–646.

Guo, H., Li, X., Wen, K., and Lin, B. (2000). Discussion on design of solid waste disposal site in petroleum refining enterprise. *Petroleum Refinery Engineering* 30 (5): 52–55.

Guo, B., Piao, Y., Wang, X. et al. (2018). Comprehensive treatment technology for odour pollution of waste gas in refiner II. Study of treatment technology for waste gas from loading. *Petroleum Processing and Petrochemicals* 49 (11): 102–109.

Gutierrez, G., Lobo, A., Allende, D. et al. (2008). Influence of coagulant salt addition on the treatment of oil-in-water emulsions by centrifugation, ultrafiltration, and vacuum evaporation. *Separation Science and Technology* 43: 1884–1895.

Hafker, W.R. (2018). A framework for credible 2 degree Celsius climate planning: Engaging the petroleum sector as part of the global climate solution *Proceedings of the Air and Waste Management Association's Annual Conference and Exhibition, AWMA 2018 June*.

Han, K. and Levenspiel, O. (1988). *Biotechnology and Bioengineering* 32 (4): 430–447.

Han, S., Liu, Z., Liu, Y., and Gu, K. (1999). Application of desulfurized activated carbon for desulfurizing ammonia in refinery plant. *Linchan Huaxue Yu Gongye/Chemistry and Industry of Forest Products* 19 (2): 55–60.

Han, R., Zhang, S., Xing, D. et al. (2010). Desalination of dye utilizing copoly(phthalazinone biphenyl ether sulfone) ultrafiltration membrane with low molecular weight cut-off. *Journal of Membrane Science* 358: 1–6.

Hansen, B.R. and Davies, S.R.H. (1994). Review of potential technologies for the removal of dissolved components from produced water. *Chemical Engineering Research & Design* 72: 176–188.

Harvey, L.D.D. (2018). Resource implications of alternative strategies for achieving zero greenhouse gas emissions from light-duty vehicles by 2060. *Applied Energy* 212: 663–679.

Hayes T, Gowelly S, Moon P, et al (2006). Electrodialysis treatment of coal bed methane produced water: application issues and projections of costs. *International Petroleum Environmental Conference*. San Antonio, Texas, *17–20 October*.

He, Y. and Jiang, Z.W. (2008). Technology review: treating oilfield wastewater. *Filtration & Separation* 45: 14–16.

He, M., Chen, W.-J., Tian, L. et al. (2019). Plant-microbial synergism: an effective approach for the remediation of shale-gas fracturing flowback and produced water. *Journal of Hazardous Materials* 363: 170–178.

Heidarzadeh, N., Gitipour, S., and Abdoli, M.A. (2010). Characterization of oily sludge from a Tehran oil refinery. *Waste Management and Research* 28 (10): 921–927.

Heins WF, McNeill R . Vertical-tube evaporator system provides SAGD-quality feed water. *World Oil Magazine* 2007, pp. 228.

Henshaw, P.F., Bewtra, J.K., Biswas, N., and Franklin, M. (1992). Biological removal of hydrogen sulfide from refinery wastewater and conversion to elemental sulfur. *Water Science and Technology* 25 (3): 265–267.

Hobson, T. (1996). Skimming oily wastewater. *Pollution Engineering* 28 (10): 52–54.

Hojageldiyev, D. (2019). Artificial intelligence in HSE Society of Petroleum Engineers. *Abu Dhabi International Petroleum Exhibition and Conference 2018, ADIPEC 2018*.

Holubar, P., Grudke, T., Moser, A. et al. (2000). Effects of bacterivorous ciliated protozoans on degradation efficiency of a petrochemical activated sludge process. *Water Research* 34 (7): 2051–2060.

Hou, F.-S. (2005). Optimizing refining processing for the development of China's petroleum refining industry. *Shiyou Xuebao, Shiyou Jiagong/Acta Petrolei Sinica (Petroleum Processing Section)* 21 (3): 7–16.

Hoxha, B.B., Dervishi, D., Sweeney, K., and Bahja, E. (2018). Waste-to-fuel technology in Albania – development system to support an active drilling industry. In: *European Biomass Conference and Exhibition Proceedings 2018 (26thEUBCE)*, 1603–1615.

Hu, Z. and Grasso, D. (2006). Chemical Oxygen Demand. In: *Encyclopedia of Analytical Science –Water Analysis*, 325–330. Elsevier Ltd.

Hu, X.-J., Yang, Y.-N., Liu, H. et al. (2007). Study on the treatment of oilfield produced wastewater with different salinities using halophile enhanced biological activated carbon. *Huanjing Kexue/Environmental Science* 28 (10): 2213–2218.

Huang, H., Cai, C., Yu, S. et al. (2019). Emission behaviors of nitro- and oxy-polycyclic aromatic hydrocarbons during pyrolytic disposal of electronic wastes. *Chemosphere*: 267–274.

Huchler, L.A. (2004). Understanding refinery wastewater treatment basics – Part 2. *Hydrocarbon Processing* 83 (2 Section 1): 108.

Igunnu, E.T. and Chen, G.Z. (2012). Produced water treatment technologies. *International Journal of Low-Carbon Technologies* 9: 1–2.

Ishak, S., Malakahmad, A., and Isa, M.H. (2012). Refinery wastewater biological treatment: a short review. *Journal of Scientific and Industrial Research* 71 (4): 251–256.

Ismail, E.M., Rajah, B., Suppiah, A.J., Ghani, S.M. (2018). Low pressure-condensate recovery system (LP-CRS). Creating value through waste. *SPE Russian Petroleum Technology Conference 2018, RPTC 2018*

Jerez Vegueria, S.F., Godoy, J.M., Miekeley, N. et al. (2002). Environmental impact studies of barium and radium discharges by produced waters from the 'Bacia de Campos' oil-field offshore platforms, Brazil. *Journal of Environmental Radioactivity* 62: 29–38.

Jiménez, S., Micó, M.M., Arnaldos, M. et al. (2018). State of the art of produced water treatment. *Chemosphere* 192: 186–208.

Judd, S. and Jefferson, B. (2003). *Membranes for Industrial Wastewater Recovery and Re-use Oxford*, 14–169. Elsevier.

Juljumroensub, C., Sonsayan, P., Thippayawarn, A., Panichpongsakorn, N., Nitayaphan, S. (2018). First mobile CNG: Conversion of waste gas for improving oil recovery and for gas monetisation. *SPE Asia Pacific Oil and Gas Conference and Exhibition 2018, APOGCE 2018*.

Junttila, J., Dijkstra, N., and Aagaard-Sørensen, S. (2018). Spreading of drill cuttings and sediment recovery of three exploration wells of different ages, SW Barents Sea, Norway. *Marine Pollution Bulletin* 135: 224–238.

Kara, K., Ouanji, F., Lotfi, E.M. et al. (2018). Biodiesel production from waste fish oil with high free fatty acid content from Moroccan fish-processing industries. *Egyptian Journal of Petroleum* 27 (2): 249–255.

Kassotis, C.D., Nagel, S.C., and Stapleton, H.M. (2018). Unconventional oil and gas chemicals and wastewater-impacted water samples promote adipogenesis via PPARγ-dependent and independent mechanisms in 3T3-L1 cells. *Science of the Total Environment* 640–641: 1601–1610.

Kaur, G., Mandal, A.K., Nihlani, M.C. et al. (2009). Control of sulfidogenic bacteria in produced water from the Kathloni oilfield in northeast India. *International Biodeterioration & Biodegradation* 63: 151–155.

Kawaguchi, H., Li, Z., Masuda, Y., and Sato, K. (2012). Dissolved organic compounds in reused process water for steam-assisted gravity drainage oil sands extraction. *Water Research*: 5566–5574.

Kenoth, S.A., Kottappuram, J., Henry, S.I. (2019). Case study of pilot application and efficiency analysis of waste heat recovery from gas engine generator jacket cooling water to heat waxy multiphase fluid at offshore platform. *Society of Petroleum Engineers – Abu Dhabi International Petroleum Exhibition and Conference 2018, ADIPEC 2018*

Kfir, O., Tal, A., Gross, A., and Adar, E. (2012). The effect of reservoir operational features on recycled wastewater quality. *Resources, Conservation and Recycling* 68: 76–87.

Khawaji, A.D., Kutubkhanah, I.K., and Wie, J. (2008). Advances in seawater desalination technologies. *Desalination* 221: 47–69.

Khemakhem, S., Larbot, A., and Ben Amar, R. (2009). New ceramic microfiltration membranes from Tunisian natural materials: application for the cuttlefish effluents treatment. *Ceramics International* 35: 55–61.

Khosravi, J. and Alamdari, A. (2009). Copper removal from oil-field brine by coprecipitation. *Journal of Hazardous Materials* 166: 695–700.

Knight, R.L., Kadlec, R.H., and Ohlendorf, H.M. (1999). The use of treatment wetlands for petroleum industry effluents. *Environmental Science and Technology* 33 (7): 973–980.

Kondrashev, N.K., Shaidulina, A.A., Kondrashev, D.O., Georgieva, E.Y, Vasil'ev, V.V. (2018). The nepheline concentrate in synthesis of nax-type zeolites. In: *Innovation-Based Development of the Mineral Resources Sector: Challenges and Prospects – 11th conference of the Russian–German Raw Materials*, 407–412.

Konieczny, K., Bodzek, M., and Rajca, M. (2006). 2006 A coagulation-MF system for water treatment using ceramic membranes. *Desalination* 198: 92–101.

Kriipsalu, M., Marques, M., and Maastik, A. (2008). Characterization of oily sludge from a wastewater treatment plant flocculation–flotation unit in a petroleum refinery and its treatment implications. *Journal of Material Cycles and Waste Management* 10 (1): 79–86.

Kubsad, V., Gupta, S.K., and Chaudhari, S. (2005). Treatment of petrochemical wastewater by rotating biological contactor. *Environmental Technology* 26 (12): 1317–1326.

Kujawski, D. and Wong, A. (2011). Optimizing biological water treatment in petroleum refining. *Chemical Engineering* 118 (5).

Kulik, N., Trapido, M., Veressinina, Y., and Munter, R. (2007). Treatment of surfactant stabilized oil-in-water emulsions by means of chemical oxidation and coagulation. *Environmental Technology* 28 (12): 1345–1355.

Kwok, N., Dong, S., Lo, W., and Wong, K. (2005). An optical biosensor for multi-sample determination of biochemical oxygen demand (BOD). *Sensors and Actuators B: Chemical* 110 (2): 289–298.

Lee, D.W., Lee, H., Lee, A.H. et al. (2018). Microbial community composition and PAHs removal potential of indigenous bacteria in oil contaminated sediment of Taean coast, Korea. *Environmental Pollution* 234: 503–512.

Lee, W.J., Goh, P.S., Lau, W.J. et al. (2019). Antifouling zwitterion embedded forward osmosis thin film composite membrane for highly concentrated oily wastewater treatment. *Separation and Purification Technology*: 40–50.

Lefebvre, O. and Moletta, R. (2006). Treatment of organic pollution in industrial saline wastewater: a literature review. *Water Research* 40 (20): 3671–3682.

Leng, W.H., Zhu, W.C., Ni, J. et al. (2006). Photoelectrocatalytic destruction of organics using TiO_2 as photoanode with simultaneous production of H_2O_2 at the cathode. *Applied Catalysis A: General* 300: 24–35.

Leshuk, T., Peru, K.M., de Oliveira Livera, D. et al. (2018). Petroleomic analysis of the treatment of naphthenic organics in oil sands process-affected water with buoyant photocatalysts. *Water Research* 141: 297–306.

Letterman, R.D. and Clifford, D.A. (1999). Ion exchange and inorganic adsorption. In: *Water Quality and Treatment* (ed. R.D. Letterman). McGraw-Hill.

Li, Z. and Lai, G. (1999). Application of vortex separator in wastewater treatment of petroleum refining unit. *Petroleum Refinery Engineering* 29 (10): 45.

Li, Y. and Yao, P.-J. (2003). Wastewater minimization in petroleum refineries. *Shiyou Xuebao, Shiyou Jiagong/Acta Petrolei Sinica (Petroleum Processing Section)* 19 (4): 57–63.

Li, G., An, T., Chen, J. et al. (2006). Photoelectrocatalytic decontamination of oilfield produced wastewater containing refractory organic pollutants in the presence of high concentration of chloride ions. *Journal of Hazardous Materials* 138: 392–400.

Li, G., An, T., Nie, X. et al. (2007). Mutagenicity assessment of produced water during photoelectrocatalytic degradation. *Environmental Toxicology and Chemistry* 26: 416–423.

Li, R., He, C., Chen, L. et al. (2011a). Flocculation treatment of wastewater from low-level penetrative oil fields in Northern Shaanxi. In: *ISWREP 2011 – Proceedings of 2011 International Symposium on Water Resource and Environmental Protection*, vol. 2 , Art. no. 5893232, 1207–1210.

Li, Y., Xie, Q., Zhang, X. et al. (2011b). Study on new method of microorganism acclimation for biological treatment of high-salinity oilfield wastewater. In: *Proceedings – International Conference on Computer Distributed Control and Intelligent Environmental Monitoring, CDCIEM 2011*, Art. no. 5748158, 1760–1763.

Li, D., Tian, X., Hu, H. et al. (2019). Removal of dispersive borehole waves and beam imaging of fractures around the wellbore using sonic logging data. In: *2018 SEG International Exposition and Annual Meeting*, 699–703. SEG.

Liduino, V.S., Servulo, E.F.C., and Oliveira, F.J.S. (2018). Biosurfactant-assisted phytoremediation of multi-contaminated industrial soil using sunflower (*Helianthus annuus* L.). *Journal of Environmental Science and Health – Part A Toxic/Hazardous Substances and Environmental Engineering* 53 (7): 609–616.

Lin, K.-H., Hsu, H.-T., Ko, Y.-W. et al. (2009). Pyrolytic product characteristics of biosludge from the wastewater treatment plant of a petrochemical industry. *Journal of Hazardous Materials* 171 (1–3): 208–214.

Lindquist, S.E. and Fell, C. (2009). *Fuels—Hydrogen Production, Encyclopedia of Electrochemical Power Sources*, vol. 3, 369–383. Elsevier.

Liu, Z. (2019). Gasification of municipal solid wastes: a review on the tar yields. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects* 41 (11): 1296–1304.

Liu, Z., Wang, H., Wang, X. et al. (2018a). New technologies for treatment of VOCs and odor for tanks in petroleum refineries. *Petroleum Refinery Engineering* 48 (6): 60–64.

Liu, Z., Wang, X., Wang, H. et al. (2018b). Removing VOCs and odour from waste water and gas in sewage treating plant. *Petroleum Processing and Petrochemicals* 49 (5): 85–91.

Lobo, A., Cambiella, Á., Benito, J.M. et al. (2006). Ultrafiltration of oil-in-water emulsions with ceramic membranes: influence of pH and crossflow velocity. *Journal of Membrane Science* 278: 328–334.

Lourenço, R.A., Francioni, E., da Silva, A.H.M.F.T., de Fátima Guadalupe Meniconi, M., de Souza Bindes Gomes Lopes M.A.F. (2018). Bioaccumulation study of produced water discharges from Southeastern Brazilian offshore petroleum industry using feral fishes. *Archives of Environmental Contamination and Toxicology* 74 (3): 461–470.

Lu, M., Zhang, Z., Yu, W., and Zhu, W. (2009). Biological treatment of oilfield-produced water: a field pilot study. *International Biodeterioration and Biodegradation* 63 (3): 316–321.

Lyman, S.N. and Mansfield, M.L. (2018). Organic compound emissions from a landfarm used for oil and gas solid waste disposal. *Journal of the Air and Waste Management Association* 68 (7): 637–642.

Ma, H. and Wang, B. (2006). Electrochemical pilot-scale plant for oil field produced wastewater by M/C/Fe electrodes for injection. *Journal of Hazardous Materials* 132: 237–243.

Ma, Y., Zhang, J.-Y., Wong, M.-H., and Wu, W.-Z. (2001). Optimization of control parameters for petroleum waste composting. *Journal of Environmental Sciences* 13 (4): 385–390.

Madaeni, S.S. (1999). 1999 The application of membrane technology for water disinfection. *Water Res* 33: 301–308.

Madaeni, S.S. and Eslamifard, M.R. (2010). Recycle unit wastewater treatment in petrochemical complex using reverse osmosis process. *Journal of Hazardous Materials* 174 (1–3): 404–409.

Majid, A. and Sparks, B.D. (1999). Potential applications of oil sands industry wastes. *Journal of Canadian Petroleum Technology* 38 (11): 29–33.

Mallick, S.K. and Chakraborty, S. (2017). Treatment of synthetic refinery wastewater in anoxic–aerobic sequential moving bed reactors and sulphur recovery. *Journal of Environmental Science and Health – Part A Toxic/Hazardous Substances and Environmental Engineering* 52 (13): 1257–1268.

Mamma, D., Gerontas, S., Philippopoulos, C.J. et al. (2004). Combined photo-assisted and biological treatment of industrial oily wastewater. *Journal of Environmental Science and Health – Part A Toxic/Hazardous Substances and Environmental Engineering* 39 (3): 729–740.

Mansuy-Huault, L., Regier, A., and Faure, P. (2009). Analyzing hydrocarbons in sewer to help in PAH source apportionment in sewage sludges. *Chemosphere* 75 (8): 995–1002.

Maqueda, M.A.M., Martinez, D.S.A., Narváez, D. et al. (2006). Dynamical modelling of an activated sludge system of a petrochemical plant operating at high temperatures. *Water Science and Technology* 53 (11): 135–142.

Mark, W. (2007). *The Guidebook to Membrane Desalination Technology: Reverse Osmosis, Nanofiltration and Hybrid Systems Process, Design, Applications and Economic*, 1e, 160–180. L'Aquila Desalination Publications.

Marrone, P.A., Elliott, D.C., Billing, J.M. et al. (2018). Bench-scale evaluation of hydrothermal processing technology for conversion of wastewater solids to fuels. *Water Environment Research* 90 (4): 329–342.

McKinney, R.E. (1967). Biological treatment systems for refinery wastes. *Journal of the Water Pollution Control Federation* 39 (3): 346–359.

Meehan, D., El-Houjeiri, H.M., Rutherford, J.S. (2018). Carbon intensity: Comparing carbon impacts of middle east and US shale oils. *SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition 2018, SATS 2018*.

Meijer, D.T. and Madin, C. (2010). Removal of dissolved and dispersed hydrocarbons from oil and gas produced water with MPPE technology to reduce toxicity and allow water reuse. *The APPEA Journal*: 1–11.

Meijer, D.T., Kuijvenhoven Cor, A.T., and Karup, H. (2004). Results from the latest MPPE field trials at NAM and total installations. In: *NEL Produced Water Workshop*, 21–22. Aberdeen.

Merlo, R., Gerhardt, M.B., Burlingham, F. et al. (2011). Petroleum refinery stripped sour water treatment using the activated sludge process. *Water Environment Research* 83 (11): 2067–2078.

Metcalf and Eddy (2003). *Wastewater Engineering: Treatment Disposal Reuse*, 4e. New York: McGraw-Hill.

Mijaylova Nacheva, P., Ramírez Camperos, E., and Sandoval Yoval, L. (2008). Treatment of petroleum production wastewater for reuse in secondary oil recovery. *Water Science and Technology* 57 (6): 875–882.

Mohanakrishna, G., Al-Raoush, R.I., Abu-Reesh, I.M., and Aljaml, K. (2019). Removal of petroleum hydrocarbons and sulfates from produced water using different bioelectrochemical reactor configurations. *Science of the Total Environment* 665: 820–827.

Mojammal, A.H.M., Back, S.-K., Seo, Y.-C., and Kim, J.-H. (2019). Mass balance and behavior of mercury in oil refinery facilities. *Atmospheric Pollution Research* 10 (1): 145–151.

Mondal, S. and Wickramasinghe, S.R. (2008). Produced water treatment by nanofiltration and reverse osmosis membranes. *Journal of Membrane Science* 322: 162–170.

Morrison, A.E., Dhoonmoon, C., and White, H.K. (2018). Chemical characterization of natural and anthropogenic-derived oil residues on Gulf of Mexico beaches. *Marine Pollution Bulletin* 137: 501–508.

Moser, P.B., Ricci, B.C., Alvim, C.B. et al. (2018). Removal of organic matter of electrodialysis reversal brine from a petroleum refinery wastewater reclamation plant by UV and UV/H_2O_2 process. *Journal of Environmental Science and Health – Part A Toxic/Hazardous Substances and Environmental Engineering* 53 (5): 430–435.

Murray-Gulde, C., Heatley, J.E., Karanfil, T. et al. (2003). Performance of a hybrid reverse osmosis-constructed wetland treatment system for brackish oil field produced water. *Water Research* 37 (3): 705–713.

Muscolo, A., Papalia, T., Settineri, G. et al. (2019). Three different methods for turning olive pomace in resource: benefits of the end products for agricultural purpose. *Science of the Total Environment* 662: 1–7.

Mustapha, H.I., van Bruggen, H.J.J.A., and Lens, P.N.L. (2018). Vertical subsurface flow constructed wetlands for the removal of petroleum contaminants from secondary refinery effluent at the Kaduna refining plant (Kaduna, Nigeria). *Environmental Science and Pollution Research* 25 (30): 30451–30462.

Nadav, N. (1999). Boron removal from seawater reverse osmosis permeate utilizing selective ion exchange resin. *Desalination* 124: 131–135.

Nadim, F. et al. (2000). *Journal of Petroleum Science and Engineering* 26: 169–178.

Napp, A.P., Pereira, J.E.S., Oliveira, J.S. et al. (2018). Comparative metagenomics reveals different hydrocarbon degradative abilities from enriched oil-drilling waste. *Chemosphere* 209: 7–16.

National Energy Board (2006). Canada's Oil Sands – Opportunities and Challenges to 2015: An Update. 85 pp. June.

Ni Ketut, C., Sudrajad, A., Permana, M. et al. (2018). The comparison of Genset machine CS 1000 L performance between LPG and methane gas usage as the fuel. *MATEC Web of Conferences* 218: 04031.

Niasar, H.S., Das, S., Xu, C.C., and Ray, M.B. (2019). Continuous column adsorption of naphthenic acids from synthetic and real oil sands process-affected water (OSPW) using carbon-based adsorbents. *Chemosphere* 214: 511–518.

Novriansyah, A., Mursyidah, U., Novrianti et al. (2018). Effect of silica-palm shell carbon composite additive in enhancing the strength of the concrete in the oil-well cementing job. *IOP Conference Series: Materials Science and Engineering* 348 (1): 012012.

Nowak, J.A., Shrestha, P.M., Weber, R.J. et al. (2018). Comprehensive analysis of changes in crude oil chemical composition during biosouring and treatments. *Environmental Science and Technology* 52 (3): 1290–1300.

Ontario Ministry of the Environment (1992). Background Document on the Development of the Draft Petroleum Refining Sector Effluent Limits Regulation, Water Resources Branch, Ontario Ministry of the Environment, August 1992. Canada.

Ortiz-Gallarza, S.M. and Ramírez-López, J.A. (2003). Water quality of the Tula River related to the petroleum refining industry: accumulation factors and treatments. *Progress in Water Resources* 9: 261–268.

OSHA Interim Final Rule for Hazardous Waste Operations and Emergency Response – Recommended Practice D (1605). ASTM, Annual Book of ASTM Standard Volume 11.03, NIOSH Manual of Analytical Methods, – OSHA Analytical Method Manual.

Osin, O.A., Yu, T., and Lin, S. (2017). Oil refinery wastewater treatment in the Niger Delta, Nigeria: current practices, challenges, and recommendations. *Environmental Science and Pollution Research* 24 (28): 22730–22740.

Otadi, N., Hassani, A.H., Javid, A.H., and Khiabani, F.F. (2010). Oily compounds removal in wastewater treatment system of pars oil refinery to improve its efficiency in a lab scale pilot. *Journal of Water Chemistry and Technology* 32 (6): 370–377.

Panchal, Y., Mohamad, I., Abou-Sayed, O., Abou-Sayed, A., Bruno, M. (2018). Formation evaluation, economic and environmental assessment for the slurry injection for biosolids management in the city of Houston *Proceedings – SPE Annual Technical Conference and Exhibition 2018-September*.

Pars HM, Meijer DT, (1998). SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production. *Caracas, Venezuela; 1998*. Removal of dissolved hydrocarbons from production water by macro porous polymer extraction (MPPE). June, SPE paper no. 46577.

Parsons, W.A. (1978). Polishing biological plant effluents. *Hydrocarbon Processing* 57 (10 Sect 1): 125–126.

Pavlova, A. and Ivanova, R. (2003). Determination of petroleum hydrocarbons and polycyclic aromatic hydrocarbons in sludge from wastewater treatment basins. *Journal of Environmental Monitoring* 5 (2): 319–323.

Pelizzetti, E., Pramauro, E., Minero, C. et al. (1990). Sunlight photocatalytic degradation of organic pollutants in aquatic systems. *Waste Management* 10: 65–71.

Petri, I., Martins, A.L., Duarte, C.R., and Ataíde, C.H. (2019). Development and performance of a continuous industrial microwave dryer for remediation of drill cuttings. *Journal of Petroleum Science and Engineering*: 362–368.

Pettygrove, G.S. and Asano, T. (eds) (1985). Irrigation with reclaimed municipal wastewater – A guidance manual. Chelsea, Michigan: Lewis Publishers, Inc.

Pinzón Pardo, A.L., Brdjanovic, D., Moussa, M.S. et al. (2007). Modelling of an oil refinery wastewater treatment plant. *Environmental Technology* 28 (11): 1273–1284.

Piubeli, F., Grossman, M.J., Fantinatti-Garboggini, F., and Durrant, L.R. (2012). Enhanced reduction of COD and aromatics in petroleum-produced water using indigenous microorganisms and nutrient addition. *International Biodeterioration and Biodegradation* 68: 78–84.

Potokin, A. (2018). Prospects of electric pulse technology for the discovery and development of oil fields. In: *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management*, 727–734. SGEM 18(1.4).

Potumarthi, R., Mugeraya, G., and Jetty, A. (2008). Biological treatment of toxic petroleum spent caustic in fluidized bed bioreactor using immobilized cells of *thiobacillus* RAI01. *Applied Biochemistry and Biotechnology* 151 (2–3): 532–546.

Priyadarshi, D. and Paul, K.K. (2018). Engine performance and emission study of waste cooking oil and sewage sludge derived biodiesel blend. *IOP Conference Series: Earth and Environmental Science* 167 (1): 012035.

Rajkumar, K., Muthukumar, M., and Sivakumar, R. (2010). Novel approach for the treatment and recycle of wastewater from soya edible oil refinery industry – an economic perspective. *Resources, Conservation and Recycling* 54 (10): 752–758.

Ramasamy, J., Amanullah, Md. (2018). A novel superfine fibrous lost circulation material derived from date tree for seepage loss control. *SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition 2018, SATS 2018*.

Rana, S. (2009). Environmental risks – Oil & gas operations reducing compliance cost using smarter technologies. In: *SPE/IATMI Asia Pacific Health Safety, Security and Environment Conference and Exhibition 2009*, 30–40. Society of Petroleum Engineers.

Ray, J.P., Engelhardt, F.R., and Stephenson, M.T. (1992). A survey of produced water studies. In: *Produced Water: Technological/Environmental Issues and Solutions* (eds. J.P. Ray and F.R. Engelhardt), 1–12. Plenum Publishing Corp.

Reed, B.E., Carriere, P., Lin, W. et al. (1998). Oily wastewater treatment by ultrafiltration: pilot-scale results and full-scale design. *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management* 2 (3): 100–107.

Rehman, K., Imran, A., Amin, I., and Afzal, M. (2019). Enhancement of oil field-produced wastewater remediation by bacterially-augmented floating treatment wetlands. *Chemosphere*: 576–583.

Reis, J.L.R., Dezotti, M., and Sant'Anna, G.L. Jr. (2007). Toxicity evaluation of the process effluent streams of a petrochemical industry. *Environmental Technology* 28 (2): 147–155.

Restrepo, R., Forero, J.E., Cardenosa, M., and Gonzalez, J. (2009). Application of combined technologies for the treatment of phenols in wastewater oil productions. In: *Latin American and Caribbean Petroleum Engineering Conference Proceedings*, vol. 2, 977–981. SPE.

Reynolds RR . (2003). Produced water and Associated Issues: A Manual for the Independent Operator. Vol. 6. Oklahoma Geological Survey Open-file Report; p. 1–56.

Saberian, M. and Khabiri, M.M. (2018). Effect of oil pollution on function of sandy soils in protected deserts and investigation of their improvement guidelines (case study: Kalmand area, Iran). *Environmental Geochemistry and Health* 40 (1): 243–254.

Saeedi, M. and Khalvati-Fahlyani, A. (2011). Treatment of oily wastewater of a gas refinery by electrocoagulation using aluminum electrodes. *Water Environment Research* 83 (3): 256–264.

Saien, J. and Nejati, H. (2007). Enhanced photocatalytic degradation of pollutants in petroleum refinery wastewater under mild conditions. *Journal of Hazardous Materials* 148 (1–2): 491–495.

Salahi, A. and Mohammadi, T. (2011). Oily wastewater treatment by ultrafiltration using Taguchi experimental design. *Water Science and Technology* 63 (7): 1476–1484.

Samat, A.F., Safiah Muhamad, N.A., Abd Rasib, N.A. et al. (2018). The potential of biodiesel production derived from fish waste. *IOP Conference Series: Materials Science and Engineering* 318 (1): 012017.

Santo, C.E., Vilar, V.J.P., Botelho, C.M.S. et al. (2012). Optimization of coagulation–flocculation and flotation parameters for the treatment of a petroleum refinery effluent from a Portuguese plant. *Chemical Engineering Journal* 183: 117–123.

Santos, F.V., Azevedo, E.B., Sant'Anna, G.L. Jr., and Dezotti, M. (2006). Photocatalysis as a tertiary treatment for petroleum refinery wastewaters. *Brazilian Journal of Chemical Engineering* 23 (4): 451–460.

Sarathy, B.P., Hoy, P.M., and Duff, S.J.B. (2002). Removal of oxygen demand and acute toxicity during batch biological treatment of a petroleum refinery effluent. *Water Quality Research Journal of Canada* 37 (2): 399–411.

Scheren, P.A., Ibe, A.C., Janssen, F.J., and Lemmens, A.M. (2002). Environmental pollution in the Gulf of Guinea – a regional approach. *Marine Pollution Bulletin* 44 (7): 633–641.

Schultz, T.E. (2005). Cover story: biological wastewater treatment. *Chemical Engineering* 112 (10): 44–51.

Sengupta, P., Saikia, N., and Borthakur, P.C. (2002). Bricks from petroleum effluent treatment plant sludge: properties and environmental characteristics. *Journal of Environmental Engineering* 128 (11): 1090–1094.

Shamseddini, A., Mowla, D., and Esmaeilzadeh, F. (2019). Continuous treatment of petroleum products in a tailor-made flow-through sonoreactor. *Journal of Petroleum Science and Engineering*: 1149–1162.

Shoaib, A.M., El-Adly, R.A., Hassanean, M.H.M. et al. (2018). Developing a free-fall reactor for rice straw fast pyrolysis to produce bio-products. *Egyptian Journal of Petroleum* 27 (4): 1305–1311.

Siedlecka, E.M. and Stepnowski, P. (2006). Treatment of oily port wastewater effluents using the ultraviolet/hydrogen peroxide photodecomposition system. *Water Environment Research* 78 (8): 852–856.

Siedlecka, E.M., Stepnowski, P., and Jastorff, B. (2002). Effect of H_2O_2 on characteristics and biological treatment of petroleum refinery wastewater. *Fresenius Environmental Bulletin* 11 (5): 223–226.

Silva, V.L.O., Melo, J.A., Oliveira, L.B. et al. (2019). Esters from frying oil, sewage scum, and domestic fat trap residue for potential use as biodiesel. *Renewable Energy*: 945–950.

Sirivedhin, T., McCue, J., and Dallbauman, L. (2004). Reclaiming produced water for beneficial use: salt removal by electrodialysis. *Journal of Membrane Science* 243: 335–343.

Sorkin, Y.G. (1968). Methods for improving the utilization of water in a petroleum refinery. *Chemistry and Technology of Fuels and Oils* 4 (2): 77–81.

Spellman, F.R. (2003). *Handbook of Water and Wastewater Treatment Plant Operations*, 3–630. CRC Press.

Srikanth, S., Kumar, M., and Puri, S.K. (2018). Bio-electrochemical system (BES) as an innovative approach for sustainable waste management in petroleum industry. *Bioresource Technology* 265: 506–518.

Stamper, D.M. and Montgomery, M.T. (2008). Biological treatment and toxicity of low concentrations of oily wastewater (bilgewater). *Canadian Journal of Microbiology* 54 (8): 687–693.

Stepnowski, P., Siedlecka, E.M., Behrend, P., and Jastorff, B. (2002). Enhanced photo-degradation of contaminants in petroleum refinery wastewater. *Water Research* 36 (9): 2167–2172.

Stergar, V., Zagorc-Končan, J., and Zgajnar-Gotvanj, A. (2003). Laboratory scale and pilot plant study on treatment of toxic wastewater from the petrochemical industry by UASB reactors. *Water Science and Technology* 48 (8): 97–102.

Stoporev, A.S., Semenov, A.P., Manakov, A.Y., and Vinokurov, V.A. (2018). Study of oil sludge, waste oil and other auxiliary substances influence on the methane hydrate dissociation. *IOP Conference Series: Earth and Environmental Science* 193 (1): 012064.

Su, D., Wang, J., Liu, K. et al. (2007). Kinetic performance of oil-field produced water treatment by biological aerated filter. *Chinese Journal of Chemical Engineering* 15: 591–594.

Tavasoli, A., Aslan, M., Salimi, M. et al. (2018). Influence of the blend nickel/porous hydrothermal carbon and cattle manure hydrochar catalyst on the hydrothermal gasification of cattle manure for H_2 production. *Energy Conversion and Management* 173: 15–28.

Tayab, M.R., Kashwani, G., Sandra, D.N., Mohammed, T.H., Alhammami, M.A. (2018). An integrated approach to manage drilling waste to minimise environmental impacts. *SPE International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility 2018*.

Thahir, R., Altway, A., Juliastuti, S.R., and Susianto (2019). Production of liquid fuel from plastic waste using integrated pyrolysis method with refinery distillation bubble cap plate column. *Energy Reports* 5: 70–77.

Tien, H.T. and Chen, J.W. (1992). Photoelectrolysis of water in semiconductor septum electrochemical photovoltaic cells. *Solar Energy* 48: 199–204.

Tony, M.A., Purcell, P.J., and Zhao, Y. (2012). Oil refinery wastewater treatment using physicochemical, fenton and photo-fenton oxidation processes. *Journal of Environmental Science and Health – Part A Toxic/Hazardous Substances and Environmental Engineering* 47 (3): 435–440.

Tu, Y.T., Ou, J.H., Tsang, D.C.W. et al. (2018). Source identification and ecological impact evaluation of PAHs in urban river sediments: a case study in Taiwan. *Chemosphere* 194: 666–674.

U (n.d.) United State Resource Conservation and Recovery Act (RCRA) 1974 and Hazardous Solid Waste 1984 (HSWA).

Urban, D., Frisbie, S., and Croce, S. (1997). Compliance strategy for cyanides in petroleum refinery wastewater: Part 1 – Source characterization and treatment. *Environmental Progress* 16 (3): 171–178.

Vagapov, R.R., Khokhlov, N.G., and Shagitov, Z.M. (2006). Field treatment of waste waters on Askinskaya group of petroleum deposits. *Neftyanoe Khozyaistvo – Oil Industry* 3: 126–128.

Veil, J.A., Puder, M.G., Elcock, D. et al. (2004). *A White Paper Describing Produced Water from Production of Crude oil, Natural Gas, and Coal Bed Methane*. US Department of Energy, Argonne National Laboratory.

Velmurugan, V. and Srithar, K. (2008). Prospects and scopes of solar pond: a detailed review. *Renewable and Sustainable Energy Reviews* 12: 2253–2263.

Vershinina, K.Y., Lyrshchikov, S.Y., and Strizhak, P.A. (2018). Ignition of fuel slurries based on waste products of coal processing and oil refining. *Combustion, Explosion and Shock Waves* 54 (3): 376–384.

Vialkova, E. and Maksimova, S. (2018). Features of wastewater treatment systems of the oil and gas field infrastructure. *IOP Conference Series: Earth and Environmental Science* 181 (1): 012035.

Vinokurov, V.A., Frolov, V.I., Lesin, S.V., and Gushchin, P.A. (2018). Activated low-temperature viscosity breaking of heavy oil with additives of iron particles and asphaltene and paraffin deposits. *Theoretical Foundations of Chemical Engineering* 52 (4): 681–685.

Vlasopoulos, N., Memon, F.A., Butler, D., and Murphy, R. (2006). Life cycle assessment of wastewater treatment technologies treating petroleum process waters. *Science of the Total Environment* 367 (1): 58–70.

Wang, M. (2018). Analysis on treatment measures of tank exhausting waste gas in oil-refining enterprises, Open Access. *IOP Conference Series: Earth and Environmental Science* 186 (4): 012013.

Wang, L., Barrington, S., and Kim, J.-W. (2007). Biodegradation of pentyl amine and aniline from petrochemical wastewater. *Journal of Environmental Management* 83 (2): 191–197.

Wang, S., Dai, X., and Sun, Y. (2011). Study on the treatment of wastewater of oil shale retorting by photocatalytic degradation with TiO_2. In: *International Conference on Remote Sensing, Environment and Transportation Engineering, RSETE 2011 – Proceedings* , Art. no. 5966025, 7190–7193.

Wang, Q., Zhu, D., Xia, G. et al. (2018). Technological series supporting the "green-development" of shale gas in China: a case study. *Natural Gas Industry* 38 (2): 125–130.

Welz, M.L.S., Baloyi, N., and Deglon, D.A. (2007). Oil removal from industrial wastewater using flotation in a mechanically agitated flotation cell. *Water SA* 33 (4): 453–458.

Whittaker, M., Pollard, S.J.T., and Fallick, T.E. (1995). Characterisation of refractory wastes at heavy oil-contaminated sites: a review of conventional and novel analytical methods. *Environmental Technology* 16 (11): 1009–1033.

Wicks, Z.W. (2007). *Organic Coatings: Science and Technology*, 544. Wiley.

Willyard, K.A. (2019). An historical political economy analysis and review of Texas oil and gas well flaring laws and policy. *Energy Policy*: 639–647.

Wong, J.M. (1999). Petrochemicals. *Water Environment Research* 71 (5): 828–833.

Wright, D. (2018). Upstream energy benchmarking: Identifying energy improvement and GHG reduction opportunities for current and future operations, including technology gaps. *SPE International Conference and Exhibition on Health, Safety, Security, Environment, and Social Responsibility 2018*.

Wu, J., Zeng, R.J., Zhang, F., and Yuan, Z. (2019). Application of iron-crosslinked sodium alginate for efficient sulfide control and reduction of oilfield produced water. *Water Research*: 12–20.

Xianling, L., Jianping, W., Qing, Y., and Xueming, Z. (2005). The pilot study for oil refinery wastewater treatment using a gas–liquid–solid three-phase flow airlift loop bioreactor. *Biochemical Engineering Journal* 27 (1): 40–44.

Xie, W., Chen, J., Zhong, L., and Zhong, H. (2008). Treatment of slightly polluted wastewater in a petroleum refinery by combined process of circulating biological aerated filter and filtration. *Huagong Xuebao/Journal of Chemical Industry and Engineering (China)* 59 (5): 1251–1256.

Xie, W., Chen, J., Zhong, H., and Li, D. (2011). Treatment of alkaline wastewater from oil refinery using circulating biological aerated filter. In: *Proceedings – International Conference on Computer Distributed Control and Intelligent Environmental Monitoring, CDCIEM 2011*, Art. no. 5748298, 2360–2365.

Xu, P. and Drewes, J.E. (2006). Viability of nanofiltration and ultra-low pressure reverse osmosis membranes for multi-beneficial use of methane produced water. *Separation and Purification Technology* 52: 67–76.

Xu, P., Cath, T., Wang, G. et al. (2009). *Critical Assessment of Implementing Desalination Technology*. Water Research Foundation.

Xu, K., Lv, B., Huo, Y.-X., and Li, C. (2018a). Toward the lowest energy consumption and emission in biofuel production: combination of ideal reactors and robust hosts. *Current Opinion in Biotechnology* 50: 19–24.

Xu, T., Wang, L., Wang, X. et al. (2018b). Heavy metal pollution of oil-based drill cuttings at a shale gas drilling field in Chongqing, China: a human health risk assessment for the workers. *Ecotoxicology and Environmental Safety* 165: 160–163.

Yang, Y., Zhang, G., Yu, S. et al. (2010). Efficient removal of organic contaminants by a visible light driven photocatalyst Sr6Bi2O9. *Chemical Engineering Journal* 162: 171–177.

Yang, L., Wang, S., Peng, X. et al. (2019). Gas chromatography-Orbitrap mass spectrometry screening of organic chemicals in fly ash samples from industrial sources and implications for understanding the formation mechanisms of unintentional persistent organic pollutants. *Science of the Total Environment* 664: 107–115.

Yao, D., Zhang, Y., Yang, Q., and Li, J. (2004). Commercial application of refinery sewage deep treating technology for wastewater reuse. *Petroleum Processing and Petrochemicals* 35 (8): 76–78.

Yeong, T.K., Jiao, K., Zeng, X. et al. (2018). Microalgae for biobutanol production – technology evaluation and value proposition. *Algal Research* 31: 367–376.

Zaker, A., Chen, Z., Wang, X., and Zhang, Q. (2019). Microwave-assisted pyrolysis of sewage sludge: a review. *Fuel Processing Technology*: 84–104.

Zangana, M.H.S., Ibraheem, F.H., Khaleel, S.I., and Al-Dahhan, M.H. (2017). Recycling of spent molecular sieves from oil and gas industry: North gas company as a case study. In: *2017 International Conference on Environmental Impacts of the Oil and Gas Industries: Kurdistan Region of Iraq as a Case Study*, 54–58. EIOGI.

Zenati, B., Chebbi, A., Badis, A. et al. (2018). A non-toxic microbial surfactant from *Marinobacter hydrocarbonoclasticus* SdK644 for crude oil solubilization enhancement. *Ecotoxicology and Environmental Safety* 154: 100–107.

Zhang, X. (2018). Study on recent advances of waste drilling fluid treatment. *Fresenius Environmental Bulletin* 27 (6): 4460–4468.

Zhang, Y., Minaret, J., Yuan, Z. et al. (2018a). Mild hydrothermal liquefaction of highwater content agricultural residue for bio-crude oil production: a parametric study. *Energies* 11 (11): 3129.

Zhang, L., Pan, Z., Ma, G.-Y. et al. (2018b). Thermodynamic analysis of combined cooling heating and power (CCHP) system based on waste heat recovery in heavy oil extraction with steam assisted gravity drainage (SAGD) process. *Kung Cheng Je Wu Li Hsueh Pao/Journal of Engineering Thermophysics* 39 (9): 1890–1898.

Zhang, X., Yao, A., and Ren, Z. (2018c). Pilot test on oily solid waste disposal by thermal desorption of moving bed. *IOP Conference Series: Materials Science and Engineering* 392 (4): 042024.

Zhang, Z., Yan, X., Gao, F. et al. (2018d). Emission and health risk assessment of volatile organic compounds in various processes of a petroleum refinery in the Pearl River Delta, China. *Environmental Pollution* 238: 452–461.

Zhang, R., Zheng, X., Li, S. et al. (2018e). Environmentally friendly hydraulic fracturing and water-free fracturing technologies. *International Journal of Oil, Gas and Coal Technology* 17 (4): 375–390.

Zhao, S., Zhou, X., Wang, C., and Jia, H. (2018). Dewatering and low-temperature pyrolysis of oily sludge in the presence of various agricultural biomasses. *Environmental Technology (United Kingdom)* 39 (21): 2715–2723.

Zhou, Q. and Shen, B. (2010). Biodegradation potential and influencing factors of a special microorganism to treat petrochemical wastewater. *Petroleum Science and Technology* 28 (2): 135–145.

Zhou, Q., Sun, F., and Liu, R. (2005). Joint chemical flushing of soils contaminated with petroleum hydrocarbons. *Environment International* 31 (6): 835–839.

Zhou, W., Li, Y., Min, M. et al. (2011). Local bioprospecting for high-lipid producing microalgal strains to be grown on concentrated municipal wastewater for biofuel production. *Bioresource Technology* 102: 6909–6919.

Index

above-ground treatment of groundwater
  activated carbon adsorption, 299–300
  air stripping, 298–299
activated carbon adsorption, 106–108
activated sludge effects, 151–152
activated sludge feed, 153–154
activated sludge process (ASP), 14, 146
activated sludge units, 248–249
  applications, 151
  design considerations, 158–160
  effects, 151–152
  feed composition, 152–157
  process design, 157
adjustable flow controls, 100
adsorption, 178
  isotherm, 107
advanced wastewater treatment
  chemical constituents, effects of, 250, 252
  operations and processes, 250, 253
  untreated domestic wastewater composition, 250, 251
advanced wastewater treatment/reclamation, 13
aerobes, 144
aerobic digester design data, 277
aerobic digestion
  advantages, 276–277
  of biosludge, 324
  disadvantages, 277
aerobic sludge digester, 159
agricultural wastewater reuse, 255
air bubbles, 88
air floatation float recycle, 324
air floating unit, 330
air monitoring of waste
  area monitoring, 345
  knowledge of materials, 344
  at operational site, 344
  sampling method, 343–344
  test protocol, 343
  worker sampling, 344–345
air-stripping methods
  diffused aeration, 298
  packed towers, 299
  spray aeration, 299
  tray aeration, 299
air vents, 100
alpha particle counter, 132
alternating current, 122, 127
alum, 115
aluminum chloride, 210
American Petroleum Institute (API) separator, 51, 55
  components
    inlet section, 56
    pre-separator flume, 57
  forebay skimming of, 326–327
  oil skimmer, 57–59
  trash rack, 57
ammonia, 152
ammoniacal nitrogen, 33–34
anaerobes, 144

Waste Management in the Chemical and Petroleum Industries, Second Edition. Alireza Bahadori.
© 2020 John Wiley & Sons Ltd. Published 2020 by John Wiley & Sons Ltd.

anaerobic digester design data, 276, 277
analyzers, 100–101
aromatic plants, 37
ash handling and disposal, 318 *see also* waste disposal
atomic absorption spectroscopy, 128
automated laboratory equipment for monitoring water and wastewater
  emissions to water, 134
    point source discharge, 134–135
  loading losses, 133
    total volatile organic compound estimation, 133–134

back filling, 336
backwashing, 97–98
bacteria
  growth without inhibition, 140–142
  removal/destruction, 117
ballast water treatment, 21
belt filter press, 282
benzene contaminated streams, 208–209
beta particle counter, 132
biochemical oxygen demand (BOD)
  characteristics of wastewater, 2
  chemical contents and conditions, 171
  chemical oxygen demand, 44, 220
  degrade organic compounds, 172
  determination of organic constituents, 131
  measurement of, 219, 220
biodegradable organics, 19
biokinetic theoretical model, 140–142
biological activated carbon (BAC) process, 139–140
biological aerated filtration (BAF), 180–181
biological filters, 246–249
biological oxidation basin(s), 158
biological pathogens, 3
biological sludges, 323, 325
biological solids (cells), 152
biological treatment processes
  aerobic and anaerobic treatment, 144–149
  used for wastewater treatment, 143–144
  waste constituents, 23
biomass, 38
  yield coefficient, 139
biorestoration, 289
biosludge from water treatment, 324
bottom sludge collector, 83
by-product phospho-gypsum (BPG) composition, 319

carbon adsorption, 23
carcinogenic substances, 8
catalase enzyme, 160
catalyst regeneration unit, 37
Catalyx fluid solutions (CFS), 191
caustic scrubs (heavy oils), 205
CBM-WTS, 191
ceiling samples, 345
centrifugal pumps, 267
centrifugation, 281–282, 331
ceramic MF/UF membranes, 178
chemical addition systems, 115–116
chemical agents, disinfection, 116
chemical and advanced oxidation, 104
chemical biodegradable organics, 3
chemical cleaning waste, 211
chemical coagulation, 103–104
chemical fixation/solidification process, 286
chemical flocculation, 109–110, 331
  clarifiers, 112–114
  definition and applications, 110–112
  design considerations, 112
chemical oxidation treatment, 178–179
chemical oxygen demand (COD), 131
  biochemical oxygen demand, 44, 219, 220
  determination of, 44–45
  in wastewater systems, 44–46
chemical precipitation, 103, 109
chemical sewer system(s)
  chemical waste, types of, 202–203
  disposal of chemical sewers, 202
  neutralization systems, 202
chemicals facilities, 87
chemical stabilization, 106
chemical treatments, 106
chemical unit processes, 103
chloride, 128
chlorination
  applications, 119
  chlorine dosages, 118–119
  design considerations, 119–120
chromate inhibitor reuse, 325
clarification system, 122
clarifiers, 112–114
climatic constraints, 41
coagulation/sedimentation, 23

coal bed methane (CBM)
timing, 175
treatment methods, 191
coal bed water
surface treatment, 174, 175
toxicity limitations of, 171–173
coal seam gas (CSG), 167, 168, 174
co-incineration, 284–285
coke fines, 259–260
colorimeter, alternative current, 122
color, in water, 126
combustible gas indicator, 130
comminution, 50
composting systems, 278
compound nitrogen/phosphorus/potassium fertilizers, 32–33
compression (type 4), 74
conductivity, 127–128
constructed wetlands, 179
contaminant plume, 295–296
contaminant vapors, 288
continuous counter-current ion exchange (CCIX) method, 191
continuous monitoring, 122
continuous water sampling, 122
and monitoring system, 124
conventional ASP system, 146–147
conventional oil–water separator, 52
conventional, rectangular channel separators, 53–65
conventional secondary treatment, 12
coordinate sampling system, 339
cyanides, 129, 210
cycle time, 98
cyclic activated sludge system (CASS), 147

deep well injection, 180
degradable (non-conservative) pollutants, 3
dense non-aqueous phase liquid (DNAPL), 292, 293
desalter wastewater effluent, 205–206
detention time, 76
dewatering methods, sludge
advantages and disadvantages, 279–281
belt filter press, 282
centrifugation, 281–282
drying beds, 282–283
lagoons, 283
vacuum filtration, 279, 281
diaphragm pumps, 268
diffused aeration, 298
digested primary sludge composition and properties, 263
dilution steam generator blow down, 35
direct contact wastewater, 9
discharge options and quality requirements, 11–13
discrete particle (type 1), 74
disinfection
chemical agents, 116
mechanical of, 116–117
dispersed hydrocarbon components, 169
dissolved air flotation (DAF)
air concentration estimation in, 87–93
chemicals facilities, 87
design considerations, 81–86
efficiency, 80
general, 78–79
instruments and control, 86
material, 87
piping, 86–87
system configuration, 79–80
treatability testing, 80–81
dissolved gases, 170
dissolved gas flotation (DGF), 78
dissolved hydrocarbon components, 169
dissolved inorganic compounds/minerals, 169
dissolved inorganic solids, 3, 7, 19
dissolved organic carbon (DOC), 134
domestic water, 5
down-flow sand filters, 96
drag coefficient, 72–73
drilling discharge, 321
drilling fluids (mud), function of, 320
dropping mercury electrode (DME), 128

effluents, 199
disposal
boiler blow down and water treating rinses, 204
concrete paved process and utility areas drains, 204
cooling water drains, 204–205
diked tank areas, 204
flare seal drum blow-down, 205
floating roof drain of tanks, 205
laboratory wastewater, 205
process and utility paved areas, 204
process drum drains, 205

effluents (*Continued*)
pump and compressor cooling, 204
tank bottom draws, 204
undiked tank areas, 204
unpaved areas, 203
gas treatment plant, 216
liquefied natural gas, 215–216
natural gas liquids, 215–216
petrochemical plant special effluents, 212–215
in refinery and petrochemical plants
aluminum chloride, 210
benzene contaminated streams, 208–209
caustic scrubs (heavy oils), 205
chemical cleaning waste, 211
cyanides, 210
desalter wastewater effluent, 205–206
emulsifying agents, 212
ferric chloride, 211
foul/sour water, 206
heavy viscous oils drainage, 212
hydrofluoric acid, 211
loading systems, 211–212
MTBE/leaded contaminated streams, 208
nitrogen base components, 210
phosphoric acid, 211
polyelectrolyte, 210–211
solvent processes drainage, 212
spent catalysts, 211
spent caustic solutions, 206–208
spent sulfuric acid products, 209–210
sulfur solidification and crushing facilities, 211–212
toxic metal contaminated streams, 212
treating processes drainage, 212
water containing solids, 212
source streams, 203
terminals, depots, and product handling area, 216
wastewater characteristics
flow, 218
light hydrocarbon solubility in water, 220–221
oil content, 220
oxygen demand, 219
pH, 218–219
phenol content, 219
sulfide content, 219
temperature, 218
water–hydrocarbon systems, mutual solubility of, 221, 223–226
water pollution control, 13–18
effluent weir, 65
electrochemical methods, 128
electrodes, 124, 127
electrodialysis reversal, 179–180
electron donor, 138
emulsifying agents, 212
environmental consequence factor (ECF), 301, 304–306
environmental protection, for industrial waste, 37–44
equalization basin, 69–70
ethane, aqueous solubility of, 221, 222
evaporation ponds, 174
excavation, 290–291

facultative bacteria, 149
fecal microbes, 2
ferric chloride, 211
fertilizer industry waste, 319
filter clays, 325
filter presses, 282
filtration, 179, 331
flare system effluent, 35
flight scraper or chain type, 62–64
floating non-aqueous phase liquid
pumping well installation, 297
recovery of, 298
trench excavation, 297
volume of, 292–294
floating oil skimmers, 57–58
floating vortex oil skimmer, 57–58
float skimmer and sludge scrapers, 83
float/sludge receiving tank, 83
float/sludge transfer pumps, 83
flocculant (type 2), 74
flow equalization
application and location, 68–69
volume requirements, 69–70
flow measurement, 47
fluidized-bed incineration, 284
fluoride, 129
fly ash, 260, 335–336
formation water, 173, 174
fouled condensate, 35
foul water, 206
fracking, 168
free oil, 152

freeze-thaw evaporation, 178
Freundlich isotherm, 107
frictional drag force, 71

GAC *see* granular activated carbon (GAC)
gamma-ray monitoring, 132–133
gas pipelines, leak detection in, 313–314 *see also* pipeline leak
granular activated carbon (GAC), 139–140, 299–300
granular-media filtration
  cycle time, 98
  filter types and applications, 94–96
  general, 93–94
  instrumentation and controls, 100–101
  system design parameters, 96–98
  vessels and appurtenances, 99–100
gravitational force, 71
gravity-type separators
  application, 52
  conventional, rectangular channel (API) separators, 53–65
  general, 51–52
  oil traps, 67–68
  oil–water separators, 53
  parallel-plate separators, 65–67
grease and oil, 129
grit removal, 50–51
groundwater
  above-ground treatment technologies, 298–300
  mass of dissolved contaminants, 294–295
  monitoring devices, 17, 346–347
  pollution control
    preventive measures, 16–17
    types of devices, 17–18
  recharge, 255
  sampling, 126
  sorption of dissolved contaminants, 294–295

hazardous waste *see also* solid wastes
  characteristics, 329
  from chemical industry pesticides, 319
  environmental impacts, 320
  facility, permit requirements, 319
  fertilizer industry waste, 319
  generators/handlers, 329
  landfill, 335–336
  petrochemical industry waste, 318
  reduction, 328–330
  refinery waste, 318
  transportation, 329
  treatment, storage, and disposal, 329–330
hazardous waterborne pollutants, 3
heat drying, of sludge, 283–284
heavy metals, 3, 6–7, 19
heavy viscous oils drainage, 212
helical flight screw conveyor, 83
high pressure piston pumps, 268
hindered (type 3), 74
horseshoe-type floating skimmer, 59–60
hydraulic fracturing process, 168
hydraulic loading rate (HLR), 81
hydraulic methods, 290
hydrodynamic protection, 17
hydrofluoric acid, 211
hydrogen peroxide, 159–160
hydrolysis, of biosludge, 324

ideal chemical disinfectant, 117
ideal sedimentation basin, 73
incineration, 331–332
incinerators, 317
  design considerations, 332
  types, 332
indirect contact wastewater, 9
industrial wastewater reuse, 252
influent wastewater characteristics, 41
infrared spectrophotometry, 130
inorganic suspended matter, 152
in situ oil sands production method *see* steam-assisted gravity drainage (SAGD) process
instantaneous wetting rate, 162–163
integrated fixed film activated sludge (IFAS), 147–148
iodide, 129
ion exchange, 176
  system, 104–106
isotopic tracers method, 312

laboratory instruments, 122–125
lagoons, 283
land application, of sludge, 285–286
land farming, 336
landfill, of hazardous waste, 335–336
land treatment
  advantages and disadvantages, 333–334
  air quality, 335

land treatment (*Continued*)
area and facility layout, 334
design and operational considerations, 334
potential environmental impacts, 334
site characteristics, 333
soil characteristics, 333
waste characteristics, 332
waste degradation, 333
water quality, 334–335
Langmuir isotherm, 107
light hydrocarbon solubility in water, 220–221
light non-aqueous phase liquid (LNAPL), 292–294
lime stabilization, 275
liquefied gas spill, 215–216
liquefied natural gas (LNG), 215–216
liquid effluent, 34
liquid pipelines, leak detection in, 313 *see also* pipeline leak

macro-porous polymer extraction (MPPE) technology, 181
Marcellus shale, 167
mass of dissolved contaminants, 294–295
mechanical aerators, 158
media filtration technology, 179
membrane bioreactor (MBR), 148–149
membrane filtration technology, 176
microfiltration and ultrafiltration, 177–178
polymeric and ceramic membranes, 178
reverse osmosis, 177
metals
content in wastewater sludge, 264
determination of, 128
heavy, 3, 6–7, 19
methane, aqueous solubility of, 221, 222
methylene blue active substance (MBAS), 7
microfiltration (MF), 177–178
micro-organisms, 44
minor constituent, 34
miscellaneous solid waste, 323
mitigation measures, 17–18
mixed liquor suspended solid (MLSS), 140
mixers
application, 70–71
description and type, 70
MLSS/mixed liquor volatile suspended solid (MLVSS), 148
Monod equation, 138–140
moving bed bioreactor (MBBR), 147
MTBE/leaded contaminated streams, 208
multi-effect distillation (MED), 185
multiple-hearth incineration, 284
multistage flash (MSF) distillation, 181
municipal wastewater reuse, 251–252

naphtha hydro-treating units, 37
natural gas liquids (NGL), 215–216
naturally occurring radioactive materials (NORMS), 173
neutralization/flocculation, 84
neutralized acid and caustic solutions, 325
nitrate, levels of, 34
nitrogen, 19, 129
ammoniacal nitrogen, 33–34
and urea, 33–34
nitrogen base components, 210
nitrogenous fertilizers, 32
non-aqueous phase liquid (NAPL), 287, 291
removal, 297
volume of floating NAPL, 292–294
non-biodegradable residues, 152
non-biological organic suspended material, 152
non-degradable (conservative) pollutants, 3
non-hazardous waste, 320–321 *see also* solid wastes
non-oily wastes, 323
non-oily water sewer system, 201–202
nutrients
contaminant in wastewater treatment, 3
feed composition, 155
feed systems, 158
removal or control, 12
unit operations, processes, and systems, 19

offshore drilling, 337
offshore pipelines
safety consequences assessment, 302
oil field produced water, 169
oil holding basins, 68
oil reclamation, 325
oil retention baffle, 60, 65
oil sands mining, 191
adsorbents, 192
advanced oxidation, 193
biological treatment, 192–193
constructed wetlands, 193
micro-and ultrafiltration, 192
nanofiltration, 192

oily water treatment, 193, 195–197
reverse osmosis, 192
sonochemical oxidation, 193
water treatment technologies, 192–193
oil skimmer
American Petroleum Institute separator, 57–59
floating, 57–58
horseshoe-type floating skimmer, 59–60
rotary drum, 58–59
separator forebay, 60
oil skimming device, 65
oil/sludge moving devices, 61
oil terminals
wastewater pollutant sources in, 6
wastewater pollution, 19–21
oil traps, 67–68
oil, water accidentally contaminated with, 5
oil–water separators, 51–53
oily drain, 34–35
oily process sludges, 321, 323
oily water sewer system, 200–201
olefin plants
aromatic plants, 37
polymeric plants, 35–36
polyvinyl chloride plants, 36
online fixed measurement, 122
onshore drilling, 336–337
on-site portable instruments forwater pollution control
alternative current colorimeter, 122
and clarification system, 122
continuous monitoring, 122
continuous water sampling, 122
groundwater sampling, 126
laboratory instruments, 122–125
online fixed measurement, 122
soil water sampling, 125–126
organic compounds, 9, 155–156
organic constituents, 129–130
organic material
soluble, 5
water free of oil and, 5
organic shocks, 156
oscillator, 127
oxy-chlorination effluent drum, 37

packed bed biotowers, 147
packed tower air stripper, 299
paddle mixers, 70
parallel-plate separators, 52, 65–67
particle size, 77
particulate matter, 260
pathogens, 19
petrochemical industry
cooling water, 29
fertilizer, 31–33
hazardous waste, 318
petrochemical waste treatment, 30–31
typical pollutants in, 29–30
washing water and process water, 29
water pollution, 29
petrochemical plant special effluents, 212–215
petroleum products, 233
basic release information, 233
site-specific parameters, 234
pH adjustment, 115
phosphate, 129
fertilizers, 32
levels of, 34
phosphoric acid, 211
phosphorus, 19
pH value, 129
physical examination, in wastewater treatment
alpha particle counter, 132
atomic absorption spectroscopy, 128
beta particle counter, 132
biochemical oxygen demand, 131
chemical oxygen demand, 131
color, 126
combustible gas indicator, 130
conductivity, 127–128
determination of metals, 128
gamma-ray monitoring, 132–133
organic constituents, 129–130
polarography, 128–129
total organic carbon, 130
turbidity, 128
water and wastewater radioactivity, 131–133
physical suspended solids, 3
physical unit operations, 47
applications of, 48
pipeline leak
characteristic signals, monitoring of, 310–311
combined pressure decrease/flow increase method, 310
detection techniques, 306–312
dynamic simulation method, 307

pipeline leak (*Continued*)
environmental consequence factor, 301, 304–306
fluid hazard factors, 302, 303
leak consequence evaluation, 300–301
leak expectancy factor, 301
mass balance principle, 307
negative pressure wave techniques, 311
off-line leak detection, 311–312
population density factor, 302, 303
potential leak rate and mass, 302–303
safety and environmental consequences, 301
safety consequence factor, 301
statistical pipeline leak detection system, 307, 310
plastic media trickling filters, 147
plunger pumps, 264, 267
polarography, 128–129
polar organics, 197
pollution effect
ammoniacal nitrogen and urea, 33–34
minor constituents, 34
nitrate, 34
phosphate, 34
polyelectrolyte, 210–211
handling and mixing system, 115–116
polymeric MF/UF membranes, 178
polymeric plants, 35–36
polyvinyl chloride plants, 36
pore water, contaminant dissolved in, 288
powdered activated carbon (PAC), 299
preliminary wastewater treatment, 12
pre-separator flume, 57
pressure filters, 331
pressure gauge, 100
pressurized flow recycle system, 85–86
primary settlement tanks, 242–244
primary wastewater treatment, 12
priority pollutants, 4, 9
process to further reduce pathogens (PFRP) stabilization, 285–286
process to significantly reduce pathogens (PSRP) stabilization, 285, 286
process water, 5, 29
produced solids, 170
produced water membrane treatment technologies, 182–184, 186–190
adsorption, 178
biological aerated filtration, 180–181
ceramic MF/UF membranes, 178
chemical oxidation treatment, 178–179
constructed wetlands, 179
deep well injection, 180
electrodialysis and ED reversal, 179–180
evaporation ponds, 174
filtration technology, 179
freeze-thaw evaporation, 178
ion exchange, 176
media filtration technology, 179
membrane filtration technology, 176–178
polymeric MF/UF membranes, 178
surface-stream disposal, 174–176
thermal water treatment technologies, 181–185
produced water treatment process
oil sands mining, 193, 194
problems and potentials, 194
production chemicals, 169–170
product terminals, 6
programmable controller for automatic operation, 101
progressive cavity pumps, 267
proportional detector, 132
pumping well installation, 297, 298
pyrolysis, 332

qualities, wastewater, 11

radioactive tracers, leakproof control using, 312–314
radionuclide pollutants, 3
reaction-jet inlet, 61
recovery measures, groundwater, 18
recreational reuse, 255
refinery effluent, 134, 135
refinery/plant waste, release of
discharge site characteristics and receiving environment, 217
waste characteristics and composition, 216–217
waste reduction and discharge methods, 217–218
refinery solid wastes, 318
biological sludges, 323
miscellaneous waste, 323
non-oily wastes, 323
oily process sludges, 321, 323
quantities and characteristics, 323
sanitary wastes, 323

segregation, 321, 323
sources and classification, 321, 322
refinery treatment sequence options, 25
refractory organics, 3, 19
renovated water, uses of, 255
residual liquid contaminant, 288
residual suspended matter
biological treatment, 22
combination of simple gravity separation systems, 21
physical and chemical purification, 22
spills, 22
reverse osmosis, 177
rotary drum oil skimmer, 58–59
rotary-lobe pumps, 268
rotating biological contactor (RBC) systems, 163–164

safety consequence factor (SCF), 301
salt content, 156
sampling, of wastes
composite liquid waste sample (coliwasa), 339, 340
coordinate sampling system, 339
dipper, 341
equipments, 339–342
grid system, 339
quality assurance considerations, 346
safety precautions, 345–346
sampling plan, 338–339
thief sampler, 341, 342
trier sampler, 341, 342
weighted-bottle sampler, 339, 340
sanitary sewer system, 203
sanitary solid wastes, 258
sanitary water, 5
saturated zone, 232, 291
contaminant phase evaluation, 292–294
mobility of contamination, 296
scintillation detector, 132
screening process, 47–50
scroll centrifuges, 331
scum skimmer, 82
secondary settlement tanks, 245–246
sedimentation
affecting factors, 76–78
application and type, 73–74
basin zones, 77
design considerations, 74–75
detention time, 76
inlet arrangements, 75–76
number of basins, 75
outlet arrangements, 76
short-circuiting, 76
surface loading rate, 76
theory, 71–73
sedimentation/flotation, 23
segregation of wastes, 321, 323
separator forebay, 60
settling velocity, 54
sewage effluents
domestic wastewater plant, 239
receiving water, 238
sewage, environments, 237, 238
sewage oxidation ponds, 164–165
sewage treatment plant
activated sludge units, 248–249
advanced wastewater treatment, 250–254
biological filters, 246–249
design of, 240, 241
drying beds, 244–246
final effluent disposal, 249
preliminary treatment, 242
primary settlement tanks, 242–244
secondary settlement tanks, 245–246
selection of, 239–240
sludge digesters, 244
small sewage treatment plant design, 240–242
tertiary treatment (polishing) process, 249
treatment methods, 239
wastewater reuse, 250–252, 255
shale gas, 167
market-changing growth, 168
short-circuiting, 76
shutdown planning, 324
side water depth (SWD), 82
silica, 129
simple gravity separation, 21
site assessment, 232
siting and design, for water pollution control
aquatic ecosystems, 25
land use, 28
terrestrial ecosystems, 25–27
water pollution control, 28
wetland ecosystems, 27–28
skimmed oil collection, 64–65
skimmer/sludge scraper, 83
sludge, 269–270 *see also* solid wastes
barge transport, 315

sludge (*Continued*)
centrifugal pumps, 267
chemical fixation/solidification process, 286
conditioning, 278
conveyance methods, 315
designing thickening facilities, 274
dewatering methods, 279–283
diaphragm pumps, 268
disinfection, 278–279
disposal targets, 261
dissolved air flotation, 272
environmental considerations in transportation, 315
expected concentrations, 272, 273
final disposal, 316–317
gravity thickening, 272
grinding process, 270–271
heat drying, 283–284
high pressure piston pumps, 268
incineration, 317
lagoons (disposal site), 317
land application, 285–286
land disposal site, 316–317
pipeline transportation, 315
piping, 268, 270
plunger pumps, 264, 267
progressive cavity pumps, 267
pumps, types and selection of, 264, 267–268
rail transportation, 315
rotary-lobe pumps, 268
sludge storage pads, 316
storage and basins, 316
thermal reduction, 284–285
thickening methods, 272, 274
truck transport, 315
volume reduction, 272
sludge age, 324
sludge collection and removal, 64
sludge concentration
by gravity differential method, 330–331
by incineration, 331–332
land treatment, 332–336
by mechanical dewatering, 331
sludge digesters, 244
sludge drying beds, 282–283
sludge processing, 13, 15
sludges and solids, from wastewater treatment plant
physical characteristics, 261–264
quantities, 265
sources of, 258, 259
sludge stabilization process, 274
anaerobic sludge digestion, 276–277
composting process, 278
design considerations, 275
heat treatment, 275–276
lime stabilization, 275
small sewage treatment plants, 240–242
soil flushing process, 289–290
soil infiltration
predictive tool, 348–351
sample calculations for practice engineers, 351–352
soil venting, 289
soil water sampling, 125–126
solid wastes *see also* land treatment
catalytic process, 259
characteristics, 261
classification, 257
cleanout wastes, 261
from coking operations, 259–260
contaminant mobility, evaluation of, 288, 294–296
contaminant-specific information, 286–287, 291
in crude oil supply, 258
disposal (*see* waste disposal)
emissions to land, 346–347
groundwater monitoring, 346–347
hazardous waste, 318–320
non-hazardous waste, 320–321
particulate matter and fly ash, 260
quantities, 261
in refineries, 321–323
remediation goals, 296
resource recovery, 324–328
sanitary wastes, 258
saturated zone, 291
site assessment, 291–294
sludges and solids (*see* sludges and solids, from wastewater treatment plant)
source reduction methods, 323–324
sources of, 261
spills, 347
from surface water, 258
UST site determination, 288–291
in water supply, 258
soluble BOD, 151–152
soluble organic material, 5

solvent processes drainage, 212
sorption of dissolved contaminants, 294–295
source reduction methods, solid wastes
  biosludge from water treatment, 324
  tank cleaning, 323
sources, of wastewater, 11
sour condensate, 205
sour water, 205, 206
special sewer systems, 203
spent catalysts, 211
  reuse, 325
spent caustic
  neutralization, 35
  solutions, 206–208
spent sulfuric acid products, 209–210
spill contaminant, 22
spill prevention and control
  bulk storage, 16
  facility drainage, 16
  techniques, 15–16
spray aeration, 299
SpülKraft (SK) rate, 162–163
statistical pipeline leak detection (SPLD) system, 307, 310
steam-assisted gravity drainage (SAGD) process, 195, 197
Stokes' law, 54, 55
stone media trickling filters, 147
storm water sewer system, 200
submerged combustion, 191
sulfate, 129
sulfide, 129
sulfur solidification and crushing facilities, 211–212
supplemental dissolved oxygen, 159–160
surface-active agents *see* surfactants
surface loading rate, 76
surface-stream disposal, 174–176
surfactants, 7
susceptible to separation (STS), 55, 67
suspended solids, 6, 19, 156

terminal velocity, 54
terminal, water pollution, 5–6
theoretical oxygen demand (ThOD), 45–46
thermal reduction, of sludge
  advantages and disadvantages, 284
  co-incineration, 284–285
  fluidized-bed incineration, 284
  multiple-hearth incineration, 284
  wet-air oxidation, 285
  wet oxidation, in vertical deep-well reactor, 285
thermal water treatment technologies, 181
  multi-effect distillation, 185
  multistage flash distillation, 181
  vapor compression distillation, 185
threshold concentrations of pollutants, 14
total dissolved inorganic solids (TDIS), 7
total dissolved solids (TDS), 156, 173
total nitrogen (TN), 2
total organic carbon (TOC), 130
total organic content analyzers, 159
total phosphorus (TP), 2
total volatile organic compound estimation, 133–134
toxic and inhibitory materials, 155
toxic metal contaminated streams, 212
toxic organic compounds, 7
toxic waste treatment/specific contaminant removal, 13
trash rack, 57
traveling bridge or span type, 61–62
tray aeration, 299
treatment selection processes, 22–24
trench, 17
  excavation, 297, 298
trickling filter, 160–161
turbidity, 128

ultrafiltration (UF), 177–178
unsaturated zone, 232
untreated primary sludge composition and properties, 263
up-flow sand filters, 97
urea
  and nitrogen, 33–34

vacuum extraction, of floating NAPL, 298
vacuum filters, 331
vacuum filtration, 279, 281
vacuum truck removal, 337
vapor compression distillation (VCD), 185
velocity head diffusion devices, 61
vertical slot baffle, 61
vessels and appurtenances, 99–100
vinyl chloride monomer (VCM), 36
volatile organic compounds (VOCs), 9

walnut shell filters, 179
washing drum, 37
waste disposal *see also* solid wastes
  evaluation and selection of, 257–258
  offshore drilling, 337
  onshore drilling, 336–337
  sampling considerations, 337–342
waste minimization, 325 *see also* solid wastes
  air cooler maximization, 326
  amine degradation prevention, 326
  API separator, forebay skimming of, 326–327
  closed cooling water system, 326
  coke fines recovery/reuse, 327
  crude tank mixers, 326
  DAF unit, pressurized air operation of, 327
  demineralized clarified river water, 326
  independent parallel bay separator design, 327
  in-line blending, 326
  integrated units, 326
  process catalyst reuse, reclamation, and recovery, 327
  separate sewer systems, 326
  slop oil recovery/reuse, 327–328
  spent naphthenic caustic reuse, 327
wastewater emissions
  effluent permissible concentrations, 228–231
  point source discharge, 226–228
wastewater reuse, 250
  agricultural reuse, 255
  groundwater recharge, 255
  industrial reuse, 252
  municipal reuse, 251–252
  recreational reuse, 255
wastewater systems, in COD, 44–46
wastewater treatment
  stages, 9–13
  unit operations, 18
  unit processes and systems for, 18
water containing solids, 212
water continuously contaminated with oil, 5
water-holding properties, of soils, 235
water–hydrocarbon systems, mutual solubility of, 221, 223–226
water level detect, 100
water monitoring, 120–121
water radioactivity, 131–133
water temperature, 77
wax tailings, from coking process, 260
weathering, 234
wet-air oxidation, 285
wet oxidation, in vertical deep-well reactor, 285
wetting rates, 162