Activated Carbon

Solutions for Improving Water Quality

Zaid K. Chowdhury
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Garret P. Westerhoff
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Laurel B. Passantino,
Technical Editor

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Contents

List of Figures ix
List of Tables xv
Authors and Editor xvii
Acknowledgments xxi
Preface xxiii
Introduction xxv
List of Abbreviations and Acronyms xxxiii

PART I ACTIVATED CARBON ADSORPTION TECHNOLOGIES 1
References 2

1 Fundamentals of Adsorption 3
Activated Carbon Manufacturing and Properties 3
Adsorption 4
Batch Adsorption Kinetics 5
Adsorption Equilibrium, or Isotherm 7
Ideal Adsorption Reactors 11
References 13

2 Powdered Activated Carbon Systems 15
Continuous Flow Stirred Tank Reactor Performance 15
References 20

3 Granular Activated Carbon Systems 21
Fixed-Bed Plug Flow Reactor Performance 21
References 28

PART II ADSORPTION APPLICATIONS 29

4 Activated Carbon Application Approaches 31
Water Quality Master Planning Approaches 31
Water Quality Master Planning Steps 32
Utility Experiences with Water Quality Master Planning 35
Application Modes for Activated Carbon 49
PAC Use to Achieve Water Quality Goals 50
GAC Use to Achieve Water Quality Goals 55
References 70

5 Dissolved Organic Matter Control 73
DOM Characteristics 73
PAC for Removal of Dissolved Organic Matter 74
PAC Applications 74

AVA Documents
Document Sharing Hub

Full document details: AWWA Activated carbon. Solutions for improving water quality 2013

PAC Performance Evaluation 74
GAC for Removal of Dissolved Organic Matter 76
GAC Applications 76
GAC Performance Evaluation 77
BAC Performance Evaluation 84
References 87

6 Taste-and-Odor Control 89
PAC for Control of Taste and Odor 90
PAC Applications 90
GAC for Control of Taste and Odor 97
GAC Applications 97
GAC Performance Evaluation 98
References 103

7 Activated Carbon for Organic Contaminant Control 107
PAC for Removal of Organic Contaminants 107
PAC Applications 107
PAC Performance Evaluation 107
GAC for Removal of Organic Contaminants 110
GAC Applications 110
GAC Performance Evaluation 110
Common Organic Contaminants Controlled Using Activated Carbon 123
Volatile Organic Compounds 123
Synthetic Organic Chemicals 125
Micropollutants 127
References 131

PART III DESIGN AND PROCUREMENT OF ACTIVATED CARBON SYSTEMS 135

8 Gravity GAC Treatment System Design 137
Design and Construction 137
Review Key Design Parameters 138
Filter Layout 141
Design Details of Treatment Units 142
Pretreatment 161
Retrofit Limitations 162
Operation and Maintenance 162
Filling a GAC Treatment Unit 162
Emptying a GAC Treatment Unit 163
On-Site Storage of GAC 165
Backwashing 167
Water Quality Monitoring 168
Chlorination 168
GAC Safety 169
References 169

9 Pressure GAC Treatment System Design 171
Design and Construction 171
Pressure GAC System Overview 171
Review Key Design Parameters 174
Facility Layout 176

AVA Documents
Document Sharing Hub

Full document details: AWWA Activated carbon. Solutions for improving water quality 2013

Construction Details of Treatment Units 180
References 196

10 Vapor-Phase GAC Treatment Design 197

Design and Construction 198
Vapor-Phase GAC Treatment System Overview 198
Determine Key Design Parameters 199
Apply Regulatory Requirements 204
Obtain Manufacturer Information 204
Construction Details of Treatment Units 206
GAC Handling 212
Facility Layout 213
Operation and Maintenance 214
GAC Replacements 214
References 214

11 On-Site GAC Reactivation Design 215

Reactivation Methods 216
Thermal Reactivation 216
Chemical Regeneration 221
Biological Regeneration 221
Indicators of Reactivation Efficiency 222
Effects of Inorganic Compounds on GAC Reactivation 222
Reactivated GAC Quality Monitoring 223
Air Quality Considerations 223
Emissions Evaluation 224
Addressing Public Perception 225
Design of On-Site Reactivation Systems 226
Facility Layout 226
Process Design Criteria 227
GAC Handling 232
Plant Service Water Requirements 234
Permitting 235
Air Quality Permitting 235
Preconstruction Permits 235
Operating Permits 236
Air Toxics/HAPs 236
Accidental Release Prevention 236
Solid Waste Handling Requirements for Spent GAC 236
Process Water Control and Discharge 237
Operational Considerations 237
GAC Safety 238
References 238

12 PAC Feed System Design 241

Design and Construction 241
Review Key Design Parameters 241
Construction Details of PAC Systems 243
Operation and Maintenance 255
Operational Considerations 255

AVA Documents
Document Sharing Hub

Full document details: AWWA Activated carbon. Solutions for improving water quality 2013

Maintenance Requirements. 256
Preoxidation 256
PAC Safety 256
References 257

13 Activated Carbon System Implementation and Economic Considerations 259

Capital Project Delivery Goals and Issues 259
Pathways to Higher Performance (The Synergy of Integration) 260
Capital Project Delivery Methods 261
Guarantor 265
Pathways for Selecting an Appropriate Delivery Method 267
Pathways to Creating Lasting Solutions 269
Activated Carbon Procurement Considerations 270
Physical Properties 271
Special Considerations in Developing Technical Specifications for PAC 271
Special Considerations in Developing Technical Specifications for GAC . . . 273
Considerations for Developing Cost Estimates. 276
References 277

Appendix A Example Environmental Life-Cycle Assessment 279

System Boundaries 279
Key Assumptions Used in Developing the LCA. 279
Scenario Descriptions. 280
Life-Cycle Inventory Analysis. 282
Impact Assessments of Example 282
Example Results 282

Appendix B Case Studies 287

1 Post-Filtration GAC Treatment with On-Site GAC Reactivation 288
2 Water Quality Master Plan and GAC Implementation. 289
3 Water Quality Road Map 290
4 Design-Build-Operate WTP 291
5 PAC Treatment 292
6 Continually Mixed PAC Contactor 293
7 Post-Filtration GAC Treatment 294
8 Design–Build–Operate WTP 295
9 GAC Filter Adsorbers 296
10 Ozone-Enhanced GAC Biofiltration 297
11 Groundwater GAC Demonstration Facility 298
12 Groundwater GAC Treatment 299
13 Groundwater GAC Treatment 300
14 Wellhead GAC Treatment 301
15 Post-Filtration GAC Treatment 302
16 GAC Filter Adsorber Demonstration Project 303
17 Post-Filtration GAC Treatment 305

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List of Figures

1-1 Illustration of the mass transfer–adsorption process 5
1-2 Activated carbon adsorption in a completely mixed batch reactor 5
1-3 Adsorbate uptake kinetics in a CMBR shown as both (a) liquid-phase and (b) solid-phase concentrations 6
1-4 Adsorbate uptake kinetics and equilibrium liquid-phase concentration in a CMBR as affected by (a) the adsorbent dose and (b) adsorbent size (d_{AC}), adsorbate diffusivity (D), and system mixing or shear 6
1-5 Example isotherm (a) arithmetic plot and (b) logarithmic plot 9
1-6 Effect of Freundlich parameters (a) K_F and (b) 1/n on isotherm 9
1-7 Equilibrium isotherm in a binary mixture (a) strongly adsorbing Compound 1 and (b) weakly adsorbing Compound 2 10
1-8 Equilibrium adsorption isotherms of DOM at two different initial concentrations . 11
1-9 Flow-through reactors: CFSTR for PAC and PFR for GAC 12

2-1 PAC application points in a conventional surface water treatment plant 16
2-2 Continuous PAC addition to a CFSTR 16
2-3 Steady-state CFSTR performance followed by an increase in the influent concentration and a transition in the effluent concentration to new steady-state condition 16
2-4 Effect of operating, adsorbate, and background factors on steady-state effluent concentration of a PAC–CFSTR system 17
2-5 Effect of PAC dose, background DOM, and initial geosmin concentration on fractional removal 18

3-1 Fixed-bed GAC contactor 22
3-2 Unsteady-state PFR effluent concentration history in a fixed-bed GAC contactor for a single solute: (a) constant influent concentration and (b) pulse influent concentration 22
3-3 Unsteady-state PFR concentration profile in a fixed-bed GAC contactor for a single solute: (a) ideal adsorption front and (b) mass transfer zone (MTZ) 23
3-4 Unsteady-state PFR performance for a GAC fixed-bed contactor as affected by (a) dispersion and mass transfer kinetics, (b) KF and EBCT, (c) C_0, and (d) increasing C_0 at different 1/n values 24
3-5 GAC breakthrough expressed on a throughput basis for two EBCTs: (a) ideal results and (b) practical results for organic micropollutants and DOM . . . 26

Documents
Document Sharing Hub

Full document details: AWWA Activated carbon. Solutions for improving water quality 2013

3-6 Breakthrough behavior of multisolute systems: (a) effect on target compound breakthrough and (b) DOM breakthrough as measured by DOC 26
3-7 Common GAC application points 27

4-1 Richard G. Miller Treatment Plant TTHM concentration through the treatment process 38
4-2 Richard G. Miller Treatment Plant turbidity removal through GAC 39
4-3 BWWB Road Map to improved water quality 44
4-4 PAC addition and removal points 52
4-5 Post-filter contactor schematic. 56
4-6 Schematic cross-section of a gravity post-filter contactor 56
4-7 Filter adsorber schematic. 58
4-8 Schematic cross-section of a gravity filter adsorber 59
4-9 Schematic cross-section of a GAC cap. 60
4-10 BAC application schematic 61
4-11 Schematic cross-section of a gravity biologically enhanced activated carbon filter 61
4-12 Adsorber operation schematics 64
4-13 Operation of two adsorbers in series for the removal of MTBE. 65
4-14 Combined adsorber effluent versus time profile for adsorbers operated in staged parallel model. 66

5-1 (a) Removal of DOC by three PAC products and (b) boxplot of DOC fraction remaining with time regardless of PAC type 75
5-2 Typical DOM breakthrough behavior. 77
5-3 Effect of EBCT on DOC breakthrough 78
5-4 Effect of GAC media size on DOC breakthrough. 78
5-5 Sensitivity of DOC to influent concentration on a normalized DOC basis (a) and a concentration basis (b) 79
5-6 Influence of pH on breakthrough of DOM 80
5-7 Typical post-GAC DBP formation results 80
5-8 Zachman and Summers prediction of GAC performance 83

6-1 MIB adsorption isotherms prepared using the same water at three different pH values 92
6-2 MIB remaining versus PAC dose for several commercially available PACs 95
6-3 MIB breakthrough profiles (generated via RSSCTs) corresponding to deionized and natural waters. 98
6-4 MIB breakthrough profiles for several commercially available GACs (generated via RSSCTs). 99
6-5 MIB breakthrough profiles (generated via RSSCTs) corresponding to influent MIB concentrations of 50 and 150 ng/L 100
6-6 MIB breakthrough (generated via RSSCTs) on a mass concentration (a) and normalized (b) basis 101

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Full document details: AWWA Activated carbon. Solutions for improving water quality 2013

7-1 Dose-response curves for an organic contaminant for three PAC products (C_0 < 1 µg/L) 108
7-2 Bisphenol A breakthrough exhibits dependence on EBCT 111
7-3 2,4-dichlorophenoxyacetic acid breakthrough at two concentrations shown on concentration and normalized concentration basis 113
7-4 Mass balance on GAC adsorber 113
7-5 Effect of influent DOC on erythromycin breakthrough 114
7-6 Desorption behavior compared to a model prediction calibrated to the adsorption performance 116
7-7 Backwashing shown to have a negligible effect on breakthrough of target organic contaminants 117
7-8 Typical results of RSSCTs versus pilot results 118
7-9 Apparent capacity model simulations 122

8-1 Example head loss curves for GAC 140
8-2 Relationship between filter area and filter depth; total filter depth does not include freeboard 141
8-3 Example of a plastic block underdrain with media retention layer. 145
8-4 Example of a semi-circular wedgewire screen underdrain 145
8-5 Example cylindrical wedgewire screen underdrain 145
8-6 Example folded plate underdrain 146
8-7 Example longitudinal underdrain layout. 148
8-8 Example radial underdrain layout. 148
8-9 Example tile/block underdrain layout 149
8-10 Variation of GAC bed expansion during backwash at multiple temperatures 150
8-11 Example of stepped backwashing sequence 151
8-12 Example post-filter contactor with U-shaped trough. 152
8-13 Seal well 154
8-14 Bulk delivery of GAC by tanker truck (a); 1,000-lb virgin GAC bags staged for loading a GAC treatment unit (b) 157
8-15 1,000-lb virgin GAC sack and skid-mounted hopper-eductor unit 158
8-16 Spent GAC dewatering equipment used with 1,000-lb bags 158
8-17 Post-filter contactor facility access drive with GAC transfer station connections at each contactor location 159
8-18 Schematic of an eductor 160
8-19 Example eductor performance curves 161
8-20 Flushing connection on a GAC transfer pipe 161
8-21 Accumulation/mounding of GAC during treatment unit filling 163
8-22 Permanently installed eductor with service water (1), wall connection to gravity treatment unit through knife-gate valve (2), and discharge piping to transfer station (3). 163
8-23 Eduction of GAC from a GAC treatment unit with temporary piping and a mobile eductor. 164

Documents
Document Sharing Hub
Full document details: AWWA Activated carbon. Solutions for improving water quality 2013

8-24 (a) GAC treatment unit wall washdown schematic 164
8-24 (b) Model FF spray nozzle; (c) spray pattern of the Model FF spray nozzle 165
8-25 Post-filter contactor with center trench and center flushing line 165
8-26 Reactivated GAC storage silos. 166

9-1 Dual GAC pressure vessel installation (large vessel) 172
9-2 Typical pressure GAC system features. 172
9-3 Operation of vessels—series flow 173
9-4 Operation of vessels—parallel flow 173
9-5 Operation of vessels—backwashing 174
9-6 Examples of modular treatment unit configurations 175
9-7 Series operation of modular treatment system with varying lead-treatment units 175
9-8 False bottom underdrain system 182
9-9 External header underdrain. 182
9-11 Ladder and platform vessel accessories 183
9-10 Bed sampling ports (Celina) 183
9-12 Three- and four-tier manifolds 184
9-13 Pressure vessel system with 2-vessel grouping arrangement 185
9-14 Pressure vessel system with 4-vessel grouping arrangement 185
9-15 HP systems pressure drop curves 187
9-16 Positive head loop example 187
9-17 Effect of temperature and flow rate on bed expansion 188
9-18 Sand separators 196

10-1 System schematic for packed column air stripper followed by vapor-phase GAC. . 197
10-2 System schematic for multi-stage diffused bubble aeration followed by vapor-phase GAC 198
10-3 Vapor-phase single-bed adsorber 199
10-4 TCE example vapor-phase isotherm 201
10-5 Comparison of vapor-phase and liquid-phase breakthrough curves. 203
10-6 Example head-loss curves for VoCarb® 46 and VoCarb® 410 GAC 204
10-7 Example schematic: Packed column air-stripping facility with vapor-phase GAC treatment 205
10-8 Example schematic: Packed column air-stripping facility with combined vapor-phase GAC treatment 205
10-9 Example schematic: Packed column air-stripping facility with split, parallel vapor-phase GAC treatment 206
10-10 Example schematic: Packed column air-stripping facility with series vapor-phase GAC treatment 206
10-11 Transportable adsorber 207
10-12 Single-bed adsorber cross section. 207
10-13 Dual-bed adsorber installation 208
10-14 Dual-bed adsorber cross section 208

Documents
Document Sharing Hub

Full document details: AWWA Activated carbon. Solutions for improving water quality 2013

10-15 Example blower. 210
10-16 Example vapor-phase pressure drop curves 210
10-18 Example psychrometric chart 211
10-17 Gas-fired duct heater. 211
10-19 Series operation of treatment units with varying lead treatment unit 214

11-1 GAC thermal reactivation. 216
11-2 Infrared oven schematic 217
11-3 Rotary kiln schematic 218
11-4 Rotary kiln at Lake Pleasant Water Treatment Plant. 218
11-5 Example of fluidized bed furnace 219
11-6 Fluidized bed furnace 219
11-7 Multiple hearth furnace 219
11-8 Example of a multiple-hearth furnace. 220
11-10 Venturi scrubber 231
11-11 Tray-tower scrubber schematic 231
11-9 Venturi scrubber schematic. 231
11-12 Baghouse schematic 232
11-13 Donaldson® Torit® Modular baghouse structure 232

12-1 Pallets of 50-lb PAC bags at a Wilmington, Del., WTP 244
12-3 Concrete PAC slurry tanks 245
12-5 Dippers in volumetric feeder 245
12-6 Dry PAC feed schematic 246
12-7 Dry PAC storage silos 246
12-8 Emergency pressure vent and manhole cover. 247
12-9 PAC storage and feed system for 1,000-pound bags 247
12-10 Bin activator 248
12-11 Silo fluidizer disc. 248
12-12 Air fluidizer. 249
12-14 Rotary feeder 249
12-13 Live bottom with air fluidization connections. 249
12-15 Donaldson® Torit® cast-iron rotary valve 249
12-16 Screw feeder 250
12-17 Volumetric screw feeder 250
12-18 Loss-in-weight feeder 251
12-19 Wetting cone 251
12-20 Inside of wetting cone. 251
12-21 Long-radius bend on PAC piping 253
12-22 Flexible tubing used for PAC 253
12-23 Silo dust collection system 254

AVA Documents
Document Sharing Hub

Full document details: AWWA Activated carbon. Solutions for improving water quality 2013

12-24 Silo dust collection cartridges 254
12-25 PAC fill line below water surface 255

13-1 Participants and relationships in design–bid–build 262
13-2 Participants and relationships in CM@Risk 264
13-3 Participants and relationships in design–build 265
13-4 Participants and relationships in design–build–operate 266

A-1 Major scenario components 280
A-2 GAC filter adsorber schematic 281
A-3 Post-filter contactor schematic 281
A-4 EC/chloramines schematic 281
A-5 Analaysis of contributions by activity 284
A-6 LCA results normalized to North American emissions 2001 285

Documents
Document Sharing Hub

Full document details: AWWA Activated carbon. Solutions for improving water quality 2013

List of Tables

1-1 Typical activated carbon physical characteristics 4
1-2 Example isotherm results 8
1-3 Use rate definitions using isotherm parameters and Example 1-3 calculations. 13

4-1 Activated carbon applications 50
4-2 Comparison of several types of powdered activated carbon. 51
4-3 Comparison of gravity GAC technologies. 69

5-1 Fitting parameters for the PAC removal of DOC 76
5-2 Zachman and Summers (2010) models. 83

6-1 Fitting parameters for the PAC removal of MIB 97

7-1 Surrogate water coefficients and properties 120
7-2 Correction factors for different classes of compounds 120
7-3 State guidelines and enforceable standards for MTBE in drinking water 124
7-4 Relative adsorbability of selected compounds 130

8-1 Comparison of GAC underdrain alternatives 147
8-2 Potential auxiliary systems required for GAC treatment 153

9-1 Number of GAC delivery trucks required. 177

11-1 Recommended testing for reactivated GAC 223
11-2 Criteria pollutants found in reactivation furnace exhaust 224
11-3 Emission contributions for drinking water facility with TTHM goal of 10 µg/L 225
11-4 Air pollution controls 229
11-5 Low-NO_x burner emissions reductions 230
11-6 Afterburner exhaust constituents 230

13-1 Key features of delivery methods. 268
13-2 Comparison of delivery methods. 269
13-3 Alternative delivery methods for chapter 4 GAC systems 270

A-1 LCA Inputs, functional unit = 1 day at 20 mgd 283
A-2 Overall LCA results for 1 day of product water (20 mil gal) 284
A-3 Additional sustainability measures for 1 day of product water (20 mil gal) 285

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continued next page

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Preface

Determining the appropriate treatment regime to provide safe drinking water for customers continues to challenge drinking water purveyors. Source water quality is becoming more compromised as global demand increases, high-quality sources are depleted, and improvements in analytical methods reveal increasingly lower concentrations of contaminants in treated water. Regulatory agencies struggle with adequate resources to make sound scientific judgments regarding safe levels of contaminants in drinking water while media reports of detected levels of chemicals and microbes leave customers apprehensive about the safety of what comes out of their faucets every day.

Maintaining microbiological quality continues to be a cornerstone of water treatment as reinforced by the unfortunate incidence of waterborne disease in impoverished and developing nations. Nevertheless, conventional disinfectants used effectively in treatment for more than a century produce by-products that may have long-term chronic health effects, and sources degraded by anthropogenic inputs increase the portfolio of chemical contaminants that must be addressed. Personal care products and pharmaceuticals in drinking water are reported with increasing frequency in the global media, while the effects on humans remain unresolved.

Through all of this uncertainty, proactive measures that can reduce a wide variety of contaminants to low concentrations through multi-objective treatment remain an important element of robust and reliable drinking water production. Activated carbon, one of the oldest treatment technologies, is once again demonstrating its value in these challenging times. Activated carbon is simple to operate as an adsorption medium, serves as a proactive barrier for contamination, and does not produce by-products from its use. It can be reactivated and reused. And it removes compounds that customers can perceive with their senses—taste-and-odor compounds—as well as reduces a suite of potentially harmful chemical contaminants to low concentrations.

Many books have been written about granular activated carbon. Some focus on the theory of performance and removal mechanisms while others focus on design features. This book focuses on solutions. It describes the challenges facing water providers to provide safe water that is acceptable to their customers, utility experiences using activated carbon, activated carbon applications, and design and procurement approaches. The appendices include detailed case studies and a life-cycle assessment demonstrating favorable sustainability considerations for activated carbon when compared with other treatment technologies.

Never before has all of this information been brought together in one location. The what, why, where, and how of this treatment technology are connected in this book and demonstrate why activated carbon has maintained its status as an integral treatment technology in the quest for pure water over millennia.

Enjoy the story!

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Introduction

Water purveyors throughout the globe have been, and continue to be, challenged to support existing and growing populations with an adequate and safe water supply. Historically, communities developed where water supplies were available and abundant. For example, the settlements resulting from the westward migration in the United States in the 1800s were often determined according to where water supplies were found. Now, however, there are few new locations where safe water supplies are available and abundant, either in the United States or globally. Instead, the challenge of maintaining and protecting drinking water supplies from further degradation is high on the minds of water purveyors and environmentally minded individuals and groups. Existing supplies continue to be threatened by microbiological and chemical contaminants introduced by increasing populations and associated economic development as well as by natural sources of contamination.

Water scarcity is a constant area of concern in major metropolitan areas in arid regions, and climate change is affecting how regions that previously had sufficient resources view their supplies into the future. These scarcity issues are driving water purveyors to use lower-quality water sources to meet increasing demand. At the same time, improved analytical techniques are able to detect compounds at lower and lower concentrations, either revealing contaminants that previously had not been detected or indicating the presence of contaminants that have been recently introduced into the water supply. Although health effects of many of these micropollutants are not currently known and may not be known for decades or longer, consumers are rightfully concerned about their presence in drinking water, and water purveyors must respond.

In the fundamental charge to protect public health, water purveyors rely on a combination of treatment and watershed protection to meet water quality goals and regulations. In meeting these goals, water purveyors should consider both the quantity and quality of the supply and choose suitable treatment approaches. The approaches are often a combination of physical, chemical, adsorption, and biological processes. The challenge is to determine the best combination of processes that protect public health and meet customer desires and regulatory requirements for water quality while doing so in a financially responsible manner.

The Case for Activated Carbon

Activated carbon is an adsorption medium and its use is considered an advanced technique for meeting many water quality demands. Treatment with activated carbon is not new and has in fact been used for thousands of years to improve the quality of drinking water. It has been used in various forms (powdered and granular) around the globe in a multi-objective manner, removing heterogeneous compounds that produce

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color and are precursors to contaminants upon disinfection, trace organic and inorganic contaminants, and taste-and-odor compounds. Activated carbon also has the flexibility to be operated in both adsorption and biological modes. In the latter, it provides a large surface area for organisms to populate and biologically degrade contaminants. Utilities may implement activated carbon for several reasons, including regulatory compliance, positioning for future regulations, public health protection and customer confidence, and sustainability considerations.

Compliance With Existing Regulations

For most water systems, the biggest driver for implementing activated carbon treatment is to gain compliance with water quality regulations. The US Congress originally passed the Safe Drinking Water Act (SDWA) in 1974 to protect public health by regulating the nation's public drinking water supplies. The law was subsequently amended in 1986 and 1996. The two categories of drinking water standards in the SDWA are:

1. *Primary Standards:* Legally enforceable standards that limit the levels of specific hazardous contaminants having an adverse effect on human health.
2. *Secondary Standards:* Nonenforceable guidelines for nonhazardous contaminants that may cause cosmetic effects (such as skin or tooth discoloration) or aesthetic effects (such as taste, odor, or color) in drinking water. USEPA recommends secondary standards to water systems but does not require systems to comply unless the state chooses to require compliance.

Several individual regulations fall under the umbrella of the SDWA. The following components are most likely to influence a water purveyor's decision to implement activated carbon.

Disinfectants and Disinfection By-products (D/DBP) Rule

For more than 100 years, the practice of disinfecting drinking water using chlorine and its compounds has protected consumers from waterborne diseases by inactivating pathogens. However, disinfectants react with organic matter in the water supply, and many of the by-products formed are of concern to public health. The primary objective of the D/DBP Rule, which was promulgated in two stages, is to reduce exposure of drinking water consumers to DBPs such as total trihalomethanes (TTHMs), the sum of five haloacetic acids (HAA5), bromate, and chlorite while still providing adequate disinfection. The rule also contains requirements for removing DBP precursors, as demonstrated by total organic carbon (TOC) removal using a treatment technique termed *enhanced coagulation*, which means achieving additional TOC removal by adding increased amounts of coagulant over what is required for turbidity removal.

To adequately protect public health from many waterborne diseases, the practice of disinfection must be continued. Activated carbon helps water purveyors comply with the D/DBP Rule by providing an additional removal mechanism for TOC. Because TOC is a major contributor to TTHM and HAA formation upon chlorination, reducing the TOC will also reduce the formation potential of these DBPs.

Enhanced Surface Water Treatment Rule

The Enhanced Surface Water Treatment Rule (ESWTR) also has two stages, corresponding to the two stages of the D/DBP Rule. The objective of the ESWTR is to

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confirm that disinfection is not compromised by utilities in their effort to minimize DBP formation. Compliance is demonstrated by providing treatment processes that remove or inactivate microorganisms. The final stage of this rule, the Long-Term 2 Enhanced Surface Water Treatment Rule, requires additional removal or inactivation of *Cryptosporidium*, depending on the source water quality. The USEPA's treatment toolbox for *Cryptosporidium* grants 0.5 log removal when granular activated carbon (GAC) filters or contactors are placed in series with another filtration process (granular media or membrane).

Unregulated Contaminant Monitoring Rule (UCMR) and Contaminant Candidate List (CCL)

The CCL is used by USEPA to identify contaminants that may be regulated in future, and the UCMR is used to gather data on the occurrence of unregulated contaminants in drinking water systems. Although there are no enforceable standards for UCMR contaminants, data are collected and reported to USEPA to assist with future regulatory policymaking. The first CCL was published in March 1998 and contained 60 contaminants under regulatory consideration. Based on the data from the first monitoring cycle of the UCMR, USEPA published the second drinking water CCL (CCL2) in 2005. The list carried forward 51 of the original 60 contaminants, and 9 were removed because sufficient data were collected and indicated that further regulating action was not required. In addition to the CCL2 list, the USEPA published the UCMR2, which required monitoring of 26 contaminants.

The third CCL (CCL3) was published as a draft in February 2008 and was finalized in 2009. After evaluating approximately 7,500 potential contaminants based on occurrence, production, and toxicology, an expert panel under the direction of the National Research Council (NRC), National Drinking Water Advisory Council (NDWAC), and Science Advisory Board (SAB) helped USEPA systematically narrow down the list of potential contaminants in the CCL3 to 104 chemicals and 12 microbiological contaminants. UCMR3 was proposed in February 2011. When it is finalized, this rule will require monitoring of 30 contaminants during the 2013–2015 time frame.

Many of the contaminants on the CCL and monitored in the UCMR can be effectively removed using activated carbon. Consequently, should any of them be regulated either individually or as a class of contaminants in the future, activated carbon will become an important part of the process train for many utilities.

Positioning for Future Regulations

The continued pressure to improve water quality is mounting as source waters are challenged with a variety of micropollutants. These contaminants include those being detected because of improved analytical methods and those being introduced into source waters at higher concentrations, such as personal care products and pharmaceutically active compounds. Although effective for reducing concentrations of these micropollutants, chemical oxidation does not convert them into carbon dioxide and water, and it is often unknown what compounds form in their place. Therefore, true removal processes are being revisited with renewed vigor. Membrane processes are improving, but only higher-pressure options such as nanofiltration and reverse osmosis can address most of these micropollutants. The following emerging issues are likely to affect utility strategies for using activated carbon in their treatment systems.

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MTBE and Perchlorate

Both MTBE (methyl-*tert*-butyl-ether) and perchlorate continue to gain public interest and deserve more scrutiny. As two of the original contaminants on the CCL in March 1998, MTBE and perchlorate have undergone UCMR monitoring to determine the viability of regulating the chemicals or removing them from the list.

In UCMR monitoring of more than 3,400 systems, MTBE was detected in only 0.5 percent of the systems, and perchlorate was detected in nearly 4.5 percent of samples. It is still unclear whether the MTBE concern is in localized regions or widespread throughout the country. It is very likely that if MTBE detections are localized, the monitoring would spark state regulation rather than federal. While the USEPA is still in the process of revising its MTBE risk assessment, California has set an enforceable standard of 14 µg/L for MTBE. Because perchlorate is more widespread, it is more likely to warrant federal regulation.

Endocrine Disrupting Compounds (EDCs) and Pharmaceuticals

Pharmaceuticals, personal care products, and some household compounds are starting to appear in drinking water systems around the United States and in Europe. Some of these compounds are known to be endocrine disrupting compounds (EDCs), but their significance in drinking water is still not clear. Future monitoring and testing are needed to determine which of these compounds, if any, pose a threat to human health and at what dose. At that point, monitoring water systems for such compounds and evaluating ways to remove the compounds from the water may be necessary.

Nitrogenous Disinfection By-Products

The potential exists for future regulation of nitrogenous disinfection by-products (N-DBPs). Many N-DBPs can be found in treated drinking water; however, the most common ones include the various species of nitrosamines, particularly *N*-nitrosodimethylamine (i.e., NDMA) and halonitromethanes. Six of the nine possible nitrosamines are currently included in the CCL3 list. Based on the results of UCMR2 monitoring, NDMA is the most commonly occurring nitrosamine in drinking water. Because of the significant occurrence and the associated high carcinogenic potency of NDMA, it is anticipated that USEPA will consider developing a regulation for NDMA in the near future.

Carcinogenic Volatile Organic Compounds (cVOCs)

Under the auspices of six-year review, USEPA is currently reviewing the standards for trichloroethylene (TCE) and perchlorethylene (PCE). With USEPA's strategic direction to regulate contaminants by groups, USEPA is considering the revised TCE/PCE standards in a combined regulation for carcinogenic VOCs. Eight different cVOCs are currently regulated, and USEPA is considering regulating up to eight more in the group of cVOCs. A group regulation for cVOCs is expected to be proposed in 2013. Although the regulatory limits for specific VOCs are not known at the time of preparing this book, it is widely anticipated that the current regulatory limits for TCE and PCE will be lowered from the current limits of 5 µg/L. The existing limits were based on the limits of the analytical techniques available at the time; however,

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because analytical methods have been refined, lower detection limits are feasible compared to when the first VOC regulations were developed.

Activated carbon is the most widely accepted technology used to adsorb many of the organic compounds of concern. Many water utilities around the world are currently using activated carbon for removal of Natural Organic Matter (NOM), Synthetic Organic Chemicals (SOCs), and taste-and-odor compounds. It also helps with N-DBPs because systems that lower their TTHM and HAA formation potential are less likely to use chloramine, thereby avoiding formation of N-DBPs.

Public Health Protection and Customer Confidence

The state and federal drinking water regulations that provide legally enforceable standards are the foundation for a water utility's public health commitment to its customers and the public. However, meeting the standards does not result in zero risk; rather, the standards are based on peer-reviewed science, including data on how often the regulated contaminant occurs in the environment, how humans are exposed to it, the health effects of exposure, and cost considerations. A water system can elect to provide treatment to a quality higher than that required by a standard. However, most systems find it difficult to obtain the financial resources that may be needed to provide treatment levels above those required to comply with state and federal standards.

Science is continually identifying the presence of additional chemicals in the drinking water supply, often in minute concentrations. While evidence is lacking that many of these pose a significant threat to public health, customers may become concerned at the presence of these compounds in their water supply, especially when reported by various media outlets. Because we are in an era of information overload, multitasking, and sound bites, few people have the time, desire, or even sufficient technical expertise to fully examine and form their own educated opinion on all of the issues and challenges facing them today. Hence, opinions are often based on perceptions formed by instincts and input received from a variety of sources.

Much of the media only focus on water issues during droughts, floods, proposed rate increases, reported failure, inefficiencies, or health emergencies. Seldom is there a positive story of how well a water utility is performing, the quality of life it supports, or the health protection it is providing. With most of the media information reporting the negative, it is understandable that many customers are biased with negative perceptions and concerns about the quality of their water.

To counter these negative perceptions, it is critical for utilities to provide their customers with outstanding customer service and to become trusted partners in the goal to protect public health. During a Gallup Organization's Drinking Water Customer Satisfaction Survey for the USEPA of 1,000 households nationwide in 2002, general drinking water consumer knowledge and public confidence with information sources were assessed. Findings from the survey demonstrated that Americans recognize the importance of receiving information on aspects of their drinking water and value being informed. This accentuates the need for honest, unbiased information reaching the customer. Another way for utilities to demonstrate their commitment to understanding customer concerns is to provide additional treatment barriers for unregulated contaminants such as micropollutants, taste- and odor-causing (T&O) compounds, or aesthetic issues. However, the decision to implement additional treatment must be sensitive to the ability of the community to afford the increased level of treatment.

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The bottom line is that while most of our water treatment systems do a good job with the technologies they have in place, a broad spectrum of chemicals in a water supply remain that are not being removed or reduced to the degree they could be by using activated carbon technologies. Although implementation of GAC treatment technologies costs money and will result in increased water rates, implementation needs to be considered in the light of improved public health protection. The current economic conditions may inhibit the ability to incur these costs; however, the value should be considered in strategic long-range planning.

Sustainability Considerations

It is sometimes thought that the use of a GAC treatment technology would result in a significant environmental burden. This needs to be considered in light of other options that could be used to achieve a desired treatment effect. In an effort to reduce the environmental burdens associated with producing drinking water, many water utilities have begun evaluating the sustainability of potential treatment scenarios prior to implementation. As a water utility evaluates the potential use of various processes to reduce disinfection by-products, one approach to assessing sustainability is a life-cycle assessment (LCA). LCA, which is often referred to as *cradle-to-grave*, is a systematic approach that follows the International Organization of Standardization (ISO) 14040 standard to quantify potential environmental burdens of a product or process over its lifetime.

Appendix A contains an example illustrating the use of LCA to evaluate the environmental impacts of typical processes to reduce DBPs. Three treatment technology scenarios were evaluated in the example: (1) GAC filter adsorbers, (2) GAC post-filter contactors, and (3) enhanced coagulation followed by disinfection using chloramines. In the appendix A example, no single scenario had significantly lower results across all LCA categories and sustainability measures analyzed, challenging the thought that GAC results in a significant environmental burden.

Concerns With Activated Carbon

Despite its merits, activated carbon has yet to be accepted as a "baseline" process in water treatment. Nevertheless, the USEPA recognized the significant benefits of activated carbon in its seminal 1986 Amendments to the Safe Drinking Water Act and chose GAC as a best available technology (BAT) for treating a suite of chemical contaminants. Since that time, some water purveyors have chosen to implement GAC as a treatment technique, while others have found different and often less expensive ways to meet federal and state water quality requirements. The use of GAC treatment is expensive, both in initial capital cost as well as in on going operational costs associated with reactivating and replacing the media. The information in this book describes methods and techniques to minimize these costs. The cost of GAC treatment should be considered in light of the benefits accrued by significant removal of a broad spectrum of organic contaminants from a water supply and the ability to furnish customers with a water quality that not only meets current regulations but also reduces risks that may result from currently unregulated contaminants and the risks of unintended consequences that may be associated with other treatment methods. The end result is the ability to furnish customers with a very high-quality water that is likely to improve their quality of life and protect human health.

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Book Organization

Many books and book chapters have been written on activated carbon treatment. Most focus on removal mechanisms and capabilities, with some discussion of process approaches and applications. This book puts the fundamentals of activated carbon treatment, adsorption applications, and design of systems in the context of today's and tomorrow's water quality concerns, presenting the reader with a holistic view of the role of activated carbon in the water treatment process.

The intent of the book organization is to serve the needs of various water utility leaders, managers, and professionals; water treatment providers, scientists, students, and engineers; and water utility consultants in three distinct areas related to planning for and designing activated carbon systems:

- Part 1 *Activated Carbon Adsorption Technologies* covers fundamentals and is targeted at assisting engineers and students who will use the book to gain a basic understanding and knowledge of activated carbon technologies for drinking water technologies.
- Part 2 *Adsorption Applications* is for those who will benefit from approaches to planning the use of activated carbon treatment. In addition, the numerous case studies presented in part 2 demonstrate how and where activated carbon has been successfully implemented to solve specific water quality challenges.
- Part 3 *Design and Procurement of Activated Carbon Systems* provides practical approaches to designers and system operators for effective and efficient design and use of activated carbon technologies as well as strategies for procuring and implementing the systems.

To address the concerns of sustainability related to the reactivation process, the authors included an appendix on sustainability, illustrating the full life-cycle assessment of activated carbon compared to other options for reducing TOC and complying with the Stage 2 D/DBP Rule. A similar process could be used to evaluate removal of micropollutants, comparing activated carbon to technologies such as reverse osmosis membranes and advanced oxidation processes using ozone.

Seventeen case studies comprise appendix B at the end of this book. These case studies will be useful to those readers seeking further practical information and experience from others using activated carbon technologies to improve the quality of their drinking water.

The book is not intended to be a textbook, although instructors can use portions of it to give students information on the basic mechanisms of the technology and practical guidance for training them as practicing engineers. It is assumed that different readers of the book will seek out relevant sections of the book as their needs dictate. Consequently, the book is written such that each of the three parts could be useful for a given audience without detailed study of the remainder.

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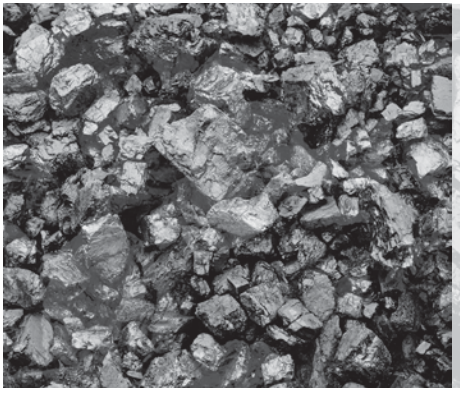
List of Abbreviations and Acronyms

AC activated carbon
AOC assimilable organic carbon
AOP advanced oxidation process
AWWA American Water Works Association
BAC biologically enhanced activated carbon
BAF biologically active filter
BAT best available technology
BDOC biodegradable dissolved organic carbon
BOM biodegradable organic matter
BTEX benzene, toluene, ethyl benzene, and xylene
BV bed volume
BWWB Water Works Board of the City of Birmingham
CAP Central Arizona Project
CCL Contaminant Candidate List
CCL2 second Contaminant Candidate List
CCL3 third Contaminant Candidate List
CFSTR continuous flow stirred tank reactor
CGTF Central Ground Water Treatment Facility
CIP capital improvements program
CLSA closed-loop stripping analysis
CM construction manager
CMBR completely mixed batch reactor
CMWC Consolidated Mutual Water Company
CSO combined sewer overflow
cVOCs carcinogenic volatile organic compounds
D/DBP Disinfectants and Disinfection By-products
DBP disinfection by-product
DDT dichlorodiphenyl trichloroethane
DHS Department of Health and Safety (California)
DOC dissolved organic carbon
DOM dissolved organic matter
EBCT empty bed contact time
EDC endocrine disrupting compound
EfOM effluent organic matter
ESWTR Enhanced Surface Water Treatment Rule
EMT external mass transfer
GAC granular activated carbon
GC-MS gas chromatography and mass spectrometry
GCWW Greater Cincinnati Water Works
HAA5 sum of five haloacetic acids
HLR hydraulic loading rate
HNM halonitromethanes
HOCs hydrophobic organic compounds
HSDM homogenous surface diffusion model
IAST ideal adsorbed solution theory
IMT internal mass transfer
ISO International Organization of Standardization
LCA life-cycle assessment
MCL maximum contaminant level
MF microfiltration
MIB 2-methylisoborneol
MIEX® magnetic ion exchange
MSDBA mulitstage diffused bubble aeration
MTBE methyl-tert-butyl-ether
MTZ mass transfer zone
N-DBPs nitrogenous disinfection by-products
NDMA N-nitrosodimethylamine

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NDWAC National Drinking Water Advisory Council
NJDEP New Jersey Department of Environmental Protection
NOM natural organic matter
NRC National Research Council
O&M operations and maintenance
OTC odor threshold concentration
PAC powdered activated carbon
PAH polycyclic aromatic hydrocarbon
PCB polychlorinated biphenyl
PCE perchlorethylene
PD-RSSCT proportional diffusivity RSSCT
PFOA perfluorooctanoic acid
PFR plug flow reactor
PhAC pharmaceutically active compound
PPCP pharmaceuticals and personal care products
PSDM pore and surface diffusion model
pzc point-of-zero-charge
RSSCT rapid small-scale column test
SAB Science Advisory Board
SCADA supervisory control and data acquisition
SDS simulated distribution system
SDWA Safe Drinking Water Act
SOCs synthetic organic chemicals
SUVA specific ultraviolet absorbance
T&O taste- and odor-causing
TCE trichloroethylene
TDS total dissolved solids
TOC total organic carbon
TTHMs total trihalomethanes
TTHMFP TTHM formation potential
UCMR Unregulated Contaminant Monitoring Rule
UF ultrafiltration
USEPA United States Environmental Protection Agency
USGS US Geological Society
UV ultraviolet
UVA ultraviolet absorbance
VOCs volatile organic compound
WQMP Water Quality Master Plan
WTP water treatment plant
WWTP wastewater treatment plant

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PART 1

ACTIVATED CARBON ADSORPTION TECHNOLOGIES

For drinking water treatment, activated carbon is primarily used in two ways: fixed bed reactors with granular activated carbon (GAC) and slurry application of the smaller powdered activated carbon (PAC). In general, the manufacturing process is similar for both products. PAC is applied in a manner such that it cannot be economically recovered from the water treatment stream, so it is removed with the process solid residuals. For surface water treatment, GAC can be applied as media in a filter, termed a *filter adsorber*, or applied in a reactor positioned after the filter, a post-filter contactor. For direct groundwater treatment, reactors similar to post-filter contactors are used. After the adsorption capacity of GAC is exhausted, it must be removed from the fixed-bed reactor and reactivated either on-site or off-site.

While the physical and chemical characteristics of activated carbon can give some insight into the potential adsorption behavior, actual adsorption tests with the specific activated carbon and the compound of interest in the actual water yield the most useful information. These tests are described in the next chapters and include: (a) batch equilibrium capacity tests, i.e., "isotherms"; and (b) methods that assess both capacity and kinetics, including PAC jar tests and GAC bench-scale and pilot-scale column tests.

One critical factor that affects the adsorption efficiency is the influence of the background matrix on the adsorption capacity of the target compound, whether it is naturally occurring compounds like the odorants 2-methylisoborneol (MIB) and geosmin, or anthropogenic compounds like trichloroethylene and atrazine. Increases in the concentration of the compounds that compose the background matrix decrease the adsorption capacity for the target compound. Activated carbon can also be used to control the formation of disinfection by-products (DBPs) through the adsorption of dissolved organic matter (DOM). The critical factor here is understanding the effect of the influent DOM concentration on the adsorption efficiency.

The objective of part 1 of this book is to provide an understanding of the fundamentals of adsorption by activated carbon from a practical perspective. The chapters include adsorption fundamentals (chapter 1), the basics of PAC systems (chapter 2), and the basics of GAC systems (chapter 3). The approach taken herein is a semi-quantitative one that intends to educate the reader on the factors that affect activated carbon adsorption. The approach is based on well-established principles, and the reader is referred to several existing monographs on activated carbon adsorption that provide the extensive literature review and the quantitative basis that underline the approach taken herein (e.g., Sontheimer et al. 1988 and Summers et al. 2010).

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References

Summers, R.S., D.R.U. Knappe, and V.L. Snoeyink. 2010. Adsorption of organic compounds by acivated carbon. In *Water quality and treatment*, 6th ed. J.K. Edzwald, ed. New York: McGraw-Hill and American Water Works Association.

Sontheimer H., J.C. Crittenden, and R.S. Summers. 1988. *Activated carbon for water treatment*, 2nd ed. Karlsruhe, Germany: DVWG Forschungsstelle.

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Chapter 1

Fundamentals of Adsorption

Adsorption is used in water treatment to remove dissolved contaminants by physical phase separation in either a steady-state (PAC) or a nonsteady-state (GAC) process. Adsorbates accumulate on the surface of the adsorbent until the adsorption capacity is consumed. In the PAC process, the PAC is removed from the water treatment stream as a process solids residual. In the GAC process, once the effluent concentration of the adsorbate reaches the treatment objective, the GAC must be replaced in order to continue satisfactory performance. The high internal surface area of activated carbon provides enough adsorption capacity to make it an economical choice of adsorbent. However, regardless of how much surface area is provided for adsorption, different target compounds have various affinities for the surface phase versus the water phase, making adsorption dependent on the properties of the target compound and the background matrix.

This chapter first provides an introduction to the process of manufacturing activated carbon. Then the physical-chemical process fundamentals of adsorption systems are discussed.

Activated Carbon Manufacturing and Properties

Activated carbons are manufactured from a wide range of carbonaceous materials. The most common precursor materials for use in drinking water treatment are bituminous coal, lignite coal, coconut shells, and wood. The choice of raw material affects the internal pore structure, surface area distribution, and surface chemistry. Commercial activated carbon production is a two-step process of carbonization of the precursor materials and activation. In the pyrolytic carbonization process, the temperature of the raw material is raised to the range of 500 to 800 °C in the absence of oxygen. Volatile organic matter of the raw material is thermally released, and the carbon atoms realign to form a more crystalline structure. The carbonized product at this point in the process is heavily influenced by the raw materials used. For activated carbon products used in water treatment, a thermal or physical activation process then follows in which the temperature of the carbonized product is increased to the range of 850 to 1,000 °C in the presence of an oxidizing agent, typically steam or carbon dioxide. Activation increases the pore sizes and creates a continuous pore structure, which increases the micropore volume (pore width < 2 nm) and the internal surface area. The mesopore and macropore volumes (pore width > 2 nm) are critical to the internal transport of the compound to the micropore surface area, which is where most of the adsorption occurs. Activated carbon can be produced in a

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Table 1-1. Typical activated carbon physical characteristics

Porosity	Surface area (m^2/g)	Particle density (kg/m^3)	Apparent dry density (kg/m^3)		Average particle diameter (mm)	
			GAC	PAC	GAC	PAC
0.5–0.8	500–1,200	600–850	300–650	200–750	0.6–3.0	0.01–0.03

* $1\ lb/ft^3 = 16\ kg/m^3$

direct activation process in which the raw material is crushed and then activated, or in a reagglomeration process in which the raw material is crushed, reagglomerated, crushed again, and then activated. Table 1-1 lists some typical physical properties of commercial activated carbon used in water treatment.

The apparent density of GAC is the as-received density of unstratified dry material. The bed density is the density after the GAC is placed in the filter or contactor, backwashed, and drained. Bed density is generally about 90 percent of the apparent density due to stratification.

Once the adsorption capacity of GAC is exhausted, it is removed from the filter or contactor and the adsorption capacity is restored in a reactivation process. The reactivation requires conditions very similar to the activation process used in the original production. During reactivation, some adsorbed compounds are thermally desorbed, but most compounds, including the adsorbed DOM, are oxidized on the GAC surface.

The surface chemistry of activated carbon is a product of the raw materials and the activation process. The noncarbon content of activated carbon varies but is typically in the 10 to 20 percent range and is mostly made up of surface oxygen functional groups and minerals (e.g., ash), both of which can negatively affect the adsorption of some compounds.

Adsorption

Adsorption is the accumulation of a substance (the adsorbate) on the surface of a solid (the adsorbent). While most, but not all, organic compounds of interest in drinking water quality are adsorbable by activated carbon, it is the degree of adsorbability that is important, as it dictates the cost of using activated carbon. For example, DOM consists of a mixture of compounds of which about 90 percent are adsorbable to some degree. Large-molecular-weight compounds are excluded from internal adsorption sites, and hydrophilic DOM compounds of any size are not attracted to the adsorbent surface. The most strongly adsorbed DOM components are low- and medium-molecular-weight hydrophobic compounds.

Adsorption of compounds of interest in drinking water by activated carbon occurs mostly by nonspecific physical adsorption as opposed to site-specific chemical adsorption. Physical adsorption is caused by nonspecific secondary binding mechanisms, in which electrons are shared between the adsorbate and the adsorbent rather than electrons being transferred, as occurs in chemical adsorption. Physical adsorption can be reversed in response to a change in the concentration gradient between the bulk liquid phase and the adsorbed solid phase. Because activated carbon has a

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nonhomogeneous surface with specific function groups, a limited degree of chemical adsorption for some compounds is possible.

Batch Adsorption Kinetics

As illustrated in Figure 1-1, removal of a compound by activated carbon is a three-step process: external mass transfer (EMT), internal mass transfer (IMT), and adsorption. The first step is external mass transfer of the compound from the bulk liquid phase through the hydrodynamic layer that surrounds the activated carbon particle. External mass transfer, or film diffusion, can be important and control the overall kinetics of the adsorbate uptake when the flow through a GAC bed is very low or when the mixing in a PAC reactor, like the flocculation basin, is low. After external mass transfer delivers the adsorbate to the external surface of the activated carbon particle, internal mass transfer conveys the adsorbate to an adsorption site on the surface of the activated carbon where adsorption occurs. The adsorption reaction of the compound at the activated carbon surface is very fast and is not considered to be rate limiting. Thus, the overall uptake is thought of as a two-step mass transfer process of external and internal mass transfer. Because external diffusion and internal diffusion occur in series, the slowest step is rate limiting. Both external and internal mass transfers are diffusion-based phenomena where the driving force is the concentration gradient of the adsorbate: the difference between the bulk concentration, C_b, and the internal concentration at equilibrium, C_e. Internal mass transfer is often the slowest and thus controls the overall uptake of an adsorbate. Internal mass transfer may occur through the pore fluid or along the pore wall in parallel processes. Both pore diffusion and surface diffusion are controlled by both the activated carbon pore structure and the adsorbate properties. Because the processes occur in parallel, the faster step, which is typically pore diffusion under most conditions relevant to water treatment, controls the overall uptake of an adsorbate.

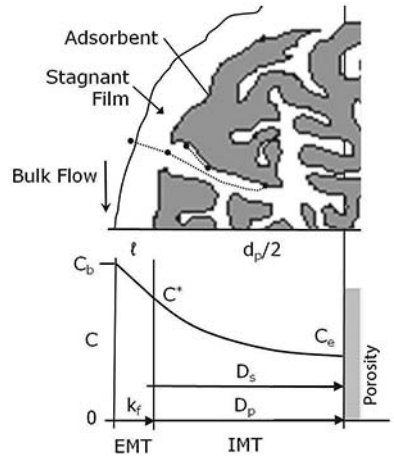


Figure 1-1. Illustration of the mass transfer–adsorption process

The kinetics of the overall adsorbate uptake can be illustrated using a completely mixed batch reactor (CMBR) such as shown in Figure 1-2, where V is the reactor volume, M_{GAC} is the mass of activated carbon added, and C_0 is the initial liquid phase adsorbate concentration. Mixing in the reactor is important as the external mass transfer resistance can be reduced by increasing the mixing enough to reduce the thickness of the stagnant film surrounding the particle.

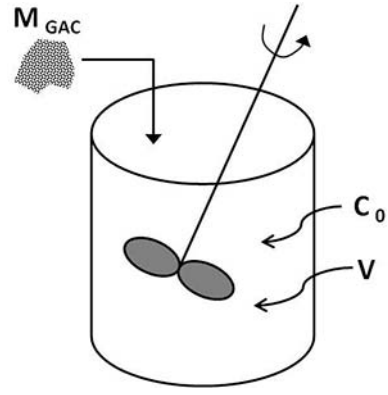


Figure 1-2. Activated carbon adsorption in a completely mixed batch reactor

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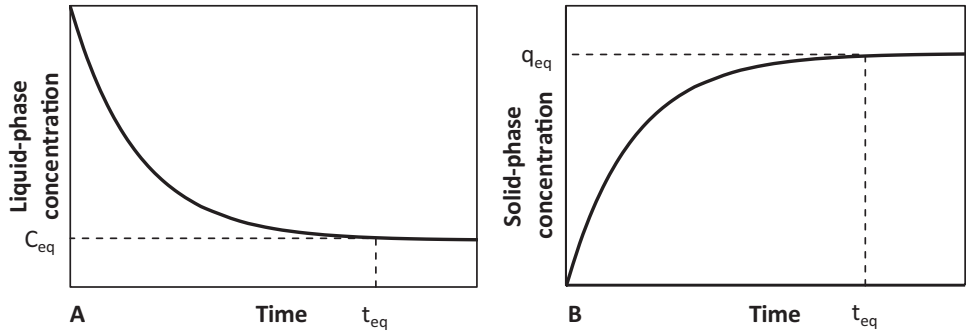


Figure 1-3. Adsorbate uptake kinetics in a CMBR shown as both (a) liquid-phase and (b) solid-phase concentrations

After the addition of the activated carbon, the liquid phase concentration of the adsorbate in the reactor will decrease as a function of time. Eventually, the net uptake of the adsorbate reaches zero. The adsorbate-adsorbent pair is now at equilibrium. The liquid phase concentration at this point is termed the *equilibrium liquid-phase concentration*, C_{eq}, and the time is termed the *time to equilibrium*, t_{eq}. Figure 1-3 illustrates the liquid-phase concentration history in a batch test along with the kinetics of the adsorbate concentration on the adsorbent surface, solid-phase concentration, q. The solid phase concentration at equilibrium, q_{eq}, is attained at the same time as C_{eq}.

As the adsorbent dose increases, the equilibrium liquid-phase concentration decreases as shown in Figure 1-4a. In addition to C_{eq} being affected by the dose increase, the time to equilibrium is also affected. Other factors that affect the kinetics or time to equilibrium, but not the equilibrium liquid-phase concentration, include the size of the adsorbent, expressed here as the diameter (d_{AC}); diffusion coefficient of the adsorbate (D); initial liquid phase concentration; and amount of shear or mixing imparted on the external surface of the adsorbent. The adsorbent size affects the internal mass transfer. As the adsorbent size decreases, the internal diffusion path length the adsorbate must travel to an adsorption site decreases, and the adsorption sites can be reached more quickly. The same mass of smaller adsorbent particles

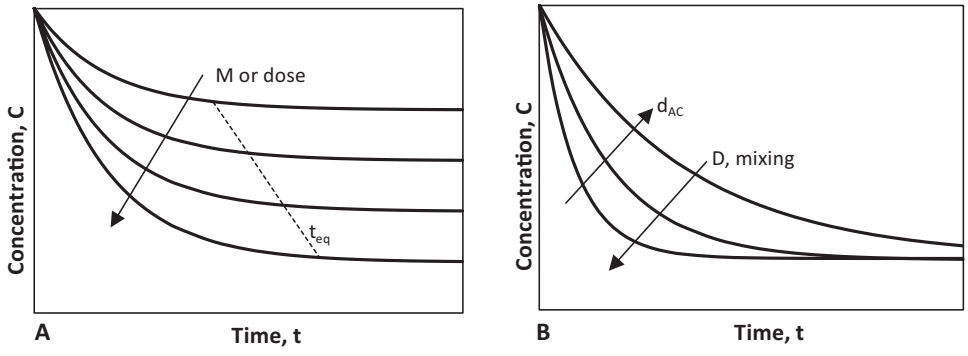


Figure 1-4. Adsorbate uptake kinetics and equilibrium liquid-phase concentration in a CMBR as affected by (a) the adsorbent dose and (b) adsorbent size (d_{AC}), adsorbate diffusivity (D), and system mixing or shear

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achieves equilibrium state more rapidly, lower t_{eq}, than that of large adsorbent particles. As the diffusion coefficient and the concentration of the adsorbate increases, the flux into the adsorbent increases and the adsorption sites can be reached more quickly, also decreasing the time to equilibrium. Factors affecting time to equilibrium are summarized in Eq 1-1:

$$t_{eq} = f\,(d_{AC}^{2},\ D^{-1},\ C_0^{-1}) \qquad \text{(Eq 1-1)}$$

When external mass transfer is an important factor, increasing the mixing in the CMBR or the fluid velocity decreases the boundary layer around the particle, thus increasing the overall uptake kinetics.

Adsorption Equilibrium, or Isotherm

Mass Balance

As was shown in Figure 1-4a, increasing the mass of activated carbon added to a batch reactor will decrease the equilibrium liquid-phase concentration, and the equilibrium solid-phase concentration increases by mass balance as shown in Eq 1-2:

$$q_{eq} = (C_0 - C_{eq}) \times V/m = (C_0 - C_{eq})/\text{dose} \qquad \text{(Eq 1-2)}$$

If an experiment is run that varies the adsorbent dose and/or initial concentration, the equilibrium solid-phase concentration can be calculated, and a relationship with the equilibrium liquid-phase concentration can be established. This adsorption equilibrium relationship, often termed *isotherm*, allows the adsorption capacity of the adsorbent to be calculated at any given liquid-phase concentration.

Example 1-1. Different masses of activated carbon are added to bottles that contain an adsorbate of interest to yield the doses noted in Table 1-2. Two different initial concentrations of the adsorbate were used. To facilitate the mass transfer, small activated carbon sizes were used, and the bottles were shaken. Preliminary experiments determined the time needed to achieve equilibrium (Figure 1-3). After waiting the prescribed equilibrium time, activated carbon was filtered from the solution, and the adsorbent equilibrium liquid-phase concentration was measured. Calculate the equilibrium solid-phase concentration at each dose and plot as a function of the equilibrium liquid-phase concentration.

Solution. Using the mass balance (Eq. 1-2), the equilibrium solid-phase concentration was calculated. The results are shown in Table 1-2 and Figure 1-5.

The shape of the isotherm plot is typical of the adsorption of target compounds by activated carbon from laboratory clean water. As can be seen for single-solute isotherms, the equilibrium relationship is not a function of the initial concentration.

Equilibrium Adsorption Isotherm Models

To be more useful, equilibrium isotherm relationships can be fit with model equations. The two most common are the Langmuir and Freundlich models. The Langmuir model is more fundamental, has conceptual endpoints as it asymptotically approaches a maximum solid-phase concentration at the very high liquid-phase concentration range, and has a linear equilibrium relationship at the very low–concentration ranges. However, experience has shown that the empirical Freundlich model (Eq 1-3), which

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Table 1-2. Example isotherm results

Initial concentration, C_0 2.00 mg/L			Initial concentration, C_0 0.500 mg/L		
Dose (mg/L)	C_{eq} (mg/L)	q_{eq} (mg/g AC)	Dose (mg/L)	C_{eq} (mg/L)	q_{eq} (mg/g AC)
5	1.53	92.77	5	0.295	40.74
10	1.18	81.47	10	0.18	31.82
25	0.575	56.87	25	0.056	17.75
50	0.224	35.50	65	0.01	7.50
100	0.066	19.27	150	0.002	3.35
200	0.0175	9.92	335	0.0004	1.50
400	0.0044	4.97	610	0.00012	0.82
800	0.00111	2.50			
1,600	0.00028	1.25			
3,000	0.00008	0.67			

is a power function, works best. The Freundlich model can be derived theoretically from the Langmuir model assuming a distribution of adsorption site energies.

$$q_{eq} = K_F C_{eq}^{1/n} \quad \text{(Eq 1-3)}$$

Where

K_F = Freundlich constant
$1/n$ = Freundlich exponent

To simplify the notation in this chapter, the equilibrium liquid-phase and solid-phase concentrations are expressed as shown in Eq 1-4:

$$q = K_F C^{1/n} \quad \text{(Eq 1-4)}$$

To fit the Freundlich parameters to the data, the Freundlich equation can be linearized as shown in Eq 1-5:

$$\log q = \log K_F + 1/n \log C \quad \text{(Eq 1-5)}$$

When the isotherm data are plotted on a log scale as shown in Figure 1-5b, the slope of the line is the 1/n value, and K_F is evaluated on the y-axis at a concentration of 1 mg/L. For data expressed in the units shown, the value of 1/n is 0.5 and K_F is 75 (mg/g)/(mg/L)$^{1/n}$. The value of K_F depends on the units of the isotherm data. For the same data as above, but if C is in units of µg/L instead of mg/L, the value of K_F is 2.37 (mg/g)/(µg/L)$^{1/n}$.

The value of the Freundlich constant (K_F) can be useful in gauging the difference in the adsorption capacity of a given activated carbon for a range of compounds or

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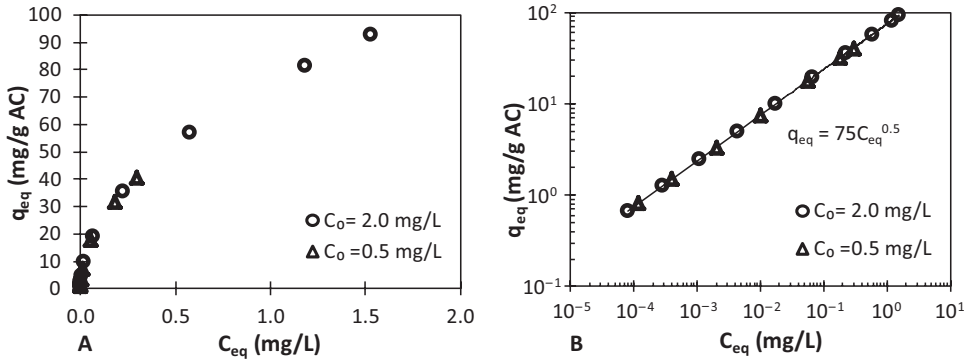


Figure 1-5. Example isotherm (a) arithmetic plot and (b) logarithmic plot

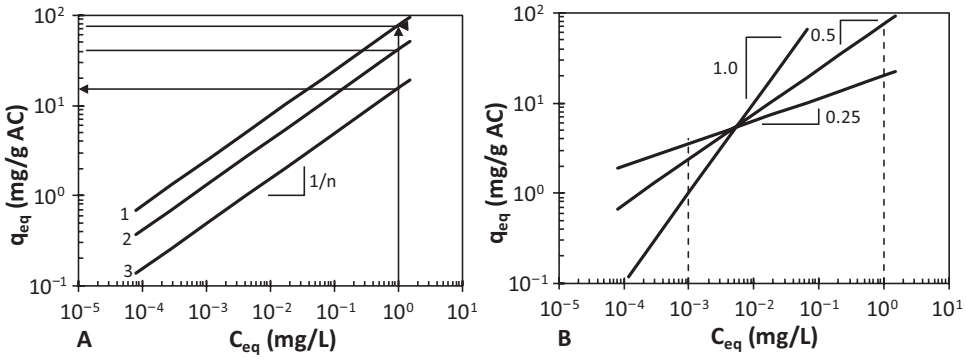


Figure 1-6. Effect of Freundlich parameters (a) K_F and (b) 1/n on isotherm

the adsorption capacity of a given compound for a range of activated carbons, as long as the Freundlich exponent (1/n) value is relatively constant. Figure 1-6a illustrates three isotherms that all have a 1/n value of 0.50. The larger the K_F value, the higher the adsorption capacity for a given adsorbate-adsorbent pair.

However, when the 1/n values of the different isotherms are significantly different, as shown in Figure 1-6b, the K_F value is only useful in the concentration range around 1, in this case 1 mg/L. The isotherm plots converge at lower concentration ranges, and to compare adsorption capacities both the K_F and 1/n values are needed, or comparisons can be made on the basis of a solid-phase concentration at a given liquid-phase concentration (q_C). For example, $q_{0.001}$ can be use to represent the solid-phase concentration at a liquid-phase concentration of 0.001 mg/L (1 µg/L). For this example, the isotherm that yielded the lowest capacity in the mg/L range now has the highest capacity in the µg/L range.

Summers et al. (2010) have compiled a list of single-solute Freundlich parameters for more than 70 compounds of interest; the K_F values range from 100 to 0.1(mg/g)/(µg/L)$^{1/n}$, and the 1/n values range from approximately 0.8 to 0.1. In general, for the K_F values expressed in the units (mg/g)/(µg/L)$^{1/n}$ and in a concentration range around 1 µg/L, compounds with K_F values above 10 (mg/g)/(µg/L)$^{1/n}$ can be considered well removed by activated carbon, and compounds with K_F values below 1 (mg/g)/(µg/L)$^{1/n}$ can be considered poorly removed by activated carbon. These Freundlich parameter

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values have been generated from isotherms with a single type of activated carbon, and the adsorption capacity for these compounds may be increased or decreased by the use of other activated carbon products.

A major limitation of the Freundlich model is that it should only be used to model the equilibrium data in the concentration range for which it was developed; it does not asymptotically approach a maximum adsorption capacity on the high concentration end, nor does it approach a linear isotherm on the low concentration range.

Competitive Adsorption

Caution must be exercised in not overusing single-solute Freundlich parameter values, as they are affected by the background matrix in the water to be treated. If other adsorbates are present in the water, as they are in nearly all practical cases, then the adsorption capacity for a specific compound decreases, even if the background contains only weaker adsorbing compounds. Figure 1-7 illustrates competitive adsorption behavior for a binary system in which Compound 1 is more strongly adsorbed than Compound 2 (i.e., $K_{F,1} > K_{F,2}$). In Figure 1-7a, the effect of the more weakly adsorbed Compound 2 on the adsorption of Compound 1 is shown. Increasing the initial concentration of Compound 2 causes the adsorption capacity of Compound 1 to decrease relative to the single-solute isotherm at $C_{2,0} = 0$. Figure 1-7b shows that increasing the initial concentration of more strongly adsorbing Compound 1 causes the adsorption capacity of Compound 2 to decrease relative to the single-solute isotherm at $C_{1,0} = 0$. As expected, the presence of the same amount of Compound 1 is more detrimental to the adsorption of Compound 2 (Figure 1-7b) than the other way around (Figure 1-7a). While not illustrated in Figure 1-7, the slope and shape of the isotherm in a mixture can also be affected.

Multisolute systems, like the adsorption of a target compound in the presence of DOM, add additional complexity to adsorption behavior. Competing adsorbates in the same molecular size range as the target adsorbate compete directly for adsorption sites (Li et al. 2003). Larger competing adsorbates may not be able to access micropores because of size exclusion. However, size exclusion may also result in partial or complete blockage of a pore. Partial blockage of a pore may slow kinetics of the target adsorbate, whereas complete blockage of a pore results in surface area behind the

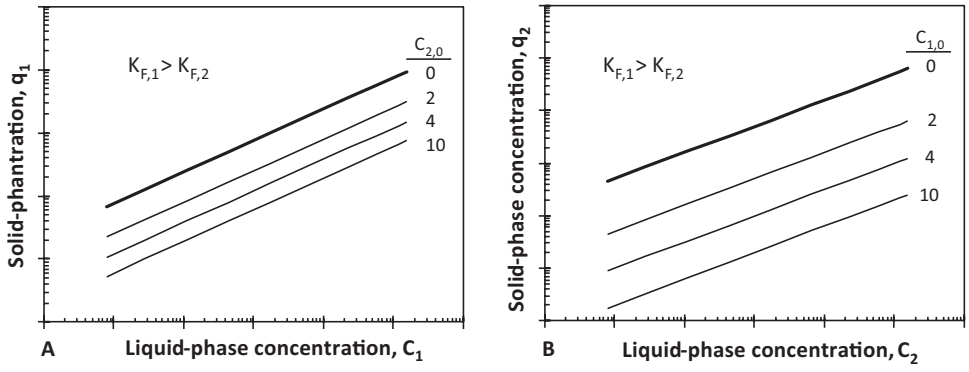


Figure 1-7. Equilibrium isotherm in a binary mixture (a) strongly adsorbing Compound 1 and (b) weakly adsorbing Compound 2

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blockage not being available for further adsorption. Because of its tendency to adsorb at multiple sites, adsorbed DOM is nondisplaceable to a large degree (Summers et al. 2010). Pore blockage and nondisplaceable adsorption cannot be described by ideal adsorbed solution theory (IAST). Therefore, reductions in adsorption capacity due to these mechanisms are often termed *fouling*.

DOM Equilibrium Adsorption Behavior

An understanding of DOM adsorption is important, as DOM serves as a precursor for the formation of DBPs. DOM is a heterogeneous mixture of organic compounds and normally dominated by hydrophobic organic acids such as humic and fulvic acids but also contains hydrophilic compounds that are weakly adsorbable or nonadsorbable. To measure DOM collectively, the total organic carbon (TOC) concentration is measured. Figure 1-8 illustrates the adsorption equilibrium relationship of DOM, as measured by TOC, at two initial DOM concentrations. The adsorption behavior of both isotherms displays a nonadsorbable fraction of about 10 percent, and as the equilibrium liquid-phase concentration increases, so does the adsorbability of the DOM in a nonlinear manner. The behavior shown in Figure 1-8 cannot be modeled by the Freundlich or Langmuir isotherms. When the initial DOM concentration decreases to a TOC = 2.5 mg/L, the adsorption capacity increases in all concentration ranges. The complex adsorption behavior of the DOM mixture limits the use of the isotherm in comparing the DOM adsorption behavior from different waters. Because the initial DOM concentration must be the same, it requires the use of complex adsorption models.

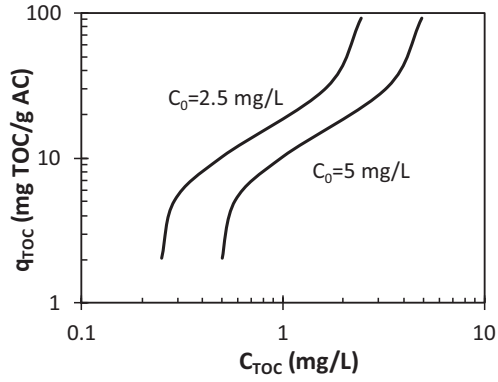


Figure 1-8. Equilibrium adsorption isotherms of DOM at two different initial concentrations

Several other adsorbate properties can also affect the adsorption equilibrium relationship. Large-molecular-weight molecules (i.e., > 1,000 Daltons) are often larger in size than the micropores where much of the surface area is located; thus size exclusion can limit the amount adsorbed. Weak organic bases and acids, like humic and fulvic acids in DOM, can be affected by pH because adsorption capacity is higher in the neutral form than the ionized form.

Ideal Adsorption Reactors

The above adsorption fundamentals were developed for CMBRs that have no volumetric flow, Q, into the reactor. Reactors used in water treatment are flow-through reactors and behave in the envelope of performance of the two idealized flow-through reactors: the plug flow reactor (PFR) and the continuous flow stirred tank reactor (CFSTR), shown in Figure 1-9. The difference in behavior is critical in understanding activated carbon performance. These will be described in detail in the next two chapters, but an overview at this point is instructive.

The mixing required to suspend PAC media also destroys the spatial concentration gradient of the target compound, yielding CFSTR behavior. In the ideal CFSTR

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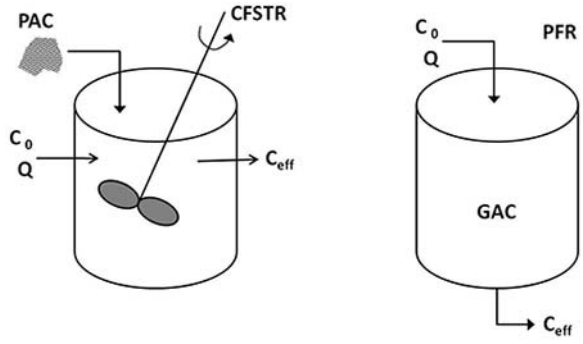


Figure 1-9. Flow-through reactors: CFSTR for PAC and PFR for GAC

(Figure 1-9), the mixing conditions make the concentration of the target compound equal to the effluent concentration, C_{eff}, at all points in the reactor. On the other end of the spectrum, the generally laminar flow through a packed GAC bed maintains the concentration gradient from the reactor influent to the effluent and yields PFR behavior. With long enough run times, the GAC will come to equilibrium with the influent concentration, C_0. The adsorbent in the CFSTR comes to equilibrium with the effluent concentration in Eq 1-4, whereas a PFR will come to equilibrium with the influent concentration.

Example 1-2. Calculate the solid phase concentration, q_{eq}, of atrazine in laboratory clean water at equilibrium in a PFR and a CFSTR. The influent concentration of atrazine is 50 µg/L, K_F is 38.7 $(mg/g)(L/\mu g)^{1/n}$, and 1/n is 0.291. The treatment objective or desired effluent concentration for atrazine is the maximum contaminant level (MCL) of 3 µg/L.

Solution. The solid-phase concentration is calculated directly from Eq 1-3 or 1-4. The PFR comes to equilibrium with the influent concentration of 50 µg/L:

$$q_{eq\,PFR} = K_F \times C_0^{1/n} = 38.7 \frac{mg}{g} \times \left(\frac{L}{\mu g}\right)^{1/n} \times \left[50 \frac{\mu g}{L}\right]^{0.291} = 121 \frac{mg\ atrazine}{g_{AC}}$$

The CFSTR comes to equilibrium with the effluent concentration, in this case 3 µg/L:

$$q_{eqCFSTR} = K_F \times C_e^{1/n} = 38.7 \frac{mg}{g} \times \left(\frac{L}{\mu g}\right)^{1/n} \times \left[3 \frac{\mu g}{L}\right]^{0.291} = 53.3 \frac{mg\ atrazine}{g_{AC}}$$

Thus the GAC in the PFR adsorbs over twice the amount of atrazine per mass of activated carbon compared to the PAC in a CFSTR. The PFR is a more efficient reactor.

Another way of comparing the efficiency of the PAC in a CFSTR to GAC in a PFR is the use rate. Table 1-3 defines the use rate in two different forms for each reactor: mass of AC per volume of water treated or mass of AC used per day. As such, lower use rates are more favorable. Note that the ideal PFR removes all the contaminant until breakthrough is reached; therefore, the effluent concentration is zero.

These calculated use rates are representative of single-solute systems (no background natural organic matter [NOM]). Typical use rates in drinking water treatment may be more than an order of magnitude higher.

Example 1-3. For the problem given in Example 1-2, calculate use rate in kg/1,000 m^3 and in kg/day if the flow rate is 4.0×10^4 m^3/day (10.6 mgd).

Solution. See Table 1-3. The GAC system requires less than half the amount of AC compared to the PAC system. *Note:* in practical use, the adsorption capacity for

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Table 1-3. Use rate definitions using isotherm parameters and Example 1-3 calculations

Use Rate	PAC–CFSTR	GAC–PFR
Mass of AC/volume water treated	$(C_0 - C_{eff})/q_{eqCFSTR}$ $= (C_0 - C_{eff})/K_F \times C_{eff}^{1/n}$	$(C_0 - C_{eff})/q_{eq\ PFR}$ $= (C_0 - C_{eff})/K_F \times C_0^{1/n}$
Mass of AC/day	$Q \times (C_0 - C_{eff})/ q_{eq\ CFSTR}$ $= Q \times (C_0 - C_{eff})/ K_F \times C_{eff}^{1/n}$	$Q \times (C_0 - C_{eff})/ q_{eq\ PFR}$ $= Q \times (C_0 - C_{eff})/ K_F \times C_0^{1/n}$

Example 1-3

Use Rate	PAC–CFSTR	GAC–PFR
Mass of AC/volume water treated	= (50 µg/L – 3 µg/L) / 53.3 µg atrazine/mg AC	= (50 µg/L – 0 µg/L) / 121 µg atrazine/ mg AC
	= 0.88 mg AC/L	= 0.41 mg AC/L
	= 0.88 g AC/m^3	= 0.41 g AC/m^3
	= 0.88 kg AC/1,000 m^3	= 0.41 kg AC/1,000 m^3
	= 0.0074 lb/1,000 gal	= 0.0035 lb/1,000 gal
Mass of AC/day	= Q × (50 µg/L – 3 µg/L) / 53.3 µg atrazine/mg AC	= Q × (50 µg/L – 0 µg/L) / 121 µg atrazine/mg AC
	= 4.0 × 10^4 m^3/day × 0.88 g AC/m^3	= 4.0 × $10^4$$m^3$/day × 0.41 g AC/$m^3$
	= 35 kg/day	= 16 kg/day
	= 78 lb/day	= 36 lb/day

the target compound is much lower due to the competitive effects from background organic matter, resulting in higher use rates.

References

Li, Q.L., V.L. Snoeyink, B.J. Marinas, and C. Campos. 2003. Elucidating competitive adsorption mechanisms of atrazine and NOM using model compounds. *Water Res.* 37(4):773–784.

Summers, R.S., D.R.U. Knappe, and V.L. Snoeyink. 2010. Adsorption of organic compounds by activated carbon. In *Water quality and treatment*, 6th ed. J.K. Edzwald, ed. New York: McGraw-Hill and American Water Works Association.

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Chapter 2

Powdered Activated Carbon Systems

Powdered activated carbon (PAC) can be an effective and economical treatment approach under the appropriate conditions. PAC is contacted with the contaminated water as a slurry, adsorbs the contaminants, and is removed with particles in the solids management process. PAC is not recovered and reactivated, thus its carbon use rate (lb/day) or dose (lb/MG) can be high. However, the low capital cost associated with the PAC feed system combined with the ability to apply PAC seasonally or for periodic issues can make it an economic alternative based on an annualized cost. The most common PAC use is to control seasonal occurrences of taste-and-odor compounds and pesticides. Many utilities that treat surface waters affected by municipal and industrial wastewater discharges and agricultural runoff also keep PAC on-site for the emergency control of periodic spikes and spills. In a few cases, PAC has also been used for the periodic reduction of cyanotoxins, DOM for DBP control, and micropollutants (Summers et al. 2010).

PAC is applied as a slurry, and it is effective in removing adsorbable compounds while it is suspended in the water. However, once it is removed from suspension and is not in contact with the contaminated water, it is no longer effective. As was shown in chapter 1, the full capacity of the PAC is achieved when the equilibrium concentration, C_{eq}, is reached (Figure 1-3). Several factors affect the time that it takes to reach equilibrium, t_{eq} (Figure 1-4), including the PAC size (d_{AC}) and mixing. This chapter explores the influence of these and other operating factors, as well as the adsorbate and background matrix chemistry, on the effective use of PAC.

Continuous Flow Stirred Tank Reactor Performance

The most common point of PAC application is before or at the rapid mixer (Figure 2-1). The rapid mixer and the subsequent flocculation basins are designed to keep coagulated particles in suspension such that if PAC is added at the rapid mixer, it will remain in suspension through the rapid mixer, the flocculation basin, and part of the sedimentation basin. The rapid mixer can be modeled as continuous flow stirred tank reactor (CFSTR), and most flocculation basins can be modeled as a series of CFSTRs. While CFSTRs are not efficient reactors from a chemical conversion perspective, they achieve the main objective of rapid mixers and flocculation basins: disperse the coagulants in the water so that they come into contact with the raw water particles and subsequently promote floc growth.

Figure 2-2 shows a diagram of a CFSTR. The PAC is added on a continuous basis and on average is in contact with the CFSTR for a residence time (τ) defined as

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