Second Edition

WASTE MANAGEMENT PRACTICES

Municipal, Hazardous, and Industrial







John Pichtel

CRC Press
Taylor & Francis Group

WASTE MANAGEMENT PRACTICES Second Edition

Municipal, Hazardous, and Industrial

WASTE MANAGEMENT PRACTICES Second Edition

Municipal, Hazardous, and Industrial

John Pichtel

CRC Press
Taylor & Francis Group
Boca Raton London New York

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

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

© 2014 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works
Version Date: 20140114

International Standard Book Number-13: 978-1-4665-8519-5 (eBook - PDF)

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

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

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

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

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

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

Contents

List of Illustrations xxiii
Preface xxxiii
Acknowledgments xxxv
About the Author xxxvii

Part I Historical and Regulatory Development

Chapter 1 Introduction 3

1.1 Definition of a Solid Waste 5
1.2 Categories of Wastes 5
1.2.1 Municipal Solid Waste 6
1.2.2 Hazardous Waste 8
1.2.3 Industrial Waste 8
1.2.4 Medical Waste 9
1.2.5 Universal Waste 9
1.2.6 Electronics Waste 10
1.2.7 Construction and Demolition Debris 10
1.2.8 Radioactive Waste 10
1.2.9 Mining Waste 11
1.2.10 Agricultural Waste 12
1.3 Generation of MSW 13
1.4 Solid Waste Management 15
1.4.1 Source Reduction 16
1.4.2 Recycling 16
1.4.3 Incineration 16
1.4.4 Land Disposal 18
1.4.5 Goals at the Federal Level 18
Questions 18
References 19
Suggested Readings and Websites 20

Chapter 2 A Brief History of Waste Management 21

2.1 Introduction 21
2.2 Earliest Civilizations 21
2.3 Greece 22
2.4 Rome 22
2.5 Europe 23
2.6 United States 28
2.7 Recent Waste Management Initiatives 35
2.8 Solid Waste Incineration and Other Thermal Processes 36
2.9 Land Disposal and the Sanitary Landfill 40
2.10 Recycling/Reuse 43

Questions 44
References 44

Chapter 3 Regulatory Development 47

3.1 Introduction 47
3.2 Significant U.S. Legislation 47
3.2.1 Solid Waste Disposal Act 47
3.2.2 Resource Recovery Act 48
3.2.3 Resource Conservation and Recovery Act 48
3.2.4 Solid Waste Management under RCRA 48
3.2.5 Hazardous Waste Management under RCRA 49
3.2.6 Underground Storage Tank Management 50
3.2.7 Amendments to RCRA 51
3.2.7.1 1980 Amendments 51
3.2.7.2 Comprehensive Environmental Response, Compensation, and Liability Act of 1980 51
3.2.7.3 Hazardous and Solid Waste Amendments of 1984 52
3.2.7.4 Medical Waste Tracking Act 52
3.2.7.5 Federal Facility Compliance Act 52
3.2.7.6 1996 Amendments 53
3.3 Other Recent Laws Affecting Waste Management 53
3.3.1 Public Utility Regulation and Policy Act of 1978 53
3.3.2 Sanitary Food Transportation Act 54
3.3.3 Clean Air Act 54
3.3.4 Pollution Prevention Act 54
3.3.5 Indian Lands Open Dump Cleanup Act 54
3.3.6 Mercury-Containing and Rechargeable Battery Management Act 55
3.4 Relationship of RCRA with Other Environmental Statutes 55
3.5 Laws, Regulations, and Other Actions at the Federal Level 55
3.5.1 Lawmaking Process 55
3.5.2 Regulations 56
3.5.3 Policy and Guidance 57
3.5.4 Public Involvement in RCRA 58
Questions 58
References 59
Suggested Readings 59

Part II Municipal Solid Wastes

Chapter 4 Characterization of Solid Waste 63

4.1 Introduction 63
4.2 Sampling Protocols for MSW 63
4.2.1 Direct Sampling 63
4.2.2 Material Flows 64
4.2.3 Surveys 64
4.2.4 Multipliers for Projecting Waste Quantities 65
4.3 Variability Affecting Waste Sampling 66
4.3.1 Seasonal 66
4.3.2 Regional 67

4.3.3 Household 68
4.3.4 National Economy 68
4.4 Common Components in Municipal Solid Waste 68
4.4.1 Paper Products 68
4.4.2 Glass 71
4.4.3 Aluminum 71
4.4.4 Ferrous Metals 71
4.4.5 Other Nonferrous Metals 71
4.4.6 Plastics 72
4.4.7 Rubber and Leather 73
4.4.8 Textiles 74
4.4.9 Food Wastes 74
4.4.10 Yard Waste 74
4.4.11 Household Hazardous Wastes 75
4.4.11.1 Toxic Metals 76
4.4.11.2 Organic Compounds 77
4.5 Chemical Properties of MSW 78
4.5.1 Ultimate Analysis of Solid Waste Components 78
4.5.2 Proximate Analysis of MSW 82
4.5.3 Energy Content of MSW 82
4.5.4 Fusion Point of Ash 86
4.5.5 Content of Nutrients and Other Substrates 86
4.5.6 Carbohydrates 88
4.5.7 Crude Fibers 88
4.5.8 Proteins 89
4.5.9 Lipids 90
4.5.10 Biodegradability of MSW Fractions 90
4.6 Physical Properties of MSW 90
4.6.1 Density 90
4.6.2 Moisture Content 93
4.6.3 Particle Size Distribution 94
4.6.4 Field Capacity 96
4.6.5 Hydraulic Conductivity of Compacted Waste 97
Questions 97
Exercise: Waste Characterization 99
References 99
Suggested Readings 100

Chapter 5 Municipal Solid Waste Collection 103

5.1 Introduction 103
5.2 Developing a Waste Collection System 103
5.2.1 Characterization of Wastes 103
5.2.2 Service Area and Level of Service 103
5.2.3 Public versus Private Collection 104
5.2.4 Funding the Collection System 104
5.3 Logistics of the Collection Program 105
5.3.1 Storage Container Requirements 105
5.3.2 Set-Out Requirements 105
5.3.3 Waste Separation 105
5.3.4 Frequency of Collection 106

5.3.5 Waste Pickup Locations 106
5.3.6 Collection Equipment 107
5.3.7 Automated Waste Collection 108
5.3.8 Developing Collection Routes 111
5.3.9 Route Development 112
5.3.10 Waste Transfer 113
5.3.11 Types of Transfer Stations 113
5.3.11.1 Small to Medium Transfer Stations (Capacity of Less than 100–500 Tons per Day) 116
5.3.11.2 Large Transfer Stations 116
5.3.11.3 Transfer Station Design Considerations 117
5.3.12 Transfer Vehicles 120
5.3.12.1 Trucks and Semitrailers 120
5.3.12.2 Rail Cars 120
Questions 120
References 121
Suggested Readings 122

Chapter 6 Recycling Solid Wastes 125

6.1 Introduction 125
6.2 Recycling Terminology 126
6.3 Recycling Progress and Statistics 127
6.4 Recovery and Markets for Components of the Waste Stream 128
6.5 Market Issues 128
6.6 Purity of Materials 129
6.7 Paper 129
6.7.1 Paper Manufacture 129
6.7.2 Paper Recycling 131
6.7.3 Other Paper Markets 133
6.7.4 Benefits of Paper Recycling 134
6.8 Glass 134
6.8.1 Glass Manufacture 134
6.8.2 Glass Recycling 134
6.8.3 Glass Recycling Process 135
6.8.4 Color 136
6.8.5 Contamination 136
6.8.6 Glass Markets 137
6.8.7 Container Glass 137
6.8.8 Other Uses for Recycled Glass 137
6.8.9 Benefits of Glass Recycling 138
6.9 Aluminum 139
6.9.1 Aluminum Manufacturing 139
6.9.2 Aluminum Recycling 140
6.9.3 Specifications for Recovered Aluminum 142
6.9.4 Benefits of Aluminum Recycling 142
6.9.5 One Final Note on Aluminum 143
6.10 Ferrous Metals 143
6.10.1 Steel Manufacture 143
6.10.2 Ferrous Recycling 145
6.10.3 Benefits of Ferrous Recycling 147

6.11 Plastics 148
6.11.1 Plastics Manufacture 148
6.11.2 Extrusion 149
6.11.3 Blow Molding 150
6.11.4 Injection Molding 150
6.11.5 Compression Molding 151
6.11.6 Plastics Recycling 151
6.11.7 Processing for Recycling 152
6.12 Yard Waste 153
6.13 Food Waste 154
6.14 Tires and Rubber 154
6.14.1 Design and Manufacture 154
6.14.2 Disposal and Recycling 154
6.14.2.1 Recycling 158
6.14.2.2 Crumb Rubber 158
6.14.2.3 Retreaded Tires 158
6.15 Goals for the Nation 158
Questions 160
References 161
Suggested Readings 163

Chapter 7 Municipal Solid Waste Processing: Materials Recovery Facilities 165

7.1 Introduction 165
7.2 Materials Recovery Facility 165
7.2.1 Unit Operations 166
7.2.2 Weigh Station 166
7.2.3 Receiving Area 167
7.2.4 Storage Area 167
7.2.5 Mobile Equipment in the MRF 170
7.2.6 Fixed Equipment in the MRF 171
7.2.7 Conveyors 171
7.2.8 Scales 174
7.3 Materials Recovery at MRF Unit Operations 175
7.4 Materials Separation and Processing at the MRF 176
7.4.1 Hand-Sorting 176
7.4.2 Screening 177
7.4.2.1 Trommel Screens 177
7.4.2.2 Disk Screens 181
7.4.2.3 Vibrating Screens 182
7.4.3 Size Reduction 182
7.4.3.1 Compactors 182
7.4.3.2 Balers 182
7.4.3.3 Densifiers 184
7.4.3.4 Shredders 184
7.4.3.5 Hammermills 185
7.4.3.6 Horizontal-Shaft Hammermills 187
7.4.3.7 Vertical-Shaft Hammermills 187
7.4.3.8 Rotary Shear 189
7.4.3.9 Flail Mill 189
7.4.3.10 Hammer Wear 189

7.4.3.11 Safety Issues Related to Size Reduction 190
7.4.4 Magnetic Separation 191
7.4.5 Eddy Current Device 195
7.4.6 Air Classifier 195
7.4.7 Efficiency of Separation in an Air Classifier 199
7.4.8 Miscellaneous Processing 201
7.4.8.1 Dryers 201
7.5 Materials Flow in the MRF 202
7.6 Contamination Issue 202
7.7 Environmental Control 204
7.7.1 Dust Collection 204
7.7.2 Odors and Their Control 204
7.7.3 Noise Suppression 205
7.7.4 Aesthetics 206
Questions 206
References 207
Suggested Readings 208

Chapter 8 Composting MSW 209

8.1 Introduction 209
8.2 Benefits of Composting 209
8.3 Overview of the Composting Process 210
8.4 Role of Microorganisms in Composting 210
8.5 Factors Affecting the Composting Process 212
8.5.1 Preprocessing of the Feedstock 213
8.5.2 Environmental Factors 213
8.5.3 Nutrients 214
8.5.4 C:N Ratio 214
8.5.5 Aeration 214
8.5.6 Moisture Content 218
8.5.7 Temperature 218
8.5.8 pH 219
8.6 Composting Stage 219
8.6.1 Turned Piles 220
8.6.2 Turned Windrows 220
8.6.3 Aerated Static Piles 221
8.6.4 In-Vessel Systems 222
8.7 Curing Stage 222
8.8 Environmental Concerns during Composting 223
8.8.1 Air Quality 224
8.8.2 Odor 224
8.8.3 Noise 225
8.8.4 Toxins within the Pile 225
8.8.5 Leachate 227
8.8.6 Runoff 228
8.8.7 Vectors 229
8.8.8 Fires 229
8.8.9 Litter 229
8.9 Occupational Health and Safety Concerns during Composting 230

8.9.1 Bioaerosols 230
8.9.2 Potentially Toxic Chemicals 231
8.10 Facility Siting 231
8.10.1 Topography 232
8.10.2 Land Area Requirements 232
8.10.3 Other Factors Affecting Siting Decisions 233
8.11 Design 233
8.11.1 Preprocessing Area 233
8.11.2 Processing Area 233
8.11.3 Buffer Zone 234
8.11.4 Site Facilities and Security 234
8.12 MSW Composting by Anaerobic Processes 234
8.12.1 Process Description 235
8.12.2 Subsystems 236
Questions 237
Exercise: Soil and Groundwater Quality at a Composting Facility 238
References 240
Suggested Readings 241

Chapter 9 Incineration of MSW 243

9.1 Introduction 243
9.2 Combustion Concepts 243
9.3 Mass-Burn Incinerator 246
9.4 Environmental Considerations of Mass Burn 250
9.4.1 Fuel Quality 250
9.4.2 Resource Recovery 250
9.4.3 Air Quality 250
9.4.4 Particulates 251
9.4.5 Acid Gases 252
9.4.6 Trace Gases 253
9.4.7 Toxic Metals 257
9.4.8 Aesthetics 259
9.5 Air Pollution Control 260
9.5.1 Electrostatic Precipitator 260
9.5.2 Fabric Filters (Baghouses) 261
9.5.3 Gas Washing 264
9.6 Ash Quality from Mass Burn 266
9.6.1 Metals 268
9.6.2 Health Effects of Metals in Incinerator Ash 268
9.6.3 Leachability of Metals in Incinerator Ash 268
9.6.4 Ash Management 270
9.7 MSW Incineration in the United States: The Future 271
9.8 Refuse-Derived Fuel 271
9.8.1 Overview of RDF Preparation 272
9.8.2 Grades of RDF 272
9.8.3 Properties of RDF 272
9.8.4 Utilization of RDF: Practical Issues 274
9.8.5 Gaseous Emissions and Corrosion Issues 276
9.8.6 Properties of RDF Ash 276

9.8.7 Process-Engineered Fuel 277
9.8.8 Tire-Derived Fuel 278
Questions 278
References 279
Suggested Readings 282

Chapter 10 The Sanitary Landfill 283

10.1 Introduction 283
10.2 Relevant Definitions under the RCRA Regulations 283
10.3 Siting the Landfill 284
10.3.1 Airport Safety 284
10.3.2 Floodplains 285
10.3.3 Wetlands 285
10.3.4 Fault Areas 285
10.3.5 Seismic Impact Zones 285
10.3.6 Unstable Areas 286
10.4 Requirements of Operation 286
10.4.1 Receipt of Hazardous Waste 286
10.4.2 Inspections 287
10.4.3 Training 288
10.4.4 Landfill Design 289
10.4.5 Clay Liners 289
10.4.6 Hydraulic Conductivity 291
10.4.7 Geomembrane Liners 292
10.4.8 Compatibility of Liners with Wastes 293
10.4.9 Survivability Tests 295
10.4.10 Permeability 295
10.4.11 Stress 297
10.4.12 Geomembrane Liner Handling and Placement 297
10.4.13 Construction Quality Assurance 298
10.4.14 Daily Operations and Issues 299
10.4.14.1 Filling Sequences 299
10.4.14.2 Cover Materials 301
10.4.14.3 Disease Vector Control 302
10.4.14.4 Biological Control of Pests 302
10.4.14.5 Generation of Landfill Gases 304
10.4.14.6 Predicting Gas Production 307
10.4.14.7 Control of Explosive Gases 310
10.4.15 Trace Gases 312
10.4.16 Landfill Gas Control 312
10.4.16.1 Passive Systems 313
10.4.16.2 Active Systems 315
10.4.17 Gas Utilization 315
10.4.18 Other Air Criteria 319
10.4.19 Public Access 319
10.4.20 Control of Run-on and Runoff 319
10.4.21 Management of Surface Water 319
10.4.22 Restrictions on Liquids in Landfills 320
10.4.23 Leachate Formation 322
10.4.23.1 Estimation of Leachate Volume Produced 322

10.4.23.2 Leachate Collection and Removal System 327
10.4.23.3 Area Collector 328
10.4.24 Geosynthetic Materials 328
10.4.25 Collection Laterals 330
10.4.26 Sumps 332
10.4.27 Leachate Treatment 332
10.4.28 Groundwater Monitoring and Corrective Action 332
10.4.29 Record Keeping 333
10.5 Closure 333
10.5.1 Low-Permeability (Barrier) Layer 335
10.5.2 Drainage Layer 335
10.5.3 Erosion Control Layer 335
10.5.4 Gas Collection System 336
10.5.5 Landfill Cap 336
10.5.6 Subsidence Effects 337
10.5.7 Weather Effects 337
10.6 Postclosure 337
10.7 Bioreactor Landfill 338
10.7.1 Anaerobic Bioreactors 339
10.7.2 Aerobic Bioreactor 340
10.7.3 Anaerobic vs. Aerobic 341
10.7.4 Hybrid Bioreactors (Sequential Aerobic–Anaerobic) 341
10.7.5 Practical Operational Issues 341
10.7.5.1 Waste Preprocessing 341
10.7.5.2 Daily Cover 341
10.7.5.3 Liquid Addition and Recirculation 341
10.7.5.4 Alternative Liquid Sources 341
10.7.5.5 Fires 342
10.7.6 Other Considerations 342
10.7.6.1 Leachate Strength Reduction 342
10.7.6.2 Waste Mass Shear Strength 342
10.7.6.3 Waste Settlement 342
10.7.6.4 Metals 343
10.7.6.5 Advantages of Bioreactor Landfills 343
10.7.6.6 Summary of Bioreactor Landfills 344
10.8 Landfill Reclamation 344
Questions 345
Exercise: Groundwater Quality at a Midwest Landfill 347
References 348
Suggested Readings 350

Part III Hazardous Waste Management

Chapter 11 Identification of Hazardous Waste 355

11.1 Introduction 355
11.2 RCRA Subtitles 355
11.3 Subtitle C: The Hazardous Waste Management Program 357
11.3.1 Definition of a Solid Waste 357
11.3.2 What Is a Hazardous Waste? 358

11.3.3 Exemptions and Exclusions 358
11.3.4 Hazardous Waste Lists 359
11.3.4.1 Hazardous Wastes from Nonspecific Sources 359
11.3.4.2 Hazardous Wastes from Specific Sources 359
11.3.4.3 Discarded Commercial Products, Off-Specification Materials, Container Residues, and Spill Residues 359
11.3.5 Characteristic Tests 360
11.3.6 Ignitability 360
11.3.7 Corrosivity 360
11.3.8 Reactivity 361
11.3.9 Toxicity 361
11.3.10 Mixtures of Hazardous Wastes with Other Materials 363
11.3.11 Mixture Rule 363
11.3.12 Contained-in Rule 364
11.3.13 Derived-from Rule 364
11.4 Generation of Hazardous Wastes 364
11.4.1 Quantities of Toxics Release Inventory Chemicals in Waste by Industry 364
11.4.2 Quantities of TRI Chemicals in Waste by Chemical 365
Questions 366
References 370
Suggested Readings and Websites 370

Chapter 12 Hazardous Waste Generator Requirements 371

12.1 Introduction 371
12.2 Determining the Generator Category 371
12.3 Generator Types 372
12.3.1 LQG 372
12.3.2 SQG 372
12.3.3 EPA Waste Codes for Common SQG Wastes 372
12.3.4 Conditionally Exempt SQG 378
12.3.5 Episodic Generators 379
12.4 Requirements for LQGs and SQGs 379
12.4.1 EPA Identification Number 379
12.4.2 Managing Hazardous Waste On-Site 382
12.4.3 Requirements for New Tank Systems 383
12.4.4 Containment Buildings 383
12.4.5 Emergency Preparation 383
12.4.6 Emergency Response 384
12.4.7 Personnel Training 385
12.4.8 Emergency Response Requirements for SQGS 385
12.4.9 Reporting 385
12.4.10 Shipment of Wastes Off-Site 386
12.4.11 Uniform Hazardous Waste Manifest 386
12.4.12 Record Keeping 386
12.4.13 Management of Empty Containers 386
12.4.14 Hazardous Waste at Satellite Accumulation Points 390
12.5 Requirements of CESQGs 390
12.A.1 Appendix: Hazardous Waste Management Scenarios 390
12.A.1.1 Introduction 390

12.A.1.2 The Scenarios 390
12.A.1.3 Responses to Questions about Scenarios 397
Questions 400
References 401
Suggested Readings and Websites 402

Chapter 13 Hazardous Waste Transportation 403

13.1 Introduction 403
13.2 Modes of Hazardous Waste Transportation 404
13.3 Transportation Requirements 405
13.3.1 Shipping Papers 405
13.3.2 Uniform Hazardous Waste Manifest 406
13.3.3 Hazard Communication 406
13.3.3.1 Identification of the Waste Being Transported 406
13.3.3.2 Hazardous Materials Table 406
13.3.3.3 Hazardous Material Classes 408
13.3.3.4 Packing Groups 410
13.3.3.5 Identification Numbers 410
13.3.3.6 Placards, Labels, and Markings 414
13.3.3.7 Hazard Warning Labels 414
13.3.3.8 Marking 415
13.3.3.9 Packaging 418
13.4 Emergency Response Information 421
13.5 Segregation (49 CFR Part 177, Subpart C) 421
13.6 Hazardous Materials Incidents (49 CFR Part 171) 422
13.6.1 Immediate Notice of Certain Hazardous Materials Incidents (49 CFR 171.15) 422
13.6.2 Hazardous Materials Incidents Reports (49 CFR 171.16) 425
13.A.1 Appendix: Hazardous Waste Management Scenarios 428
13.A.1.1 Introduction 428
13.A.1.2 Scenarios 428
13.A.1.3 Responses to Scenarios 430
Questions 431
References 433
Suggested Readings 433

Chapter 14 Treatment, Storage, and Disposal Facility Requirements 435

14.1 Introduction 435
14.2 Subpart A—General Issues Regarding Treatment, Storage, and Disposal 436
14.3 Subpart B—General Facility Standards 437
14.3.1 Notification of Hazardous Waste Activity 437
14.3.2 Waste Analysis 437
14.3.3 Security 438
14.3.4 Inspections 438
14.3.5 Reactive and Ignitable Wastes 439
14.3.6 Training 439
14.4 Subpart C—Preparedness and Prevention 439
14.4.1 Facility Design and Operation 440
14.4.2 Arrangements with Local Authorities 441

14.5 Subpart D—Contingency Plan and Emergency Procedures 441
14.5.1 Contingency Plan 441
14.5.2 Emergency Procedures 442
14.6 Subpart E—Manifest System, Record Keeping, and Reporting 442
14.6.1 Manifest Discrepancies 442
14.6.2 Operating Record 442
14.6.3 Biennial Report 443
14.7 Subpart F—Releases from Solid Waste Management Units 443
14.7.1 Groundwater Protection Standard 443
14.7.2 Groundwater Monitoring Requirements 444
14.7.3 Detection Monitoring Program 444
14.7.4 Corrective Action Program 445
14.8 Subpart G—Closure and Postclosure 445
14.8.1 Closure Plan (264.112) 445
14.A.1 Appendix: Hazardous Waste Management Scenarios 446
14.A.1.1 Introduction 446
14.A.1.2 Scenarios 446
14.A.1.3 Responses to Scenarios 448
Questions 449
References 449
Suggested Readings and Websites 450

Chapter 15 Incineration of Hazardous Wastes 451

15.1 Introduction 451
15.2 Combustion and Its Residues 452
15.3 Overview of Regulatory Requirements 453
15.4 Combustion Standards under RCRA, Subpart O 453
15.4.1 Organic Compounds 453
15.4.2 Hydrogen Chloride 454
15.4.3 Particulate Matter 455
15.4.4 Fugitive Emissions 456
15.4.5 Metals 456
15.4.6 Waste Analysis 456
15.4.7 Operating Conditions and the RCRA Permit 456
15.4.8 Obtaining the RCRA Permit 457
15.4.9 Monitoring and Inspections 458
15.4.10 Management of Residues 458
15.4.11 Closure 458
15.5 MACT Standards under the CAA 459
15.5.1 Organics 459
15.5.2 HCl and Chlorine Gas 459
15.5.3 Particulate Matter 459
15.5.4 Metals 459
15.5.5 Operating Requirements 459
15.5.6 Additional Requirements 460
15.6 Incineration Devices 460
15.6.1 Liquid Injection 461
15.6.2 Air Requirements in Liquid Injectors 463
15.6.3 Overview of Liquid Injection 464
15.6.4 Rotary Kilns 464

15.6.5 Overview of Rotary Kiln Incineration 467
15.6.6 Boilers and Industrial Furnaces 467
15.6.7 Industrial Boilers 468
15.6.8 Cement Kilns 468
15.7 Air Pollution and its Control 470
15.7.1 Atmospheric Products from Combustion 470
15.7.2 Products of Incomplete Combustion 471
15.7.3 Air Pollution Control 473
Questions 475
References 477
Suggested Readings 477

Chapter 16 Hazardous Waste Treatment 479

16.1 Introduction 479
16.2 Land Disposal Restrictions 479
16.3 Waste Treatment Prior to Land Disposal 480
16.3.1 Neutralization 480
16.3.2 Chemical Precipitation 484
16.3.3 Oxidation and Reduction 486
16.3.4 Sorption 488
16.3.5 Sorption Systems 490
16.3.6 Stabilization 491
Questions 492
References 492
Suggested Readings 493

Chapter 17 Land Disposal of Hazardous Waste 495

17.1 Introduction 495
17.2 Land Disposal Restrictions Revisited 495
17.2.1 General Requirements 496
17.3 Secure Landfill 496
17.3.1 Regulatory Requirements 496
17.3.2 Secure Landfill Design, Construction, and Operation 498
17.3.3 Liner Materials 498
17.3.3.1 Clay Liners 498
17.3.3.2 Synthetic Liner Materials 498
17.3.3.3 Composite Liners 499
17.3.4 Compatibility of Liners with Wastes 499
17.3.5 Leachate Management 500
17.3.6 Drainage Materials 501
17.3.7 Leachate Removal Systems 501
17.3.8 Closure of the Secure Landfill 501
17.3.9 Geomembrane Caps 501
17.3.10 SWCR System 502
17.3.11 Gas Control Layer 503
17.3.12 Biotic Barrier 503
17.3.13 Vegetative Layer 503
17.4 Deep Well Injection of Hazardous Wastes 504
17.4.1 Underground Injection Control Program 504
17.4.2 Well System Design 504

17.4.3 Classes of Injection Wells 506
17.4.3.1 Deep Wells (Class I) 507
17.4.3.2 Oil and Gas Injection Wells (Class II) 509
17.4.3.3 Mining Wells (Class III) 509
17.4.3.4 Shallow Hazardous and Radioactive Injection Wells (Class IV) 510
17.4.3.5 Shallow Injection Wells (Class V) 510
17.4.3.6 Carbon Dioxide Injection Wells (Class VI) 511
17.4.4 Practical Considerations of Deep-Well Injection 511
Questions 512
References 512
Suggested Readings 513

Part IV Special Categories of Waste

Chapter 18 Universal Wastes 517

18.1 Introduction 517
18.2 Universal Wastes Defined 518
18.3 Categories of Universal Waste Handlers 519
18.3.1 Large Quantity Handlers 519
18.3.2 Small Quantity Handlers 519
18.4 Management of Universal Wastes 519
18.4.1 Universal Waste Batteries 519
18.4.2 Lead–Acid Battery Recycling 520
18.4.3 Nickel–Cadmium Battery Recycling 521
18.4.4 Universal Waste Pesticides 521
18.4.5 Universal Waste Thermostats 521
18.4.6 Universal Waste Lamps 522
18.5 Response to Releases 524
18.6 Tracking Universal Waste Shipments 524
18.7 Small Quantity Handlers of Universal Waste 525
18.8 Universal Waste Transporters 525
18.9 Destination Facilities 526
18.10 Responsibility of the States 527
Questions 529
References 529
Further Readings and Websites 530

Chapter 19 Management of Used Oil 531

19.1 Introduction 531
19.2 Production and Properties of Lubricating Oils 531
19.3 Chemical Composition of Used Motor Oil 532
19.4 Chemical and Physical Changes of Oil during Engine Operation 533
19.5 Potential Hazards with Used Oil 533
19.6 History of Used Oil Management 535
19.7 Requirements of the Used Oil Management Standards 537
19.7.1 Used Oil Generators 537
19.7.2 Used Oil Collection Centers 537

19.7.3 Marketers of Used Oil 537
19.7.4 Transporters and Transfer Facilities 538
19.7.5 DOT Requirements 538
19.7.6 Used Oil Recycling 538
19.8 Used Oil Recycling Methods 539
19.8.1 Re-Refining 539
19.8.2 Slipstreaming 540
19.8.3 Processing 540
19.8.4 Direct Burning 541
19.8.5 Off- vs. On-Specification Used Oil 541
19.9 Disposal 543
19.9.1 Prohibitions 543
19.9.2 Exemption from CERCLA Liability 543
19.A.1 Appendix: Scenarios 543
19.A.1.1 Responses to Scenarios 544
Questions 545
References 546
Suggested Readings 547

Chapter 20 Medical and Infectious Wastes 549

20.1 Introduction 549
20.2 Medical Waste Tracking Act 549
20.3 Definitions and Sources of Medical Waste 550
20.3.1 Potentially Infectious Waste 551
20.3.2 Regulated Medical Waste (40 CFR Part 259.30) 551
20.3.3 Exemptions to the Definition of RMW 552
20.3.4 RCRA Hazardous Waste 552
20.3.5 Radioactive Waste 552
20.3.6 Mixtures 553
20.4 Management of Medical Wastes Prior to Transport 553
20.4.1 Handling and Packaging 553
20.4.2 Labeling and Marking Medical Waste 554
20.4.3 Generator Requirements 554
20.4.4 Transporter Requirements 555
20.4.5 Treatment and Disposal of Medical Waste 556
20.4.6 Requirements for the Destination Facility 556
20.4.7 Record Keeping 557
20.4.8 Disposal Options for Medical Waste 557
20.4.9 Incineration of Medical Waste 557
20.4.10 Regulatory Requirements for Medical Waste Incinerators 557
20.4.11 Siting Requirements 557
20.4.12 Operator Training and Qualification Requirements 557
20.5 Facility Operations 558
20.5.1 Waste Management Plan 558
20.5.2 Compliance and Performance Testing 558
20.5.3 Emission Limits 559
20.5.4 Monitoring Requirements 560
20.5.5 Documentation 560
20.5.6 Reporting and Record Keeping 561

20.6 Types of Medical Waste Incinerators 561
20.6.1 Rotary Kiln 562
20.6.2 Multiple-Chamber Incinerator 562
20.6.3 Controlled Air Incinerators 563
20.7 Modes of Incinerator Operation 564
20.8 Advantages and Disadvantages of Incineration 566
20.9 Microbial Inactivation 566
20.9.1 Autoclaving (Steam Sterilization) 568
20.9.2 Operational Issues 568
20.9.3 Testing the Efficiency of Sterilization by Autoclaving 569
20.9.4 Health Considerations with Autoclaving 570
20.9.5 Advantages and Disadvantages of Autoclaving 570
20.9.6 Chemical Disinfection 570
20.9.7 Types of Disinfection Agents 571
20.9.8 Testing the Efficiency of Chemical Disinfection 571
20.9.9 Operational Issues 573
20.9.10 FIFRA Registration 574
20.9.11 Advantages and Disadvantages of Chemical Disinfection 574
20.9.12 Microwave Irradiation 574
Questions 574
References 575
Suggested Readings 576

Chapter 21 Construction and Demolition Debris 577

21.1 Introduction 577
21.2 Characteristics of C&D Debris 577
21.3 Management of C&D Debris 581
21.4 Management of Selected C&D Waste Components 581
21.4.1 Aggregate 581
21.4.2 Drywall (Sheetrock, Gypsum) 582
21.4.3 Wood Waste Recycling 584
21.4.4 Metals Recycling 584
21.4.5 Asphalt Shingles 584
21.4.6 Asbestos Shingles 585
21.5 Reduction of C&D Debris 585
21.6 Deconstruction 586
21.7 Hazardous Materials 587
Questions 588
References 588
Suggested Readings 589

Chapter 22 Electronics Waste 591

22.1 Introduction 591
22.2 Major Types of Electronic Equipment 592
22.2.1 Personal Computers 594
22.2.2 Laptop Computers 594
22.2.3 Cathode Ray Tube Computer Monitors 594
22.2.4 Computer Central Processing Units 594
22.2.5 Computer Peripherals 595

22.2.6 Desktop Telecommunications Equipment (Telephones, Fax Machines) 595
22.2.7 Mainframe Computers and High-End Telecommunications Equipment 595
22.2.8 Televisions with CRTs 595
22.2.9 Flat Screen Televisions 595
22.2.10 Mobile Telephones 596
22.3 Hazards of e-Waste 596
22.3.1 Cathode Ray Tubes 597
22.3.2 Flat Screen TVs and Laptop Computers 598
22.4 RCRA and e-Wastes 599
22.4.1 Hazardous Waste 599
22.4.2 EPA CRT Rule 600
22.4.3 Circuit Boards 600
22.5 Electronics Recycling 600
22.5.1 Residential Collection Programs 601
22.5.2 Reuse and Resale 603
22.5.3 Deconstruction 603
22.5.4 Processing and Recycling e-Waste Components 604
22.5.4.1 CRT Glass 606
22.5.5 Metals 607
22.5.6 Circuit Boards 607
22.6 International Issues in Electronics Management 608
22.7 Barriers to Recycling e-Waste 609
22.8 Product Stewardship and Electronics 609
22.9 Conclusions 610
Questions 610
References 611
Suggested Readings and Websites 613

Part V Appendix

List of Acronyms and Abbreviations 617

Glossary of Terms 619

Solubility Product Constants at 25°C 631

Metric Conversion Chart 635

List of Illustrations

FIGURE 1.1 The ill-fated "garbage barge" from Islip, Long Island, NY 4

FIGURE 1.2 Legacy of the *Khian Sea* 4

FIGURE 1.3 Municipal solid waste as a component of Subtitle D wastes 6

FIGURE 1.4 Mining wastes are typically returned to the site of operation 12

FIGURE 1.5 Animal manures applied to agricultural fields serve as a low-cost soil conditioner and source of nutrients 12

FIGURE 1.6 We all have paid the cost of our success—M. F. Moonzajer. Jim Borgman © *Cincinnati Enquirer* 13

FIGURE 1.7 Trends in total solid waste generation and per capita waste generation in the United States 14

FIGURE 1.8 Current waste management priorities in the United States 15

FIGURE 1.9 Decline of the sanitary landfill over recent decades 18

FIGURE 2.1 Medieval woodcut showing fecal matter being dumped from a window 24

FIGURE 2.2 London slum, 19th century 27

FIGURE 2.3 The waste problem in New York City 29

FIGURE 2.4 Sanitation worker and the horse problem, New York City, 1900 29

FIGURE 2.5 Unloading garbage from scows off the Atlantic Coast 30

FIGURE 2.6 Coney Island beach pollution from disposal off the New York City coast, late 19th Century 31

FIGURE 2.7 Rag pickers removing materials of value from waste 31

FIGURE 2.8 Early waste separation activities 32

FIGURE 2.9 Waste reduction plant, Barren Island, New York city, ca. 1897 33

FIGURE 2.10 One of New York City's White Wings, 1905 34

FIGURE 2.11 Unloading garbage from scows at Barren Island 34

FIGURE 2.12 Convicts unloading scows of ash at Riker's Island 35

FIGURE 2.13 An unsanitary open dump 38

FIGURE 2.14 Diagram of a California sanitary landfill, 1939 39

FIGURE 2.15 Early MSW incinerator 39

FIGURE 2.16 Traveling municipal waste burner 40

FIGURE 2.17 Early waste-to-energy plant 41

FIGURE 3.1 *Federal Register* 56

FIGURE 3.2 Code of Federal Regulations 57

FIGURE 3.3 Example of a guidance document 58
FIGURE 4.1 Variability in quantities of MSW according to size of household 68
FIGURE 4.2 Relationship between GDP and per capita MSW generation for various countries 69
FIGURE 4.3 Composition of MSW in the United States, 2010 70
FIGURE 4.4 "Tox-away day" allows for community residents to properly dispose of HHW 77
FIGURE 4.5 HHW drop-off and storage facility at a city materials recovery facility 78
FIGURE 4.6 Chart showing steam production at a heating plant 83
FIGURE 4.7 Bomb calorimeter 84
FIGURE 4.8 General structure of a carbohydrate molecule 88
FIGURE 4.9 Structure of the glucose molecule 88
FIGURE 4.10 Structure of cellulose 89
FIGURE 4.11 Structure of lignin 89
FIGURE 4.12 Generic structure of a protein molecule 90
FIGURE 4.13 Structure of a lipid molecule 90
FIGURE 5.1 Bags and stickers may be used in a "pay-as-you-throw" waste collection program 104
FIGURE 5.2 Compactor-type truck common in urban and suburban neighborhoods 108
FIGURE 5.3 Automated collection vehicles for residential wastes and commercial wastes 109
FIGURE 5.4 Routing patterns for one-way street collection 112
FIGURE 5.5 Routing patterns for three- and four-block configurations 114
FIGURE 5.6 Routing patterns for a multiblock configuration 115
FIGURE 5.7 Comparison of waste hauling costs with and without a transfer station 116
FIGURE 5.8 Pit-type noncompaction transfer station 117
FIGURE 6.1 Drop-off centers are one means of segregating MSW components 126
FIGURE 6.2 Papermaking process 130
FIGURE 6.3 Cullet stored outdoors and unprotected will inevitably become contaminated 138
FIGURE 6.4 Baled aluminum UBCs ready for shipping to a container manufacturer 141
FIGURE 6.5 Schematic of the steelmaking process 144
FIGURE 6.6 Metal processing facilities may accept ferrous waste from municipalities, demolition operations, industrial plants, and individual consumers 145
FIGURE 6.7 White goods set aside for recycling 146
FIGURE 6.8 Auto entering shredder 146
FIGURE 6.9 Electromagnet for moving ferrous wastes onto rail cars 147
FIGURE 6.10 Shredder housing at a metal recovery facility 147

FIGURE 6.11 Ethylene monomers joining to form a polyethylene polymer 149
FIGURE 6.12 Plastics numbering system 149
FIGURE 6.13 Thermoset polymer showing cross-links 150
FIGURE 6.14 Plastics extruder 150
FIGURE 6.15 Injection molding apparatus 151
FIGURE 6.16 Recycled polyethylene beads (shown next to millimeter scale) ready for extrusion 153
FIGURE 6.17 Illegal tire dumps pose hazards from fires and insect breeding and are unsightly 155
FIGURE 6.18 Destinations for scrap tires 157
FIGURE 7.1 Weigh station at a materials recovery facility 168
FIGURE 7.2 Receiving area at a MRF 169
FIGURE 7.3 Tipping floor of a MRF 169
FIGURE 7.4 Front-end loader on the tipping floor 171
FIGURE 7.5 Cross-section of a belt conveyor 172
FIGURE 7.6 Base of a conveyor belt showing rollers 173
FIGURE 7.7 Transfer point along a conveyor belt 174
FIGURE 7.8 Small scale for weighing bales and other small- and medium-sized objects 174
FIGURE 7.9 A binary separator receiving a mixed feed of x_0 175
FIGURE 7.10 Hand-sorting along a conveyor belt 176
FIGURE 7.11 Trommel screen 178
FIGURE 7.12 Schematic of a trommel screen 178
FIGURE 7.13 Cascading, cataracting, and centrifuging of waste input in a trommel screen 179
FIGURE 7.14 Hypothetical particle size distribution as relates to screening MSW 180
FIGURE 7.15 Disk screen 181
FIGURE 7.16 Schematic of a disk screen 181
FIGURE 7.17 Baler at a MRF 183
FIGURE 7.18 Bales of OCC awaiting shipment to a recycling facility 183
FIGURE 7.19 Pelletizer (densifier) for shredded organic wastes in the manufacture of RDF 184
FIGURE 7.20 Three major types of shredders 185
FIGURE 7.21 Tub grinder for yard wastes 187
FIGURE 7.22 A new hammer for a horizontal hammermill 187
FIGURE 7.23 Vertical hammermill 188
FIGURE 7.24 Old hammer 189
FIGURE 7.25 Drum magnet 191

FIGURE 7.26 Magnetic head pulley 191
FIGURE 7.27 Magnetic belt pulley 192
FIGURE 7.28 Two-drum magnet configuration 192
FIGURE 7.29 Overhead belt magnet in operation 193
FIGURE 7.30 The height of a magnet above the waste stream affects the efficiency of ferrous recovery 194
FIGURE 7.31 An eddy current separator in operation 195
FIGURE 7.32 Schematic of a typical air classifier 196
FIGURE 7.33 Vortex effect occurring within an air classifier 197
FIGURE 7.34 Horizontal air classifier 198
FIGURE 7.35 Air knife 198
FIGURE 7.36 Complete air classification system including cyclone 199
FIGURE 7.37 Terminal settling velocities of MSW components 200
FIGURE 7.38 Actual and ideal performance of air classifiers 200
FIGURE 7.39 MRF flow scheme for a dirty MRF 202
FIGURE 7.40 A second materials flow plan, dirty MRF 203
FIGURE 7.41 The exterior of the MRF should be aesthetically appealing in order to limit NIMBY attitudes 205
FIGURE 8.1 Flow chart showing the steps involved in the aerobic composting process 211
FIGURE 8.2 Temperature trends in the early stages of composting 212
FIGURE 8.3 Biological compost reactor 213
FIGURE 8.4 Portable O_2 meter 216
FIGURE 8.5 Composting of MSW by using the windrow system 220
FIGURE 8.6 Schematic of windrow composting showing scarab compost turner 221
FIGURE 8.7 The aerated static pile 222
FIGURE 8.8 A drum composter 223
FIGURE 8.9 A cured pile ready to go to market 223
FIGURE 8.10 Methods to divert runoff water from a compost pile for eventual collection 229
FIGURE 8.11 Compost fire presumably initiated by spontaneous combustion 230
FIGURE 8.12 Suggested layout of a compost facility 232
FIGURE 8.13 Schematic for a high-solids anaerobic digestion facility 235
FIGURE 9.1 Cross-section of a typical mass-burn incinerator 247
FIGURE 9.2 Common grate types for an MSW combustor 248
FIGURE 9.3 Boiler system used in a mass-burn incinerator 249
FIGURE 9.4 Cooling tower for cooling exhaust gases from an MSW incinerator 250

FIGURE 9.5 Structures of a generic PCDD molecule, a generic PDCF molecule, and 2,3,7,8-tetrachlorodibenzodioxin....254
FIGURE 9.6 Structures of some common polycyclic aromatic hydrocarbons....257
FIGURE 9.7 Formation of a PAH molecule from a simple aliphatic compound....257
FIGURE 9.8 Transformations of inorganics during combustion of MSW....259
FIGURE 9.9 Electrostatic precipitator....261
FIGURE 9.10 Electrodes within the ESP....261
FIGURE 9.11 Schematic of a baghouse for particulate removal....262
FIGURE 9.12 Scrubber (packed tower) for washing acid gases....265
FIGURE 9.13 Gravity spray tower scrubber for washing acid gases....266
FIGURE 9.14 Exposure pathways for emissions from an MSW incinerator....269
FIGURE 9.15 Two types of densified RDF: pellets and cubettes....273
FIGURE 9.16 Piles of coal and RDF to be mixed in the field prior to shipment to heating plant....274
FIGURE 9.17 Truck loading a coal–RDF mixture for combustion at a heating plant....274
FIGURE 9.18 Concentration of gaseous SO_2, NO_x, and HCl with varied coal/RDF ratios....276
FIGURE 10.1 Landfill operated and closed prior to the enactment of RCRA regulations....284
FIGURE 10.2 The layers beneath a sanitary landfill as required under RCRA....289
FIGURE 10.3 Installation of a layer of low-permeability clay....290
FIGURE 10.4 Geomembrane material being installed at a land disposal facility....293
FIGURE 10.5 Puncture apparatus for geomembrane testing....295
FIGURE 10.6 Seaming methods for landfill liners....298
FIGURE 10.7 Compactor vehicle at a sanitary landfill....300
FIGURE 10.8 Density of MSW in a landfill cell as related to thickness of the waste layer....300
FIGURE 10.9 Density of MSW in a landfill cell as related to the number of passes by machinery over the waste....301
FIGURE 10.10 Application of daily cover prevents pest infestations and controls odors....302
FIGURE 10.11 The stages of decomposition in a sanitary landfill....305
FIGURE 10.12 Effects of surrounding geology and surface features on landfill gas migration....311
FIGURE 10.13 The lower explosive limit, upper explosive limit, and explosive range for a hypothetical gas....312
FIGURE 10.14 Typical gas-monitoring probe....313
FIGURE 10.15 Portable organic vapor analyzer....314
FIGURE 10.16 Passive gas control systems showing venting to the atmosphere by convective forces, and a barrier wall....315

FIGURE 10.17 A flaring system for landfill gas 316
FIGURE 10.18 Gas recovery systems for active landfill gas removal 317
FIGURE 10.19 Schematic of run-on and runoff controls at a landfill 320
FIGURE 10.20 Landfill runoff ready for treatment 320
FIGURE 10.21 Testing for free liquids 321
FIGURE 10.22 Mass balance of moisture in a sanitary landfill 326
FIGURE 10.23 Common geosynthetic materials 328
FIGURE 10.24 Schematic of the base of a landfill liner (not to scale) 331
FIGURE 10.25 A low-volume sump 332
FIGURE 10.26 Landfill sump installation 333
FIGURE 10.27 Typical groundwater monitoring well 334
FIGURE 10.28 Cover design for a closed landfill 335
FIGURE 10.29 Two different cover types for a sanitary landfill 336
FIGURE 10.30 Landfill cap under construction showing overlapping sheets of geomembrane cap 337
FIGURE 10.31 Schematic of a bioreactor landfill 339
FIGURE 12.1 Notification of Regulated Waste Activity form 380
FIGURE 12.2 Schematic of a tank showing interstitial monitoring capability 383
FIGURE 12.3 Aisle space must be sufficient to allow the movement of persons and equipment 384
FIGURE 12.4 The Uniform Hazardous Waste Manifest 387
FIGURE 12.5 Flow chart for the manifest paper trail 388
FIGURE 12.6 Questionable Uniform Hazardous Waste Manifest 389
FIGURE 12.A.1 Portions of MSDS for methylene chloride 393
FIGURE 12.A.2 Used rags left out for volatilization of TCE and PCE 394
FIGURE 12.A.3 Spray booths indicating waste paint and solvent storage 395
FIGURE 12.A.4 Drum with questionable dates on label 395
FIGURE 12.A.5 Roll-off container storing wastewater treatment sludge 396
FIGURE 12.A.6 Sludge migration 396
FIGURE 12.A.7 Hazardous waste storage area 398
FIGURE 12.A.8 Satellite accumulation area 399
FIGURE 12.A.9 Roll-off containers 399
FIGURE 13.1 Copy of a bill of lading 405
FIGURE 13.2 Portion of the HMT as created by DOT (49 CFR 172.101) 407
FIGURE 13.3 Types of placards required for transportation of hazardous materials 415

FIGURE 13.4 A placard is required on each side and end of the vehicle....416
FIGURE 13.5 Primary and subsidiary labels for hazardous materials....416
FIGURE 13.6 Hazardous materials warning labels....417
FIGURE 13.7 Markings for nonbulk hazardous materials....418
FIGURE 13.8 Performance-oriented packaging label....420
FIGURE 13.9 The North American Emergency Response Guidebook....422
FIGURE 13.10 Segregation table for hazardous materials (49 CFR)....423
FIGURE 13.11 Hazardous materials incident on the highway....424
FIGURE 13.12 Aftermath of a hazardous materials railway incident....424
FIGURE 13.13 DOT form 5800.1, Incident Report....426
FIGURE 13.A.1 Hazardous waste spilled on road adjacent to a secure landfill....430
FIGURE 13.A.2 Truck transporting solid hazardous waste....431
FIGURE 13.A.3 How *not* to manage drums of a listed hazardous waste....432
FIGURE 14.1 Warning signs at the entrance to a TSDF....438
FIGURE 14.A.1 Truck filled with plastic chips from battery casings....447
FIGURE 14.A.2 Storage area for bulk hazardous wastes....448
FIGURE 15.1 Performance standards for hydrogen chloride, chlorine gas, and metals....454
FIGURE 15.2 The tiered system of modeling and monitoring gaseous air pollutants....457
FIGURE 15.3 Schematic showing the orientation of incinerator subsystems and process component options....461
FIGURE 15.4 A liquid injection incinerator....462
FIGURE 15.5 Hazardous waste storage tanks....462
FIGURE 15.6 A mechanical atomizing burner, one of many possible nozzle designs for a liquid injection incinerator....463
FIGURE 15.7 Rotary kiln incinerator....464
FIGURE 15.8 Injection ports for the introduction of liquid hazardous wastes to a rotary kiln....465
FIGURE 15.9 Mechanical feeding of containerized hazardous wastes into a kiln....465
FIGURE 15.10 Cement kiln schematic....469
FIGURE 15.11 Dual cement kilns, each measuring 450 ft in length with a 1 in. steel shell lined with 9–12 in. of firebrick....470
FIGURE 16.1 Chemical treatment of hazardous wastes: neutralization, precipitation, and oxidation–reduction....481
FIGURE 16.2 Precipitation of metals as a function of solution pH....483
FIGURE 16.3 Schematic of a precipitation process....485
FIGURE 16.4 Electron micrograph of activated....489

FIGURE 17.1 Schematic of a landfill base showing liners and leachate collection and removal systems 496
FIGURE 17.2 Geosynthetic landfill liner being installed 497
FIGURE 17.3 Leachate infiltration in a clay and a composite liner system 500
FIGURE 17.4 Photograph of an LCR system 500
FIGURE 17.5 SWCR system, humid climate 502
FIGURE 17.6 Profile of a Subtitle C hazardous waste landfill 503
FIGURE 17.7 Schematic of a deep well for injecting hazardous liquid wastes 505
FIGURE 17.8 Tanks for storage and blending of liquid hazardous wastes 506
FIGURE 17.9 Well head at deep-well injection facility 506
FIGURE 18.1 Clearly *not* the proper method to manage universal waste lamps 518
FIGURE 18.2 Recycling of spent lead–acid batteries 521
FIGURE 18.3 Recycling of pesticides and pesticide containers 522
FIGURE 18.4 Pledge program form for mercury thermostat reduction 523
FIGURE 18.5 Universal waste programs in the United States 528
FIGURE 19.1 Chemical composition of hydrocarbons in used motor oil 533
FIGURE 19.2 The chemical structures of some important aliphatic and aromatic compounds in used oil 534
FIGURE 19.3 A vacuum distillation or hydrotreatment re-refining system for used oil 540
FIGURE 19.4 A used-oil processing schematic 541
FIGURE 19.A.1 Drum storage area 545
FIGURE 19.A.2 Drum storage in a facility basement 545
FIGURE 20.1 Categories of wastes from medical facilities 550
FIGURE 20.2 Puncture-resistant packaging for used sharps 553
FIGURE 20.3 Biohazard symbol for the labeling of infectious wastes 554
FIGURE 20.4 Tracking form (State of New York) to accompany medical waste shipments off-site 555
FIGURE 20.5 Major components of an incineration system for medical wastes 562
FIGURE 20.6 In-line and retort design of medical waste incinerators 563
FIGURE 20.7 Controlled-air incinerator 564
FIGURE 20.8 Hopper and mechanical feed system for a medical waste incinerator 565
FIGURE 20.9 Autoclave system 568
FIGURE 20.10 Combined shredding and disinfection system 571
FIGURE 21.1 C&D debris results from construction, demolition, and renovation of residential and nonresidential structures 578
FIGURE 21.2 Generation of C&D debris from buildings 578

FIGURE 21.3 Comparison of wastes generated by construction and demolition 580
FIGURE 21.4 C&D debris as a component of Subtitle D wastes 581
FIGURE 21.5 Cross-section of a road showing the various base layers 582
FIGURE 21.6 Buildings undergoing demolition must be assessed for possible asbestos content 586
FIGURE 22.1 Schematic of a plasma screen 596
FIGURE 22.2 Cross-section of a CRT showing Pb contents 599
FIGURE 22.3 Residential collection and drop-off programs have become popular in many U.S. communities 602
FIGURE 22.4 To resell, deconstruct, or scrap? Testing PC components 604
FIGURE 22.5 PC monitors approved for donation 604
FIGURE 22.6 Old CRTs awaiting shipment to a recycler 605
FIGURE 22.7 Disassembly of a PC 605
FIGURE 22.8 PC hard drives separated for eventual recycling 605
FIGURE 22.9 Unit operation for CRT recycling 606
FIGURE 22.10 Flow chart showing options for electronics recycling 608

Preface

> When written in Chinese, the word "crisis" is composed of two characters—one represents danger, and one represents opportunity.
>
> **John F. Kennedy**

> Even if you're on the right track, you'll get run over if you just sit there.
>
> **Will Rogers**

In his *Laws of Ecology*, Dr. Barry Commoner declared: "In nature there is no waste; everything is connected to everything else; everything must go someplace; and there is no such thing as a free lunch." These laws have been faithfully followed for eons by all biota on planet Earth—all, however, except for humans. This "lack of respect for the law" has become particularly evident in recent centuries. Worldwide, human population continues to grow exponentially. The quantities of nonrenewable natural resources extracted and used and the consequent generation of air, water, and soil pollution also follow an upward trend.

The "garbage crisis," as it became known in the late 1980s, will not go away; the number of sanitary landfills in the United States continues to decline, and the amount of waste generated per capita has only recently begun to stabilize. Demands for convenient and disposable consumer products have reached unprecedented levels. Mankind is producing substances that nature simply does not possess the capability to decompose. Payment for our "lunch" is indeed due.

In the United States, regulators, scientists, policy makers, and the general public have belatedly recognized that the context in which we have managed our waste, whether household, industrial, commercial, or hazardous, has been inadequate, if not outright flawed. In the 1970s, disasters, including Love Canal, New York; Times Beach, Missouri; and Valley of the Drums, Kentucky, underscored the lack of a comprehensive strategy for hazardous waste management. In the 1980s, the Islip, New York, "Garbage Barge" made headlines, as did the washing ashore of medical waste on to New Jersey, New York, and California beaches. The *Khian Sea*, transporting incinerator ash from Philadelphia, Pennsylvania, experienced a lengthy and frustrating odyssey in the hope of finding a home for its toxic cargo. The recently closed Fresh Kills landfill, located in Staten Island, New York, is now the world's largest landfill, constructed without a liner on porous sandy soils. It has become apparent that our earlier mindset on management and disposal of waste was neither adequately serving public health nor protecting the environment.

In response to the above-mentioned and similar events, federal and state legislation has been enacted addressing the proper storage, collection, transportation, processing, treatment, recovery, and disposal of wastes from varied sources. The Resource Conservation and Recovery Act (RCRA) established a comprehensive framework for the overall management of existing and future hazardous waste generation, transportation, treatment, storage, and disposal activities. The Act also called for a more effective management of both hazardous and nonhazardous wastes via reduction, reuse, and recycling. Amendments to RCRA now cover the management of used oil, medical waste, and other residues that do not fit conveniently into either category—hazardous or nonhazardous wastes.

There is a need for well-trained scientists, regulatory personnel, and policy makers to appreciate and integrate the technical and regulatory complexities of waste management. The public must make well-informed decisions concerning the allocation of resources toward future management efforts. They must accept the consequences of their lifestyle choices on the local, regional, and global environment. Complacency has brought us to where we are today; we now need comprehensive knowledge combined with committed action to establish a new framework in managing wastes.

There are few reference materials that collectively address the management of the above listed wastes, although the engineer, scientist, or regulatory person may ultimately be responsible for the proper disposition of one or more types. This book is intended to serve as a comprehensive manual for the identification and management of a wide spectrum of wastes, ranging from those considered merely a nuisance to the extremely hazardous. This is an introductory manual for waste management as mandated by the RCRA and related statutes, with an emphasis on basic environmental science and related technical fields.

Part I of this book provides an overview of the historical and regulatory development of waste management. Part II delineates the management of municipal solid wastes, that is, those we encounter on a daily basis. Both conventional (e.g., sanitary landfill, aerobic composting) and innovative (bioreactor landfill, high-solids anaerobic digestion) technologies are discussed. Part III addresses hazardous wastes and their management, from the perspectives of identification, transportation, and requirements for generators to that of treatment, storage, and disposal facilities. Disposition via incineration, chemical treatment, and land disposal is also presented. Part IV is devoted to special categories of waste that may not fit precisely into either RCRA Subtitle D (Solid Wastes) or Subtitle C (Hazardous Wastes). These include used motor oil, medical waste, and electronics waste, among others.

In addition to the end-of-chapter problems provided in all chapters of this book, Chapters 4, 8, and 10 contain exercises using data from field situations.

Regardless of how passionately some Americans may adhere to the “reduce, reuse, and recycle” mantra, wastes of varying toxicity and mobility in the biosphere will continue to be produced in incomprehensible quantities. It is therefore critical that Americans become aware of the hazards and potential benefits of wastes in order to manage them in the safest and the most environmentally sound manner.

Acknowledgments

The author wishes to acknowledge Kyle Meyer, Joseph Clements, Kari Budyk, and Andrea Dale of Taylor & Francis/CRC Press, who have been so supportive in preparing this work for publication. Their assistance and professionalism have helped to make this book a rewarding experience. Sincere thanks also to the technical editorial team, Srikanth Gopaalan, R. Seshadri, Derrick Davis, and K. Balaji, for their fine work in editing the manuscript.

I am indebted to Nam Youngwoo for preparing the fine figures in this text.

Thanks to those loved ones who provided their unfailing support and encouragement throughout the course of this project: Rose and Ed Gonzalez; Stan Pichtel; Theresa, Leah, and Yozef Pichtel; and my respected colleague Joseph Timko.

Sincere gratitude is expressed to Werner Erhard, a true genius who assisted me in realizing the possibilities for growth through countless avenues.

Finally, special thanks to my students; your desire to understand the underlying mechanisms, trends, and other concepts of environmental science provided me with the incentive to pursue this work.

About the Author

John Pichtel is a professor of natural resources and environmental management at Ball State University in Muncie, Indiana, where he has been on the faculty since 1987. He earned his PhD degree in environmental science and his MS degree in soil chemistry/agronomy from The Ohio State University, and his BS degree in natural resources management from Rutgers University. His primary research and professional activities have been in management of hazardous and municipal wastes, remediation of contaminated sites, reclamation of mined lands, and environmental chemistry. He teaches courses in management of solid and hazardous wastes, environmental site assessment, site remediation, and emergency response to hazmat incidents.

Dr. Pichtel is a Certified Hazardous Materials Manager and holds memberships in the Institute of Hazardous Materials Managers, Sigma Xi Scientific Society, and the Indiana Academy of Science. He was selected as a Fulbright Scholar in 1999 and again in 2005.

In addition to *Waste Management Principles*, Dr. Pichtel has written *Site Remediation Technologies*, a book on cleanup of contaminated sites, and *Terrorism and WMDs: Awareness and Response*. He has also authored or co-authored approximately 40 research articles. He has served as a consultant in hazardous waste management projects and has conducted environmental assessments and remediation research in the United States, the United Kingdom, Ireland, Finland, and Poland.

Part I

Historical and Regulatory Development

Solid waste is a generic term that describes those materials that are of little or no value to humans; in this context, disposal may be preferred over usage. Solid wastes have also been termed *municipal solid waste*, *domestic waste*, and *household waste*. As we shall see, however, the regulatory definition of solid waste is an inclusive one, incorporating hazardous wastes, nonhazardous industrial wastes, and sewage sludges from wastewater treatment plants, along with garbage, rubbish, and trash. However, not all of the above wastes are necessarily managed in the same manner or disposed in the same facility. The definition only serves as a starting point for more detailed management decisions.

Until recently, waste was given a low priority in the conference rooms of municipal, state, and federal offices responsible for public health and safety. Waste management has since emerged as an urgent, immediate concern for industrial societies—a result of generation of massive waste quantities as a consequence of economic growth and lifestyle choices. Concomitant concerns have arisen regarding the inherent hazards of many such materials, as well as the cost of their overall management and disposal.

Over the past three decades, significant legislation has been enacted for the purpose of protecting humans and the environment from the effects of improper waste management and disposal. In addition, a wide range of economic incentives (e.g., grants and tax breaks) have been made available to municipalities, corporations, and universities to support waste reduction, recycling, and other applications of an integrated waste management program. Some have proven highly successful.

Part 1 provides the reader with a framework for the management of many types of wastes. The Introduction is followed by a history of waste management and then a discussion of regulatory development in waste management.

1 Introduction

> Conspicuous consumption of valuable goods is a means of reputability to the gentleman of leisure.
>
> **Thorstein Veblen**
> *The Theory of the Leisure Class, 1899*

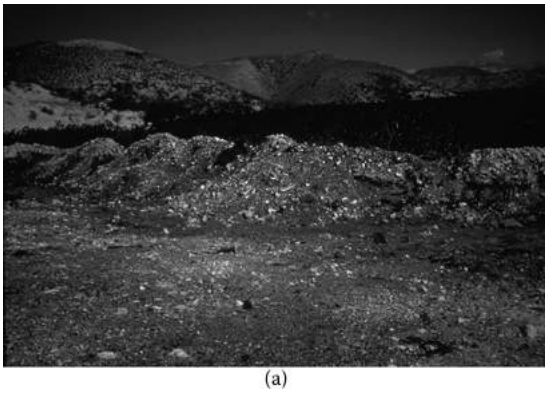
As recently as a few decades ago in the United States, the chemical, physical, and biological properties of the municipal solid waste stream were of little or no concern to the local hauling firm, the city council, or the citizens who generated the waste. Similarly, little thought was given to the total quantities of waste produced. Waste volumes may have appeared fairly consistent from year to year, since few measurements were made. Wastes were transported to the local landfill or perhaps the town dump alongside the river for convenient final disposal. The primary concerns regarding waste management were, at that time, aesthetic and economic, that is, removing nuisance materials from the curb or the dumpster quickly and conveniently, and at the lowest possible cost.

By the late 1980s, however, several events were pivotal in alerting Americans to the fact that the present waste management system was not working. When we threw something away, there was really no "away":

1. *The Islip Garbage Barge*. On March 22, 1987, the *Mobro 4000* left Islip, Long Island, NY, with another load of about 3100 tons of garbage for transfer to an incinerator in Morehead City, NC. Upon learning that the barge may be carrying medical waste, concerns were raised by the receiving facility about the presence of infectious materials on board, and the *Mobro* was refused entry. From March through July, the barge was turned away by six states and several countries in Central America and the Caribbean (Figure 1.1). The Mexican Navy intercepted the barge in the Yucatan Channel, forbidding it from entering Mexican waters. The ongoing trials of the hapless barge were regular features on many evening news programs. The waste was finally incinerated in Brooklyn, NY, and the ash was disposed in the Islip area.
2. *Beach washups*. In 1988, medical wastes began to wash up on the beaches of New York and New Jersey. In 1990, the same phenomenon occurred on the West Coast. Popular beaches along the East Coast and in California closed because of potentially dangerous public health conditions. Outraged officials demanded to know the sources of the pollution, arranged for cleanups, and attempted to assure the public that the chances of this debris causing illness were highly remote; however, public fears of possible contact with hepatitis B and HIV viruses led to a concomitant collapse in local tourist industries.
3. *The Khian Sea*. This cargo ship left Philadelphia, PA, in September 1986, carrying 15,000 tons of ash from the city's municipal waste incinerator for transfer to a landfill (Figure 1.2). It was soon suspected, however, that the ash contained highly toxic chlorinated dibenzodioxins; as a result, the ship was turned away from ports for 2 years, during which it wandered the high seas searching for a haven for its toxic cargo (Holland Sentinel 2002). About 4000 tons of the ash was dumped on a beach in Haiti near the port of Gonaives. An agreement was arranged 10 years later for the return of the ash to the United States.



FIGURE 1.1 The ill-fated "garbage barge" from Islip, Long Island, NY. (Courtesy of Greenpeace/Dennis Capolongo.)



(a)



(b)

FIGURE 1.2 Legacy of the *Khian Sea*: (a) ash pile dumped on Haitian beach; (b) *Khian Sea* sailor eating ash on the beach, attempting to disprove any hazard. (Courtesy of Greenpeace/Annie Leonard.)

4. *The plight of the sanitary landfill*. The mainstay for convenient waste disposal in the United States is becoming increasingly difficult and costly to operate. Stringent and comprehensive regulations for landfill construction, operation, and final closure were forcing underperforming landfills to shut down. Those facilities that remained in operation were compelled to charge higher tipping (i.e., disposal) fees, often in the form of increased municipal taxes.

5. *Love Canal*. This event galvanized American society into an awareness of the acute problems that can result from mismanaged wastes (particularly hazardous wastes). In the 1940s and 1950s, the Hooker Chemical Company of Niagara Falls, NY, disposed over 100,000 tons of hazardous petrochemical wastes, many in liquid form, in several sites around the city. Wastes were placed in the abandoned Love Canal and also in a huge unlined pit on Hooker's property. By the mid-1970s, chemicals had migrated from the disposal sites. Land subsided in areas where containers deteriorated, noxious fumes were generated, and toxic liquids seeped into basements, surface soil, and water. The incidence of cancer, respiratory ailments, and certain birth defects was well above the national average. A public health emergency was declared for the Love Canal area, many homes directly adjacent to the old canal were purchased with government funds, and those residents were evacuated. Numerous suits were brought against Hooker Chemical, both by the U.S. government and by local citizens. At the time, however, there was simply no law that assigned liability to responsible parties in the event of severe land contamination.

With greatly enhanced environmental awareness by U.S. citizenry, and with public health, environmental as well as economic concerns, a paramount focus of many municipalities, a proactive and *integrated* waste management strategy has evolved. The new mindset embraces waste reduction, reuse, resource recovery, biological processing, and incineration, in addition to conventional land disposal. Given these new priorities, the importance of documenting the composition and quantities of municipal solid wastes (MSWs) produced, and ensuring its proper management (including storage, collection, segregation, transport, processing, treatment, disposal, recordkeeping, and so on) within a community, city, or nation cannot be overstated.

1.1 DEFINITION OF A SOLID WASTE

We can loosely define solid waste as a solid material possessing a negative economic value, which suggests that it is cheaper to discard than to use. Volume 40 of The U.S. Code of Federal Regulations (40 CFR 240.101) defines a solid waste as:

> garbage, refuse, sludges, and other discarded solid materials resulting from industrial and commercial operations and from community activities. It does not include solids or dissolved material in domestic sewage or other significant pollutants in water resources, such as silt, dissolved or suspended solids in industrial wastewater effluents, dissolved materials in irrigation return flows or other common water pollutants.

1.2 CATEGORIES OF WASTES

American consumers, manufacturers, utilities, and industries generate a wide spectrum of wastes possessing drastically different chemical and physical properties. In order to implement cost-effective management strategies that are beneficial to public health and the environment, it is practical to classify wastes. For example, wastes can be designated by generator type, that is, the source or industry that generates the waste stream. Some major classes of waste include:

- Municipal
- Hazardous
- Industrial
- Medical
- Universal
- Construction and demolition
- Radioactive

- Mining
- Agricultural

In the United States, most of the waste groupings listed above are indeed managed separately, as most are regulated under separate sets of federal and state regulations.

1.2.1 Municipal Solid Waste

Municipal solid waste (MSW), also known as domestic waste or household waste, is generated within a community from several sources, and not simply by the individual consumer or household. MSW arises from residential, commercial, institutional, industrial, and municipal origins. Examples of the types of MSW generated from each major source are listed in Table 1.1.

Municipal wastes are extremely heterogeneous and include durable goods (e.g., appliances), nondurable goods (newspapers, office paper), packaging and containers, food wastes, yard wastes, and miscellaneous inorganic wastes (Figure 1.3). For ease of visualization, MSW is often divided

TABLE 1.1
Municipal Solid Waste Generation as a Function of Source

Residential (single- and multifamily homes)	Food scraps, food packaging, cans, bottles, newspapers, clothing, yard waste, old appliances
Commercial (office buildings, retail companies, restaurants)	Office paper, corrugated boxes, food wastes, disposable tableware, paper napkins, yard waste, wood pallets
Institutional (schools, hospitals, prisons)	Office paper, corrugated boxes, cafeteria waste, restroom wastes, classroom wastes, yard waste
Industrial (packaging and administrative; *not* process wastes)	Office paper, corrugated boxes, wood pallets, cafeteria wastes
Municipal	Litter, street sweepings, abandoned automobiles, some construction and demolition debris

Source: Adapted from Franklin Associates, *Characterization of Municipal Solid Waste in the United States: 1998 Update,* EPA 530-R-01-014, Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 1999.

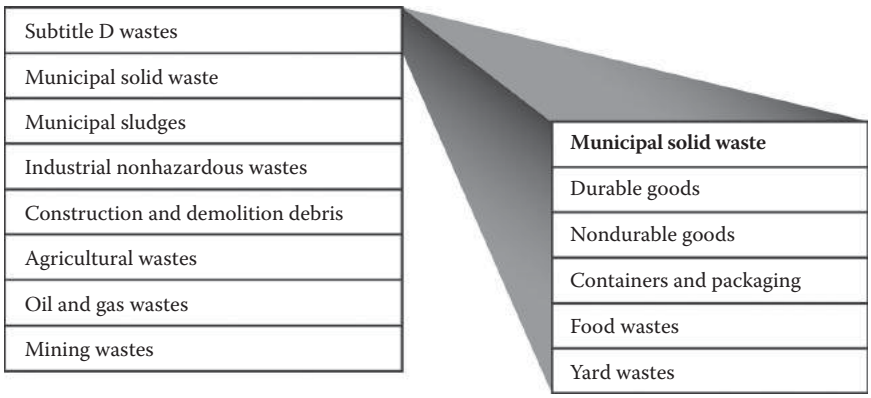


FIGURE 1.3 Municipal solid waste as a component of subtitle D wastes. (Reproduced with kind permission of Franklin Associates, *Characterization of Building-Related Construction and Demolition Debris in the United States,* EPA530-R-98-010, U.S. Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste, U.S. EPA, Prairie Village, KS, 1998.)

TABLE 1.2
Physical Composition of Municipal Solid Waste

Chemical Class	General Composition	
Organic	Paper products	Office paper, computer printout, newsprint, wrappings
		Corrugated cardboard
	Plastics	Polyethylene terephthalate (1)[a]
		High-density polyethylene (2)
		Polyvinyl chloride (3)
		Low-density polyethylene (4)
		Polypropylene (5)
		Polystyrene (6)
		Multilayer plastics (7)
		Other plastics including aseptic packaging
	Food	Food (putrescible)
	Yard waste	Grass clippings, garden trimmings, leaves, wood, branches
	Textiles/rubber	Cloth, fabric
		Carpet
		Rubber
		Leather
Inorganic	Glass	Clear ("flint")
		Amber, green, brown
	Metals	Ferrous
		Aluminum
		Other nonferrous (copper, zinc, etc.)
	Dirt and others	Dirt
		Stones
		Ash
	Bulky wastes	Furniture, refrigerators, stoves, etc. ("white goods")

[a] Plastics coding system, Society of the Plastics Industry, Inc.

into two categories: garbage and rubbish. Garbage is composed of plant and animal waste generated as a result of preparing and consuming food. This material is putrescible, meaning that it can decompose quickly enough through microbial reactions to produce foul odors and harmful gases. Rubbish is the component of MSW excluding food waste, and it is nonputrescible. Some, but not all, of rubbish is combustible. Table 1.2 lists materials that constitute MSW.

The heterogeneity of the waste stream is further demonstrated at the disposal site. As we shall see in Chapter 3, subtitle D of the Resource Conservation and Recovery Act (RCRA) regulates the management of wastes other than hazardous wastes. As shown in Figure 1.3, RCRA subtitle D landfills accept many kinds of wastes beyond MSW—household items such as old newspapers, food waste, plastic packaging, and refrigerators may occur along with construction and demolition debris. It has been a common practice to landfill nonhazardous industrial wastes, such as those from the oil and gas industry, as well as residues from automobile salvage operations, along with MSW. A small percentage of municipal landfills are used for disposal of sewage sludges (*biosolids*) from wastewater treatment plants. Such codisposal practices are fairly common because wastewater treatment plants are often owned and operated by the same municipal body, thus encouraging cooperation between the two facilities. Finally, MSW landfills contain a significant proportion of potentially hazardous materials from households. Households generate used motor oil, pesticide and paint containers, batteries, household solvents, and many other hazardous wastes, albeit in small volumes.

1.2.2 Hazardous Waste

Hazardous wastes are produced by most, if not all, of the sources listed in Table 1.1. However, when the monthly quantity generated exceeds a certain limit, both wastes and generator are subject to compliance with federal and state regulations. RCRA defines hazardous waste as (40 CFR 240.101):

> Any waste or combination of wastes which pose a substantial present or potential hazard to human health or living organisms because such wastes are non-degradable or persistent in nature or because they can be biologically magnified, or because they can be lethal, or because they may otherwise cause or tend to cause detrimental cumulative effects.

In other words, a RCRA hazardous waste is a solid waste that, owing to its quantity, concentration, or physical, chemical, or infectious characteristics; may (1) cause or contribute to an increase in mortality, serious illness, or incapacitation; or (2) pose a substantial hazard to human health or the environment when improperly treated, stored, transported or disposed of, or otherwise managed.

Solid wastes are classified as hazardous under the RCRA regulations if they exhibit one or more of the following characteristics:

- Ignitability
- Corrosivity
- Reactivity
- Toxicity

Examples of hazardous wastes include residues from solvent manufacture, electroplating, metal treating, wood preserving, and petroleum refining. Regulations require that these wastes be managed with significantly greater care as compared with ordinary MSW. For example, an extensive paper trail is required, indicating the status of the waste from the point of generation, through interim storage, treatment (if any), transportation, and ultimate disposal. Requirements are stringent for facilities that generate waste; as well as for transporters; and treatment, storage and disposal (TSD) facilities. This “cradle-to-grave” approach to handling hazardous wastes has been central to promoting sound management.

1.2.3 Industrial Waste

Billions of tons of industrial solid waste are generated and managed on-site at industrial facilities each year; the amount generated is many times greater than the amount of MSW produced (U.S. EPA 2012). Generated by a broad spectrum of U.S. facilities, industrial wastes are by-products from manufacturing and other processes. Many (but not all) of these wastes are of low toxicity and are often produced in large quantities by a generator. Examples of an industrial waste stream are coal combustion solids, including bottom ash, fly ash, and flue gas desulfurization sludge. Other common sources of industrial wastes are the pulp and paper industry, the iron and steel industry, and the chemical industry.

If an industrial waste stream, based on regulatory designation, knowledge of the processes involved or laboratory testing, is designated as hazardous waste, the waste must be managed as such and shipped to a licensed treatment, storage, and disposal facility. Wastes designated as nonhazardous are placed in landfills, land application units (typically installed on company property), or incinerated. A large proportion of industrial waste is composed of wastewater that is stored or treated in surface impoundments. Treated wastewaters are eventually discharged into surface waters under

Clean Water Act permits issued by the U.S. EPA or state governments via the National Pollutant Discharge Elimination System (NPDES).

State and some local governments have regulatory responsibility for ensuring appropriate management of industrial waste. Regulatory programs will therefore vary widely.

1.2.4 Medical Waste

Medical waste is generated during the administration of healthcare by medical facilities and home healthcare programs and as a result of research by medical institutions. Institutions generating the most medical waste include hospitals; offices of physicians, dentists, and veterinarians; long-term healthcare facilities; clinics; laboratories; blood banks; and funeral homes. The majority of regulated medical waste is generated by hospitals. Although not all waste generated by the above sources is considered infectious, many facilities choose to handle most or all of their medical waste streams as potentially infectious.

Specific classes of regulated medical waste include: cultures and stocks of infectious agents (e.g., cultures from medical, pathological, research, and industrial laboratories); pathological wastes (tissues, organs, body parts, body fluids); waste human blood and blood products; sharps (both used and unused hypodermic needles, syringes, scalpel blades, etc.) for animal or human patient care or in medical, research, or industrial laboratories; animal waste (contaminated carcasses, body parts, and the bedding of animals exposed to infectious agents); and isolation wastes (discarded materials contaminated with fluids from humans who are isolated to protect others from highly communicable diseases) (40 CFR part 259).

Congress passed the Medical Waste Tracking Act in November 1988, which directed the EPA to develop protocols for comprehensive management of infectious waste. RCRA was subsequently amended to include medical waste management. The Act established a cradle-to-grave medical waste tracking program. The tracking program had limited participation, and expired in June 1991 without reauthorization by Congress; however, the course of U.S. medical waste management was changed significantly as a result of this legislation.

1.2.5 Universal Waste

Universal wastes include: (1) batteries such as nickel–cadmium and small lead–acid batteries found in electronic equipment, mobile telephones, and portable computers; (2) agricultural pesticides that have been recalled, banned from use, or are obsolete; (3) thermostats that contain liquid mercury; and (4) lamps that contain mercury or lead.

Universal wastes are generated by small and large businesses regulated under RCRA; early on, businesses were required to classify the above materials as hazardous wastes. The Universal Waste Rule, first published in the May 1995 Federal Register, was implemented to ease the regulatory burden on businesses that generate such wastes. Specifically, the rule simplifies requirements related to notification, labeling, marking, prohibitions, accumulation time limits, employee training, response to releases, off-site shipments, tracking, exports, and transportation. Universal wastes are also generated by households that are not regulated under RCRA and are permitted to dispose these in the trash.

Many industries strongly support the Universal Waste Rule because it facilitates company efforts to establish collection programs and participate in manufacturer take-back programs required by a number of states. Also appealing to industry are substantial cost savings when these wastes do not have to be managed as hazardous. The implementation of universal waste programs varies from state to state; for example, some states have designated additional universal wastes beyond those listed by federal regulations.

1.2.6 Electronics Waste

Electronics waste (e-waste) includes consumer and business appliances, products, components, and accessories nearing the end of their useful life due to obsolescence and malfunction. Common examples of e-waste include personal computers (inclusive of peripherals such as keypads and mice), printers, mobile phones, computer game components, televisions, videocassette recorders, stereos, copiers, and fax machines.

e-Waste was not given serious notice until the 1990s. Now it comprises more than 5% of the U.S. municipal solid waste stream and is one of the fastest growing fractions of the waste stream (Electronics TakeBack Coalition 2010).

Of great significance to the management of e-waste is its composition of hazardous metals, including cadmium, chromium, mercury, lead, and many others; in addition, several plastics generate toxins when burned. Little is known regarding how these elements and compounds behave in a sanitary landfill or an MSW incinerator.

Many obsolete and malfunctioning electronic products can be reused, rebuilt, or recycled. Unfortunately, only 13.6% of discarded computers were recycled, compared with 34% of MSW (U.S. EPA 2012). Most were disposed or are simply stockpiled—it is estimated that about 68% of unwanted electronics are in storage (Electronics TakeBack Coalition 2010), in part because of the uncertainty of how to manage such items.

1.2.7 Construction and Demolition Debris

Construction and demolition (C&D) debris is waste material produced during construction, renovation, or demolition of structures. Structures include residential and nonresidential buildings as well as roads and bridges. Components of C&D debris include concrete, asphalt, wood, metals, gypsum wallboard, and roofing. Land-clearing debris such as tree stumps, rocks, and soil are also included in C&D debris.

1.2.8 Radioactive Waste

Radioactive wastes comprise a unique category of industrial wastes. The main generators are electricity-producing nuclear plants, nuclear waste reprocessing facilities, and nuclear weapons facilities. Radioactive wastes are also produced by research and medical (e.g., pharmacological) laboratories. Radioactive wastes are, by definition, unstable; certain atoms possess nuclei that undergo radioactive decay. Energy is released from the nucleus to convert it into some stable form. Radiation can be emitted as particles or electromagnetic waves. Particles include alpha radiation, which is composed of two protons and two neutrons (the equivalent of a helium atom stripped of its planetary electrons); beta particles, essentially identical to electrons; and neutrons. Gamma radiation is a form of electromagnetic energy similar to x-rays.

A major concern with radioactive materials (including wastes) is their capability to cause effects from a distance; some forms of radiation can travel for miles. Neutrons and gamma waves can penetrate matter, including living tissue. Alpha, beta, neutron, and gamma emissions are designated *ionizing radiation* because they can ionize other matter, that is, create a charge on a previously uncharged atom or molecule. This effect is potentially hazardous to health, as ionized nucleic acids (DNA and RNA) can lead to genetic mutations and cancer.

High-level radioactive wastes are generated in nuclear plants by the fission of uranium nuclei in a controlled reaction. The Nuclear Regulatory Commission (NRC) defines high-level radioactive waste as (10 CFR part 72):

1. The highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations;

2. Other highly radioactive material that the commission, consistent with existing law, determines by rule requires permanent isolation.

Spent uranium fuel is an example of a highly radioactive waste that contains many radionuclides. Generators of this waste include commercial nuclear plants that produce electricity, nuclear waste reprocessing facilities, and nuclear weapons facilities. These wastes are highly regulated and rigorously managed; there are strict licensing requirements for the storage of spent nuclear fuel and high-level radioactive waste (10 CFR part 72).

Due to the inherent hazards, disposal of high-level wastes is fraught with controversy. For most nuclear-technology countries, the primary disposal choice involves some form of sophisticated burial in deep, stable geologic formations. In the United States, the Yucca Mountain site, located about 90 miles north of Las Vegas, NV, had been designated as the primary choice for a repository. However, this project was widely opposed from its inception. Some of the key concerns were long-distance transportation of toxic radioactive waste to this site, the possibility of accidents, and the uncertainty of isolating nuclear waste from the environment essentially ad infinitum. In 2009, the Obama Administration rejected use of the site.

Low-level radioactive wastes comprise diverse materials generated from industrial, research, educational, and other processes. Sources include private and government laboratories, industries, hospitals, and educational and research institutions. The NRC defines low-level radioactive waste as radioactive material that (10 CFR part 62):

1. Is not high-level radioactive waste, spent nuclear fuel, or by-product material as defined in the Atomic Energy Act of 1954 (42 U.S.C. 2014(e)(2)).
2. The NRC, consistent with existing law and in accordance with 10 CFR part 61, classifies as low-level radioactive waste.

Low-level radioactive wastes consist of trash and other materials that have come into contact with radioactive materials and may have become measurably radioactive themselves. Such wastes include cleanup items such as mops and rags, lab gloves, protective clothing, filters, syringes, tubing, and machinery. Hundreds of different radionuclides can occur in low-level waste (Tammemagi 1999). Approximately 2 million cubic feet of low-level radioactive wastes are disposed at commercial disposal sites annually (Liu and Liptak 2000).

Several techniques are available for disposal of low-level radioactive wastes. In the United States, some wastes are buried in trenches situated in thick clay formations. Some are permitted for disposal in a subtitle D sanitary landfill. In France, low-level wastes are stored in heavily reinforced concrete vaults (Tammemagi 1999).

1.2.9 Mining Waste

Mine waste includes the soil and overburden rock removed during extraction of a desired resource (e.g., coal, metals) from the subsurface. Mine waste also includes the tailings or spoils produced during the processing of minerals, such as by smelting operations. In addition, heap wastes are produced when metals such as gold, silver, or copper are recovered from piles of low-grade waste rock or tailings by spraying with acid or cyanide solutions.

In mining operations, overburden wastes and tailings are returned to the surrounding environs (Figure 1.4). Due to the enactment of federal and state mining reclamation laws—for example, the Surface Mining Control and Reclamation Act (SMCRA) of 1977—mine operators are required to return the affected site to its previous contours and land use, and must post a sufficient bond until all operations are satisfactorily completed.

Quantitative estimates of mine wastes produced in the United States are limited; estimates range from one to two billion tons annually. Approximately half occurs as overburden spoils and the remaining half as heap leach waste (Rhyner et al. 1995).



FIGURE 1.4 Mining wastes are typically returned to the site of operation.



FIGURE 1.5 Animal manures applied to agricultural fields serve as a low-cost soil conditioner and source of nutrients.

1.2.10 Agricultural Waste

The largest proportion of agricultural wastes occurs as animal manures and crop residues; however, other wastes such as pesticide containers and packaging also contribute to this category.

In the United States, agricultural wastes are produced in much greater quantities than is MSW. Much of this waste goes unnoticed by most Americans, however, as the sources are diffuse and wastes are generated in areas of low population density. In small-scale agricultural operations, animal and plant wastes can be recycled directly on to the soil surface. Used on-site, this process can be viewed as the application of an inexpensive soil amendment (Figure 1.5). However, when large numbers of animals are concentrated in a relatively small area, for example, in livestock feedlots and poultry operations, the accumulation and management of the wastes pose a pressing challenge. Manures may need to be moved off-site for disposal; cost and other practical issues become significant, as manures are composed mostly of water and are therefore only a dilute source of plant nutrients. Problems related to odor, pathogen content, salt concentration, and ammonia production are also common. In such cases, more sophisticated management techniques

may be required to reduce the volume and potential toxicity of the wastes (e.g., anaerobic digestion or composting), thereby rendering the material more cost-effective for transport as well as hygienically safe.

The management of municipal, hazardous, medical, universal, electronics, C&D, and other special wastes will be discussed in detail in subsequent chapters. The management of radioactive, mining, and agricultural wastes is not covered in this book.

1.3 GENERATION OF MSW

At the close of the Second World War, economic activity expanded greatly for many Americans. Following the fulfillment of basic material needs, expenditures for personal consumption reached new levels. Americans have enjoyed a growing amount of discretionary spending dollars; we have increasingly become a nation of consumers. Waste generation is inevitably correlated with this increased consumption.

Advertising has been central to stoking the current level of overconsumption in American society. In addition, new marketing and production practices, such as disposable products and the planned obsolescence of various goods, have been introduced (Tammemagi 1999). To exacerbate the situation, packaging has become important in the marketing of consumer goods. Packaging now comprises more than one-third of the U.S. waste stream. The overall result of these trends has been an explosive growth in the variety and volume of consumer goods, and concurrently in the volumes and heterogeneity of solid wastes (Figure 1.6). The need for adequate management of wastes, therefore, continues to grow in urgency.

Table 1.3 and Figure 1.7 show trends in MSW generation, materials recovery, and disposal in the United States over five decades. The generation of MSW has increased steadily, from 80 million metric tons (88 million tons) in 1960 to 227 million metric tons (229 million tons) in 2010 (U.S. EPA 2011). Per capita waste generation increased from 1.2 kg (2.7 lb) per person per day in 1960 to 2.0 kg (4.4 lb) per person per day in 2010. Only recently have annual per capita waste generation rates begun to stabilize. Such trends have occurred partly because the public is more informed of environmental concerns and environmental responsibility (i.e., awareness of reduce, reuse, and recycling), and partly because of the increase in disposal costs.

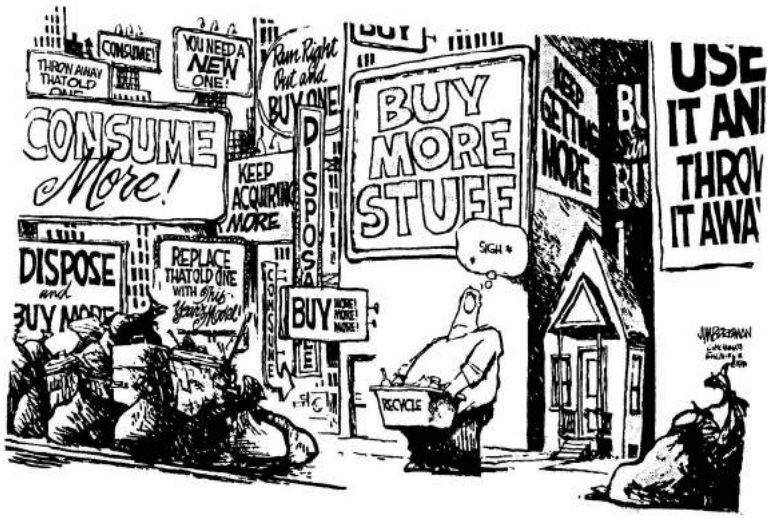


FIGURE 1.6 We all have paid the cost of our success. (From M.F. Moonzajer. Jim Borgman © Cincinnati Enquirer. Reprinted with kind permission of UNIVERSAL UCLICK. All rights reserved.)

TABLE 1.3
Materials Generated (Thousands of Tons) in MSW, 1960–2010

Material	1960	1970	1980	1990	2000	2010
	Thousands of Tons					
Wastes from Specific Products						
Paper and paperboard	29,990	44,310	55,160	72,730	87,740	71,310
Glass	6720	12,740	15,130	13,100	12,770	11,530
Metals						
Ferrous	10,300	12,360	12,620	12,640	14,150	16,900
Aluminum	340	800	1730	2810	3190	3410
Other nonferrous	180	670	1160	1100	1600	2100
Total	10,820	13,830	15,510	16,550	18,940	22,410
Plastics	390	2900	6830	17,130	25,530	31,040
Rubber and leather	1840	12,970	4200	5790	6670	7780
Textiles	1760	2040	2530	5810	9480	13,120
Wood	3030	3720	7010	12,210	13,570	15,880
Other	70	770	2520	3190	4000	4790
Total	54,620	83,280	108,890	146,510	178,700	177,860
Other Wastes						
Food Wastes	12,200	12,800	13,000	20,800	28,810	34,760
Yard Wastes	20,000	23,200	27,500	35,000	30,530	33,400
Miscellaneous inorganic wastes	1300	1780	2250	2900	3500	3840
Total other wastes	33,500	37,780	42,750	58,700	63,840	72,000
Total MSW generated	88,120	121,060	151,640	205,210	242,540	249,860

Source: U.S. EPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States Tables and Figures for 2010,* 2011, Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.

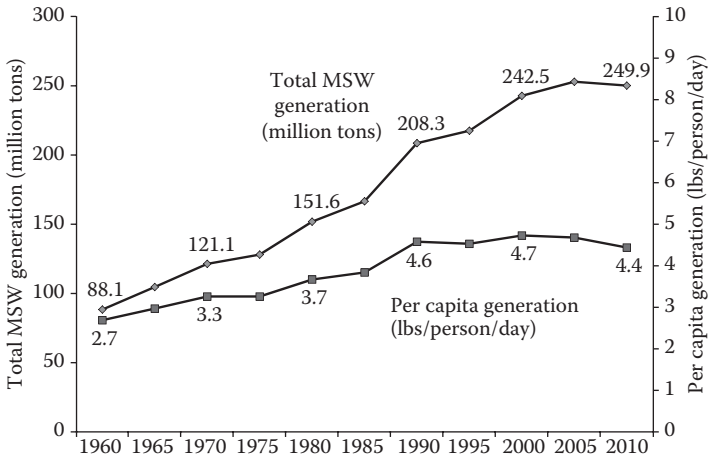


FIGURE 1.7 Trends in total solid waste generation and per capita waste generation in the United States. (From U.S. EPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States Tables and Figures for 2010*, 2011, Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.)

1.4 SOLID WASTE MANAGEMENT

Solid waste management is concerned with the generation, on-site storage, collection, transfer, transportation, processing and recovery, and ultimate disposal of solid wastes.

The EPA Agenda for Action of 1989 (U.S. EPA 1989) promoted an innovative and comprehensive program for *integrated waste management*, that is, the utilization of technologies and management programs to achieve waste management objectives. The EPA integrated waste management hierarchy includes the following components, in order of preference:

- Reducing the quantity and toxicity of waste
- Reusing materials
- Recycling materials
- Composting
- Incineration with energy recovery
- Incineration without energy recovery
- Sanitary landfilling

Strategies that emphasize the top of the hierarchy are encouraged whenever possible; however, all components are important within an integrated waste management system. The integrated management program is customized to meet a particular community's capabilities and needs based on criteria such as population size, presence of industry and business, existing infrastructure, and financial resources. The integrated approach has made great strides over the past two decades in educating the American consumer about individual responsibility in waste management, in fostering industry cooperation in waste reduction, and, ultimately, in reducing some of the massive volumes of wastes targeted for landfill disposal.

In 2010, 85.1 million tons of MSW was recycled (including composting), a recovery of 34.1%. In total, 29.3 million tons was combusted (11.7%), and 135.5 million tons (54.2%) was landfilled. Relatively small amounts of this total were littered or illegally dumped. Figure 1.8 shows, MSW recovered for recycling (including composting) and disposed by combustion and landfilling in 2010.

Most states have aggressively encouraged recycling and have established goals for recycling rates of selected components of the waste stream (e.g., paper, metals, yard waste). Many businesses and industries have responded by setting goals for reducing wastes from manufacturing processes. Through such participation, businesses have discovered that reducing the quantities of hazardous and nonhazardous materials from product manufacture actually results in substantial cost savings. Many states have responded to the integrated waste management initiative by providing financial incentives for source reduction and recycling.

These committed approaches, using state-mandated recycling targets and financial incentives, have experienced their share of difficulties, however. At the initiation of such programs,

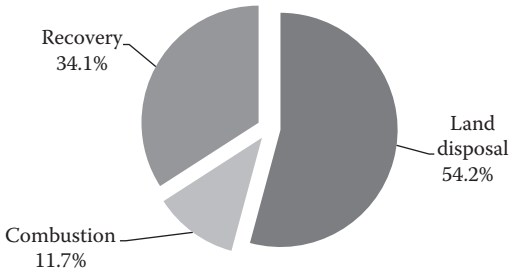


FIGURE 1.8 Current waste management priorities in the United States. (U.S. EPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States Tables and Figures for 2010*, 2011, Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.)

the supply of diverted materials grows, but often without a corresponding demand. Consequently, collected materials may have to be stockpiled or sometimes disposed until new markets are created through incentives, legislation, or the market system. Such pitfalls are addressed in later chapters.

1.4.1 Source Reduction

Source reduction, also known as waste prevention, includes the design, manufacture, purchase, or use of materials (e.g., products and packaging) such that their quantities or toxicity are reduced before they enter the waste management system. In other words, by not producing the waste, there is no longer a concern over storage, collection, disposal costs, and liabilities. Examples of source reduction activities include (U.S. EPA 2001):

- Designing products or packaging to reduce the quantity or toxicity of the materials used, or making easy-to-reuse materials
- Reusing existing products or packaging; for example, refillable bottles, reusable pallets, and reconditioned barrels and drums
- Lengthening the lives of products such as tires to postpone disposal
- Using packaging that reduces the amount of damage or spoilage to the product
- Managing nonproduct organic wastes (e.g., food scraps and yard waste) through on-site composting or other alternatives to disposal (e.g., leaving grass clippings on the lawn)

Source reduction practices for selected materials in the waste stream are presented in Table 1.4.

The disposal of some materials has increased in recent decades. In particular, clothing shows significantly increased disposal rates, as do plastic containers. Some of the rise in the use of plastics is attributed to the trend of manufacturers substituting glass packaging with plastic. A waste category experiencing explosive growth is that of electronic wastes, such as personal computers and mobile telephones. The management of electronic wastes is dealt with in Chapter 22.

Until the late 1980s, there had been few incentives for industry to manufacture more durable products, reduce the amount of material used in the product, design products that could be easily repaired, use minimal packaging, use potentially recyclable packaging materials, or purchase postconsumer wastes as raw materials for manufacturing processes. Many of these approaches are now supported enthusiastically. Government incentives and mandates, legislated recycling targets, public support, and concern for the "bottom line" (via reducing waste removal and disposal costs) have all contributed to the growing interest and participation in integrated waste management.

1.4.2 Recycling

Recycling, including community composting programs, recovered 34.1% (85 million tons) of the total 250 million tons of MSW generated in 2010 (U.S. EPA 2011). The percentage recycled was up markedly, compared with 16% in 1990 and 10% in 1980. Over 9000 curbside recycling programs were active in the United States in 2010, and thousands of yard waste composting programs were reported. Waste recycling will be discussed in detail in Chapter 6.

1.4.3 Incineration

Incineration is defined as the controlled burning of solid, liquid, or gaseous wastes. "Controlled" conditions may include an oxygen-enriched combustion chamber under elevated temperatures, the use of auxiliary fuel, and vigorous agitation of the incoming waste. About 12% of all MSW generated is disposed via incineration.

TABLE 1.4
Examples of Source Reduction Practices

Source Reduction Practice	Durable Goods	Nondurable Goods	Containers and Packaging	Organics
		Redesign		
Materials reduction	Use less metals in appliances	Paperless purchase orders	Concentrates; container lightweighting	Xeriscaping
Materials substitution	Use of composites in appliances and electronic circuitry		Cereal in bags; coffee brick; multiuse products	
Lengthen life	High mileage tires; electronic components reduce moving parts	Regular servicing; look at warranties; extend warranties	Design for secondary uses	
		Consumer Practices		
	Purchase long-lived products	Repair; duplexing; sharing; reduce unwanted mail	Cereal in bags; coffee brick; multiuse products	
		Reuse		
By design	Modular design	Envelopes	Reusable pallets; returnable secondary packaging	
Secondary	Borrow or rent for temporary use; give items to charity; buy or sell at garage sales	Clothing; waste paper; scratch pads	Loose fill; grocery sacks; dairy containers; glass and plastic jars	
		Reduce/eliminate Toxins		
	Eliminate PCBs	Soy ink; water-based solvents; reduce mercury	Replace lead foil on wine bottles	
		Reduce Organics		
Food waste				Backyard composting; vermicomposting
Yard waste				Backyard composting; grasscycling

Source: U.S. EPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States Tables and Figures for 2010*, 2011, Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.

The main purpose of incineration is volume reduction, with the ultimate result of extending the lifetime of a land disposal facility. A second purpose is termed *waste to energy*, that is, the recovery of heat energy for water heating, space heating, or electricity generation. A third benefit of incineration is detoxification—the destruction of microbial and other pathogenic organisms—within the waste. Incineration of MSW, hazardous waste, and medical waste will be discussed in Chapters 9, 15, and 20, respectively.

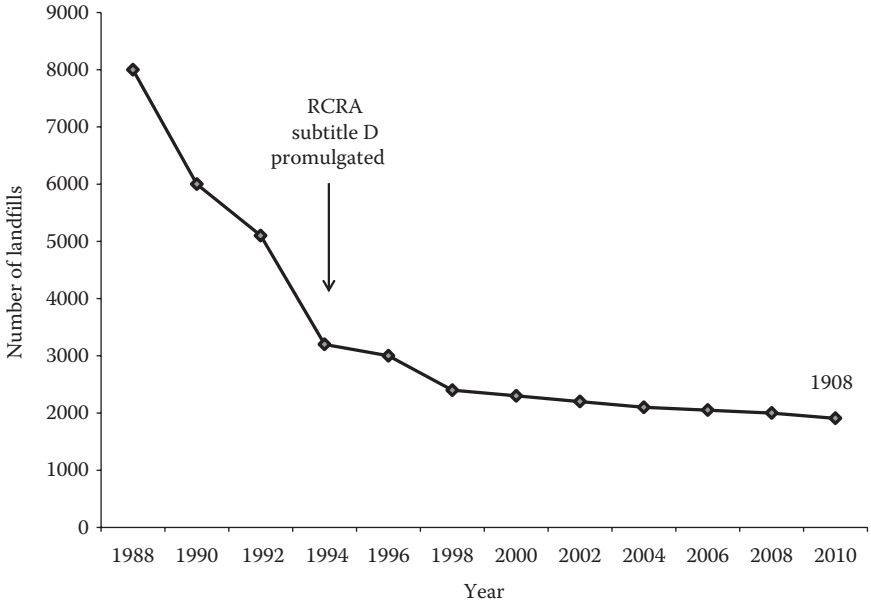


FIGURE 1.9 Decline of the sanitary landfill over recent decades. (U.S. EPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States Tables and Figures for 2010*, 2011, Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.)

1.4.4 Land Disposal

Presently, about 54% of all MSW generated is disposed in landfills. Figure 1.9 shows that the number of municipal solid waste landfills in the U.S. has decreased substantially, from about 8000 landfills in 1988 to 1908 landfills in 2011. Average landfill size increased during this period. At the national level, capacity does not appear to be an issue, although problems of insufficient capacity have been experienced in certain regions of the United States, for example, in the northeast.

With recovery rates increasing and combustion remaining relatively constant, there has been a decrease in the percentage of MSW discarded in landfills, from the 1980s to the present, which has remained relatively steady. Sanitary landfilling will be presented in Chapter 10, and secure landfilling of hazardous waste will be presented in Chapter 17.

1.4.5 Goals at the Federal Level

The EPA had set a goal for the nation to recycle at least 35% of MSW by the year 2005, while reducing the generation of solid waste to 1.9 kg (4.3 lb) per person per day. Because economic growth results in the generation of more products, there will be an increased need to further develop recycling and composting infrastructure, purchase more recycled products, create opportunities for source reduction activities such as reuse of materials and products, and modify manufacturing processes (e.g., making containers with fewer materials) in order to meet these goals.

QUESTIONS

1. The Love Canal (Niagara Falls, NY) disaster was considered by some public health officials, and environmental regulators and scientists to be a "blessing in disguise." Explain.
2. Municipal solid waste is generated within a community from several sources, not just the household. List and discuss these sources.

3. "Sanitary landfills and incinerators are no longer adequate to address America's waste management concerns." Do you agree or disagree with this statement? Discuss.
4. According to the U.S. EPA definition, "solid waste" includes: (a) discarded solids; (b) discarded semisolids (sludges); (c) contained gases; (d) materials from commercial, industrial, and domestic sources; or (e) all of the above.
5. Under the RCRA regulations, how can a solid waste become designated as a hazardous waste?
6. Industrial waste may or may not include hazardous waste. Explain and provide examples.
7. Livestock feedlot wastes are an environmental concern due to which of the following: (a) high water content of the wastes; (b) potential for eutrophication of surface water by nitrogen; (c) high pathogen content; or (d) low fertilizer value.
8. What is the primary purpose of the Medical Waste Tracking Act? What event(s) catalyzed this legislation?
9. Why was the Universal Waste Rule enacted? What are its benefits and whom does it serve?
10. Why is ionizing radiation a human health hazard? Explain its mode of action on living organisms.
11. How is the majority of mining waste disposed? Agricultural waste? Low-level radioactive waste?
12. How are high-level nuclear wastes to be managed and disposed in the near-future? Discuss the pitfalls, in your opinion, associated with the single repository approach of nuclear waste disposal.
13. MSW generation is influenced by both population size and consumer lifestyle. How do these two factors differ for the United States and a less developed country, for example, India or Mexico?
14. Describe the waste management hierarchy under RCRA. What is the ultimate goal of such a hierarchy?
15. What factors have occurred over the past 50 years to increase significantly the quantities of MSW generated in the United States?
16. Explain why the manufacturing of consumer products using more durable, long-lived materials had been slow to catch on by both industry and the American consumer. If you have traveled to Europe or Japan, did you notice a difference in the quality (e.g., durability) of consumer products or in the amount of packaging? Explain.
17. Based on parameters such as population, economic trends, and personal lifestyles, identify the issues you feel will significantly affect waste management in the coming decade.
18. What is your state's position on integrated waste management? If there is a formal program, discuss its administration and practical application, including the waste management hierarchy.

REFERENCES

CFR (Code of Federal Regulations). 2004. *Vol. 10, Part 61, Licensing Requirements for Land Disposal of Radioactive Waste*. Washington, DC: U.S. Government Printing Office.

CFR (Code of Federal Regulations). 2004. *Vol. 10, Part 62, Criteria and Procedures for Emergency Access to Non-federal and Regional Low-level Waste Disposal Facilities*. Washington, DC: U.S. Government Printing Office.

CFR (Code of Federal Regulations). 2004. *Vol. 10, Part 72, Licensing Requirements for the Independent Storage of Spent Nuclear Fuel and High-level Radioactive Waste*. Washington, DC: U.S. Government Printing Office.

CFR (Code of Federal Regulations). 2004. *Vol. 40, Part 240, Guidelines for the Thermal Processing of Solid Wastes*. Washington, DC: U.S. Government Printing Office.

CFR (Code of Federal Regulations). 2004. *Vol. 40, Part 259, Medical Wastes*. Washington, DC: U.S. Government Printing Office.

Electronics TakeBack Coalition. 2010. *Facts and Figures on E-Waste and Recycling*. Available from: http://www.electronicstakeback.com/wp-content/uploads/Facts_and_Figures

Franklin Associates. 1998. *Characterization of Building-Related Construction and Demolition Debris in the United States,* EPA 530-R-98-010. Prairie Village, KS: Municipal and Industrial Solid Waste Division, Office of Solid Waste, U.S. EPA.

Franklin Associates. 1999. *Characterization of Municipal Solid Waste in the United States: 1998 Update*. EPA 530-R-01-014. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.

Holland Sentinel. 2002. *Wandering Ash Arrives Home in Pennsylvania*. Available from: http://hollandsentinel.com/stories/062802/new_062802029.shtml [cited 28 June 2002].

Liu, D.H.F. and Liptak, B.G. 2000. *Hazardous Waste and Solid Waste*. Boca Raton, FL: Lewis Publishing.

Rhyner, C.R., Schwartz, L.J., Wenger, R.B., and Kohrell, M.G. 1995. *Waste Management and Resource Recovery*. Boca Raton, FL: Lewis Publishing.

Tammemagi, H. 1999. *The Waste Crisis. Landfills, Incinerators, and the Search for a Sustainable Future*. Oxford, UK: Oxford University Press.

U.S. EPA (U.S. Environmental Protection Agency). 1989. *The Solid Waste Dilemma: An Agenda for Action, Final Report of the Municipal Waste Task Force*. EPA 530 SW-89-019. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2001. *Municipal Solid Waste in the United States*: 1999 Facts and Figures. EPA530-R-01-014. Washington DC: Office of Solid Waste and Emergency Response, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2011. *Municipal Solid Waste Generation, Recycling, and Disposal in the United States Tables and Figures for 2010*. Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf

U.S. EPA (U.S. Environmental Protection Agency). 2012. *Waste Disposal*. Available from: http://www.epa.gov/region7/waste/solidwaste/waste_disposal.htm

SUGGESTED READINGS AND WEBSITES

Eriksson, O., Carlsson Reich, M., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J.-O., Granath, J., Baky, A., and Thyselius, L. 2005. Municipal solid waste management from a systems perspective. *J Cleaner Prod*, 13(3), 241–252.

Essential Action. *Philadelphia Ash Dumping Chronology*. Available from: http://www.essentialaction.org/return/chron.html

Henry, R.T., Yongsheng, Z., and Jun, D. 2006. Municipal solid waste management challenges in developing countries – Kenyan case study. *Waste Manag*, 26(1), 92–100.

Rathje, W. and Murphy, C. 1992. *Rubbish! The Archaeology of Garbage.* New York: Harper Collins.

Reed, J. 2002. *Love Canal*. Philadelphia, PA: Chelsea House.

Sharholy, M., Ahmad, K., Mahmood, G., and Trivedi, R.C. 2008. Municipal solid waste management in Indian cities—a review. *Waste Manag*, 28(2), 459–467.

van Haare, R., Themelis, N., and Goldstein, N. 2010. The state of garbage in America. *BioCycle*. Available from: http://www.biocycle.net/images/art/1010/bc101016_s.pdf

2 A Brief History of Waste Management

Man is everywhere a disturbing agent.
Wherever he plants his foot, the harmonies of nature are turned to discords.

George Perkins Marsh, 1874

2.1 INTRODUCTION

When early man roamed the earth, solid waste was composed of the remains from hunting, gathering, and food preparation. Human fecal matter comprised another category of the prehistoric waste stream. When wastes accumulated, inhabitants would simply move to a new location. Natural processes of scavenging and microbial decomposition easily absorbed and incorporated the wastes. As a result, and also due to the very low human populations at the time, characteristic problems associated with wastes such as disease, air pollution, and groundwater contamination were insignificant.

In about 9000 BCE, people began to abandon nomadic life and create permanent communities. Human beings advanced from hunters and gatherers to farmers and craftsmen, and became civilized and urbanized. Waste quantities increased and began to accumulate for longer periods. As a result, wastes became more harmful to human health and to natural environments. Stationary human societies have since had to confront the logistical problem of how to manage their residues.

The types of materials predominantly in use by early societies, such as tools, weapons, and handiworks have helped to identify various eras: for example, the Stone Age, the Bronze Age, the Iron Age, and so on. When archaeologists excavate and examine the villages of ancient societies, they search waste piles, cooking hearths, tombs, and structures of the former inhabitants. By sorting through the refuse of ancient habitations, archaeologists have gained insights into the lifestyle, diet, and social order of the inhabitants of early societies. For example, Stone Age humans left behind nondegradable items such as tools, weapons, and utensils. During times of economic decline, the Mayans of Central America buried defective utensils, ornaments, and other household items, which were no longer useful in homes, in their royal tombs. Some wastes appear to have been recycled as well—debris such as broken pots and ceramics have been found within the high platforms and walls of some temples (Alexander 1993).

2.2 EARLIEST CIVILIZATIONS

When civilizations first arose in Mesopotamia, Egypt, and elsewhere, the effects of solid wastes became significant; as a result, certain rules and practices emerged to encourage some rudimentary programs of waste management. As early as 8000–9000 BCE, dumps were established away from settlements, probably to protect populated areas from odors, insects and wild animals (Bilitewski et al. 1997). The Minoans (3000–1000 BCE) placed their wastes, covered periodically with layers of soil, in large pits, thus operating the first protosanitary landfills (Priestley 1968; Wilson 1977). By 2100 BCE, cities on the island of Crete had trunk sewers connected to homes to carry away wastes (Melosi 1981; Vesilind et al. 2002). In the Egyptian city of Heracleopolis (founded about 2100 BCE), efforts were made for collection and disposal of waste in the elite and religious areas, which usually

ended up in the Nile River. However, the wastes in the "non-elite" area were ignored (Melosi 1981). At Koulouri, in the ancient Crete capital of Knossos (ca. 1500 BCE), an effective composting effort was established (Kelly 1973). By 800 BCE, old Jerusalem established sewers and had installed a primitive water supply. In the Indus Valley, the city of Mohenjo-daro had houses equipped with waste chutes and trash bins, and may have had waste collection systems (Melosi 1981). Harappa, in the Punjab region, now a part of modern-day India, installed toilets and drains in bathrooms. Many Asian cities collected waste in clay containers that were hauled away (Vesilind et al. 2002).

The first recorded regulations for the management of solid wastes were established during the Minoan civilization (Tammemagi 1999). Around 2000 BCE, Israel provided guidelines as to how to manage wastes; instructions for the management of human waste are provided in the Bible (Deuteronomy 23:12–13). By 200 BCE, many cities in China employed "sanitary police," who were responsible for the enforcement of waste disposal laws (Vesilind et al. 2002).

2.3 GREECE

During the fifth century BCE, Greek municipalities began to establish town dumps that were maintained in a relatively orderly condition. Solid waste normally consisted of food waste, fecal matter, potsherds, and the remains of abandoned babies (e.g., malformed or illegitimate) (Kelly 1973). In Athens (ca. 320 BCE), each household was responsible for collecting and transporting its wastes (Tammemagi 1999). Residents were required by law to sweep the streets daily, and it was mandated that wastes be transported to sites beyond the city walls (Bilitewski et al. 1997).

During the early Bronze Age, it was common for the Trojans to allow much of their wastes (e.g., bones, rubbish) to accumulate on floors, which were eventually covered by a layer of soil and packed into a new surface. It is speculated that floor levels may have been raised by as much as 20 inches, possibly requiring inhabitants to raise the roofs and doors of their dwellings periodically (Blegen 1958; Alexander 1993). Putrescible and bulky garbage was thrown into the streets, and scavengers such as pigs or geese were allowed to forage among the piles. In some locations, slaves and other "underclass" inhabitants were given the right to pick through the wastes that they carried away (Alexander 1993). For the most part, however, city dwellers lived amid waste and squalor. Direct action for waste management was implemented only when the volume of wastes affected local defense. For example, in Athens in 500 BC, a law was passed that required all wastes to be deposited at least 2 km outside of town limits because piles next to the city walls provided an opportunity for invaders to scale over them (Bilitewski et al. 1997).

Greek and Persian scholars were among the first to suggest an association between personal hygiene, contaminated water, spoiled food, and disease outbreaks and epidemics. Hippocrates (ca. 400 BCE) and the Persian Ibn Sina (980–1037 CE) suggested a relationship between waste and infectious disease (Bilitewski et al. 1997).

2.4 ROME

In ancient Rome, wastes were dumped into the Tiber River, tossed into the streets, or dumped into open pits on the outskirts of the city. Rome was the first civilization to create an organized waste collection workforce in 14 CE (Vesilind et al. 2002). To handle the piles of wastes left on the streets, teams of sanitation workers shoveled the materials into horse-drawn wagons. The collection team transported the refuse to a pit, located either outside the city gates or at some distance from the community. The city's inhabitants, however, often preferred the convenience of a more local, neighborhood dump. Administrators replied by posting signs which read, "Take your refuse further out or you will be fined." The signs included arrows showing the way out of the city (Kelly 1973).

During the rule of the Caesars (27 BCE to CE 410), thousands of carcasses from gladiatorial combats (both human and animal) were disposed in open pits at the city's outskirts. The only known law in existence at that time concerning waste disposal was with regard to management and disposal

of fecal matter. The sanitation subcommittee of the Roman Senate decreed that fecal matter was not to be disposed in carts or open pits (Kelly 1973).

The Romans had gods for every purpose, and they unwittingly had a goddess dedicated to the consequences of their indiscriminate waste disposal, the Goddess of Fever. In spite of devoted sacrifices at their altars, Rome was a victim of plagues in 23 BCE, and 65, 79, and 162 CE. The Romans did not yet fully grasp the connection between waste and infectious diseases. During the first century CE, Roman emperors began to realize that municipal solid wastes posed a significant public health concern. Emperor Domitian (81–96 CE) ordered pest control, because his advisors noticed that lack of cleanliness in the city was associated with an increase in the population of rats, lice, bedbugs, and other vermin (Bilitewski et al. 1997). Emperor Vespasian (69–79 CE) ordered the installation of public toilets, which were designed to have running water beneath (Kelly 1973). By 300 CE, there were 144 public toilets in Rome (Bilitewski 1997).

Some researchers claim that over time, waste accumulation may have contributed to the burying of cities, which subsequently were rebuilt. The old Roman section of the city of Bath, England, is 12–20 ft beneath the existing city (Wilson 1977).

The population of Rome eventually grew to over 1.25 million. At this point, municipal wastes could no longer be handled adequately. Some historians have suggested that the intense odor of these wastes may have driven the aristocracy from the city into the mountains or along the seaside. It is speculated that such a decentralization of power may have precipitated the decline of the empire (Alexander 1993). In addition, the growing mounds of wastes outside the city walls are thought to have compromised the defense of the city (Vesilind et al. 2002).

2.5 EUROPE

With the fall of the Roman Empire came the collapse of any semblance of order and discipline that had been instituted by the imposition of laws and the presence of an organized, active military. Equally significant were the loss of technical knowledge and the science of basic hygiene. As a result, from the Dark Ages through the Renaissance, no organized method of waste disposal is documented, with street dumping among the most common practices (Kelly 1973). Routine procedure was to simply dump wastes, including fecal matter, directly out of a window (Figure 2.1). These would decompose and eventually become incorporated into the unpaved street. In some locations, a centralized receptacle was established directly in front of homes for the general dumping of sewage and other wastes.

As the population in Europe swelled and became urbanized, the impact of wastes became more acute. In London each household established its own waste "heap" outdoors. According to one report on London's sanitation (Greater London Council 1969):

> As the population density rose and pressure on land within the urban area increased a street system evolved. The pattern of refuse disposal changed accordingly. Everything from domestic refuse to cinders from foundries, offal from shambles [slaughterhouses] and manure from stables went to the streets where it was placed in the central kennel or gutter.

It was unsafe to burn wastes within the city due to the proximity of countless wooden structures (Wilson 1977). As a result, wastes remained in place. In 1297, an order was issued that required all tenants to maintain a clear pavement in front of their dwelling. The order was largely ignored. However, much waste was burned in household open fires. During the mid-1300s, scavenging ravens and kites were protected by law because they fed upon the waste heaps. According to one report of the period, "The pigs which roamed about grew fat on the offal in the streets. Dogs were innumerable" (Rawlinson 1958).

The city of Paris experienced a unique event associated with its waste management. In 1131, a law was passed prohibiting swine from running loose in the streets after young King Philip, son of Louis the Fat, was killed in a riding accident caused by a loose pig. The monks of a local abbey protested the law and were granted a dispensation. The controversy on allowing animals to run free in the streets, however, continued for years (Melosi 1981).



FIGURE 2.1 Medieval woodcut showing fecal matter being dumped from a window.

During the medieval period, fodder for livestock in winter was typically unavailable near large cities like London; hence, many farm animals were slaughtered during the fall when grazing was no longer possible. Smoking and salting meats did not preserve meats for the entire winter, which created a strong demand for spices. Spices were used to mask the foul tastes and odor of partially spoiled meat, fish, and other foods. Despite these efforts, spoiled food comprised a significant component of medieval European wastes (Alexander 1993).

In 1354, an order was issued that "filth" deposited in front of houses was to be removed weekly (Wilson 1977). London wards were assigned a beadle or bailiff, who hired assistants called "rakers." Once a week, rakers would collect rubbish and dung from the middle of the streets and from the fronts of houses, following which it was to be carted away, outside the city (Harris and Bickerstaffe 1990; Alexander 1993). As quoted by Rawlinson (1958):

> The refuse was raked together and loaded onto tumbrels [farmer's wagons], drawn by two horses. London maintained 12 of these specially designed carts.… A number of laystalls were [*sic*] established in the city suburbs and on the banks of the river. Special days were appointed when refuse was to be put outside doors for the rakers to scoop up and trundle away to the laystalls.

Another common practice during the medieval period was to discard wastes into surface water. The plague of 1347 may have been precipitated by waste disposal into watercourses such as the Thames River. Also known as "The Black Death," the plague claimed the lives of 25 million of 80 million European citizens over the period 1347–1352. The epidemic was rapidly spread by fleas whose hosts (Norway rats) flourished in the abominable sanitary conditions of the period (Alexander 1993). Edward III notified the Mayor and Sheriffs of London to discontinue the practice of dumping into waterways, after experiencing an unpleasant trip down the fouled Thames. In 1383, an ordinance was passed against river disposal by people living on the Walbrook watercourse because the preponderance of garbage plugged the river. The English Parliament prohibited dumping filth and garbage into rivers, ditches, and watercourses in 1388. It was also ordered that refuse be transported to selected sites so that it would not become the source of nuisance (Wilson 1977). The practice of dumping in water, however, continued illegally into the 19th century with the consequent contamination of roads, rivers, and groundwater by human and animal waste (Bilitewski 1997).

In 1407, the inhabitants of London were instructed to keep their refuse indoors until rakers could carry it away (Wilson 1977). "Refuse collected was sold to farmers and market gardeners; that from the riverside laystalls was taken downstream in boats to be dumped on the Essex marshes" (Rawlinson 1958). The paving of streets was also required so that inhabitants would not have to wade through fecal matter and other wastes (Bilitewski et al. 1997). In 1408, Henry IV ordered that refuse be removed or else forfeits would have to be paid. Garbage cans were introduced during this time. The streets were cleaned, animal carcasses were collected, and the possessions of people who had died from the plague were burned (Bilitewski et al. 1997).

Despite acts, ordinances, and threats, however, the mounds of solid waste persisted as a nuisance and health hazard in Europe. London city officials began paying informers to report offenders who threw garbage into the streets and who were later fined. As an example, one Londoner in 1421 (Rawlinson 1958)

> was arraigned for making a great nuisance and discomfort to his neighbours by throwing out horrible filth onto the highway, the stench of which was so odious, that none of his neighbours could remain in their shops.

Paris and some medieval German cities required that wagons, which had brought goods and supplies into the city, must depart with a load of wastes to be deposited in the countryside (Wilson 1977; Gerlat 1999).

The waste issue reached a crisis stage in Europe in about 1500. Populations continued to surge into the cities. The practice of dumping household garbage, animal manure, and industrial debris into the central gutters in the street persisted. As was the case with Athens 2000 years earlier, municipal wastes were piled so high outside the gates of Paris as to potentially interfere with the defense of the city (Tammemagi 1999).

Even with the increased efforts of English rakers, whose work included cleaning large public spaces and market squares, lawmakers were still offended by the filth in the streets (Wilson 1977). Paris was somewhat ahead of London in its institution of municipal street cleaning, paid for by public funds, in 1506 (Hosch 1967; Wilson 1977).

During the mid-1600s, the population of London reached about 400,000. The journals of Daniel Defoe and Samuel Pepys described the stench of the garbage and documented the plague that was afflicting Europe during this time. About 100,000 inhabitants of London died during the plague of 1665. Even the fashion of that period was influenced by the squalor. Doublet and hose for gentlemen and pin-up skirts for ladies were designed to keep their clothing out of the filth of the city thoroughfares; scented handkerchiefs and snuff were also used to help mask the powerful odors (Alexander 1993). The Great Fire of London in 1666 had some cleansing effect on the city environs, and complaints about refuse in the streets eased to some extent (Wilson 1977).

During the 1700s, it was ruled that London's inhabitants neither could bury dung within the city limits nor take out their garbage after 9:00 PM. By this time of night, lawmakers reasoned, any

honest person was home in bed, and those roaming the streets were presumably up to no good, that is, sneaking somewhere to dump garbage (Kelly 1973). This and other proposals such as "the removal of ordure (filth, dung, manure) and rubbish lying in the streets" and a suggestion to place the entire London area under a uniform public management so that all filth would be taken by boat on the Thames to "proper distances in the country" were offered, all to no avail (Wilson 1977).

Profitable uses could be found, however, for virtually every type of waste generated during this period, up to the beginning of the Industrial Revolution. The British were rather enterprising when dealing with certain wastes. Rush-covered floors of some houses during the Tudor period contained debris up to 3 ft thick. This debris was rich in nitrates, and in the early 17th century was "mined" for saltpeter, which was used in the manufacture of gunpowder (Wilson 1977). Around 1815, the dust from a century-old refuse heap at the bottom of Grays Inn Lane was extracted and sold to Russia to make brick for the rebuilding of Moscow after Napoleon's invasion. The refuse yards of Edinburgh, Scotland, remained the same size for 100 years because much of the waste that was brought in was sorted and eventually sold (Wilson 1977). The general composition of wastes of the period tended to be high in ash, dust, and cinder. The composition of London's wastes for over a century is shown in Table 2.1.

The Industrial Revolution had its beginnings in the 18th century, when the availability of raw materials and increased trade and population stimulated new inventions and a fervent reliance on mechanical labor. Increased production led to greatly increased waste generation.

Charles Dickens and other writers have chronicled the living conditions of the working poor in European cities during the 19th century. Industrial production was of high priority for governments and businesses, with public health and environmental quality being of lesser importance. Water supply and wastewater disposal were, by modern standards, completely inadequate. For example, Manchester, England, had on average one toilet per 200 people. About one-sixth of the city's inhabitants lived in cellars, frequently with walls oozing human waste from nearby cesspools. People often lived around small courtyards where human waste was piled, and that also served as children's playgrounds (Vesilind et al. 2002). In 1741, Lord Tyrconnel described the streets of London as "abounding with such heaps of filth as a savage would look on in amazement." In 1832, citizens complained that the streets near Westminster Abbey were "the receptacle of all sorts of rubbish which lay rotting and corrupting, contaminating the air and affording a repast to a herd of swine" (Tammemagi 1999) (Figure 2.2).

TABLE 2.1
Composition of London Solid Wastes, 1888–2007

Component	1888	1892	1926	1967	2000	2007[a]
Fine dust and cinder	81.7	83.2	54.8	19.3	—	—
Vegetable, putrescible materials and bone	13.2	8.3	14.7	19.2	38.8	29.8
Paper	—	4.3	15.0	34.0	19.5	22.6
Metals	0.4	1.0	3.6	10.6	3.6	4.3
Rags	0.4	0.4	1.8	2.4	—	—
Glass	1.3	1.4	3.0	10.9	8.4	6.6
Plastic	—	—	—	1.3	8.1	10.0
Miscellaneous	3.0	1.4	7.0	2.3	21.7[b]	36.8

Source: Adapted from Wilson, D.G. (Ed.), *Handbook of Solid Waste Management,* Van Nostrand Reinhold, New York, 1977; DEFRA, *Municipal Waste Composition: Review of Municipal Waste Component Analyses – WR0119*, Final Report, Science Directorate, Management Support and Finance Team, London, 2006.

[a] England overall.

[b] "Fines/miscellaneous" plus textiles.



FIGURE 2.2 London slum, 19th century.

In 1842, Sir Edwin Chadwick drafted the Report from the Poor Law Commissioners on an Inquiry into the Sanitary Conditions of the Labouring Population of Great Britain. The report described the sanitary conditions as follows:

> Many dwellings of the poor are arranged round narrow courts having no other opening to the main street than a narrow covered passage. In these courts there are several occupants, each of whom accumulated a heap. In some cases, each of these heaps is piled up separately in the court, with a general receptacle in the middle for drainage. In others a pit is dug in the middle of the court for the general use of all the occupants. In some the whole courts up to the very doors of the houses were covered with filth.
>
> … defective town cleansing fosters habits of the most abject degradation and tends to the demoralization of large numbers of human beings, who subsist by means of what they find amidst the noxious filth accumulated in neglected streets and bye-places.

The report included a recommendation that "public authorities undertake the removal of all refuse from habitations, streets and roads, and the improvement of the supplies of water."

In the mid-to-late 19th century, the research of physicians and scientists such as Frenchman Louis Pasteur, German Robert Koch, and German-Hungarian Ignaz Semmelweis revealed the connection between bacteria and viruses and the incidence of specific diseases. Public health officials eventually linked sanitation practices, including improper waste disposal, to the incidence of disease and other health complaints. Thus was born the "Great Sanitary Awakening." The understanding of the pathology of infectious disease may very well have been the incentive behind modern sanitation practices such as wastewater treatment and sanitary landfilling (Bilitewski et al. 1997).

By the mid-1830s, London became stricter about its enforcement policies regarding waste disposal. The Metropolitan Police Act of 1839 was enacted, which penalized those who "cut timber or stone; threw or lay coal, stone slates, lime, bricks, timber, iron or other materials; or threw or laid any dirt, litter or ashes, or any carrion, fish, offal or rubbish" into any thoroughfare (Wilson 1977). London's Public Health Act of 1875 mandated the removal of refuse by the Sanitary Authority on appointed days. All tenants were required to place their wastes into a mobile receptacle (this was, incidentally, the first legal recognition of the trash container). The Public Health Act of 1891

directed the Sanitary Authority to "employ or contract with a sufficient number of scavengers to ensure the sweeping and the cleansing of the several streets within their district and the collection and removal of street and house refuse." Until 1965, the disposal of Greater London's refuse was handled by about 90 local authorities (Wilson 1977).

2.6 UNITED STATES

As early as 1657, the residents of New Amsterdam (later New York City) prohibited the throwing of garbage into streets; furthermore, keeping streets clean was the responsibility of the individual homeowner (Gerlat 1999). Garbage was piled high near elegant homes and, reminiscent of ancient Rome, hogs, geese, dogs, and vultures rummaged for food within the heaps. In 1834, Charleston, West Virginia, enacted a law protecting garbage-eating vultures from hunters (Vesilind et al. 2002).

In early American cities, the collection of municipal solid waste (MSW) was rare. Benjamin Franklin is considered to be among the first to organize a crude form of sanitation in any of the Colonial cities. In 1792, Franklin hired servants to remove waste from the streets of Philadelphia, PA (Alexander 1993), which had already expanded to a population of 60,000. According to a plan developed by Franklin, slaves carried loads of wastes on their heads and waded into the Delaware River for waste disposal downstream from the city (Kelly 1973). In 1795, the Corporation of Georgetown adopted the first ordinance on record in America concerning waste management. The regulations forbade long-term storage of wastes on private property or dumping in the street (APWA 1976; Wilson 1977). The ordinance did not, however, provide details on collection or removal of waste. In 1800, Georgetown and Washington, DC, contracted with "carriers" to clean streets and alleys periodically.

Urban solid waste problems caused by rapid industrialization and overcrowding were acute in the northeastern United States and were probably among the worst worldwide at that time. A flood of immigrants from Europe and Asia exacerbated the ongoing population migrations from the countryside to the city (Alexander 1993). New York slums were, at that time, the most densely populated acreage in the world, worse than even those in Bombay, India (Melosi 1981). Sidewalks were piled high with garbage, and roadways were crowded with carts, horses, and people (Figure 2.3). According to Zinn (1995), the cities

> were death traps of typhus, tuberculosis, hunger, and fire. In New York, 100,000 people lived in the cellars of the slums … the garbage, lying two feet deep in the streets, was alive with rats.

As in the colonial period, pigs were allowed to run free because they scavenged some of the garbage (Alexander 1993).

Other parts of the country were not without problems of poor sanitation and inadequate waste management. Zinn (1995) noted conditions of urban populations in the south after the Civil War:

> And the slums of the southern cities were among the worst, poor whites living like the blacks, on unpaved dirt streets "choked up with garbage, filth and mud", according to a report of one state board of health.

The horse was a major contributor to the urban U.S. waste load (Figure 2.4). There were more than 3 million horses in U.S. cities at the turn of the century, 120,000 in New York City alone (Melosi 1981). Each generated about 20 lb of manure per day. Also, at that time, over 80,000 horses, mules, and cows were maintained in the city of Chicago, IL. It is estimated that these animals produced about 600,000 tons of manure annually (Melosi 1973; Wilson 1977). In 1900, 15,000 horses in Rochester, NY, "produced enough manure to cover an acre of ground to a height of 175 feet" (Bettmann 1974; Alexander 1993). Another difficult issue of this period, owing to their numbers and size, was the disposal of carcasses of dead horses and cattle.



FIGURE 2.3 The waste problem in New York City. Garbage dumped on sidewalks impeded both pedestrian and vehicular traffic.



FIGURE 2.4 Sanitation worker and the horse problem, New York City, 1900.

Waste collection at the public's expense began in 1856, and in 1895, the District of Columbia passed a bill for the construction of incinerators. These facilities, however, were used only during winter months. During summer, wastes were placed onto flat-bottomed boats called scows, and transported to a site south of Alexandria, VA, for final disposal (Figure 2.5). During the mid-1800s, health conditions in major American cities were declared deplorable. A New York City citizen, George Strong, noted in his diary in 1852 (Kelly 1973):

> Such a ride uptown! Such scalding dashes of sunshine coming in on both sides of the choky, hot railroad car. … Then the feast of fat things that come reeking filth that Center Street provided in its reeking, fermenting, putrefying, pestilential gutter! I thought I should have died of the stink, rage, and headache before I got to Twenty-first Street.

That New Yorker, however, actually loved the city despite its overall "civic filthiness."

U.S. public health officials, observing the progress in Europe, made requests for improved disposal of garbage and "night soil" (i.e., human excrement). Despite the complaints of sanitary engineers, journalists, and others, the state of refuse collection and disposal in the United States in the 1880s and early 1890s remained poor. Methods were inconsistent, technology was primitive, and the public, as a whole, did not seem to be concerned (Wilson 1977). In Chicago, St. Louis, Boston, and Baltimore, much of the waste was simply hauled to open dumps. In New York, street

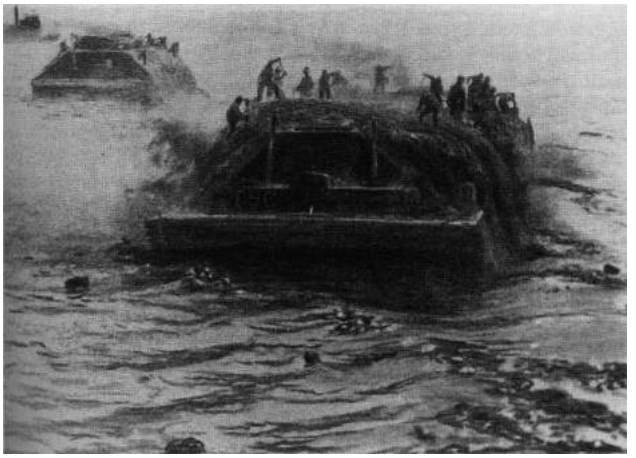


FIGURE 2.5 Unloading garbage from scows off the Atlantic Coast. According to George Waring: "About twenty Italians unload the cargo of a deck-scow in about two and one-half hours. In 1896 over 760,000 cubic yards of refuse were disposed of in this manner, on 1531 scows" (Waring 1898).

teams collected the garbage, and it was carted away in open horse-drawn wagons (with the horses fouling the streets during collection) to barges destined for dumping 25 miles offshore. This practice was still an improvement over older methods—prior to 1872, the city used simple dumping platforms built over the East River to unload the city's wastes. Given the relatively closed position of the Lower Manhattan Bay, little of the waste was dispersed into ocean waters; much of it washed up on the beaches of Long Island and New Jersey (Figure 2.6) (Bettmann 1974; Alexander 1993). Another waste disposal practice involved a public facility called a "dispose," which was used to convert animal carcasses, meat by-products, and other waste food products into raw materials for industrial products ranging from soap to explosives. These facilities disappeared with the decline in supply of raw materials and expanded local ordinances regulating the foul-smelling runoff they generated (Melosi 1981).

In the late 1800s, enterprising individuals scoured the streets and trash piles searching for material of value, essentially carrying out a simple form of recycling (Figure 2.7). Scavengers, also known as "rag pickers," removed much unwanted material in cities. In Chicago, for example, rag pickers collected over 2000 yd^3 daily (Gerlat 1999). Partly because of such efforts and partly because of the simpler lifestyles of the period, municipal collection crews collected only about 0.23 kg (0.5 lb) of waste per capita per day in 1916, compared with about ten times the amount that is collected today (Vesilind et al. 2002).

Due to sanitary problems, which were generated by the intensive industrialization and urbanization of the United States in the latter half of the 19th century, modern solid waste management programs began to emerge in the 1890s (Blumberg and Gottlieb 1989). Reformers called for city control over the collection of urban wastes. Prior to that point, waste was considered primarily the individual's responsibility, with only minor government participation. Europe had, by this time, already developed relatively sophisticated disposal systems and technologies. As late as 1880, only 43% of all U.S. cities provided some minimum form of collection (McBean et al. 1995). Just 24% of the cities surveyed maintained municipally operated garbage collection systems, and an additional 19% contracted out for the service (Blumberg and Gottlieb 1989). A 1902 MIT survey of 161 U.S. cities showed that 79% provided regular collection of wastes. By 1915, 89% of major American cities had some kind of waste collection system, and by 1930, virtually all large cities had waste collection services (Tammemagi 1999).



FIGURE 2.6 Coney Island beach pollution from disposal off the New York City coast, late 19th Century.



FIGURE 2.7 Rag pickers removing materials of value from waste. (Reproduced with kind permission from the New York City Municipal Archives.)

New York City took the lead in handling municipal waste management and promoting overall civic cleanliness. Colonel George E. Waring, Jr., a Civil War veteran and the man responsible for the establishment of a municipal sewer system in Memphis, TN, served as the city's Commissioner of the Department of Street-Cleaning from 1895 to 1898. One of Waring's first steps in managing the city's wastes was to establish a systematic classification scheme. He encouraged, at homes and businesses, segregation of organic refuse, ash, and general rubbish fractions into separate bins. He then contracted for as much recovery of salable materials from the wastes as possible, making a profit from this phase of the operations (Figure 2.8). Reduction processes were developed, for example, for the extraction from the wastes of by-products such as ammonia, glue, grease, and dry residues for fertilizer (Figure 2.9). The city obtained substantial revenue by salvaging these materials (Melosi 1973).

To make street cleaning more efficient and thorough, Waring raised the competence and status of the workers. The street sweepers were made to wear white uniforms, to associate them with the medical profession, which also became the department's trademark. The workers were eventually dubbed the "White Wings" (Figure 2.10).

Waring's reform efforts made a positive impression on city dwellers. Collection became more efficient, and the cost to clean the streets dropped to about half of 1895 figures. Public health also improved. According to the Board of Health, the city's death rate and sick rate declined substantially. The average annual death rate in New York was 19.63 per 1000 during the first half of 1897, down from 26.78 per 1000 from 1882 to 1894. Similarly, diarrheal diseases decreased significantly (Melosi 1973).

In dealing with the final disposal of refuse, Waring used both innovations and established techniques. Most of the dry waste was still dumped at sea, until experiments with controlled incineration had been completed. For ocean disposal, Waring recommended the use of the new catamaran-type vessel, the Delehanty Dumping Scow, which was self-emptying and self-propelled (Melosi 1973).

Waring encouraged experimentation to find more efficient and economical methods of waste reduction and utilization. His goal, farsighted by today's standards, was to reduce the amount of the city's wastes for ultimate disposal and place the entire program under city management. A waste reduction plant was eventually built on Barren Island (Figure 2.11). A land-reclamation program later began on Riker's Island, using ashes as fill material (Figure 2.12).

Waring's enthusiasm for reform had an impact well beyond his brief tenure as commissioner. His organization of the Department of Street-Cleaning as a quasi-military outfit drew much ridicule from the press. Criticism soon turned to lavish praise when New Yorkers, for the first



FIGURE 2.8 Early waste separation activities.

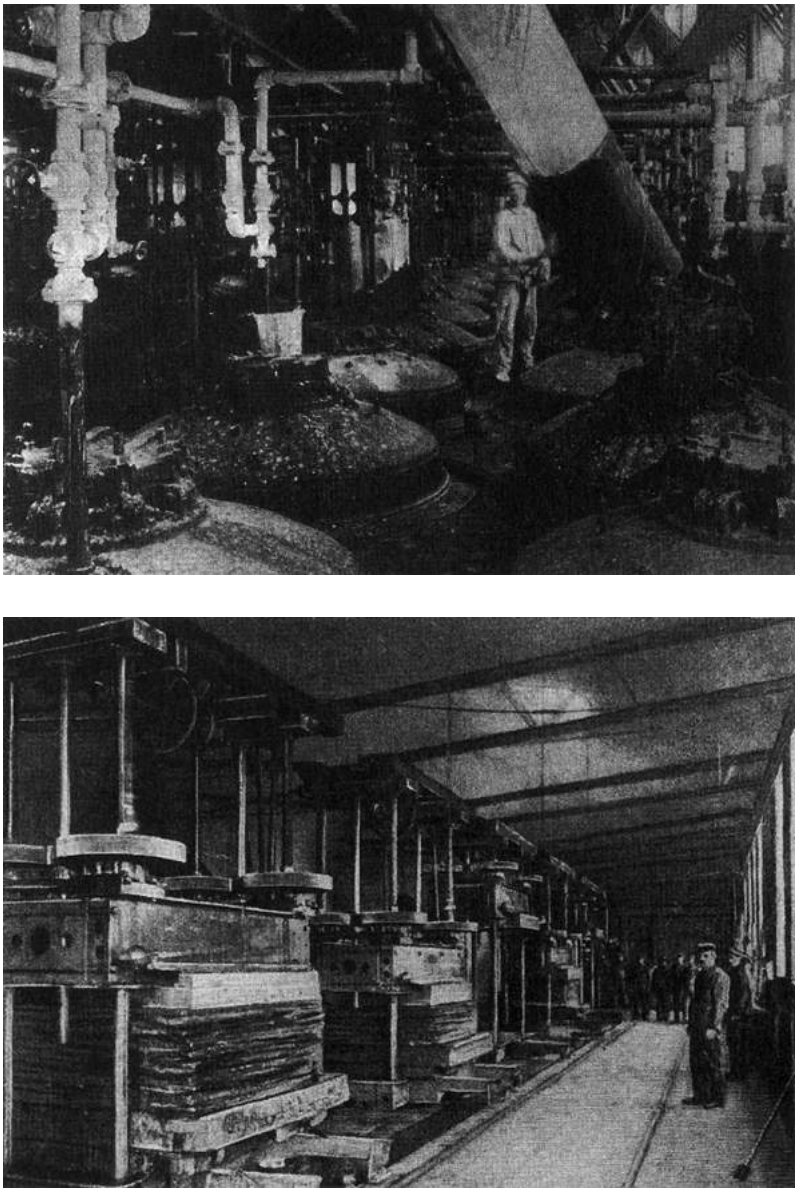


FIGURE 2.9 Waste reduction plant, Barren Island, New York city, ca. 1897.

time in many years, could walk along uncluttered sidewalks and drive through streets free of garbage and manure. High praise of Waring's handiwork became widespread (Melosi 1973; Wilson 1977).

Around the turn of the century, the average waste generated per Manhattan citizen was 160 lb of garbage (food wastes and debris), 1230 lb of ash, and 97 lb of rubbish. Total annual waste generation was about 1487 lb (675 kg), slightly higher than today's national average (Melosi 1981; Alexander 1993). The ash fraction, from the burning of coal or wood in home furnaces, comprised the major component. Coal-burning home furnaces remained in common use in much of the United States until the end of World War II.



FIGURE 2.10 One of New York City's White Wings, 1905.



FIGURE 2.11 Unloading garbage from scows at Barren Island.

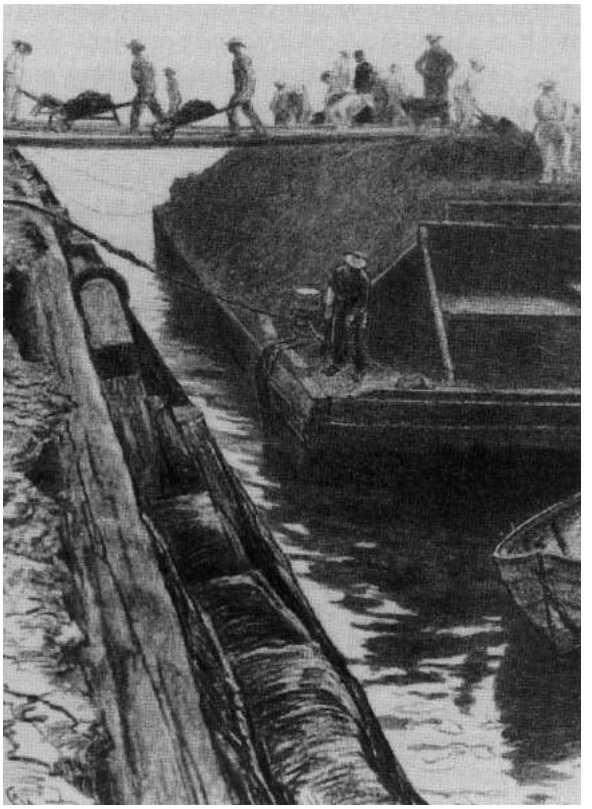


FIGURE 2.12 Convicts unloading scows of ash at Riker's Island. The ash was used for fill at the site of the future prison.

2.7 RECENT WASTE MANAGEMENT INITIATIVES

The management of municipal refuse has, fortunately, improved substantially over the years; the composition of U.S. waste has also changed. Some events that significantly altered the characteristics of solid wastes over the past century are shown in Table 2.2.

By the turn of the 20th century, a variety of waste disposal practices were adopted by municipalities, ranging from land disposal, water disposal (including ocean dumping), incineration, reduction, or some combination of methods (Table 2.3). With an increase in public awareness, ocean dumping received the greatest criticism. Dumping wastes in surface waters was seen as merely shifting one community's waste to another, with no regard for public health. The pollution of East Coast and West Coast beaches forced the passage of federal legislation in 1934, making the dumping of municipal refuse into the sea illegal. At that time, industries and commercial establishments were exempted from the regulations, however, and continued dumping into offshore waters (Vesilind et al. 2002).

From the 1880s to the 1930s, land dumping remained the most common method of waste disposal, regardless of opposition by public health officials and many sanitary engineers (Figures 2.13 and 2.14). By the 1890s, concerns were already being raised about the health risks posed by large, open dumps. Sanitary engineers at the time preferred either of two methods—incineration or reduction (Blumberg and Gottlieb 1989).

TABLE 2.2
Significant Milestones in Municipal Solid Waste Generation and Management in the United States

1868	Celluloid, the first commercial synthetic plastic, is invented.
1903	Corrugated paperboard containers are in commercial use.
1907	First paper towels developed.
1908	Paper cups replace tin cups in vending machines, in public buildings, and on trains.
1913	Corrugated cardboard becomes popular as packaging material.
1924	Kleenex facial tissues first marketed.
1930s	Kimberly-Clark markets the Kotex brand disposable sanitary pad for feminine hygiene protection.
1930	Invention of nylon.
1935	First beer can is manufactured.
1939	Arrival of 25-cent paperback books, "cheap enough to throw away".
1944	Dow Chemical invents Styrofoam™.
1949	Johnson and Johnson introduces disposable diapers to the United States (invented in Sweden).
1950s	In-house garbage disposals become popular. In some cities, 25%–30% of wastes are ground up.
1953	Swanson introduces the TV dinner.
1960	Pop-top beer cans are invented.
1960	Plastic gains popularity as a packaging material.
1963	Aluminum beverage cans are developed.
1972	Oregon passes the first refundable deposit bottle law.
1972	The Intel MCS-4-based SIM4 is the first microcomputer (but not the first personal computer).
1976	There are over 50 million microwave ovens in U.S. households.
1977	The Apple is the first highly successful mass-produced personal computer.
1977	PETE soda bottles begin to replace glass.
1981	The IBM PC is introduced.
1985	Mass-marketing begins of the Swatch® watch, a disposal wristwatch.
1986	Fuji introduces the disposable camera.
1986	The Fresh Kills Landfill on Staten Island, New York, becomes the world's largest Landfill, measuring 2000 acres (890 ha).
1998	An estimated 20 million personal computers have become obsolete.
2001	After 53 years of operation, the Fresh Kills Landfill closes.
2003	The disposable DVD is introduced.
2010	Over 380 million electronic devices (computers, monitors, mobile devices) have been disposed.
2012	Twenty-five states have passed legislation mandating statewide e-waste recycling.

2.8 SOLID WASTE INCINERATION AND OTHER THERMAL PROCESSES

England and Germany were at the vanguard in developing effective solid waste incineration systems for purposes of both volume reduction and energy production. The first municipal waste incineration system began operations in Nottingham, England, in 1874 (Murphy 1993). In 1892, a cholera epidemic swept Hamburg, Germany. Communities surrounding the city refused to accept the city's cholera-tainted waste, thus forcing the city to build and operate one of Germany's first waste incinerators, designed with the cooperation of English engineers. The incinerator suffered from a range of initial operating problems. One problem related to the significantly different composition of household waste in Hamburg compared with that of England (Erhard 1991; Bilitewski et al. 1997).

During the same period, in the United States, construction of mass-burn facilities was not considered economically justifiable. Allegheny, PA, installed the first municipal incinerator in 1885, followed by Pittsburgh, PA, and Des Moines, IA, in 1887, and Yonkers, NY, and Elwood, IN, in 1893 (Figure 2.15) (Kelly 1973). In designing waste incinerators, both mobile and stationary, engineers

TABLE 2.3
Trends of Waste Disposal Practices in the United States, Turn of the 20th Century Compared with Current Data

	1899	1902	1913	1999[a]	2010
Method			**Percent**		
Dumped on land	70	46.5	61	—	—
Dumped in water	3	2.5	3	—	—
Incineration	16	29.5	7	15	12
Sanitary landfill	—	—	7	57	54
Combination of methods	—	1.5	11	—	—
No systematic method	11	0.5	—	—	—
No data	—	19.5	11	—	—

Source: Adapted from U.S. EPA, *Municipal Solid Waste in the United States: 1999 Facts and Figures,* EPA 530-R-01-014, Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 2001; U.S. EPA, *Municipal Solid Waste in the United States: 2009 Facts and Figures,* EPA 530-R-10-012, Office of Solid Waste, U.S. EPA, Washington, DC, 2011; Hering, R. and Greeley, S.A., *Collection and Disposal of Municipal Refuse,* McGraw Hill, New York, 1921; Winslow, C.E.A. and Hansen, P., *Public Health: Pap Rep*, 29, 141–153, 1903.

[a] 1999: 28% recovered for recycling and composting.

applied methods that were under development in Europe. It was not until after 1910, however, that incineration came into widespread use in the United States. So-called "garbage crematories" appeared throughout the United States. Chicago experimented with both a stationary facility and a traveling incinerator. The latter rolled through the city's alleys, digesting refuse as it passed along. An intense competition developed between the designers of the mobile and the stationary furnaces. Out of this "picturesque rivalry grew a startlingly clean condition of alleys in the city" (Figure 2.16) (Melosi 1973; Lane 1894).

The early application of incinerators in the United States, however, was plagued with a long list of problems and failures. Faulty design and construction, in addition to inadequate preliminary studies, contributed to widespread system malfunctions. Often, U.S. incinerators burned only wet wastes without sufficient organic materials necessary to maintain combustion. Partly as a result of such initial errors, 102 of the 180 incinerators built in the United States between 1885 and 1908 were abandoned by 1904 (Wilson 1986; Blumberg and Gottlieb 1989). Shortly afterward, however, a new generation of incinerators was being promoted by engineers, and in the decade after 1910, incineration returned to widespread use. By this time, some sanitation experts were convinced that incinerators would replace open dumps in smaller communities. A 1924 report indicated that out of 96 cities surveyed, 29% burned or incinerated their wastes. This result compared with 17% that dumped or buried wastes; 38% that used wastes as fertilizer or animal feed; 2% that used reduction; and the remainder that used no systematic method at all. At its peak in the 1930s to 1940s, between 600 and 700 U.S. cities constructed incineration plants. Avoiding some of the earlier design problems, incineration from a stationary source became a significant method of disposal of municipal wastes (U.S. EPA 1973; Blumberg and Gottlieb 1989).

Another innovative thermal disposal method at the turn of the century involved the technology of *reduction*. This essentially entailed "cooking" the garbage to extract a wide range of marketable

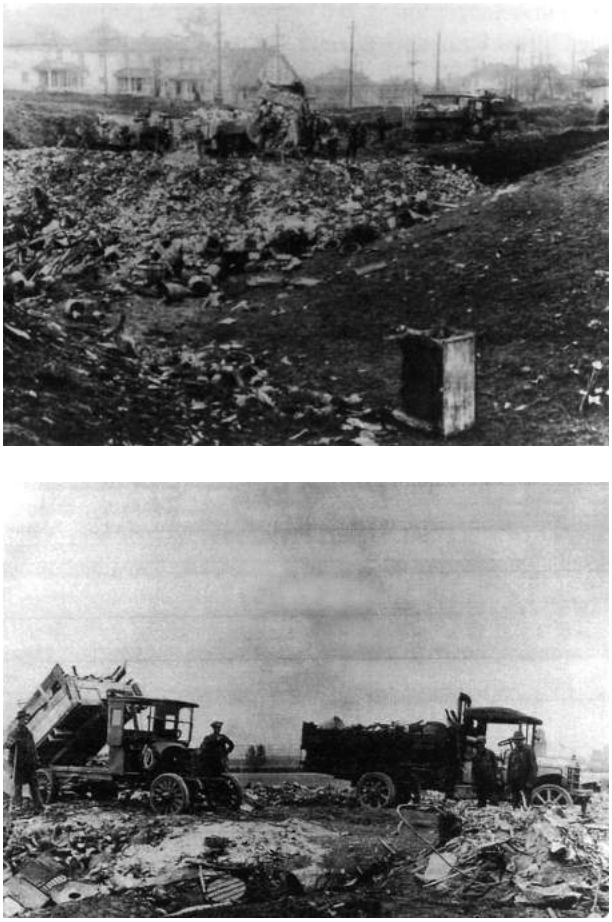


FIGURE 2.13 An unsanitary open dump. (Courtesy of Wright Environmental Management, Inc; original source unknown.)

by-products, including grease and "tankage," that is, dried animal solids that could be sold as fertilizer (Blumberg and Gottlieb 1989).

Beyond simple mass-burn incineration as a waste reduction system, the British and the Germans developed technologies to recover energy from incineration (Figure 2.17). The first plant to generate electricity from incineration was developed in Great Britain in the mid-1890s. By 1912, 76 plants in Great Britain produced energy as did 17 more in the rest of Europe. A pilot project was built in New York City in 1905. Interest in using incinerators to convert waste into energy, however, was tepid in an era of cheap energy alternatives. During this period, only two cities in North America—Westmount, Quebec, and Milwaukee, WI—derived any revenue from steam produced by incinerators (Marshall 1929; Melosi 2000). The "waste-to-energy" technology failed to gain a foothold in the United States for another 60 years (Blumberg and Gottlieb 1989).

Up through the 1960s in many large U.S. cities, household wastes were incinerated in apartment units in order to reduce waste volumes. These incinerators, unfortunately, burned unsorted wastes, operated at relatively low temperatures, and lacked air pollution control. As a result, metals, soot, and other products of incomplete combustion were released in abundance via the flue (stack). A recent study of sediments in Central Park Lake, New York City, correlates the accumulation of lead, tin, and zinc with the use of incinerators (Chillrud et al. 1999). By the late 1960s to the early

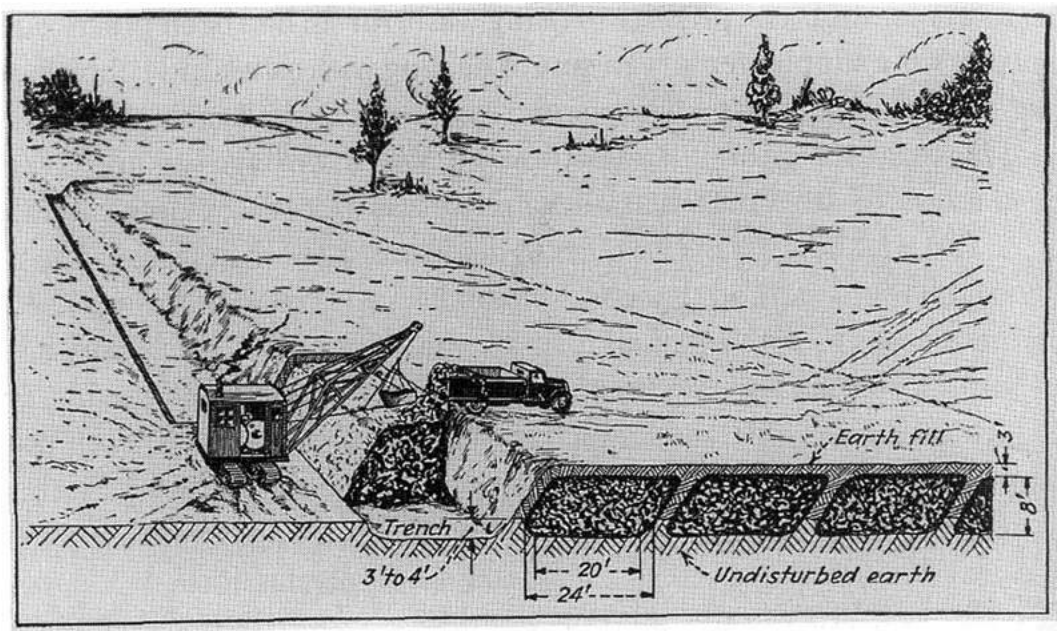


FIGURE 2.14 Diagram of a California sanitary landfill, 1939. (Courtesy of Engineering News-Record)



FIGURE 2.15 Early MSW incinerator. (Reproduced with permission from the New York City Municipal Archives.)

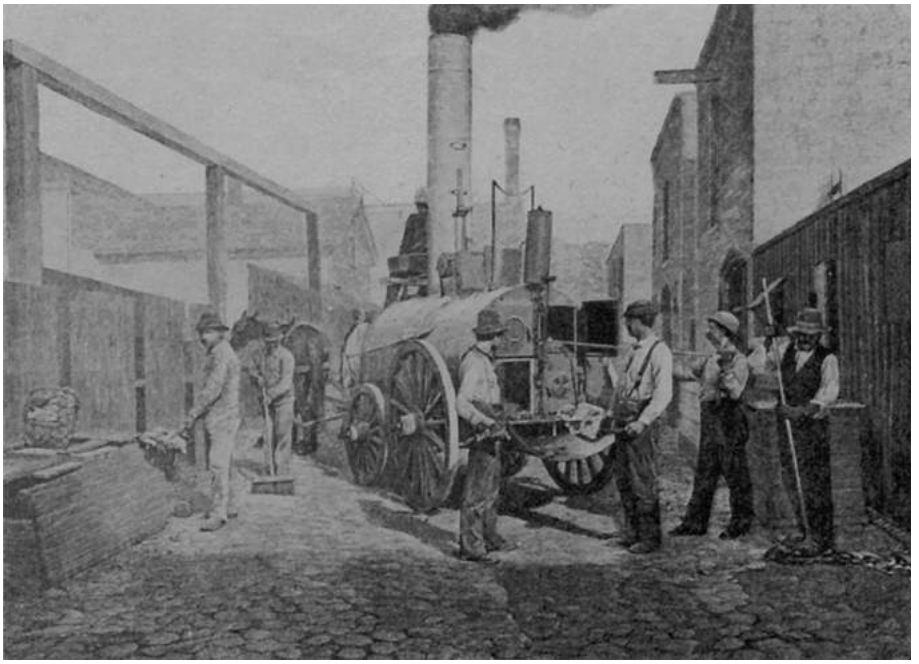


FIGURE 2.16 Traveling municipal waste burner.

1970s, public concerns with regard to the management of both domestic and toxic chemical wastes had intensified. The Air Quality Act of 1967 introduced new emissions standards that required the retrofitting of air pollution control devices, such as scrubbers and precipitators (see Chapter 9) to older incinerators. Since incinerators were already more expensive and technology-intensive than landfills, the act essentially priced incineration out of the market. Within 5 years of the act, 100 large-scale incinerators had been shut down (Tammemagi 1999).

The energy crises of the 1970s created a resurgent interest in the possibility of obtaining inexpensive energy from the thermal decomposition of MSW. So-called "waste-to-energy" plants and "refuse-derived fuel" systems were developed. Given the continued closing of sanitary landfills across the United States, incineration with production of energy began to appear as an attractive alternative. In the early to mid-1980s, approximately 100 new plants were committed and another 200 were planned in the United States (Tammemagi 1999).

2.9 LAND DISPOSAL AND THE SANITARY LANDFILL

Until the 1900s, "land disposal" of solid wastes involved nothing more than direct dumping on to the land surface followed by abandonment. On the outskirts of many cities, wetlands, often considered nuisance areas, were filled using layers of household refuse and ash. Early in the century, however, disposal methods prescient of sanitary landfills began to evolve. Simple burying was used in the United States in 1904 (Public Administration Service 1970; McBean et al. 1995). The first excavated site that was periodically covered with soil, a precursor to today's modern sanitary landfill, opened in 1935 in California (Figure 2.14). In addition to MSW, the landfill accepted industrial wastes. As a result, the site has secured a ranking on the U.S. EPA Superfund list due to its content of hazardous materials (Gerlat 1999; Vesilind et al. 2002).

Up to the 1950s, however, open-pit dumping of wastes remained the standard procedure (California 1954; McBean et al. 1995). Due to the incompatibility of wastes (e.g., disposal of hot ashes with paper products), fires were a frequent hazard. In many municipalities, controlled

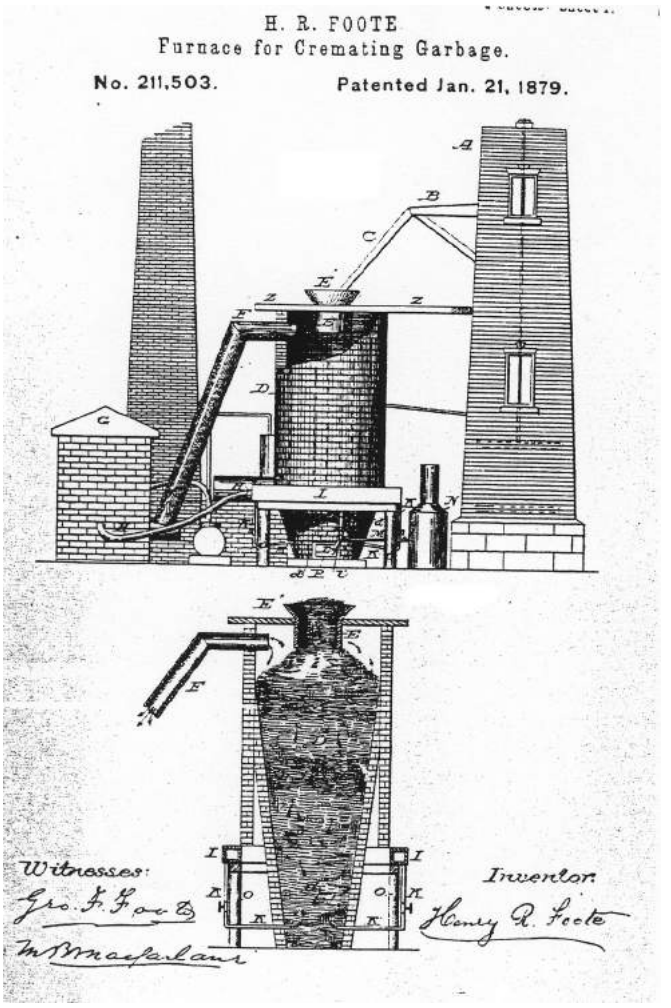


FIGURE 2.17 Early waste-to-energy plant. (Courtesy of U.S. Patent Office, Washington, DC.)

burning was allowed for the purpose of volume reduction. There were considerable problems with odor, smoke, insects, noise, and seagulls. Up to this point, most disposal sites were obviously not designed or constructed with much engineering input. Planning to address environmental protection remained inadequate. Siting of the landfill was based on convenience and efficiency rather than practical, technical concerns, such as proximity to surface water and groundwater, and soil and geologic conditions. When such early landfills were completed, they were often covered with a thin cap of soil, and the growth of surface vegetation was encouraged. Land subsidence was common, and many sites leaked for decades after closure. Subsurface liners were rarely, used and the layers of waste were usually only a few meters thick. As landfills expanded, growth occurred laterally and covered large tracts of land. Many were situated near expanding urban areas and their water supplies. As a result, public opposition to landfills became increasingly contentious.

Alternative waste disposal techniques were attempted in the United States; however, landfills remained the most common method due to the appealing costs of land and labor, and the simple, inexpensive technology involved. To address the growing criticism, the concept of the "sanitary landfill" was introduced in the 1950s. Also known as a "cut and cover" or controlled tipping system, the sanitary landfill was touted as an engineered system for disposing solid wastes on land by

spreading them into thin layers, compacting to the smallest practical volume, and covering with a layer of soil at the end of each working day (Stone 1977). The concept of controlled tipping, in which solid wastes are sealed in "cells" formed from soil or other cover material at regular intervals, was devised in order to keep wastes relatively free from odor, less attractive to vectors, and less of an overall hazard to public health. This simple step was significant as it greatly alleviated problems such as uncontrolled fires, windblown refuse, and rodent infestations.

Landfill practices gradually improved over time, although proper planning, engineering, operations, and staff training were slow to evolve. By 1959, the sanitary landfill was the primary method of solid waste disposal for U.S. communities (ASCE 1959; McBean et al. 1995). In 1959, the American Society of Civil Engineers published the first engineering guide to sanitary landfilling that detailed the compaction of refuse and the placement of a daily cover to reduce hazards of fire, odor, and rodents.

Although design and operation were a substantial improvement over earlier land disposal efforts, the sanitary landfill still suffered from a range of deficiencies. It did not sufficiently address groundwater contamination, surface runoff, odor and gas emissions, and related public health concerns. At that time, there was only limited knowledge regarding infiltration of surface water through a covered landfill and the consequent reactions of this water upon contact with wastes. There also came the belated recognition of the potential impact of escaping contaminants (leachates) on groundwater quality. Eventually, it was decided that, to ensure minimal protection of the local environment, the installation of an engineered cover system, which reduced long-term leachate generation, and an impermeable liner across the base of a landfill which prevented the escape of any leachates to the environment, were essential (Tammemagi 1999).

Many communities, however, continued open burning and open dumping into the 1960s. According to the U.S. Federal Bureau of Solid Waste Management, 94% of all land disposal operations in the mid-1960s were inadequate in terms of air and water pollution, insect and rodent problems, and physical appearance (Tammemagi 1999).

Public awareness of the potential hazards posed by MSW landfills increased. By the 1970s and 1980s, there was growing concern about the effects of landfills on contamination of aquifers. Groundwater, stored in underground strata and tapped by wells, provides drinking water for more than half of the U.S. population (U.S. EPA 2012). Once groundwater becomes contaminated, it is very difficult, slow, and expensive to remediate. The composition of some landfill leachates are considered capable of increasing the risk of cancer (Brown and Donnelly 1988; Tammemagi 1999). A number of toxic materials originating from household wastes (e.g., batteries, pesticide containers, paints) have been found in leachates along with a wide range of industrial wastes, previously not restricted from municipal landfills.

As a result of the enactment of stringent federal regulations, such as the Resource Conservation and Recovery Act and its amendments (see Chapter 3), numerous modifications were required for sanitary landfill design and operation. Caps constructed of clay or impermeable synthetic materials such as high-density polyethylene, were installed over landfills undergoing closure to decrease infiltration of precipitation, thus limiting the formation of leachate. Bottom liners, constructed of similar materials, were introduced to capture any leachate that formed within the landfill. In addition, subsurface and surface collection systems were installed to capture and remove run-off, leachate and landfill gas. Monitoring of groundwater quality and gaseous emissions became a required component of proactive landfill operation.

In spite of these technical advances, concerns persisted about groundwater contamination. Studies during the late 1970s indicated that leaking leachate was a problem facing all landfills. The EPA estimated, in 1990, that more than 75% of U.S. landfills were polluting groundwater with leachate (Lee and Jones 1991). There was also concern that even state-of-the-art municipal landfills with double liners and other modern leachate containment systems would eventually fail. In other words, the increased use and sophistication of engineering techniques could only postpone the onset of groundwater contamination.

By the 1980s, the importance of selecting a site that minimized the environmental impact of a landfill was recognized. New siting criteria emphasized the importance of sites that: (1) were situated well above the groundwater table; (2) did not occur in groundwater recharge zones; (3) were not in natural flood areas; (4) occurred where soil water moved only very slowly; and (5) were underlain by natural, impermeable clay formations to prevent contaminant migration. Over the past three decades, landfill siting has become a sophisticated process that incorporates technical as well as political and social concerns. Continuing improvement in the siting process has significantly restricted locations where landfills can be constructed.

The number of MSW landfills has dropped substantially, from about 20,000 in 1979 to 1900 in 2009 (U.S. EPA 2010) (see Chapter 1). One of the major causes for the decline is the NIMBY (not-in-my-backyard) syndrome, a result of the "dump" stigma that persists in the minds of many Americans. The NIMBY phenomenon evolved as a result of increased awareness and affluence of citizens, combined with increased attention by the media. There have also been tremendous improvements in the ability to detect contaminants with advanced technology and instrumentation. Another cause for the decline of landfills was the enactment of stringent new guidelines, both at the federal and state levels, for landfill construction, operation, and closure. Such guidelines have essentially put many older landfills out of business.

2.10 RECYCLING/REUSE

In the late 1800s recycling was carried out by individuals who scoured the streets and trash piles looking for material of value. The first organized municipal recycling program was attempted in 1874 in Baltimore, but it did not succeed (Gerlat 1999; Vesilind et al. 2002).

From the 1800s through World War I, raw garbage was fed to pigs on farms as a means of increasing food production. By 1917, 35% of all cities monitored in one survey used this method. The figure increased to 44% in 1925 and then leveled off at 39% by 1930 (Blumberg and Gottlieb 1989; Hering and Greeley 1921). Scientists discovered that this practice contributed to the infection of animals by *Trichinella spiralis* and *Vesicular exanthema*, which could be passed on to humans who ate undercooked pork. When a series of swine epidemics occurred in the 1950s and several operations were shut down, public health regulations were issued to prevent the feeding of raw garbage to pigs. The cost of cooking the garbage prior to feeding to pigs was expensive, and so the practice gradually disappeared (Alexander 1993).

In 1898, the first materials recovery facility (MRF) (see Chapter 7) was built in New York City. The facility processed the waste of over 116,000 residents and recovered up to 37% (by weight) of the wastes. Soon MRFs were constructed in Berlin, Hamburg, and Munich. Assisted by trommel screens and conveyor belts, the Munich MRF processed over 275 metric tons (300 tons) of waste per day (Bilitewski et al. 1997).

Europe led the United States in recycling. By 1939, as war approached, German householders were expected to separate rags, paper, bottles, bones, rabbit skins, iron, and other metals from their discards (APWA 1941; Alexander 1993). Prewar Japan's needs for imported scrap iron is well documented.

Regardless of advances in sanitation technology, waste composition and volumes will shift, public and governmental attitudes will vary, and new challenges will confront waste management professionals. A health official noted the sense of frustration experienced by sanitation officials when he wrote (Alexander 1993):

> Appropriate places for [refuse] are becoming scarcer year by year, and the question as to some method of disposal ... must soon confront us. Already the inhabitants in proximity to the public dumps are beginning to complain.... I can not urge too strongly upon the Commissioners the necessity for action in this direction. The waste that is taken from yards and dwelling places must be provided for, and that provision should no longer be delayed.

This warning was ignored. The letter was sent to the attention of the Commissioners of Washington, DC, in 1889.

QUESTIONS

1. Explain how the chemical and physical properties of solid wastes have evolved over the millennia. Keep in mind the specific sources that contributed to the waste stream of the period.
2. What were the most common waste disposal methods of earlier societies? Approximately when did these modes of "management" change? What were the root cause(s) for the changes?
3. Who were the first individuals to associate improper waste disposal with adverse health effects?
4. What was the first civilization to create an organized waste collection workforce? The first "landfills"?
5. After the fall of the Roman Empire, how did waste management change? What specific factors were responsible for these changes?
6. Explain how an early society's waste problems could actually compromise the security of a community.
7. Explain how the Industrial Revolution changed both the quantity and composition of solid wastes. How were human populations affected by the change in waste composition?
8. U.S. cities of the late 19th century experienced deplorable health conditions as a result of improper waste management. What were some initiatives that drastically altered urban waste management?
9. Discuss the efforts of George Waring on urban waste management. Were the benefits of his efforts long-lasting or only superficial and temporary?
10. What is the benefit of "controlled tipping" of wastes, compared with prior land disposal practices?
11. Discuss how landfills from 1920 to the mid-1970s were managed with regard to (a) siting, (b) day-to-day operations, (c) leachate collection and removal, (d) methane recovery, and (e) closure.
12. "Routine open burning of municipal wastes, in the open landfill cell, serves effectively as an expedient and cost-effective means of extending landfill lifetime." Is this statement accurate? What practical considerations are not addressed in this statement?
13. In the United States, the number of MSW landfills has declined substantially in the past 40 years, despite the fact that there seems to be ample space available to construct new facilities or expand existing ones. What are the primary reasons for this decline?
14. Discuss the evolution of MSW incineration from 19th century Europe to the present. What factors were responsible for its decline in popularity in the early 20th century? Why have incinerators increased in appeal today?
15. Search local historical records and old news articles to draft a chronology of waste management in your community. What specific events catalyzed some of the more important changes? Can you locate the long covered-over disposal sites in your town or city? What is the current land use at these sites?

REFERENCES

Alexander, J.H. 1993. *Defense of Garbage.* Westport, CT: Praeger.

APWA (American Public Works Association). 1941. *Refuse Collection Practice*. Chicago, IL: APWA.

APWA (American Public Works Association). 1976. *History of Public Works in the United States*, *1776–1976*. Armstrong, E.L., Robinson, M.C., and Hoy, S.M., (Eds.). Chicago, IL: APWA.

ASCE Committee on Sanitary Engineering Research. 1959. Refuse volume reduction in a sanitary landfill. *ASCE J Sanitary Eng Div*, 85, 37–50.

Bettmann, O. 1974. *The Good Old Days—They Were Terrible!* New York: Random House.
Bilitewski, B.B., Hardtle, G., and Marek, K. 1997. *Waste Management*, Berlin: Springer.
Blegen, C.W. 1958. *Troy.* Vol. 1. Princeton, NJ: Princeton University Press.
Blumberg, L. and Gottlieb, J. 1989. *War on Waste*. Washington, DC: Island Press.
Brown, K.W. and Donnelly, K.C. 1988. An estimation of the risk associated with the organic constituents of hazardous and municipal waste landfill leachates. *Hazardous Waste Hazardous Mater*, 5, 1–30.
California State Water Pollution Control Board. 1954. *Investigation of Leaching of a Sanitary Landfill*. Sacramento, CA: California State Water Pollution Control Board.
Chillrud, S.N., Bopp, R.F., Simpson, H.J., Ross, J.M., Shuster, E.L., Chaky, D.A., Walsh, D.C., Choy, C.C., Tolley, L., and Yarme, A. 1999. Twentieth century atmospheric metal fluxes into Central Park Lake, New York City. *Environ Sci Technol*, 33, 657–661.
DEFRA (Department for Environment, Food and Rural Affairs). 2006. *Municipal Waste Composition: Review of Municipal Waste Component Analyses – WR0119*. Final Report. London: Science Directorate, Management Support and Finance Team.
Erhard, H. 1991. Aus der Geschichte der Städtereinigung (Kennz. 110) Hösel/Schenkel/Schnurer: Müll-Handbuch. Berlin: Erich Schmidt Verlag.
Gerlat, A. 1999. Garbage: The long view. *Waste News*, May 3, pp. 22–25.
Greater London Council. 1969. *Refuse Disposal in Greater London*. London: Greater London Council.
Harris, C. and Bickerstaffe, J. 1990. *Finding out about Managing Waste. A Resource Book for National Curriculum: Science, Geography and Technology*. London: Hobsons.
Hering, R. and Greeley, S.A. 1921. *Collection and Disposal of Municipal Refuse*. New York: McGraw Hill.
Hosch, K. 1967. From donkey-drawn wheelbarrows to sanitary landfills. *Stradhygiene*, 18, 228–231.
Kelly, K. 1973. *Garbage: The History and Future of Garbage in America*. New York: Saturday Review Press.
Lane, R. 1894. Chicago garbage burning. *Harper's Weekly*, 38, 408.
Lee, G.F. and Jones, R.A. 1991. Landfills and ground-water quality. *Groundwater*, 29, 482–486.
Marshall, C.E. 1929. Incinerator knocks out garbage dump in Long Island town. *Am City*, 40, 129.
McBean, E.A., Rovers, F.A., and Farquhar, G.J. 1995. *Solid Waste Landfill Engineering and Design*. Englewood Cliffs, NJ: Prentice-Hall.
Melosi, M.V. 1973. Out of sight, out of mind: The environment and disposal of municipal refuse, 1860–1920. *Historian*, 35, 621–640.
Melosi, M.V. 1981. *Garbage in the Cities*. College Station, TX: Texas A&M Press.
Melosi, M.V. 2000. *The Sanitary City: Urban Infrastructure in America from Colonial Times to the Present*. Baltimore, MD: The Johns Hopkins University Press.
Murphy, P. 1993. *The Garbage Primer: A Handbook for Citizens*. New York: League of Women Voters.
Priestley, J.J. 1968. Civilization, water and wastes. *Chemistry and Industry, March 23,* 353–363.
Public Administration Service. 1970. *Municipal Refuse Disposal*. Danville, IL: Interstate Publishers and Printers.
Rawlinson, J. 1958. *A History of Technology*. Vol. IV. Singer, C. et al. (Eds.) Oxford: Clarendon Press.
Report on the Sanitary Condition of the Labouring Population of Great Britain. British Museum, London. Available from: https://archive.org/details/reportonsanitary00chaduoft
Stone, R. 1977. Sanitary landfill. In *Handbook of Solid Waste Management,* Wilson, D.G. (Ed.). New York: Van Nostrand Reinhold.
Tammemagi, H. 1999. *The Waste Crisis. Landfills, Incinerators, and the Search for a Sustainable Future*. New York: Oxford University Press.
U.S. EPA (U.S. Environmental Protection Agency). 1973. *An Environmental Assessment of Gas and Leachate Problems at Land Disposal Sites,* 530/SW–110–OF. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 2001. *Municipal Solid Waste in the United States: 1999 Facts and Figures,* EPA 530-R-01-014. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 2010. *Municipal Solid Waste in the United States: 2009 Facts and Figures*. EPA530-R-10-012. http://www.epa.gov/osw/nonhaz/municipal/pubs/msw2009rpt.pdf
U.S. EPA (U.S. Environmental Protection Agency). 2011. *Municipal Solid Waste in the United States: 2009 Facts and Figures,* EPA 530-R-10-012. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 2012. *What Is Ground Water?* Available from: http://water.epa.gov/learn/resources/groundwater.cfm

Vesilind, P.A., Worrell, W.A., and Reinhart, D. 2002. Solid Waste Engineering. Pacific Grove, CA: Brooks/Cole Thomson Learning.

Waring, G. 1898. *Street-Cleaning and the Disposal of a City's Wastes: Methods and Results and the Effect Upon Public Health, Public Morals, and Municipal Prosperity*. New York: Doubleday and McClure.

Wilson, D.G. (Ed.). 1977. *Handbook of Solid Waste Management*. New York: Van Nostrand Reinhold.

Wilson, D.G. (Ed.). 1986. History of solid waste management. In *The Solid Waste Handbook: A Practical Guide*. New York: Wiley.

Winslow, C.E.A. and Hansen, P. 1903. Some statistics of garbage disposal for the larger American cities in 1902. *Public Health Pap Rep*, 29, 141–153.

Worrell, W. and Vesilind, P.A. 2011. *Solid Waste Engineering*. Pacific Grove, CA: Brooks/Cole.

Zinn, H. 1995. *A People's History of the United States: 1492 – Present*. New York: Harper Collins.

3 Regulatory Development

> This country is planted thick with laws, from coast to coast—man's laws, not God's—and if you cut them down—do you really think you can stand upright in the winds that would blow then?
>
> **Robert Bolt**
> *A Man for All Seasons*

3.1 INTRODUCTION

As discussed in Chapter 2, modern solid waste collection and disposal by local authorities began with the British Public Health Act of 1875. Since then, the complexity and reach of waste management laws have increased, along with the complexity and volumes of wastes generated.

3.2 SIGNIFICANT U.S. LEGISLATION

National legislation addressing management of wastes dates back to the Rivers and Harbors Act of 1899. The act prohibits the unauthorized obstruction or alteration of any navigable waters of the United States. Numerous activities now require an Army Corps of Engineers permit; examples include erecting a structure in or over any waters of the United States, excavation or deposit of material in such waters, and various types of work performed in such waters, including filling (33 CFR part 322).

3.2.1 Solid Waste Disposal Act

Modern U.S. solid waste management legislation dates from 1965 when the Solid Waste Disposal Act, title II of Public Law 89–272, was enacted as title II of the Clean Air Act of 1965 by the U.S. Congress. The intent of the act was to

- Promote the demonstration, construction, and application of solid waste management and resource recovery systems that preserve and enhance the quality of air, water, and land resources
- Provide technical and financial assistance to state and local governments and interstate agencies in conducting surveys of waste disposal practices and problems, and in the planning and development of resource recovery and solid waste disposal programs
- Promote a national research and development program for improved management techniques; more effective organizational arrangements; new and improved methods of collection, separation, recovery, and recycling of solid wastes; and the environmentally safe disposal of nonrecoverable residues
- Provide for the promulgation of guidelines for solid waste collection, transport, separation, recovery, and disposal systems
- Provide for training grants in occupations involving the design, operation, and maintenance of solid waste disposal systems

The U.S. Public Health Service and the U.S. Bureau of Mines were responsible for enforcement of this act. The former agency had the responsibility for regulating municipal solid waste (MSW)

generation, and the latter was charged with the supervision of solid wastes generated from mining and from fossil fuel combustion (e.g., coal ash at electric generating utilities). The primary thrust of this legislation was toward the development of more efficient disposal methods, rather than on the protection of public health and the environment.

3.2.2 Resource Recovery Act

The Resource Recovery Act of 1970 (Public Law 95–512) was considered a shift in federal legislation, away from waste disposal efficiency toward efforts to recover energy and materials from solid waste. The act authorized grants for demonstrating new resource recovery technologies.

By 1970, the U.S. Environmental Protection Agency (U.S. EPA) was established by presidential order under Reorganizational Plan No. 3 of 1970. All solid waste management activities were transferred from the U.S. Public Health Service to the EPA. The Resource Recovery Act gave the EPA the responsibility of providing state and local governments with technical and financial help in planning and developing resource recovery and waste disposal systems.

3.2.3 Resource Conservation and Recovery Act

The federal acts promulgated to this point did little to establish firm regulations regarding waste management; rather, guidelines were offered. The federal government became engaged in a more active regulatory role, manifested in the Resource Conservation and Recovery Act (RCRA) of 1976, passed by Congress as Public Law 94–580. For the first time, comprehensive federal regulations were established to regulate many categories of waste. As of this writing, RCRA consists of ten subtitles, which are listed in Table 3.1.

3.2.4 Solid Waste Management under RCRA

The RCRA solid waste management program, subtitle D, encourages environmentally sound solid waste management practices that maximize the reuse of recoverable material and promote resource recovery. The term "solid waste," as used in subtitle D, is broad and includes waste materials beyond ordinary MSW, which is typically collected and disposed in municipal solid waste landfills; for example, hazardous wastes generated by conditionally exempt small quantity generators (CESQGs) (see Chapter 11 of this book) are included, as are hazardous wastes that are excluded from the subtitle C regulations (e.g., household hazardous waste). The solid waste management program also addresses MSW generated by businesses.

TABLE 3.1
Outline of RCRA Subtitles

Subtitle	Provisions
A	General Provisions
B	Office of Solid Waste; Authorities of the Administrator and Interagency Coordinating Committee
C	Hazardous Waste Management
D	State or Regional Solid Waste Plans
E	Duties of the Secretary of Commerce in Resource and Recovery
F	Federal Responsibilities
G	Miscellaneous Provisions
H	Research, Development, Demonstration, and Information
I	Regulation of USTs
J	Standards for the Tracking and Management of Medical Waste

Within the context of RCRA, the U.S. EPA promotes an integrated, hierarchical approach to managing MSW that includes source reduction, recycling, incineration, and landfilling. Waste reduction and recycling are the preferred elements of the system, whereas landfilling is the lowest priority.

Subtitle D includes technical criteria for MSW landfills to ensure that routine operations will be protective of public health and the environment. A significant provision of RCRA is the prohibition of open dumps. This ban is implemented by the states, using EPA criteria, to determine which facilities qualify as sanitary landfills and therefore may remain in operation. The EPA criteria were originally promulgated in 1979; open dumps were to close or be upgraded by September of 1984. An open dump is defined as a disposal facility that does not comply with one or more of the 40 CFR part 257 or part 258, subtitle D criteria. Using the part 257, subpart A criteria as a benchmark, each state evaluated its solid waste disposal facilities to determine which facilities were open dumps that needed to be closed or upgraded.

In the 1984 amendments to RCRA, the EPA was required to revise the sanitary landfill criteria for facilities that received small quantity generator hazardous waste (see Chapter 11) or hazardous household waste. Under this authority, the agency promulgated regulations applicable to MSW landfills to take effect in October of 1993. The new criteria required the installation of liners, leachate collection and removal systems, groundwater monitoring, and corrective action at MSW sanitary landfills.

Other provisions authorized under RCRA for MSW management include: financial and technical assistance for states and local governments (most of which was ended in 1981 due to budget cutbacks); research, development, and demonstration authority; and a procurement program, whose goal was to stimulate markets for recycled products by requiring federal agencies to purchase recycled materials. Consistent with its commitment to recycling, RCRA contains provisions for EPA to encourage recycling and promote the development of markets for items with recovered materials content. To help achieve this goal, the EPA publishes federal procurement guidelines that set minimum recovered materials content standards for designated items. RCRA requires federal procuring agencies to purchase items manufactured with the highest percentage of recovered materials practicable. These requirements are specified in Comprehensive Procurement Guidelines (CPG) and Recovered Materials Advisory Notices (RMAN) (U.S. EPA 2007, 2012a). Although EPA is the lead agency under RCRA, the Department of Commerce is given several responsibilities for promoting greater commercial use of resource recovery technologies.

EPA has established a number of innovative programs to encourage sound waste management, including Wastewise, the Jobs Through Recycling program, Plug-In To Ecycling, GreenScapes, unit pricing, and full cost accounting for MSW (U.S. EPA 2012b).

3.2.5 Hazardous Waste Management under RCRA

Subtitle C of RCRA embraces the hazardous waste management program. A waste is declared "hazardous" if it appears on a list of about 100 industrial process waste streams and more than 500 discarded commercial products and chemicals. Beyond these lists, a waste may still be deemed hazardous if it is ignitable, corrosive, reactive, or toxic as measured via specific test protocols. These requirements are discussed in detail in the Code of Federal Regulations and in Chapter 11 of this book. The 1976 law expanded the definition of solid waste, which includes hazardous waste, to include:

> Sludge … and other discarded material, including solid, liquid, semi-solid, or contained gaseous material.

This expanded definition is significant with respect to hazardous wastes because approximately 95% occur as liquids or sludges. Some hazardous wastes are specifically excluded, however, from this definition, for example, industrial point source discharges (regulated under the Clean Water Act) and nuclear wastes (regulated under the Atomic Energy Act).

RCRA grants the EPA (and, ultimately, relevant state agencies) broad enforcement authority to require all hazardous waste management facilities to comply with the regulations. The hazardous waste management program is intended to ensure that hazardous waste is managed safely from the moment it is generated to the moment it is ultimately disposed. This has been termed the "cradle to grave" concept.

For generators of hazardous waste, the subtitle C program includes procedures for proper identification and measuring ("counting") of hazardous waste. Under RCRA, hazardous waste generators must comply with regulations concerning recordkeeping and reporting; labeling of wastes; the use of appropriate containers; providing information on waste chemical composition to transporters and treatment, storage, and disposal (TSD) facilities; and the use of a hazardous waste manifest system. Initially, facilities generating less than 1000 kg (2204.6 lb) of waste per month were exempt from the regulations. The 1984 amendments to RCRA lowered this exemption to 100 kg (220.46 lb) per month. Generator requirements are presented in Chapter 12.

Under subtitle C, transporters of hazardous waste must comply with numerous specific operating standards. The RCRA regulations were integrated with existing Department of Transportation regulations that address the transport of hazardous materials. Requirements include the use of the hazardous waste manifest system, hazard communication, appropriate waste packaging and waste segregation, and handling incidents during transport. Details of transporter requirements appear in Chapter 13.

The RCRA program includes standards for facilities that treat, store, or dispose of hazardous waste. These standards include requirements for general facility management and specific hazardous waste management units (e.g., landfills, incinerators). RCRA requires TSD facility owners and operators to obtain a hazardous waste permit from the EPA or relevant state agency. All TSD facilities are required to meet financial requirements in the event of accidents and to close their facilities in compliance with EPA regulations.

The 1984 amendments imposed a number of new requirements on TSD facilities with the goal of minimizing land disposal. Bulk or noncontainerized hazardous liquid wastes were prohibited from disposal in any landfill, and certain restrictions were placed on the disposal of hazardous materials in hazardous waste landfills. Landfill disposal of several specific, highly hazardous wastes was phased out from 1986 to 1990. The EPA was directed to review the characteristics of all wastes defined as hazardous and to determine the suitability of their disposal to land. These safeguards became known as the land disposal restrictions (LDR). Minimum technological standards were set for new landfills and surface impoundments, for example, requiring the installation of double liners, a leachate collection system, and groundwater monitoring. In the 1984 amendments, the federal government set deadlines for the closure of TSD facilities not meeting minimum standards.

With the understanding that the routine management of hazardous waste may result in spills or other releases to the environment, RCRA subtitle C contains provisions governing corrective action for the cleanup of contaminated air, groundwater, and soil. Requirements for TSD facilities under RCRA appear in Chapter 14.

The subtitle C program also contains provisions that allow EPA to authorize and financially assist state governments to implement and enforce the hazardous waste program. In order to receive final authorization from the federal government, the state program must be equivalent to, no less stringent than, and consistent with the federal program. As the EPA develops new regulations, the state's program must be reviewed to determine whether the state has the authority to enforce the relevant requirements.

3.2.6 Underground Storage Tank Management

At the same time when regulators and the public were expressing alarm over environmental contamination from improper waste management practices, concerns were heightened about underground

storage of fuels and hazardous substances. To address the issue of leaking underground storage tanks (USTs), Congress established a leak prevention, detection, and cleanup program through the 1984 RCRA amendments and the 1986 Superfund Amendments and Reauthorization Act (SARA).

The RCRA subtitle I UST program regulates underground tanks that store either petroleum or hazardous substances. The UST regulations govern tank design, construction, installation, operation, release detection, release response, corrective action, closure, and financial responsibility. Similar to RCRA subtitle C, subtitle I contains provisions that allow EPA to authorize state government implementation and enforcement of the UST regulatory program.

The provisions of subtitle I created a leaking underground storage tank (LUST) Trust Fund to finance the cleanup of leaks from petroleum USTs in cases where the UST owner or operator does not remediate a site, or when a release from the tank requires emergency response. The Trust Fund provides money for EPA to administer the program and for states to direct the cleanup operations, take enforcement actions, and conduct cleanups when necessary. The money to support the fund is obtained via a 0.1 ¢ per gallon federal tax on motor vehicle fuels and other petroleum products. UST management is not covered in this book.

3.2.7 Amendments to RCRA

RCRA has been amended nine times. Some of the amendments have been relatively minor, for example, those involving clarification to portions of the law. The most significant amendments came into effect in 1980, 1984, and 1992.

3.2.7.1 1980 Amendments

The RCRA amendments of 1980 provided EPA with greater enforcement capabilities to handle illegal dumpers of hazardous waste. Funds were authorized to conduct an inventory of hazardous waste sites.

3.2.7.2 Comprehensive Environmental Response, Compensation, and Liability Act of 1980

Public law 96–510, 42 U.S.C. Article 9601, The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 was promulgated in order to address the restoration of uncontrolled and abandoned hazardous waste sites in a timely fashion. CERCLA, commonly known as Superfund, imposed a tax on chemical and petroleum industries and provided broad federal authority to respond directly to releases or threatened releases of hazardous substances that may endanger public health or the environment. Since CERCLA's creation, several billion dollars in taxes have been collected and held in a trust fund for cleaning up the nation's most hazardous sites. Of great practical importance, CERCLA established liability criteria for persons or facilities responsible for the disposal and release of hazardous waste at affected sites.

The law under CERCLA authorizes two kinds of response actions at uncontrolled hazardous waste sites:

- Short-term removals, where actions are taken to address releases or threatened releases that require a prompt response.
- Long-term remedial response actions that permanently and significantly reduce the dangers associated with releases of hazardous substances that are serious, but not immediately life-threatening. These actions can be conducted only at sites listed on EPA's National Priorities List (NPL).

CERCLA also allowed for the revision of the National Contingency Plan (NCP), which provides the guidelines and procedures necessary for response to releases and threatened

releases of hazardous substances. CERCLA was amended by the SARA on October 17, 1986 (U.S. EPA 2003a).

3.2.7.3 Hazardous and Solid Waste Amendments of 1984

The most significant set of amendments to RCRA was the Hazardous and Solid Waste Amendments of 1984 (HSWA), a complex law with many detailed technical requirements. Some of the major provisions include:

- Restrictions on land disposal of hazardous waste.
- The inclusion of small quantity hazardous waste generators (those producing between 100 kg [220 lb] and 1000 kg [2204 lb] of waste per month) in the hazardous waste regulatory program.
- A new regulatory program for USTs (described in Section 3.2.6).
- EPA was mandated to issue regulations governing those facilities that produce, distribute, and use fuels produced from hazardous waste, including used oil.
- Hazardous waste facilities owned or operated by federal, state, or local government agencies must be inspected annually, and privately owned facilities must be inspected at least every 2 years.
- Each federal agency was required to submit, to EPA, an inventory of the hazardous waste facilities that it had ever owned or operated.

The 1984 law also required that EPA establishes a timetable for issuing or denying permits for TSD facilities; required permits to be set for fixed terms not exceeding 10 years; required permit applications to contain information regarding the potential for public exposure to hazardous substances from facility operations; and authorized EPA to issue experimental permits for facilities demonstrating new technologies. EPA's enforcement powers were strengthened, the list of prohibited actions constituting crimes was expanded, penalties were increased, and citizen suit provisions were enhanced.

Other provisions of the 1984 amendments prohibited the export of hazardous waste unless the government of the receiving country formally consented to accept it; created an ombudsman's office in EPA to handle RCRA-associated complaints and requests for information; and reauthorized RCRA through fiscal year 1988 at a level of about $250 million per year. HSWA called for a National Ground Water Commission to assess and report to Congress on groundwater issues and contamination from hazardous wastes. However, the commission was never funded or established (McCarthy and Tiemann n.d.).

3.2.7.4 Medical Waste Tracking Act

RCRA also focuses on waste concerns beyond MSW and hazardous waste. A medical waste tracking program was established to ensure that such waste is properly handled from the point of generation to the point of disposal. Congress passed House Bill 3515, the Medical Waste Tracking Act in November 1988, which directed EPA to develop protocols for infectious waste disposal. EPA was required to publish an interim final rule for a 2-year demonstration of the medical waste management and tracking program. RCRA was amended by adding a subtitle J.

The medical waste tracking program ended in June of 1991, and no federal EPA tracking requirements are currently in effect; however, some states have instituted their own medical waste requirements.

3.2.7.5 Federal Facility Compliance Act

The Federal Facility Compliance Act of 1992 addressed the legal dispute as to whether federal facilities are subject to enforcement actions under RCRA. The act waived governmental immunity from prosecution with regard to the improper management of hazardous wastes. As a result,

TABLE 3.2
Solid Waste Disposal Act, Resource Conservation and Recovery Act, and Major Amendments

Year	Act	Public Law Number
1965	Solid Waste Disposal Act	P.L. 89–272, title II
1970	Resource Recovery Act of 1970	P.L. 91–512
1976	Resource Conservation and Recovery Act of 1976	P.L. 94–580
1980	Used Oil Recycling Act of 1980	P.L. 96–463
1980	Solid Waste Disposal Act Amendments of 1980	P.L. 96–482
1984	Hazardous and Solid Waste Amendments of 1984	P.L. 98–616
1988	Medical Waste Tracking Act of 1988	P.L. 100–582
1992	Federal Facility Compliance Act of 1992	P.L. 102–386
1996	Land Disposal Program Flexibility Act of 1996	P.L. 104–119

EPA, the Department of Justice, and the states can enforce the provisions of RCRA against federal facilities, and federal departments and agencies can be subject to injunctions, administrative orders, and penalties for noncompliance. In addition, federal employees may be subject to both fines and imprisonment under any federal or state solid or hazardous waste law. The act also contains provisions applicable to mixtures of radioactive and hazardous waste at Department of Energy facilities and to munitions, military ships, and military sewage treatment facilities handling hazardous wastes.

3.2.7.6 1996 Amendments

The Land Disposal Program Flexibility Act (P.L. 104–119), passed by the 104th Congress, exempts hazardous waste from RCRA regulation if the waste is treated to a point where it no longer exhibits the characteristics that made it hazardous, and is disposed in a facility regulated under the Clean Water Act or in a Class I deep-injection well regulated under the Safe Drinking Water Act (see Chapter 17). A second provision exempted small landfills sited in arid or remote areas from groundwater monitoring requirements, provided there was no prior evidence of groundwater contamination.

The chronology of the Solid Waste Disposal Act, Resource Conservation and Recovery Act, and major amendments is given in Table 3.2.

3.3 OTHER RECENT LAWS AFFECTING WASTE MANAGEMENT

Several other solid and hazardous waste-related measures have been enacted by Congress over the past two decades. Although these are technically not amendments to RCRA, they are implemented at the federal level with authority for enforcement provided to states.

3.3.1 Public Utility Regulation and Policy Act of 1978

The Public Utility Regulatory and Policy Act of 1978 (PURPA) was enacted in response to the energy crises of the 1970s. PURPA was intended to increase the diversity of fuel use and increase the production and efficiency of electricity generation, while providing better prices to customers. The new legislation was designed to boost domestic supplies of energy, which includes directing public and private utilities to purchase power from waste-to-energy facilities.

Under PURPA, a new class of electricity generators called qualifying facilities (QFs) was created. QFs were composed of co-generators using natural gas and small power producers that used renewable resources such as wind, solar, municipal waste, or biomass. PURPA required utilities to connect QFs to transmission grids and to purchase their power at a price that did not exceed the avoided

cost of installing and operating new capacity. At the same time, the Power Plant and Industrial Fuel Use Act, enacted concurrently with PURPA, restricted the use of oil and natural gas as fuel in new power plants and encouraged the use of coal, nuclear energy, and other alternative fuels.

3.3.2 Sanitary Food Transportation Act

Many waste haulers travel long distances, sometimes to other states, in order to transport MSW. In order to economize shipments, some waste hauling companies carry produce or other farm products on their return trip, which understandably raised concerns regarding food safety.

The Sanitary Food Transportation Act of 1990 (P.L. 101–500) required the regulation of trucks and rail cars that haul both food and solid waste. The act directed the Departments of Agriculture, Health and Human Services, and Transportation to promulgate regulations specifying (McCarthy and Tiemann n.d.):

- Recordkeeping and identification requirements
- Decontamination procedures for refrigerated trucks and rail cars
- Appropriate materials for construction of tank trucks, cargo tanks, and ancillary equipment

3.3.3 Clean Air Act

The Clean Air Act (CAA) Amendments of 1990 (section 305 of P.L. 101–549) contain a provision mandating more stringent federal standards for solid waste incinerators, known as the Maximum Achievable Control Technology (MACT) emission standards (see Chapter 15). The CAA amendments require EPA to issue new source performance standards to control air emissions from municipal, hospital, and other commercial and industrial incinerators, including hazardous-waste burning cement kilns and lightweight aggregate kilns. The MACT standards set emission limitations for polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), metals, particulate matter, total chlorine, hydrocarbons, and carbon monoxide, and destruction and removal efficiencies (DRE) for organic emissions.

New facilities must comply with the EPA requirements within 6 months of the time they are issued, and existing units must comply within 5 years of issuance.

3.3.4 Pollution Prevention Act

The Pollution Prevention Act of 1990 (sections 6601–6610 of P.L. 101–608) was enacted as part of the Omnibus Budget Reconciliation Act of 1991. The act declared pollution prevention to be a national policy for waste management and charged EPA with the responsibility of preventing the generation of pollutants, rather than managing them after they are created. The Pollution Prevention Act focused industry, government, and public attention on reducing the amount of pollution through cost-effective changes in production, operation, and raw materials use.

Matching grants were authorized for states to establish technical assistance programs for businesses, and EPA was directed to establish a Source Reduction Clearinghouse to disseminate information. The act also imposed new reporting requirements on industry. Firms that were required to file an annual Toxic Chemical Release form under the Emergency Planning and Community Right-to-Know Act of 1986 must also file a report detailing their source reduction and recycling efforts over the previous year.

3.3.5 Indian Lands Open Dump Cleanup Act

Public Law 103–399, The Indian Lands Open Dump Cleanup Act of 1994, acknowledged concerns that solid waste open dump sites located on American Indian or Alaskan native lands threatened the

health and safety of local residents. The purpose of the act was to identify the location of open dumps on Indian lands, assess the health and environmental hazards posed by those sites, and provide financial and technical assistance to Indian tribal governments to close such dumps in compliance with Federal regulations or standards promulgated by tribal governments or native entities (U.S. EPA 1998).

The act required the Director of the Indian Health Service (IHS) to develop an inventory of all open dump sites on Indian lands. In addition, the IHS must submit annual reports to Congress indicating a priority for addressing waste management deficiencies and progress made in addressing those needs. The act also called for the IHS to identify the level of funding necessary to bring those dump sites into compliance with all regulations and to develop comprehensive waste management plans for every tribal entity.

According to the IHS, prior to the law's enactment, only two of more than six hundred waste dumps on Indian lands met current EPA regulations.

3.3.6 Mercury-Containing and Rechargeable Battery Management Act

The Mercury-Containing and Rechargeable Battery Management Act of 1996 (Battery Act) (P.L. 104–142) was enacted in 1996 to phase out the use of mercury in batteries, and to provide for the efficient and cost-effective disposal of used nickel–cadmium batteries, used small sealed lead–acid batteries, and certain other regulated batteries. The act applies to battery and product manufacturers, battery waste handlers, and certain battery and product importers and retailers. The law also places uniform national labeling requirements on regulated batteries and rechargeable consumer products and encourages battery recycling programs.

The collection, storage, and transportation of used rechargeable batteries, used consumer products containing batteries that are not easily removable, and certain other batteries are subject to regulation under the Universal Waste Rule (60 F.R. 25492) (see Chapter 18). The rule applies to battery and product manufacturers, battery waste handlers, and certain battery and product importers and retailers. Types of batteries not covered by the Battery Act, such as the larger lead–acid batteries found in automobiles, trucks, and other equipment, are regulated as universal wastes under the RCRA hazardous waste regulations, 40 CFR subpart 273 (U.S. EPA 2003b).

3.4 RELATIONSHIP OF RCRA WITH OTHER ENVIRONMENTAL STATUTES

RCRA is only one of the several federal regulatory programs in place to protect environmental quality. The RCRA regulations work in concert with other environmental statutes such as the Clean Air Act (CAA); the Clean Water Act (CWA); the Emergency Planning and Community Right-to-Know Act (EPCRA); the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA); the Marine Protection, Research, and Sanctuaries Act (MPRSA); the Occupational Safety and Health Act (OSHA); the Safe Drinking Water Act (SDWA); and the Toxic Substances Control Act (TSCA).

3.5 LAWS, REGULATIONS, AND OTHER ACTIONS AT THE FEDERAL LEVEL

3.5.1 Lawmaking Process

The primary function of Congress is the making of laws, and the legislative process comprises a number of formal steps. The work of Congress is initiated by the introduction of a proposal in one of four principal forms: the bill, the joint resolution, the concurrent resolution, or the simple resolution. The bill is introduced to the appropriate committee for consideration. Following public hearings and markup sessions, the bill is forwarded to the House floor for consideration. If the measure passes in the House, it moves on to the Senate for consideration. A bill must pass both bodies in the same form before it can be presented to the President for signature into law. After both the House and Senate have passed a measure in identical form, the bill is considered "enrolled." It is

sent to the President, who may sign the measure into law, veto it and return it to Congress, let it become law without signature, or, at the end of a session, pocket-veto it.

3.5.2 Regulations

The Resource Conservation and Recovery Act, passed by Congress, directs EPA to develop regulations. Regulations, or rulemakings, are issued by an agency such as EPA, DOT, or OSHA, which translate the general mandate of a law into a set of requirements for the agency and the regulated community.

Environmental regulations are formulated by EPA with the support of public participation. When a regulation is proposed, it is published in the *Federal Register*, a government document, to notify the public of EPA's intent to create new regulations or modify existing ones (Figure 3.1). EPA provides the public, which includes the potentially regulated community, with an opportunity to submit comments. Following a comment period, EPA may revise the proposed rule based on both an internal review process and public comments. The final regulation is published, or promulgated, in the *Federal Register*. Included with the regulation is a discussion of the agency's rationale for the regulatory program. The final regulations are compiled annually and incorporated in the Code of Federal Regulations (CFR) (Figure 3.2). This process is termed codification, and each CFR title

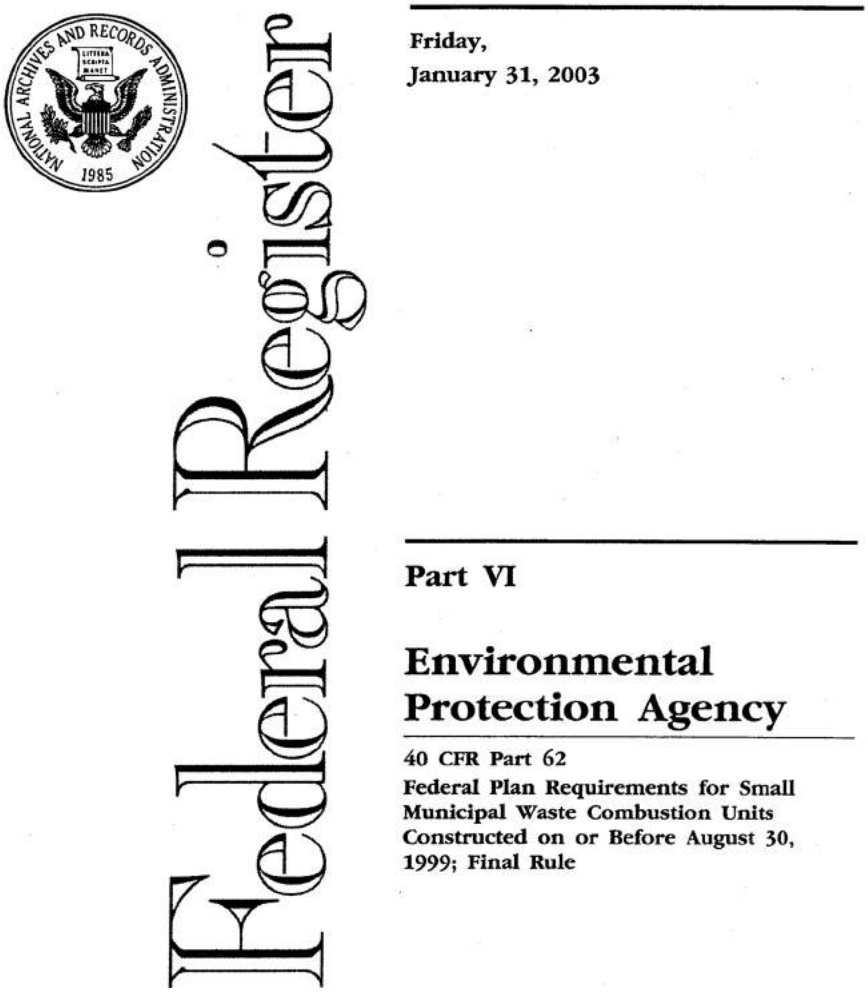


FIGURE 3.1 Federal Register.

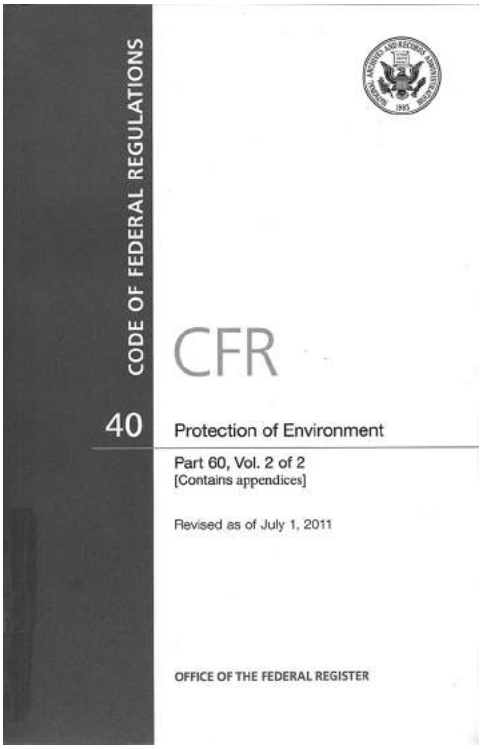


FIGURE 3.2 Code of Federal Regulations.

corresponds to a different regulatory authority. For example, the EPA regulations appear in title 40 of the CFR and the RCRA regulations are found in title 40, parts 240–282. These regulations are often cited as 40 CFR, with the part (e.g., 40 CFR part 262), or the part and section (e.g., 40 CFR §262.40) listed after the CFR title.

The above relationship between an act and the regulations is fairly typical; one exception, however, is the relationship between HSWA and its regulations. Congress, through HSWA, provided EPA with a mandate to promulgate regulations, but also included explicit instructions in the statute to develop specific regulations. Many of these requirements are so specific that EPA incorporated them directly into the regulations. HSWA is also significant because Congress established ambitious schedules for the implementation of the act's provisions. Also unique is that HSWA established "hammer provisions" or statutory requirements that would go into effect automatically with the force of regulations, if EPA failed to issue regulations by certain dates (U.S. EPA 2002).

The interpretation of statutory language does not end with the codification of regulations. EPA further clarifies the requirements of an act and its regulations through guidance documents and policy.

3.5.3 Policy and Guidance

Policy statements specify operating procedures that should be followed by a facility or an agency. They are mechanisms used by EPA program offices to indicate how the RCRA program is implemented. For example, EPA's Office of Solid Waste may issue a policy outlining what actions should be taken to achieve RCRA-corrective action cleanup goals. Policy statements are usually addressed to the staff working on implementation, but they may also be addressed to the regulated community.

Guidance documents are issued by EPA to provide direction for implementing and complying with regulations (Figure 3.3). These are not strict requirements but are "how to" documents. For example, the regulations in 40 CFR part 270 detail what is required in a permit application

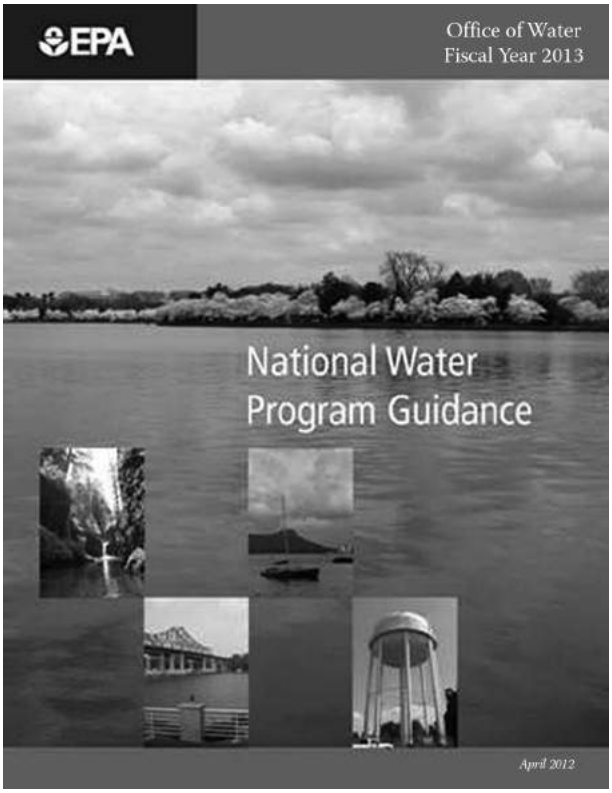


FIGURE 3.3 Example of a Guidance Document.

for a hazardous waste management facility, whereas the guidance for this part suggests how to evaluate a permit application to ensure that all required information has been included. Guidance documents also elaborate on the agency's interpretation of the requirements of the act (U.S. EPA 2002).

3.5.4 Public Involvement in RCRA

RCRA encourages public participation to facilitate permitting, corrective action, and state authorization processes. EPA, consistent with the requirements of the Administrative Procedures Act (APA), involves the public every time the agency issues a rulemaking that establishes or changes regulatory provisions. Because the RCRA program is a complex regulatory framework, EPA has established several public outreach and assistance mechanisms to foster public involvement. These mechanisms include access to information through training grants; the Freedom of Information Act (FOIA); EPA's Office of Ombudsman; the EPA Docket Center; the EPA Dockets (EDOCKET) website; and the RCRA, Superfund & EPCRA Call Center.

QUESTIONS

1. Identify the primary state and local regulations and agencies involved in MSW management in your city or county. Who is primarily responsible for MSW recycling—a local agency, private company, other? Waste reduction? Management of a landfill or incinerator?
2. Prepare a chronology of the development of MSW legislation in your state.

3. Discuss how the general public can become involved in the promulgation of RCRA regulations.
4. Explain the difference between a law, a regulation, a policy, and a guidance document. How do they differ in terms of enforcement capability?
5. Discuss the evolution of the waste regulatory process in the United States. Based on industry trends and public concerns, how do you think the laws and regulations may evolve in the next decade?
6. Define a solid waste and a hazardous waste in general terms. What materials do they include? Then refer to Volume 40 of the Code of Federal Regulations. Review the definitions of a solid waste (part 261.2) and a hazardous waste (part 261.3). What materials are included? What are some of the exemptions to the definitions of each?
7. What is the general relationship between RCRA and CERCLA? How do the two acts differ in terms of waste management?
8. Using the Internet, compare the regulations of three different states with regard to management of MSW. How do they differ in terms of sanitary landfill siting, landfill operation, siting of a composting facility, and recycling of electronics waste?
9. Compare the waste management regulations of a selected country (e.g., the Netherlands, Japan, India, Costa Rica) with those of the United States. What waste management issues and problems take greater or lesser prominence in other nations?

REFERENCES

McCarthy, J.E. and Tiemann, M. n.d. *Solid Waste Disposal Act/Resource Conservation and Recovery Act. Summaries of Environmental Laws Administered by the EPA*. Congressional Research Service Report RL 30022. Washington, DC: National Council for Science and the Environment. Available from: http://www.ncseonline.org/nle/crsreports/briefingbooks/laws/h.cfm

U.S. EPA (U.S. Environmental Protection Agency). 1998. *Report on the Status of Open Dumps on Indian Lands, 1998 Report. Waste Management in Indian Country*. Available from: http://www.epa.gov/tribalmsw/pdftxt/98report.pdf

U.S. EPA (U.S. Environmental Protection Agency). 2002. *Office of Solid Waste. RCRA Orientation Manual*. Washington, DC: U.S. Government Printing Office, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2003a. *CERCLA Overview*. Available from: http://www.epa.gov/superfund/action/law/cercla.htm

U.S. EPA (U.S. Environmental Protection Agency). 2003b. *Mercury-Containing and Rechargeable Battery Management Act (Battery Act) Enforcement*. Available from: http://www.epa.gov/Compliance/civil/programs/ba/index.html

U.S. EPA (U.S. Environmental Protection Agency). 2007. *Consolidated Recovered Materials Advisory Notice (RMAN) for the Comprehensive Procurement Guideline (CPG)*. Available from: http://www.epa.gov/osw/conserve/tools/cpg/pdf/consolrman.pdf

U.S. EPA (U.S. Environmental Protection Agency). 2012a. *Comprehensive Procurement Guidelines*. Available from: http://www.epa.gov/epawaste/conserve/tools/cpg/index.htm

U.S. EPA (U.S. Environmental Protection Agency). 2012b. *Partnership Programs*. Available from: http://www.epa.gov/partners/programs/index.htm#waste

SUGGESTED READINGS

Committee on Improving Practices for Regulating and Managing Low-Activity Radioactive Wastes and National Research Council. 2006. *Improving the Regulation and Management of Low-Activity Radioactive Wastes*. Washington, DC: National Academies Press.

Faerber, T. 2010. *Solid Waste Management and Environmental Remediation (Environmental Remediation Technologies, Regulations and Safety)*. Hauppauge, NY: Nova Science Publishers.

Johri, R. 2009. *E-waste: Implications, Regulations and Management in India and Current Global Best Practices*. New Delhi, India: The Energy and Resources Institute, TERI.

OECD (Organisation for Economic Co-operation and Development). 2010. *Radioactive Waste Management towards Transparent, Proportionate and Deliverable Regulation for Geological Disposal*. Paris, France: OECD.

Percival, R.V., Schroeder, C.H., Miller, A.S., and Leape, J.P. 2009. *Environmental Regulation: Law, Science, and Policy*, 6th ed. New York: Aspen Publishers.

Part II

Municipal Solid Wastes

Waste management applies those techniques and systems that ensure proper storage, collection, transportation, and disposal of a waste stream. State governments, industry, and citizens continue to seek avenues to reduce the volume of waste, and to manage and dispose of it properly. Integrated management of solid waste has been firmly embraced by the United States and other nations, for example, those of the European Union. In this management hierarchy, waste minimization, reuse, and recycling are assigned the highest priority, and landfilling is considered the least favored option. Up to the present, however, landfills continue to serve as the destination for the majority of U.S. solid waste.

The chemical, physical, and biological characterization of municipal solid waste is presented in the following chapter. Most of Part II, however, addresses the processing and ultimate disposition of waste, including recycling, composting, incineration, and sanitary landfilling. Both conventional and innovative approaches are presented. Discussion is primarily devoted to wastes generated from residential and commercial sources.

4 Characterization of Solid Waste

> The classification of facts, the recognition of their sequence and relative significance is the function of science, and the habit of forming a judgment upon these facts unbiased by personal feeling is characteristic of what may be termed the scientific frame of mind.
>
> **Karl Pearson**
> *The Grammar of Science, 1900*

4.1 INTRODUCTION

In order for a community to formulate an integrated solid waste management program, accurate and reliable data on waste composition and quantities are essential. Such data will encourage well-organized and smoothly functioning recycling programs; foster the optimal design and operation of materials recovery facilities and municipal incinerators; and, ultimately, reduce the amount of waste generated, thus holding down total waste management costs.

Knowledge of the chemical composition of municipal solid wastes (MSW) will guide engineers and scientists of its utility as a fuel; it will also help predict the makeup of gaseous emissions after incineration, as well as of possible hazardous substances occurring in the ash. Waste composition will provide information on the utility of the material for composting or for conversion to biogas fuel. In addition, given that the majority of U.S. MSW is disposed in landfills, knowledge of chemical composition will help in predicting leachate composition and required treatment options. Data on physical properties of MSW help forecast modes of transport, processing requirements, combustion characteristics, and a rough prediction of landfill lifetime.

4.2 SAMPLING PROTOCOLS FOR MSW

MSW consists of a range of materials that vary in composition depending on the community and its consumers' income and lifestyles, and its degree of industrialization, institutionalism, and commercialism. Given these variables, several protocols can be followed to estimate the MSW composition for a location. In order to compile accurate data, several issues must be addressed (Rhyner et al. 1995):

- How to obtain representative samples of the MSW?
- What is the desired sample size?
- How many samples are needed to achieve a desired level of accuracy?

4.2.1 Direct Sampling

Direct sampling is useful on a small scale for obtaining information about MSW composition. The direct sampling method involves physically sampling and sorting MSW at the source of generation. Although MSW can be extremely heterogeneous, direct sampling is one of the more accurate characterization methods. In order to make accurate judgments as to composition, sorting and analysis should be conducted in several randomly selected locations within the community. Waste sampling

from single- and multifamily homes, commercial establishments (restaurants and businesses), and institutions (schools, hospitals) is encouraged, as these inputs create local variations.

Another direct sampling approach is to study the waste after it has arrived at a centralized collection point or a tipping (i.e., unloading) area. This area may include a transfer station or disposal facility. ASTM Method D5231-92 (ASTM 1998) calls for a sample size of 91–136 kg (200–300 lb) to be manually sorted at the disposal facility. Whether at the source or at a disposal facility, the degree of sorting is a function of the number of product categories desired. For example, if a composting program is to be instituted, a sorting scheme might include organic and inorganic materials only. Alternatively, food and yard wastes, the highest quality compost feedstock, can be separated from all other MSW. If a comprehensive materials recovery program is being considered, however, more detailed data about waste categories will be needed—for example, wastes may be separated into aluminum, ferrous metals, glass, and paper. In some cases, paper products are further subdivided into old newspaper (ONP), old corrugated cardboard (OCC), laser-quality office paper, and colored paper.

One disadvantage of direct sampling programs based on a limited number of samples is that data may be misleading if unexpected circumstances occurred during the sampling period. Such circumstances could include the delivery of infrequent and exotic wastes, a severe wet or dry season, or errors in sampling methods. Such errors will be compounded when a small number of samples are relied upon to represent the community waste stream. Sampling studies do not provide accurate information about trends unless they are performed in a consistent manner over a long period (U.S. EPA 1999). Another disadvantage of direct sampling is that it would be prohibitively expensive for making estimates on a national scale.

4.2.2 Material Flows

Another approach to determining waste composition is to assess material flows. This method is useful for estimating waste stream composition and trends on a regional basis. The EPA uses materials flow estimation for the compilation of waste data for the United States (U.S. EPA 2011). The methodology is based on production data (by weight) for materials and products in the waste stream. For a particular municipality, inputs and outputs are recorded and compared. For example, if a community purchases 500,000 aluminum beverage cans in 1 week, it can be expected that about 500,000 aluminum cans will end up in the waste stream sometime soon afterward. This model is, of course, an oversimplification; one must also consider that the community is an open system having numerous imports and exports (U.S. EPA 1999).

4.2.3 Surveys

Waste quantity and composition can be estimated by distributing questionnaires to generators of waste. This system typically applies to generators of commercial and industrial wastes, and does not work effectively for domestic sources. A questionnaire is distributed to companies in an area, with detailed questions concerning the quantities of waste generated and its composition. Waste types may be listed in relation to product or material categories; for example, a county building may be asked to quantify laser-quality office paper; mixed, colored papers; ONP; and corrugated boxes. Other questions may pertain to seasonal variations in waste generation and any recycling programs already in operation (Williams 1998). In many cases, however, companies do not maintain accurate records of the amount of waste they generate. Data on composition may also be difficult to obtain due to concerns over the release of company and proprietary information.

Yu and MacLaren (1995) compared the accuracy of direct waste analysis with the survey method for determining waste stream composition. Table 4.1 demonstrates that there is substantial variability in material estimates between the two methods.

TABLE 4.1
Waste Composition as Estimated by Direct Analysis and Surveys (weight %; n = 78)

Waste Type	Direct Sampling	Survey
Paper	24.7	33.2
Paperboard	22.3	9.0
Ferrous metal	5.9	3.3
Nonferrous metal	0.9	0.7
Plastics	13.3	6.9
Glass	2.8	8.4
Rubber	0.4	0.5
Leather	0.0	0.0
Textiles	4.5	0.7
Wood	7.5	10.3
Vegetation	1.4	0.4
Fines	0.3	2.2
Special wastes	0.6	0.7
Construction materials	4.6	2.2
Food	10.7	20.9

Source: Reproduced with kind permission from Yu, C. and MacLaren, V., *Waste Manag Res* 13, 343–361, 1995.

4.2.4 Multipliers for Projecting Waste Quantities

Waste generation multipliers are used for estimating waste quantities from sources in a particular region. These multipliers express the relationship between the amount of waste produced and an identifiable parameter, for example, a household or a specific industry. The value of the multiplier is based upon surveys, published data, and direct sampling for an area. As an example, for a county in the midwestern United States, a household waste multiplier may be derived based on the size of the population. Agricultural waste multipliers may be formulated based on the number and type of livestock and the total land area available for grazing. Industrial waste multipliers may be based on the number of employees at a facility. The population of the area is multiplied by the appropriate value to obtain an estimate of waste production. Table 4.2 presents waste generation multipliers based on generator type.

In efforts to develop more accurate waste generation multipliers, some surveys have taken into account numerous factors, including the size of the population in a region, the type and age of residence occupied, season of the year, and the types of businesses. Also useful are economic data such as industrial output and number of employees (Rhyner and Green 1988; Savage 1996; Williams 1998).

Household waste generation multipliers vary widely. Estimates of household waste production have ranged between 1.08 and 1.22 kg per person per day (2.37 and 2.68 lb per person per day) (Rhyner and Green 1988). More accurate estimates can be generated for household waste by using multipliers based on population size of the community. Smaller communities produce a lower waste generation per person per day compared with larger communities (Table 4.3) (Yu and MacLaren 1995).

The multipliers used for predicting future waste production quantities have significant implications for planning. If waste quantities are expected to increase or if composition is expected to change (e.g., due to the arrival of new businesses or industries), changes may be needed to accommodate the new waste stream, for example, the establishment of a materials recovery facility (MRF) or expansion of a landfill.

TABLE 4.2
Typical U.S. Waste Generation Rates as a Function of Generator Type

Waste Generation Sector	Average	Units
Single family residential	1.22	kg/person/day
Apartments	1.14	kg/person/day
Offices	1.09	kg/employee/day
Eating and drinking establishments	6.77	kg/employee/day
Wholesale and retail trade[a]	0.009	kg/$ sales
Food stores	0.015	kg/$ sales
Educational facilities	0.23	kg/student/day

Source: Reproduced with kind permission from Savage, G.M., *Warmer Bull*, *J World Resour Foun* 49, 18–22, 1996.

[a] Except food stores.

TABLE 4.3
Household Waste Multipliers Based on Community Population Size

Population	Waste Generation Multiplier (kg/person/day)
<2500	0.91
2500–10,000	1.22
10,000–30,000	1.45
>30,000	1.63

Source: Reproduced with kind permission from Wisconsin Department of Natural Resources, *The State of Wisconsin Solid Waste Management Plan*, Wisconsin Department of Natural Resources, Madison, WI, 1981.

4.3 VARIABILITY AFFECTING WASTE SAMPLING

4.3.1 Seasonal

To ensure accurate generation estimates, wastes should be sampled regularly over a defined period (e.g., one calendar year) to account for seasonal variations. The season of the year strongly affects the amount of yard waste generated. During spring, summer, and fall months, the volume of grass clippings from low-density residential neighborhoods sharply increases. The quantities generated are also dependent on the yard area per living unit (Pfeffer 1992). In the fall, leaves will add to the waste load, and the number and types of trees in the community affect total quantities. Many states have banned grass clippings, leaves, and branches of certain sizes from landfills. Given that burning of these materials is often prohibited, an alternative means must be provided for their disposal. The generation of other wastes is also affected by season; for example, we can expect a greater percentage of construction and demolition waste and waste tires during warmer months (Table 4.4).

In areas that are heavily industrialized or support diverse commercial activity, patterns of the community's waste generation will be significantly affected by season. For example, industries heated with coal, or utilities burning coal for heat or electric generation, will produce significantly

TABLE 4.4
Seasonal Variations for Various MSW Components (Expressed as %)

Waste component	Autumn	Winter	Spring	Summer	Average
Organics	86.0	86.5	87.7	89.8	87.5
Paper	44.7	45.7	47.5	40.3	44.5
Plastic	6.1	6.5	7.0	6.0	6.4
Yard waste	15.0	15.1	7.4	15.0	13.1
Wood	1.4	0.8	1.0	0.8	1.0
Food	15.2	14.3	18.0	21.5	17.3
Textiles	1.5	1.3	1.3	2.0	1.5
Other	2.3	2.9	5.4	4.2	3.7
Inorganics	13.4	12.8	12.2	9.8	12.1
Metals	3.0	3.9	4.0	3.1	3.5
Glass	7.0	7.1	7.1	5.6	6.7
Soil	0.9	0.4	0.0	0.0	0.3
Other	2.5	1.4	1.1	1.2	1.5
Special wastes	0.5	0.6	0.1	0.3	0.4
Total	100	100	100	100	100

Source: Adapted from Savage, G.M., *Warmer Bull*, *J World Resour Foun* 49, 18–22, 1996.

more ash during winter months. Also, food processing plants will produce more waste during the harvest months (Rhyner 1992; Rhyner et al. 1995).

In addition to seasonal variations the quantity and overall composition of MSW will vary over the course of a week. More yard waste is produced on weekends; in contrast, more commercial and industrial wastes are produced on weekdays.

Municipal waste processing and disposal systems must take into account the shifting quantities and composition of waste over the course of a day, a week, or a year. For example, a city recycling program with a composting system should expect substantial quantities of potential feedstock in the spring, and therefore allow for sufficient space for initial storage, for establishment of the compost piles, and for stockpiling the final, cured product. Municipal incinerators will be affected by large inputs of wet grass or leaves in summer. These materials will reduce the heat content of the waste, and an auxiliary fuel may be required to maintain combustion temperatures.

4.3.2 Regional

Different parts of the country produce markedly different types and amounts of waste. Communities along the Gulf coast, by virtue of the warm, moist climate during much of the year, will produce substantially more yard and garden waste than would communities in central Arizona. Moisture will also induce specific effects; the MSW of Louisiana or western Florida would be expected to possess a higher moisture content compared to that of Phoenix, AZ, or Los Angeles, CA. Much of this higher moisture content may occur in yard waste, but the relatively higher humidity along the Gulf will also permeate stored wastes. Finally, certain marketing/community/grassroots activities in a county or state will affect waste composition. A striking example is the enactment of returnable bottle bills in various states. A financial incentive for the reuse of soda and beer bottles will sharply limit their appearance in the local waste stream.

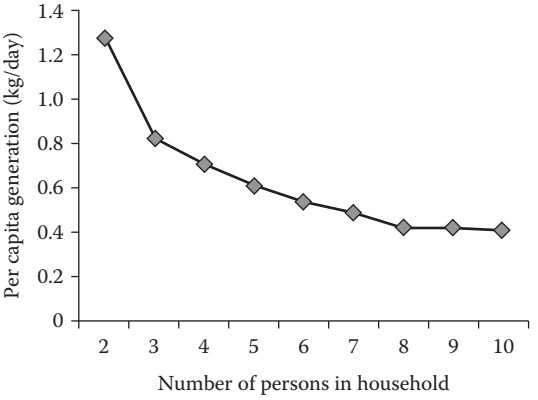


FIGURE 4.1 Variability in quantities of MSW according to size of household. (From Rhyner, C.R., *Waste Age,* 29–50, 1976. With permission.)

4.3.3 Household

The number of persons per household has a significant influence on waste generation. In Figure 4.1, daily household waste production is plotted against the number of persons per household. For two persons, total waste generation is about 2.5 kg (5.5 lb) per day, which is equivalent to 1.3 kg (2.8 lb) per person per day; for 10 people in a household, the amount of waste produced is 4 kg (8.8 lb) per day, which converts to 0.4 kg (0.9 lb) per person per day. These results are not surprising; economies of scale occur with a greater number of residents. Large families will purchase food and beverages in larger containers and will share newspapers and other consumables. Except for very low-income households, the data from this study were found to be independent of family income level.

4.3.4 National Economy

There is some correlation between waste generation rates and the overall economy of a country. Figure 4.2 presents waste generation and gross domestic product data for several developed nations. Up to a certain point, per capita waste generation does not change significantly with increase in per capita gross domestic product. However, beyond about $20,000 per capita GDP, waste generation varies sharply. The highest incomes, however, correlate with highest waste generation rates.

4.4 COMMON COMPONENTS IN MUNICIPAL SOLID WASTE

The predominant components of the U.S. municipal waste stream are discussed below. Some details on their generation are summarized in Table 4.5 and Figure 4.3. Information on manufacturing and recycling processes for these materials is given in Chapter 6.

4.4.1 Paper Products

Paper and paper products comprise the largest component of the U.S. municipal waste stream. The products that constitute paper and paperboard wastes are shown in Table 4.6. Total generation of paper products in MSW has grown from 30 million tons in 1960 (34% of the waste stream) to its highest point, 88 million tons, in 2000. That number has since declined to 71.3 million tons (28.5% of the waste stream) in 2010 (U.S. EPA 2011).

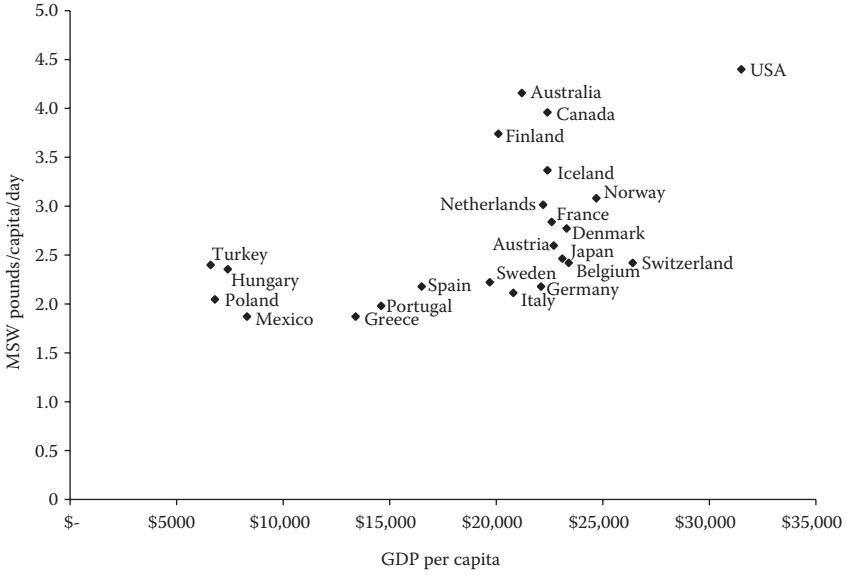


FIGURE 4.2 Relationship between GDP and per capita MSW generation for various countries.

TABLE 4.5
Materials Generated in MSW, 1960–2010

	1960	1970	1980	1990	2000	2010
Material	**Thousands of Tons**					
Paper and paperboard	29,900	44,310	55,160	72,730	87,470	71,310
Glass	6720	12,740	15,130	13,100	12,770	11,530
Metals						
Ferrous	10,300	12,360	12,620	12,640	14,150	16,900
Aluminum	340	800	1730	2810	3190	3410
Other nonferrous	180	670	1160	1100	1600	2100
Total metals	10,820	13,830	15,510	16,550	18,940	22,410
Plastics	390	2900	6830	17,130	25,530	31,040
Rubber and leather	1840	12,970	4200	5790	6670	7780
Textiles	1760	2040	2530	5810	9480	13,120
Wood	3030	3720	7010	12,210	13,570	15,880
Other	70	770	2520	3190	4000	4790
Total materials in products	54,620	83,280	108,890	146,510	178,700	177,860
Other wastes						
Food waste	12,200	12,800	13,000	20,800	29,810	34,760
Yard trimmings	20,000	23,200	27,500	35,000	30,530	33,400
Miscellaneous inorganic wastes	1300	1780	2250	2900	3500	3840
Total other wastes	33,500	37,780	42,750	58,700	63,840	72,000
Total MSW generated	88,120	121,060	151,640	205,210	242,540	249,860

Source: U.S. EPA, *Municipal Solid Waste in the United States: 2010 Facts and Figures,* Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 2011.

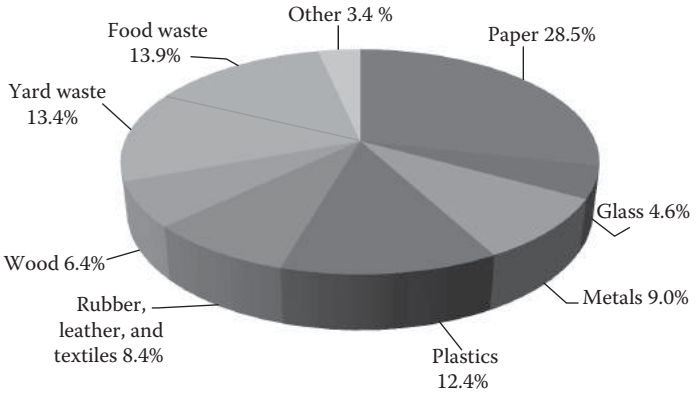


FIGURE 4.3 Composition of MSW in the United States, 2010. (From U.S. EPA, *Municipal Solid Waste in the United States: 2010 Facts and Figures*, Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 2011.)

TABLE 4.6
Paper Products in Municipal Solid Waste, 2010

Product Category	Generation (Thousands of Tons)
Nondurable Goods	
Newspapers and mechanical papers	9880
Books	990
Magazines	1590
Office papers	5260
Standard mail	4340
Other commercial printing	2480
Tissue paper and towels	3490
Paper plates and cups	1350
Other nonpackaging paper[a]	4190
Total paper and paperboard (Nondurable goods)	33,570
Containers and Packaging	
Corrugated boxes	29,050
Aseptic cartons	540
Folding cartons	5470
Other paperboard packaging	90
Bags and sacks	1040
Other paper packaging	1490
Total paper and paperboard (Containers and packaging)	37,680
Total paper and paperboard	71,250

Source: U.S. EPA, *Municipal Solid Waste in the United States: 2010 Facts and Figures,* Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 2011.

[a] Includes tissue in disposable diapers, paper in games and novelties, cards, and so on.

TABLE 4.7
Glass Products in MSW, 2010

Product Category	Generation (Thousands of Tons)
Durable goods[a]	2170
Containers and Packaging	
Beer and soft drink bottles	5670
Wine and liquor bottles	1700
Food and other bottles and jars	1990
Total glass containers	9360
Total glass	11,360

Source: U.S. EPA, *Municipal Solid Waste in the United States: 2010 Facts and Figures,* Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 2011.

[a] Glass as a component of appliances, furniture, consumer electronics, etc.

4.4.2 Glass

Glass occurs in MSW primarily in the form of containers (Table 4.7), as beer and soft drink bottles, wine and liquor bottles, and jars of food and other consumer products. Glass is also common in durable goods such as appliances and consumer electronics.

Glass accounted for 6.7 million tons of MSW in 1960, or 7.6% of total generation. The generation of glass waste increased over the next two decades; however, aluminum and plastic containers gained a strong foothold in the food container market and replaced many glass containers. Thus, the tonnage of glass in MSW declined in the 1980s. Glass comprised about 10% of MSW generation in 1980, declining to 4.6% in 2010 (U.S. EPA 2011).

4.4.3 Aluminum

The largest sources of aluminum in MSW are used beverage containers (UBCs) and other packaging (Table 4.8). In 2010, about 2 million tons of aluminum were generated in containers and packaging, whereas 1.3 million tons occurred in durable and nondurable goods. The total, 3.3 million tons, comprises 1.4% of total MSW generation in 2010. This number compares with the generation of 340,000 tons (0.4%) in 1960.

4.4.4 Ferrous Metals

Ferrous metals (iron and steel) are the predominant metals in MSW on a weight basis (Table 4.8). The majority of ferrous metals in MSW are found in appliances, furniture, and other durable goods. Containers and packaging are the other primary sources of ferrous metals (U.S. EPA 2011).

Approximately 10.3 million tons of ferrous metals were generated in 1960. Weights increased during the 1960s and 1970s, but later decreased as lighter materials, such as aluminum and plastics, replaced steel in several applications. The percentage of ferrous metals generation in MSW declined from 11.7% in 1960 to 6.8% in 2010.

4.4.5 Other Nonferrous Metals

Nonferrous metals such as copper, zinc, and lead are found in durable products such as appliances and consumer electronics. The generation of nonferrous metals has increased slowly, up from 180,000 tons in 1960 to 5.5 million tons in 2010. Lead in automotive batteries is the most prevalent of the nonferrous metals in MSW. As a percentage of total generation, nonferrous metals remain below 1% (U.S. EPA 2011).

TABLE 4.8
Metal Products in MSW, 2010

Product Category	Generation (Thousands of Tons)
Durable Goods	
Ferrous metals	14,160
Aluminum	1310
Lead	1540
Other nonferrous metals	560
Total metals in durable goods	12,740
Nondurable Goods	
Aluminum	200
Containers and Packaging	
Steel	
Food and other cans	2300
Other steel packaging	440
Total steel packaging	2740
Aluminum	
Beer and soft drink cans	1370
Food and other cans	70
Foil	460
Total aluminum packaging	1900
Total metals in containers and packaging	4640
Total metals	22,410
Ferrous	16,900
Aluminum	3410
Other nonferrous	2100

Source: U.S. EPA, *Municipal Solid Waste in the United States: 2010 Facts and Figures,* Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 2011.

4.4.6 Plastics

Plastics are used in durable and nondurable goods and in containers and packaging, with the latter being the largest category of plastics present in MSW (Table 4.9). In durable goods, plastics are found in appliances, furniture, carpets, and other products. Hundreds of different resin formulations are used.

Plastics are found in nondurable products such as disposable diapers, trash bags, cups, eating utensils, sporting goods, and household items such as shower curtains.

Plastic food service items are generally made of clear or foamed polystyrene, whereas trash bags are manufactured of high- or low-density polyethylene. A wide variety of resins occur in other nondurable goods. Plastic resins are used in container and packaging products such as polyethylene terephthalate (PET) soft drink bottles and high-density polyethylene (HDPE) bottles for milk and water. A range of other resin types are used in containers, bags, wraps, and lids.

Plastics are a rapidly growing segment of MSW. In 1960, plastics comprised an estimated 390,000 tons (<1%) of MSW generation. The quantity has increased to 31 million tons (12.4%) in 2010.

TABLE 4.9
Plastics in MSW, 2010

Product Category	Generation (Thousands of Tons)
Durable Goods	
Total plastics in durable goods	10,960
Nondurable Goods	
Plastic plates and cups	890
Trash bags	980
All other nondurables[a]	4530
Total plastics in nondurable goods	6400
Plastic Containers and Packaging	
Bottles and jars	3470
Other containers	1830
Bags, sacks, wraps	3930
Other packaging[b]	4450
Total plastics in containers and packaging, by resin	
PET	3380
HDPE	3540
PVC	400
LDPE/LLDPE	3480
PLA	10
PP	2030
PS	550
Other resins	290
Total plastics in containers and packaging	13,680
Total Plastics in MSW by Resin	
PET	3980
HDPE	5450
PVC	910
LDPE/LLDPE	7430
PLA	50
PP	7530
PS	2060
Other resins	3630
Total plastics in MSW	31,040

Source: U.S. EPA, *Municipal Solid Waste in the United States: 2010 Facts and Figures,* Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 2011.

Note: HDPE = high-density polyethylene; PET = polyethylene terephthalate; PS = polystyrene; LDPE = low-density polyethylene; PP = polypropylene; PVC = polyvinyl chloride; LLDPE = linear low-density polyethylene; PLA = polylactide.

[a] All other nondurables include plastics in disposable diapers, clothing, footwear, etc.

[b] Other plastic packaging includes coatings, closures, caps, trays, shapes, etc.

4.4.7 Rubber and Leather

Automobile and truck tires are the predominant sources of rubber in MSW (Table 4.10). Other sources include clothing and footwear and other durable and nondurable products. The generation of rubber and leather in MSW has increased from 1.8 million tons in 1960 to 7.8 million tons in 2010. One reason for the relatively slow rate of growth is that tires have been made smaller and

TABLE 4.10
Rubber and Leather in MSW

Product Category	Generation (Thousands of Tons)
Durable Goods	
Rubber in tires[a]	3300
Other durables[b]	3440
Total Rubber and Leather	
Durable goods	6740
Nondurable goods	
Clothing and footwear	790
Other nondurables	250
Total Rubber and Leather	
Total rubber and leather	7780

Source: U.S. EPA, *Municipal Solid Waste in the United States: 2010 Facts and Figures,* Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 2011.

[a] Automobile and truck tires. Does not include other materials in tires.

[b] Includes carpets, rugs, and other miscellaneous durables.

longer-wearing since the 1970s. As a percentage of total MSW generation, rubber and leather have remained steady at about 3.0%.

4.4.8 Textiles

Textiles in MSW occur in discarded clothing, although other sources include furniture, carpets, tires, footwear, and other nondurable goods such as linens and towels. A total of 13.1 million tons of textiles was generated in 2010, comprising 5.3% of total MSW generation.

4.4.9 Food Wastes

Food wastes include uneaten food and food preparation wastes from residences, commercial sources (restaurants, fast food establishments), institutional sources such as school cafeterias, and industrial sources. The generation of food wastes was estimated at 34.8 million tons in 2010 (U.S. EPA 2011).

4.4.10 Yard Waste

Yard waste includes grass clippings, leaves, and tree trimmings from residential, institutional, and commercial sources. The average composition by weight is estimated to be about 50% grass, 25% leaves, and 25% tree trimmings (U.S. EPA 1999). Quantities and relative proportions will vary according to geographic region and climate. Yard waste is the second largest component of MSW, at 13.4% of total generation.

In the past, the generation of yard waste increased steadily as the U.S. population and amount of residential housing grew, although per capita generation remained relatively constant. In recent years, however, the amounts of yard waste have declined substantially in many areas as a result of local and state legislation (usually in the form of bans) on the disposal of such wastes in landfills. With such so-called "flow control" in place, homeowners adjust by establishing backyard composting and

by using mulching lawnmowers that allow grass clippings to remain on the lawn surface. In 1992, eleven states had legislation banning or discouraging yard waste disposal in landfills. By 2012, nearly half of U.S. states had legislation restricting or banning the disposal of yard waste.

4.4.11 Household Hazardous Wastes

Household hazardous waste (HHW) includes those hazardous materials occurring in MSW regardless of their source. Most HHW occurs as heavy metals, organic compounds, or asbestos. These are considered hazardous because they may be ignitable, corrosive, reactive, or toxic. Metallic wastes such as lead, cadmium, and mercury are hazardous due to direct toxicity. Many organic wastes are deemed hazardous solely because they are flammable, although some pose inhalation hazards (e.g., paint strippers and other solvents) and others may damage or penetrate the skin (solvents and pesticides). Most of the asbestos occurring in solid waste occurs as old vinyl asbestos floor tiles and asbestos shingles. Since the primary asbestos hazard is in the form of respirable particles, asbestos tiles and shingles are typically not a significant hazard. Table 4.11 lists many common HHWs, and Table 4.12 presents hazardous compounds occurring in common household products.

The amount of HHW generated ranges between 0.2% and 0.4% of the residential waste stream (USCOTA 1989). The average U.S. household generates more than 9.1 kg (20 lb) of HHW per year. As much as 45.4 kg (100 lb) can accumulate in homes. Overall, Americans generate 1.6 million tons of HHW per year (NDSWRA 2013).

Estimates of the generation of HHW vary; possible reasons for the discrepancies include (Liu and Liptak 2000):

- Some estimates include less toxic materials such as latex paint.
- Most estimates include the weight of the containers, and many estimates include the containers even if they are empty.
- Some estimates include materials that were originally in liquid or paste form but have dried, such as aged paint and adhesives. Toxic substances can still leach from these dried materials, but drying reduces the potential leaching rate.

TABLE 4.11
Common Household Hazardous Wastes

Batteries (Ni–Cd, Pb, Hg)
Drain openers
Oven cleaners
Metal cleaners and polishers
Used motor oil
Automotive fuel additives
Grease and rust solvents
Carburetor and fuel injection cleaners
Air conditioning refrigerants
Starter fluids
Paints
Paint thinners
Paint strippers and removers
Adhesives
Herbicides
Insecticides
Fungicides/wood preservatives
Asbestos-containing materials

TABLE 4.12
Hazardous Elements and Compounds Occurring in Common Household Products

Ingredient	Products
Acrylic acid	Adhesives
Aniline	Cosmetics (perfume), wood stain
Arsenic (III) oxide	Paint (nonlatex anti-algae)
Benzene	Household cleaner (spot remover, oven cleaner) stain, varnish, adhesives, cosmetics (nail polish remover)
Cadmium	Ni–Cd batteries, paints, photographic chemicals
Chlordane	Pets (flea powders)
Chlorinated phenols	Latex paint
Chlorobenzene	Household cleaners (degreaser)
Hexachloroethane	Insect repellents
Lead	Stain/varnish, auto batteries, paint
Mercury	Batteries, paint (nonlatex anti-algae), fluorescent lamps
Methylene chloride	Household cleaners, paint strippers, adhesives
Nitrobenzene	Polish (shoe)
Silver	Batteries, photographic chemicals
Warfarin	Rodent control
Xylene	Transmission fluid, engine treatment (degreaser), paint (latex, nonlatex, lacquer thinners), adhesives, microfilm, fabric, cosmetics (nail polish)

As discussed in Chapter 11, EPA has established stringent requirements for the management of hazardous waste generated by industry. Congress chose not to regulate HHW, however, due to the impracticality of regulating every household. Some of the concern surrounding HHWs, therefore, is that unwitting consumers may dispose of these wastes, many of which are toxic and nonbiodegradable, directly into the sewer or household trash. As a result, toxic components will eventually find their way into the biosphere. During the 1980s, many communities initiated special collection days (Figure 4.4) or permanent collection sites for handling HHW. Several thousand permanent HHW programs and collection events now exist throughout the United States (Figure 4.5).

4.4.11.1 Toxic Metals

Lead is widespread in the municipal waste stream; it occurs in both the combustible and the noncombustible portions of MSW. Discards of lead in MSW are substantially greater than are items containing cadmium, mercury, and other toxic metals. Of the lead products entering the waste stream, cathode-ray tubes from computers and old television sets rank first. For decades, the major source of lead in MSW had been automotive lead–acid batteries. Lead in waste is growing in the form of discards in consumer electronics. Wastes as leaded solder in cans and lead in pigments, however, virtually disappeared between 1970 and 1986.

Cadmium is also widespread in products discarded in MSW, although it occurs in much smaller quantities. Since 1980, nickel–cadmium household batteries have been the primary contributors of cadmium in MSW. Discards of cadmium in household batteries were low in 1970, but have increased dramatically. Cadmium in consumer electronics has decreased over time. In 2004, the European Union banned the use of cadmium in most consumer electronics.

A number of sources for mercury in MSW occur—common items using or containing mercury include household batteries, electric lighting, paint residues, fever thermometers, building thermostats, pigments, dental amalgams, special paper coatings, mercury light switches, and film pack batteries.



FIGURE 4.4 "Tox-away day" allows for community residents to properly dispose of HHW.

4.4.11.2 Organic Compounds

The organic components of HHW include volatile organic compounds (VOCs) and persistent nonvolatile organics (POCs). The VOCs occur in products such as cleaners and solvents, lawn and garden products (including pesticides), fuel products, and oil-based paints. VOCs are sometimes highly toxic and may be carcinogenic, mutagenic, or teratogenic. For example, benzene, a common component of automotive gasoline, has been declared a human carcinogen, mutagen, and possible teratogen. Benzene damages the central and peripheral nervous system, is linked with blood cell disorders, and irritates the eyes and skin. Methylene chloride, an active ingredient in some paint



FIGURE 4.5 HHW drop-off and storage facility at a city materials recovery facility.

strippers, is a possible carcinogen and is linked with central nervous system, respiratory, and cardiovascular disorders.

A number of common automotive products are considered hazardous, and many states require their management as HHW. For example, antifreeze is toxic by virtue of its content of ethylene glycol; transmission fluid is toxic due to the presence of certain hydrocarbons and mineral oils; brake fluid contains both glycol and heavy metals; and used motor oil is contaminated with polycyclic aromatic hydrocarbons and other hydrocarbons, and heavy metals. Gasoline is toxic due to its content of benzene, toluene, ethylbenzene, and xylene, as well as being extremely flammable.

Persistent nonvolatile organics include pesticides, herbicides, and fungicides in common lawn and garden products. Others include hydraulic fluids and lubricants. Some POCs are probable or known carcinogens, and some damage the liver, kidneys, central nervous system, lungs, and reproductive system.

4.5 CHEMICAL PROPERTIES OF MSW

Accurate information on the chemical composition of MSW is important for a number of reasons. First, the composition of landfill leachate (see Chapter 10) is directly affected by MSW composition. Excluding materials from the waste stream (e.g., solvents, nickel–cadmium batteries) will potentially improve leachate properties and limit groundwater contamination. Second, composition must be known for evaluating MSW processing and recovery options. For example, if the organic fraction of MSW is to be composted or used as feedstock for the production of biogas or other products, information on the major elements (e.g., ultimate analysis) that comprise the waste is important. Data will be required for trace element composition in the waste as well; for example, even modest concentrations of cadmium, arsenic, or lead may be detrimental to efficient composting or biogas production. Finally, the feasibility of MSW combustion is directly affected by chemical composition. Wastes can be considered a combination of semimoist combustible and noncombustible materials. If solid wastes are to be used as a fuel, some relevant properties to determine *a priori* include ultimate analysis, proximate analysis, energy content, and particle size distribution.

4.5.1 Ultimate Analysis of Solid Waste Components

The ultimate analysis of a material is defined as its total elemental analysis, that is, the percentage of each individual element present. The results of the ultimate analysis are used to characterize the chemical composition of the organic fraction of MSW. Such a determination is essential for

assessing the suitability of the waste as a fuel and predicting emissions from combustion. The data are also used to define the proper mix of MSW materials to achieve suitable nutrient ratios (e.g., C/N) for biological conversion processes such as composting.

The ultimate analysis involves the determination of the percent values of carbon, hydrogen, oxygen, nitrogen, sulfur, and ash in a sample. Due to concerns over emissions of chlorinated compounds during combustion, the determination of halogens is often included. The percent values of carbon, hydrogen, nitrogen, sulfur, and chlorine are measured directly by established procedures. The oxygen value is calculated by subtracting the other components, including ash and moisture, from 100%.

Data on the ultimate analysis of individual combustible materials are presented in Table 4.13. The majority of MSW is composed of carbon, hydrogen, and oxygen. Five materials tend to predominate in the organic fraction of MSW: cellulose, lignin, fats, proteins, and hydrocarbon polymers. Cellulose accounts for the majority of the dry weight of MSW and is the predominant compound in paper, wood, food waste, and yard waste (Masterson et al. 1981; Liu and Liptak 2000). The relatively low sulfur and nitrogen contents are significant, as both are precursors to acid rain. Sulfur is not a component of any solid waste category except perhaps building materials (gypsum panels) or yard waste. Nitrogen occurs in food waste, grass clippings, and textiles (e.g., wool and nylon) (Liu and Liptak 2000). Chlorine is present in the organic form as polyvinyl chloride (PVC) and vinyl, and as paper products bleached with chlorine. Chlorine may also be present in the inorganic form as sodium chloride and other simple salts.

The ash fraction is the residual material after combustion and is primarily inorganic, although some organics may remain (Table 4.14). Ash can impart significant environmental and public health effects if improperly managed. Fine particulate ash is sufficiently lightweight that it may exit an incinerator and enter the atmosphere via the flue (hence, there is a need to capture it—see Chapter 9). Heavier solids may be captured by gravity. The composition of ash is largely influenced by the composition of the charge, that is, the MSW entering the incinerator. Ash from unprocessed, unsorted MSW typically contains a higher content of potentially toxic metals such as cadmium, lead, and mercury. Some of these metals may be leached readily if placed in a landfill; therefore, they may require segregation from other

TABLE 4.13
Ultimate Analysis of the Combustible Components in Household MSW

	Percent by Weight (Dry Basis)					
Component	**Carbon**	**Hydrogen**	**Oxygen**	**Nitrogen**	**Sulfur**	**Ash**
			Organic			
Paper	43.5	6.0	44.0	0.3	0.2	6.0
Plastics	60.0	7.2	22.8	—	—	10.0
Food wastes	48.0	6.4	37.6	2.6	0.4	5.0
Yard wastes	47.8	6.0	38.0	3.4	0.3	4.5
Textiles	55.0	6.6	31.2	4.6	0.15	2.5
Rubber	78.0	10.0	—	2.0	—	10.0
Wood	49.5	6.0	42.7	0.2	0.1	1.5
			Inorganic			
Glass	0.5	0.1	0.4	<0.1	—	98.9
Metals	4.5	0.6	4.3	<0.1	—	90.5
Dirt, ash, etc.	26.3	3.0	2.0	0.5	0.2	68.0
Municipal solid wastes	15–30	2–5	12–24	0.2–1.0	0.02–0.1	—

Source: Adapted from U.S. Department of Health, Education, and Welfare, *Incinerator Guidelines*, U.S. Department of Health, Education, and Welfare, Washington, DC, 1969. Data reproduced with kind permission of the American Society of Mechanical Engineers; Kaiser, 1969.

TABLE 4.14
Composition of a Sample of MSW Ash

Material	Percent by Weight
Metals	16.1
Combustibles	4.0
Ferrous metal	18.3
Nonferrous metal	2.7
Glass	26.2
Ceramics	8.3
Mineral, ash, others	24.1

Source: Reproduced with kind permission from Chesner, W.H. et al., From Hasselriis, F., Ash disposal. In *Handbook of Solid Waste Management*, Kreith, R. (Ed.), McGraw-Hill, New York, 1994.

wastes, along with specialized treatment. A number of nontoxic metals also occur, such as iron, copper, magnesium, calcium, and sodium. Table 4.17 presents representative data from an MSW ash fraction.

Example 4.1

Estimate the chemical composition of the organic fraction of a sample of MSW. Some data on waste properties are shown below.

	Wet Weight (kg)	Dry Weight (kg)
Paper	19.0	16.0
Plastics	3.7	3.5
Food wastes	5.1	1.9
Yard wastes	8.4	2.6
Textiles	1	0.8
Rubber	0.22	0.22
Wood	1.3	0.9

Solution

Determine the percentage distribution of C, H, O, N, and S occurring in the waste sample. Use the percent values of these elements from Table 4.13 (ultimate analysis).

		Percent by Weight (Dry Basis)					
	Dry weight, kg	C	H	O	N	S	Ash
Paper	16.0	43.5	6.0	44.0	0.3	0.2	6.0
Plastics	3.5	60.0	7.2	22.8	—	—	10.0
Food wastes	1.9	48.0	6.4	37.6	2.6	0.4	5.0
Yard wastes	2.6	47.8	6.0	38.0	3.4	0.3	4.5
Textiles	0.8	55.0	6.6	31.2	4.6	0.15	2.5
Rubber	0.22	78.0	10.0	—	2.0	—	10.0
Wood	0.9	49.5	6.0	42.7	0.2	0.1	1.5

Determine the percentage distribution of the elements in the sample.

			Composition, kg					
	Wet, kg	**Dry, kg**	**C**	**H**	**O**	**N**	**S**	**Ash**
Paper	19.0	16.0	6.96	0.96	7.04	0.048	0.032	0.96
Plastics	3.7	3.5	2.1	0.252	0.798	0	0	0.35
Food wastes	5.1	1.9	0.912	0.122	0.7144	0.0494	0.0076	0.095
Yard wastes	8.4	2.6	1.243	0.156	0.988	0.0884	0.0078	0.117
Textiles	1	0.8	0.44	0.053	0.2496	0.0368	0.0012	0.02
Rubber	0.22	0.22	0.172	0.022	0	0.0044	0	0.022
Wood	1.3	0.9	0.446	0.054	0.3843	0.0018	0.0009	0.0135
Total			12.27	1.618	10.174	0.2288	0.0495	1.5775

	Weight, kg
C	12.27
H	1.62
O	10.17
N	0.22
S	0.05
Ash	1.58

Determine the molar composition of the elements. Ignore the data for the ash.

Element	**Atomic Weight, g/mol**	**Moles**
C	12.01	1.022
H	1.01	1.604
O	16.0	0.636
N	14.01	0.016
S	32.07	0.002

Calculate an approximate chemical formula. Determine mole ratios (sulfur = 1).

	Mole Ratio
C	655.32
H	1028.84
O	407.71
N	10.07
S	1.00

The chemical formula for the waste mixture given above is

$$C_{655.3}H_{1028.8}O_{407.7}N_{10.1}S$$

4.5.2 Proximate Analysis of MSW

Proximate analysis is a more specific measurement compared with ultimate analysis and is used to estimate the capability of MSW as a fuel. Proximate analysis includes the following tests (Drobney et al. 1971; Singer 1981):

- Moisture content, determined by loss of moisture after heating at 105°C for 1 h.
- Volatile combustible matter, the additional loss of weight after ignition at 950°C for 7 min in a covered crucible (oxygen is excluded).
- Fixed carbon, the combustible residue left after volatile matter is removed; ignition at 600–900°C.
- Ash, the weight of residue after combustion in an open crucible.

Moisture content and ash represent the noncombustible component of MSW. Moisture and ash are undesirable in MSW, as they add weight to the fuel without enhancing heating value. Furthermore, ash retains heat when removed from the furnace; as a result, potentially useful heat is lost to the environment.

The volatile matter and fixed carbon content are the preferred indicators of the combustion capability of MSW. Volatile matter is the portion of MSW converted into gas as the temperature increases. Such gasification occurs before the onset of combustion. In many incineration systems, these carbonaceous gases are drawn away from the heating mass to a secondary chamber where combustion of the fuel gas occurs (see Chapter 9). Heat release is rapid, and combustion is complete within a short time (Pfeffer 1992).

Fixed carbon is the solid carbon residue (*char*) that has settled on the furnace grates. Combustion occurs in the solid state, that is, on the surface of this char material. The rate of combustion is affected by the temperature and surface area of the char. A waste fuel with a high percentage of fixed carbon will require a longer retention time in the combustion chamber to achieve complete combustion, as compared with a fuel low in fixed carbon (Pfeffer 1992).

The value for fixed carbon from laboratory results is calculated as follows (Liu and Liptak 2000):

$$\%\ \text{fixed carbon} = 100\% - \%\ \text{moisture} - \%\ \text{ash} - \%\ \text{volatile matter} \tag{4.1}$$

A limitation of proximate analysis is that it does not provide an indication of possible pollutants emitted during combustion. These data are determined via ultimate analysis. Proximate analysis data for the combustible components of MSW and bulk samples of MSW are presented in Table 4.15.

4.5.3 Energy Content of MSW

The energy content of the organic components of MSW can be determined by (1) combusting samples in a full-scale boiler and measuring steam output (Figure 4.6), (2) using a laboratory bomb calorimeter (Figure 4.7), or (3) calculation from elemental composition (i.e., ultimate analysis). Most data on energy content of MSW are based on the results of bomb calorimeter tests. This test measures heat release at a constant temperature of 25°C (77°F) from the combustion of a dry sample. The value of 25°C is used as a standard reference temperature for heat balance calculations.

The energy stored within the chemical bonds of a material is termed *heat of combustion*. This heat is released when the material is burned. The heat generated by combustion in a calorimeter may be determined by measuring the corresponding temperature rise:

$$U = C_V \Delta T/M \tag{4.2}$$

where U is the heat value (cal/g) of the unknown material, ΔT the rise in temperature (°C), M the mass (g) of the unknown material, and CV the heat capacity (cal/°C) of the calorimeter (measured using a standardized material).

TABLE 4.15
Typical Proximate Analysis of MSW and MSW Components

	Proximate Analysis (% by Weight)			
Waste Type	**Moisture**	**Volatiles**	**Fixed Carbon**	**Noncombustible (Ash)**
Food mixed	70.0	21	3.6	5.0
Paper mixed	10.2	76	8.4	5.4
Newspapers	6.0	81	11.5	1.4
Cardboard	5.2	77	12.3	5.0
Plastics mixed	0.2	96	2	2
Polyethylene	0.2	98	<0.1	1.2
Polystyrene	0.2	99	0.7	0.5
PVC	0.2	87	10.8	2.1
Textiles	10	66	17.5	6.5
Yard wastes	60	30	9.5	0.5
Wood mixed	20	68	11.3	0.6
Glass	2			96–99
Metals	2.5			94–99
Domestic MSW	10–40	30–60	3–15	10–30

Source: Reproduced with kind permission from Kiely, G., *Environmental Engineering*, McGraw-Hill, New York, 1997.

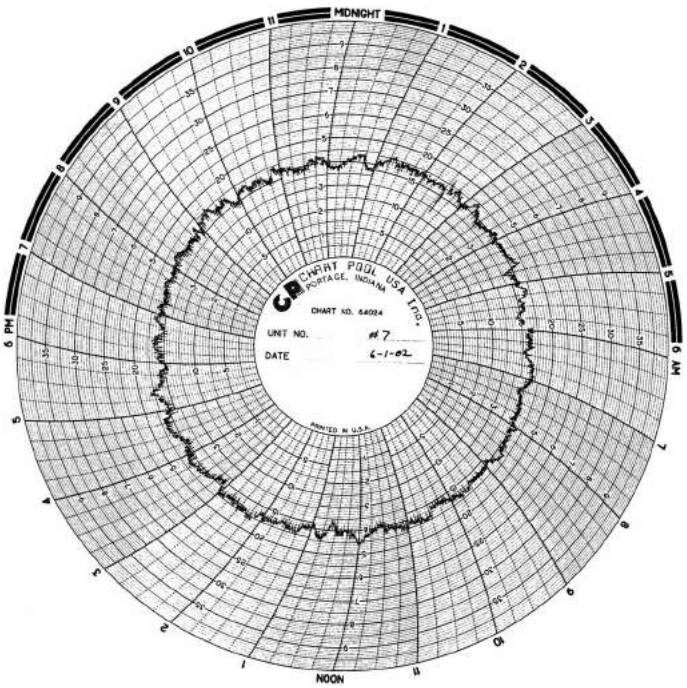
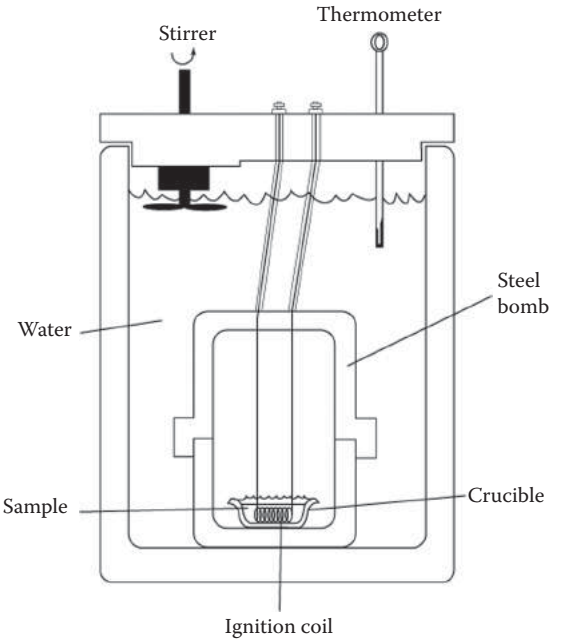


FIGURE 4.6 Chart showing steam production at a heating plant.



(a)



(b)

FIGURE 4.7 Bomb calorimeter: (a) schematic showing major components; (b) laboratory unit.

Example 4.2

A 10 g sample of mixed MSW is combusted in a calorimeter having a heat capacity of 8850 cal/°C. The temperature increase on combustion is 3.35°C. Calculate the heat value of the sample.

Solution

$$U = Cv\ \Delta T/M = (8850 \times 3.35)/10.00 = 2965\ \text{cal/g} = 5278\ \text{Btu/lb}$$

It should be obvious by now that the heat content of an MSW sample is essentially a function of composition; specifically, the percentage of materials having high Btu values such as paper, plastics, food, and yard wastes will provide the greatest heat release. Moisture and inorganics (e.g., ash) will diminish the heat of combustion in a sample.

Heat values for individual waste materials can be approximated by using Equation 4.3, known as the modified Dulong formula:

$$MJ/kg = 337C + 1419\ (H_2 - 0.125O_2) + 93S + 23N \tag{4.3}$$

where C, H_2, O_2, S, and N are given in percent by weight.

Using a more direct approach, Khan and Abu-Ghararah (1991) estimated the energy content from MSW with the equation:

$$E = 0.051\ [F + 3.6(CP)] + 0.352\ (PLR) \tag{4.4}$$

where E is the energy content in MJ/kg, F the percent by weight food in the waste, CP the percent cardboard and paper, and PLR the percent plastic and rubber.

Example 4.3

Determine the energy content of the MSW sample presented in Example 4.1.

Solution

The chemical formula for the waste mixture given in Example 4.1 was $C_{655.3}\ H_{1028.8}O_{407.7}N_{10.1}S$. Using the Dulong formula

$$\begin{aligned} MJ/kg &= 337C + 1419\ (H_2 - 0.125O_2) + 93S + 23N \\ &= 337\ (50.4) + 1419\ (6.6 - 0.125 \times 41.8) + 93\ (0.21) + 23\ (0.90) \\ &= 18{,}975\ MJ/kg \end{aligned}$$

Example 4.4

Estimate the energy content by using the Khan equation for MSW having the following properties:

Component	Percent by Weight
Paper products	37
Plastics	7
Glass	9
Metals	6
Food waste	24
Textiles	2
Miscellaneous	15
Total	100

Solution

$$\begin{aligned} E &= 0.051\ [F + 3.6\ (CP)] + 0.352\ (PLR) \\ &= 0.051\ [24 + 3.6\ (37)] + 0.352\ (7) \\ &= 10.48\ MJ/kg \end{aligned}$$

Two heat of combustion parameters are of significance: *high heating value* and *low heating value*. The higher heat of combustion includes the latent heat of vaporization of water molecules generated during the combustion process. The reaction for the combustion of cellulose and the consequent formation of water is

$$(C_6H_{10}O_5)n + 6nO_2 \rightarrow 6nCO_2 + 5nH_2O \tag{4.5}$$

This water results solely from the combustion process: that is, hydrogen is oxidized to form a water molecule. Therefore, even a seemingly dry sample of MSW will generate moisture, and this free water must be evaporated. The energy required may be substantial and may result in an inefficient combustion process. Subtracting the latent heat of vaporization of water provides a lower heat of combustion; this value represents the net heat available during incineration of MSW.

The high and low heating values can be estimated from composition data of the material. The higher heat value (HHV) is calculated using the equation

$$\text{HHV (MJ/kg)} = 0.339\,(\text{C}) + 1.44\,(\text{H}) - 0.139\,(\text{O}) + 0.105\,(\text{S}) \tag{4.6}$$

The lower heat value (LHV) is calculated as

$$\text{LHV} = \text{HHV (in MJ/kg)} - 0.0244\,(\text{W} + 9\text{H}) \tag{4.7}$$

where W represents the mass% of water and H the wt% of H in the waste.

The as-received heat value of a waste is approximately proportional to the carbon content of the waste. The heat values of plastics and, to a lesser extent, of paper are among the highest because of their high carbon content and relatively low ash and moisture contents. In contrast, yard waste and food waste, although mostly organic, possess LHVs because of their high-moisture contents.

The following four factors must be considered when evaluating MSW as a potential fuel (Pfeffer 1992):

1. Only dry organic matter yields energy.
2. Ash reduces the proportion of organic fuel per unit weight of MSW.
3. Ash retains heat when removed from the furnace, therefore wasting heat.
4. Water reduces the amount of organic fuel per unit weight of MSW and requires significant energy for removal (evaporation).

The heat contents for various fractions of MSW appear in Table 4.16.

4.5.4 Fusion Point of Ash

The fusion point of ash provides information on its physical behavior, that is, softening and melting, under high temperatures. This is the temperature at which the ash from waste combustion forms *clinker* by fusion and agglomeration. The fusion point correlates with the potential for boiler fouling by ash.

Fusion temperatures are often measured under both reducing and oxidizing conditions. Typical temperatures for clinker formation from MSW range from 1100 to 1200°C (2000–2200°F) (Tchobanoglous et al. 1993).

4.5.5 Content of Nutrients and Other Substrates

In applications where the organic fraction of MSW is used as feedstock for compost or biological conversion into methane and ethanol, data on nutrient composition of the waste are essential. Both composting and biogas production occur via the action of a diverse consortia of heterotrophic microorganisms. The microbial nutrient balance of the MSW should be assessed to result in maximal conversion for final uses. The composition of essential nutrients and elements in the organic fraction of MSW is shown in Table 4.17. Nitrogen content, both as nitrate and ammonium, is highest in food and yard wastes by virtue of their higher protein contents (see below). Sulfur, potassium, calcium, and magnesium are also markedly higher in food and yard wastes.

TABLE 4.16
Typical Values for Inert Residue and Energy Content of Residential MSW

Component	Inert Residue[a], % Range	Energy Content, kJ/kg Range	Energy Content, Btu/lb Range
		Organic	
Food wastes	2–8	3350–6700	1500–3000
Paper	4–8	11,200–18,000	5000–8000
Cardboard	3–6	13,400–16,800	6000–7500
Plastics	6–20	26,800–35,750	12,000–16,000
Textiles	2–4	14,500–17,900	6500–8000
Rubber	8–20	20,125–26,800	9000–12,000
Leather	8–20	14,500–19,000	6500–8500
Yard wastes	2–6	2225–17,900	1000–8000
Wood	0.6–2	16,770–19,000	7500–8500
Miscellaneous organics	—	—	—
		Inorganic	
Glass	96–99+	110–225	50–100
Tin cans	96–99+	225–1100	100–500
Aluminum	90–99+	—	—
Other metal	94–99+	225–1120	100–500
Dirt, ashes, etc.	60–80+	2230–11,175	1000–5000
Municipal solid wastes		8950–13,400	4000–6000

Source: Adapted from Kaiser, E.R., Chemical analyses of refuse compounds, *Proceedings of the National Incinerator Conference,* New York, ASME, 1969; Tchobanoglous, G. et al., *Integrated Solid Waste Management: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1993.

[a] After complete combustion.

TABLE 4.17
Elemental Analysis of Organic Materials Used as Feedstock for Biological Conversion Processes

Component	Newspaper	Office Paper	Yard Waste	Food Waste
K,%	0.35	0.29	2.27	4.18
Ca,%	0.01	0.10	0.42	0.43
Mg,%	0.02	0.04	0.21	0.16
NH_4-N, mg/kg	4	61	149	205
NO_3-N, mg/kg	4	218	490	4278
SO_4-S, mg/kg	159	324	882	855
P, mg/kg	44	295	3500	4900
B, mg/kg	14	28	88	17
Zn, mg/kg	22	177	20	21
Mn, mg/kg	49	15	56	20
Fe, mg/kg	57	396	451	48
Cu, mg/kg	12	14	7.7	6.9
Ni, mg/kg	—	—	9.0	4.5

Source: Data reproduced with kind permission from Tchobanoglous, G. et al., *Integrated Solid Waste Management: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1993.

The organic fraction of most MSW (i.e., food waste, yard waste, paper products, textiles) can be classified according to their relative degree of biodegradability as follows:

- Sugars
- Starches and organic acids
- Proteins and amino acids
- Hemicellulose
- Cellulose and lignocellulose
- Lignin
- Fats, oils, and waxes

4.5.6 Carbohydrates

The main sources of carbohydrates are putrescible food and yard wastes. Carbohydrates are designated by the general formula $(CH_2O)_x$ and include a range of sugars and their polymers such as starch and cellulose (Figure 4.8). Some polymers vary markedly in their resistance to hydrolysis. The starch polymers readily hydrolyze to glucose (Figure 4.9), which is a water-soluble and highly biodegradable simple sugar and essential for energy processes in heterotrophic microbes. Such polymers, when disposed, may attract pests such as flies and rats. Sugars account for 4%–6% and starches 8%–12% of the dry weight of MSW (Pfeffer 1992).

4.5.7 Crude Fibers

This category includes natural fibers such as cotton, wool, and leather, which are generally resistant to degradation. Cellulose and lignin are the predominant polymers. Cellulose is a polymer of glucose and, due to the nature of its chemical bonds, is only slowly biodegradable (Figure 4.10). Lignin is composed of a number of monomers, with benzene being the most common (Figure 4.11). The benzene ring is resistant to biodegradation. Natural fiber found in

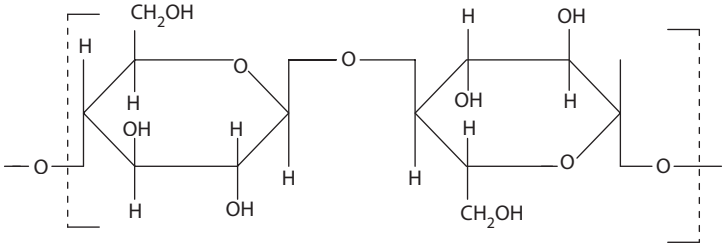


FIGURE 4.8 General structure of a carbohydrate molecule.

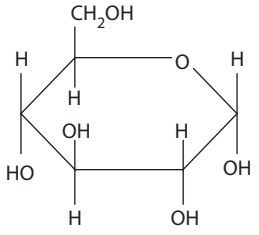


FIGURE 4.9 Structure of the glucose molecule.

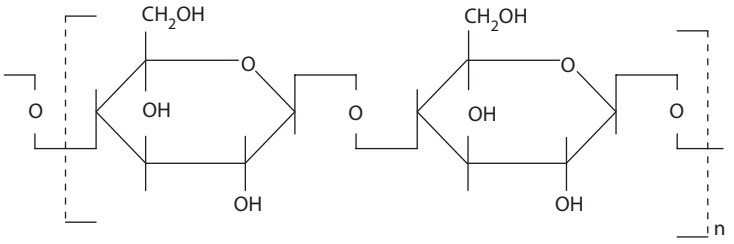


FIGURE 4.10 Structure of cellulose.

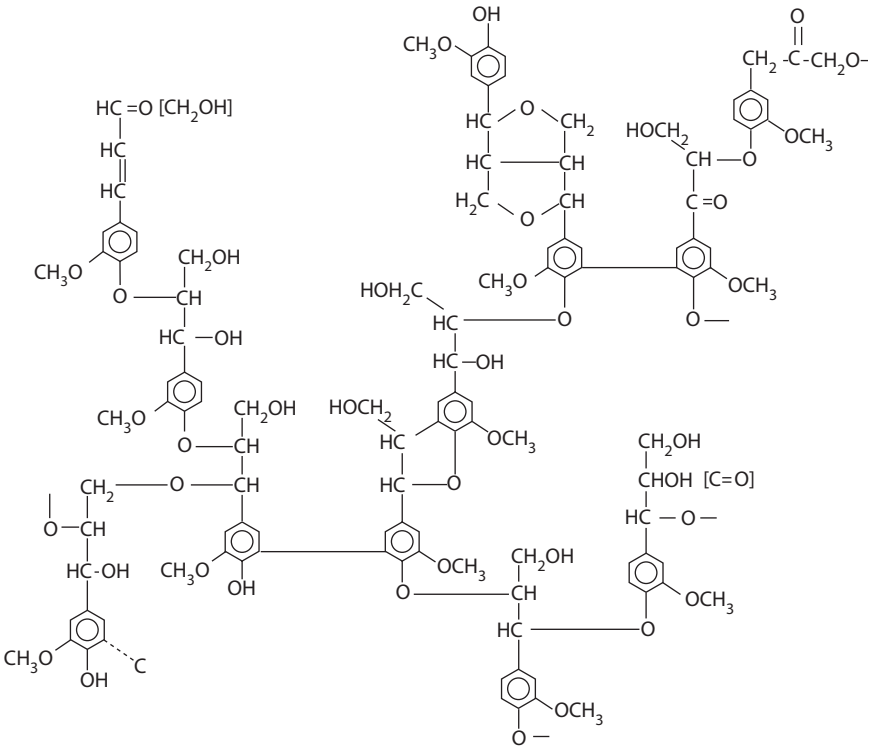


FIGURE 4.11 Structure of lignin. (Reprinted with kind permission from Pearl, I.A., *Chemical Engineering News,* July 6, 81–92, American Chemical Society, 1964.)

paper products, food waste, and yard waste is the major source of these polymers. Cellulose may account for 25%–30% of the dry weight of MSW, whereas lignin may comprise 8%–10% (Pfeffer 1992).

4.5.8 Proteins

All proteins possess a backbone of an amine group ($-NH_2$) and an organic acid (R–COOH) (Figure 4.12). Food and yard wastes are sources of proteins, which comprise about 5%– 10% of the dry solids in MSW. Proteins are important in the biodegradation of MSW, as they are a key N source for heterotrophic microorganisms. Efficient microbial degradation of carbonaceous wastes requires a sufficient supply of N. Partial decomposition of proteins can result in the production of amines that produce intense odors. Common names for some of these amines include *putrescine* and *cadaverine*.

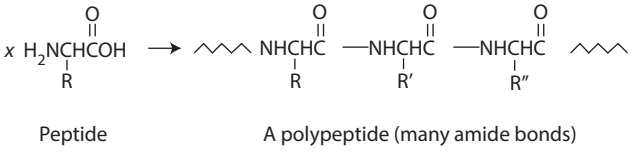


FIGURE 4.12 Generic structure of a protein molecule.

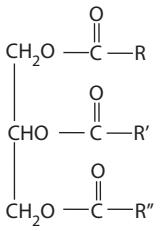


FIGURE 4.13 Structure of a lipid molecule.

4.5.9 Lipids

Also known as fats, oil, and grease, these may comprise approximately 8%–10% of MSW on a dry weight basis. A generalized structure of a lipid molecule is shown in Figure 4.13. The main sources of lipids are putrescible garbage, fat, and cooking oils. Lipids typically possess a high energy value, in the range of 35,775–38,000 MJ/kg (16,000–17,000 Btu/lb) (Pfeffer 1992). Solid wastes high in lipid content are, therefore, well suited for energy recovery processes. Lipids become fluid at slightly above ambient temperatures. This can add to the liquid content of MSW and will alter physical properties due to wetting of paper products. Lipids have low solubility in water, which renders them slowly biodegradable.

4.5.10 Biodegradability of MSW Fractions

The above compounds serve as a substrate for a wide range of micro- and macroorganisms important in composting and other biological processing of MSW. All these organic components can be biologically converted into gases and relatively stable organic and inorganic solids.

The biodegradability of the organic fraction of MSW can be determined via simple laboratory tests for volatile solids and lignin content. The biodegradability factor can be calculated by the equation (Tchobanoglous et al. 1993)

$$BF = 0.83 - 0.028LC \tag{4.8}$$

where BF represents the biodegradable fraction expressed on a volatile solids basis and LC represents the lignin content of the volatile solids expressed as a percent of dry weight.

The biodegradability of several organic compounds in MSW is shown in Table 4.18. Wastes with high lignin content, such as newspaper and cardboard, tend to be of low biodegradability. Materials with low lignin content, for example, food wastes and grass clippings, tend be highly biodegradable.

4.6 PHYSICAL PROPERTIES OF MSW

4.6.1 Density

Density is a useful parameter in waste characterization, as it allows for predicting storage volume, including as discarded at a residence or commercial facility, after compaction in a collection truck, and after compaction within a landfill cell.

TABLE 4.18
Biodegradability of Selected Organic Components in MSW

Component	Lignin Content as % of VS	BF as % of VS
Food waste	0.4	0.82
Newsprint	21.9	0.22
Office paper	0.4	0.82
Cardboard	12.9	0.47
Yard waste	4.1	0.72

Source: Data reproduced with kind permission from Tchobanoglous, G. et al., *Integrated Solid Waste Management: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1993.
Note: BF = biodegradable fraction = 0.83 – (0.028) × LC, where LC = % of VS (volatile solids).

The density of raw, uncompacted, solid waste will vary as a function of composition, moisture content, physical shape, and degree of compaction. Density increases with increase in the proportion of glass, ceramics, ashes, and metals. Moisture replaces air occurring in voids, thus increasing density until the waste becomes saturated. Excessive water content may actually displace solids, which will eventually lower overall density.

Raw wastes range in density from about 115 to 180 kg/m^3 (200–300 lb/yd^3). This low density is partly a function of the shape of the material in the waste stream. Corrugated boxes, bottles, and cans contain large void spaces that decrease density. If these materials are crushed, waste density sharply increases. Some compaction occurs during storage in piles. Shredding, baling, and other size-reduction techniques also decrease irregularity and increase density (Liu and Liptak 2000). The density of MSW compacted in a landfill ranges from 300 to 900 kg/m^3 (Sincero and Sincero 1996; Kiely 1997).

Volume reduction has a significant impact on costs of collection and hauling MSW. Collection trucks are space-limited; therefore, greater compaction capabilities will result in a greater density of MSW and more cost-effective hauling. High-pressure compaction by using stationary balers greatly increases MSW density for long-distance transport, for example, in rail cars. An upper limit of baled density is approximately 900 kg/m^3 (1500 lb/yd^3) (Pfeffer 1992). Values for waste density are shown in Table 4.19.

Example 4.5

During a sampling event at a tipping floor of an MRF in an eastern U.S. urban area, municipal solid waste is found to contain the following components:

Component	Density (kg/m^3)	Amount in Sampled Waste (% by Weight)
Food waste	290	22
Mixed plastics	60	12
Glass	200	8
Ferrous and aluminum	200	12
Textiles	60	5
Dust, dirt	500	28

What is the average density of this solid waste mixture?

Solution

$$\begin{aligned}\text{Average density} &= (0.22)(290) + (0.12)(60) + (0.08)(200) + (0.12)(200) \\ &\quad + (0.05)(60) + (0.28)(500) \\ &= 254 \text{ kg/m}^3\end{aligned}$$

TABLE 4.19
Density and Moisture Content of MSW

Waste Source	Component of Waste	Density (kg/m³)	Moisture Content (% by weight)
Domestic	Food	290	70
	Paper products	70	5
	Plastic	60	2
	Glass	200	2
	Metals	200	2
	Clothing and textiles	60	10
	Ashes, dust	500	8
Municipal			
Uncompacted		60–120	20
Baled waste		470–900	–
Compacted in collection truck		300–400	20
Compacted in landfill		300–890	25

Source: Adapted from Vesilind, P.A. et al., *Environmental Engineering*, 2nd ed., Butterworths, Boston, MA, 1988. Reproduced with kind permission of Elsevier Publishing.

Efficient use of landfill volume is an essential aspect of landfill management. During routine waste management operations (e.g., landfilling, tipping at a transfer station), trucks are weighed when entering and exiting the facility. With knowledge of the compacted density, the volume of land required at a landfill can be calculated.

The density of MSW is calculated on an as-compacted or as-discarded basis. The compaction ratio r is defined as the ratio of the as-compacted density ρ_c to the as-discarded density ρ_d and is given by

$$r = \rho_c/\rho_d \tag{4.9}$$

A final disposal compaction ratio is calculated for landfills, and a compactor machine ratio is used for densification equipment such as a baler. A common compaction ratio for a compacter machine may range from 2 to 4 (Sincero and Sincero 1996).

If materials having different densities are expressed in terms of their weight fraction, the equation for calculating the overall bulk density is

$$\frac{(M_a + M_b)}{\frac{M_a}{\rho_a} + \frac{M_b}{\rho_b}} = \rho_{(a+b)} \tag{4.10}$$

where M_a is the mass of A, M_b the mass of B, ρ_a the bulk density of A, and ρ_b the bulk density of B. When there are more than two materials to be considered, the above equation is extended.

The degree of volume reduction that occurs as a result of waste compaction, whether in a baler or landfill, is an important design variable. Waste volume reduction is calculated by the equation (Vesilind et al. 2002)

$$V_c/V_o = F \tag{4.11}$$

where F is the fraction remaining of initial volume as a result of compaction, V_o the initial volume, and V_c the compacted volume.

Example 4.6

Component	Percent by Weight	Uncompacted Bulk Density (kg/m³)
Corrugated cardboard	25	30
Paper products	15	61
Aluminum	9	38
Food waste	29	368
Yard waste	22	7.1

(a) What is the bulk density for the waste mixture prior to compaction? Assume that the compaction in the landfill cell is 500 kg/m³.
(b) Estimate the volume reduction (expressed as %) during compaction in the landfill.
(c) If the food and yard waste is diverted for composting, what is the uncompacted bulk density of the remaining waste?

Solution

a) Bulk density prior to compaction

$$\frac{(25+15+9+29+22)}{\frac{25}{30}+\frac{15}{61}+\frac{9}{38}+\frac{29}{368}+\frac{22}{7.1}} = 22.2\,\text{kg/m}^3$$

b) Percent volume reduction resulting from compaction

$$22.2/500 = 0.04 \text{ or } 4\%$$

In other words, the landfill volume required is 4% of that required without compaction.
c) When food and yard waste is removed, uncompacted bulk density is

$$\frac{(9+29+22)}{\frac{9}{38}+\frac{29}{368}+\frac{22}{7.1}} = 29.2\,\text{kg/m}^3$$

4.6.2 Moisture Content

The moisture content of solid wastes is useful for estimating heat content, landfill sizing, and transport requirements. Moisture content is expressed either as a percentage of the wet weight or of the dry weight of the material. The wet-weight method is used more commonly and is expressed as

$$M = (w - d)/w \times 100 \tag{4.12}$$

where M is the moisture content (%), w the initial weight of sample as delivered (lb [kg]), and d the weight of sample after drying at 105°C (lb [kg]).

Typical data on the moisture content for solid waste components is given in Table 4.19. For most MSW in the United States, the moisture content will vary from 15% to 40%, depending on composition, season of the year, and weather conditions (Tchobanoglous et al. 1993; Kiely 1997).

Example 4.7

Using the data for an MSW sample provided below, determine the average moisture content of the sample. Base your calculations on a 100 kg sample size.

Component	Moisture Content (%)	Weight (%)	Discarded Weight (kg)
Paper waste	7	25	25
Yard waste	55	18	18
Food waste	65	20	20
Plastic	2	5	5
Wood	20	8	8
Glass	3	7	7
Metals	3	9	9
Textiles	12	8	8
Total		100	

Solution

The dry weight of each MSW component is calculated using the following equation:
Dry weight = [(moist weight)(100 – % moisture)]/100

Component	Moisture Content (%)	Weight (%)	Moist Weight (kg)	Dry Weight (kg)
Paper waste	7	25	25	(1.0 – 0.07)(25) = 23.25
Yard waste	55	18	18	(1.0 – 0.55)(18) = 8.10
Food waste	65	20	20	(1.0 – 0.65)(20) = 7.00
Plastic	2	5	5	(1.0 – 0.02)(5) = 4.9
Wood	20	8	8	(1.0 – 0.2)(8) = 6.4
Glass	3	7	7	(1.0 – 0.03)(7) = 6.79
Metals	3	9	9	(1.0 – 0.03)(9) = 8.73
Textiles	12	8	8	(1.0 – 0.12)(8) = 7.04
Total		100		72.21

Totaling the values in the final column, the average percent moisture content of the MSW is

$$= [(100 - 72)/100](100\%) = 28\%$$

4.6.3 Particle Size Distribution

Knowledge of the size distribution of solid waste components is useful for enhancing the rate of chemical reactions—smaller particle sizes provide greater surface area and thus more rapid reaction with microorganisms in a compost pile, or more rapid combustion in an incinerator. Size distribution is also an important consideration in the recovery of materials, for example, with the use of processing equipment such as a trommel screen or a magnetic separator (see Chapter 7).

MSW tends to stratify vertically when mixed, with smaller and denser components migrating to the bottom of a pile and lighter, bulkier objects rising to the top. Such stratification has implications for efficient combustion on a traveling grate in a boiler or for materials separation in an MRF.

Size distribution is measured by passing samples of MSW over a series of screens, beginning with a coarse screen and continuing down to a fine mesh. As discussed earlier, MSW is extremely heterogeneous; therefore, neither MSW nor any of its components are considered to possess a characteristic particle size (Liu and Liptak 2000).

TABLE 4.20
Typical Particle Size Distribution of MSW

Component	Size Range (mm)	Typical (mm)
Food	0–200	100
Paper and cardboard	100–500	350
Plastics	0–400	200
Glass	0–200	100
Metals	0–200	100
Clothing and textiles	0–300	150
Ashes, dust	0–100	25

Source: Reproduced with permission from Kiely, G., *Environmental Engineering*, McGraw-Hill, New York, 1997.

The size (i.e., "diameter") of a waste component may be calculated by any of the following equations:

$$D = l \tag{4.13}$$

$$D = (l + w + h)/3 \tag{4.14}$$

$$D = (l + w)/2 \tag{4.15}$$

$$D = (l \times w)^{1/2} \tag{4.16}$$

$$D = (l \times w \times h)^{1/3} \tag{4.17}$$

where D is the diameter, l the length, w the width, and h the height.
Particle size distributions of various MSW components are given in Table 4.20.

Example 4.8

A mixture of nonspherical waste particles is uniformly sized as follows: l = 4 units, w = 1.2 units, and h = 1.5 units. Using the five equations provided above, calculate the particle diameter (D). What is the range of variation in the calculated values?

$$D = l = 4$$

$$D = (l + w + h)/3 = 2.23$$

$$D = (l + w)/2 = 2.6$$

$$D = (l \times w)^{1/2} = 2.19$$

$$D = (l \times w \times h)^{1/3} = 1.93$$

Particle diameters range from 1.93 to 4 units, that is, by a factor of 2.1.

MSW will obviously contain particles having a wide range of individual sizes. Under such circumstances, the particle size is often expressed as mean particle diameter. A number of calculations are possible:

Arithmetic mean $$D = \frac{D_1 + D_2 + D_3 + D_4 \ldots D_n}{n}$$

Geometric mean $$D = (D_1 \times D_2 \times D_3 \times D_4 \times \ldots D_n)^{1/n}$$

Weighted mean $$D = \frac{W_1D_1 \pm W_2D_2 \pm W_3D_3 \pm W_4D_4 \ldots W_nD_n}{W_1 + W_2 + W_3 + W_4}$$

Number mean $$D = \frac{M_1D_1 \pm M_2D_2 \pm M_3D_3 \pm M_4D_4 \pm \ldots M_nD_n}{M_1 + M_2 + M_3 + M_4 + \ldots M_n}$$

where W is the weight of material in each sieve size, M the total number of particles in each sieve size, and n the number of sieve sizes (diameters).

Example 4.9

Given data for the following waste sizes:

	Sieve Size (mm)				
Particle diameter, mm	100	75	50	25	5
Weight of fraction, kg	2	6	12	4	4
Number of particles	225	310	500	2000	5750

Calculate the arithmetic mean, the geometric mean, and the weighted mean.

Arithmetic mean $$D = \frac{100 \pm 75 \pm 50 \pm 25 \pm 5}{5} = 51\,\text{mm}$$

Geometric mean $D = (100 \times 75 \times 50 \times 25 \times 5)^{1/5} = 34.2$ mm

Weighted mean $$D = \frac{(2 \times 100) \pm (6 \times 75) \pm (12 \times 50) \pm (4 \times 25) \pm (4 \times 5)}{2 + 6 + 12 + 4 + 4} = 48.9\,\text{mm}$$

Numbermean $$D = \frac{(225 \times 100) \pm (310 \times 75) \pm (500 \times 50) \pm (2000 \times 25) \pm (5750 \times 5)}{225 + 310 + 500 + 2000 + 5750} = 17.0\,\text{mm}$$

Note: The term *diameter* is defined to reflect a spherical particle shape; therefore, the above equations must serve only as an approximation.

Other calculations of particle size distribution incorporate particle surface area and volume as well.

4.6.4 Field Capacity

Field capacity may be defined as the total amount of moisture retained by mixed solids against the force of gravity. Water in excess of field capacity is released by gravity as leachate. The field capacity of a waste stream is of critical importance for two reasons: first, aerobic microbial activity is optimized at or slightly below field capacity. This moisture level, therefore, is the desired target for biological processing such as composting. Second, field capacity is important in predicting leachate formation in landfills, compost piles, and storage piles.

Field capacity varies with the degree of pressure applied to the waste and the state of decomposition of the waste. The field capacity of uncompacted commingled wastes from residential and commercial sources may range from 50% to 60% (Tchobanoglous et al. 1993; Kiely 1997).

One equation for the determination of field capacity of MSW is

$$FC = 0.6 - 0.55(W/[4500 + W]) \tag{4.18}$$

where FC is the field capacity (percent of dry weight of waste) and W the overburden weight calculated at midheight of the waste pile (kg).

4.6.5 Hydraulic Conductivity of Compacted Waste

The hydraulic conductivity, K, of compacted wastes is a physical property that influences the movement of liquids (e.g., leachate) and gases in a landfill. Dense materials such as sludges tend to resist rainfall infiltration and instead promote runoff from a landfill cell. In contrast, paper and yard wastes, by virtue of having large particles and therefore large void space, exhibit little resistance to rainfall infiltration.

Loose samples of MSW have a hydraulic conductivity value of 15×10^{-5} m/s, whereas dense baled waste may have a K of 7×10^{-6} m/s. The hydraulic conductivity for shredded waste ranges from 10^{-4} to 10^{-6} m/s (Kiely 1997). Since MSW is very heterogeneous, these values serve only as an approximation.

QUESTIONS

1. Since the late 1980s, many municipalities have invested substantial sums in order to obtain accurate and reliable data on local waste composition and quantities. What is the significance to a community in obtaining such data; in other words, how are the data used?
2. Explain the different methods for sampling MSW for a characterization study. What are the advantages and disadvantages of each? Consider accuracy, feasibility, and cost.
3. How do waste generation multipliers work? In your opinion, are they accurate predictors of waste generation?
4. Fluctuations in waste composition are affected by both geographic region and season of the year. Explain.
5. What specific attributes of MSW are the preferred indicators of its combustion capabilities?
6. Explain the difference between fixed carbon and volatile matter.
7. List three methods for determining the energy content of the organic components in MSW. Which method most accurately reflects "real-world" energy production?
8. What factors must be considered when evaluating MSW as a potential fuel?
9. Why are lignin and cellulose only slowly biodegradable? Refer to their chemical structures.
10. For a city seeking to better control waste management costs, a thorough assessment of waste generated from various sources is necessary. From the city's perspective, would waste measurements by weight or by volume be the most accurate and efficient? Explain.
11. How does total moisture content affect overall management of MSW? Are there environmental or other implications to a high-moisture content waste stream?
12. Packaging makes up what percentage of the U.S. waste stream? Has this value increased, decreased, or stabilized over the past decade?
13. The heating value of raw MSW is (a) less than, (b) approximately equal to, or (c) higher than that for Midwest bituminous coal (approximately 12,000–14,000 Btu/lb)?
14. Define: heat value, putrescible.
15. The majority of U.S. domestic solid wastes occur as: (a) plastics, especially PVC and polyethylene; (b) metals; (c) animal manures and yard wastes; (d) paper and paper products; or (e) none of the above.
16. What are the primary sources of aluminum in the U.S. waste stream? Of glass? Paper?
17. What is (are) the primary source(s) of lead in MSW? Of mercury? Of cadmium?
18. In your community, are MSW quantities routinely being measured? If yes, compile data on the total population of the area being served; next, calculate the total weight of MSW collected and convert to number of kilograms (or pounds) of waste generated per person per day. Are your values affected by commercial or other wastes in the calculations?
19. For your community, are data being collected regarding waste composition? Compute the percentage distribution of each waste component in the local waste stream. How does this distribution compare with the data of Figure 4.3? What factors may account for any

differences? If possible, perform calculations for daily generation of specific waste types, for example, pounds of food waste per person per day.

20. In your community, what are possible future trends (10 years, 20 years) in the generation of food wastes, yard wastes, paper, plastic, and hazardous wastes? Consider population trends, personal lifestyles, the movement of businesses in or out of the area, and urban sprawl.
21. MSW composition is a critical factor in formulating waste management programs. What changes in waste composition do you predict for the next 10 years in U.S. waste composition? Justify your reasoning.
22. Three decades ago, it was predicted that the use of personal computers would result in a "paperless society." Although this prediction obviously did not become a reality, has computer use affected waste paper production? In what ways? Be specific.
23. Estimate the chemical composition of the organic fraction of the MSW sample described below.

Component	Wet Weight, kg	Dry Weight, kg
Food waste	63.2	24.5
Yard waste	95.5	29.7
Paper products	174.0	152.2
Plastics	29.7	28.2

24. For the waste sample in Question 23, calculate the heat content (MJ/kg) by using the modified Dulong formula.
25. Estimate the energy content from MSW, using the Khan equation, having the following properties:

Component	Percent by Weight
Paper products	25
Corrugated cardboard	15
Plastics	6
Glass	8
Metals	12
Food waste	15
Ash, dirt, miscellaneous	19
Total	100

26. For the following waste mixture,

Component	Percent by Weight	Uncompacted Bulk Density, kg/m^3
Paper products	39.5	61
Ferrous	10	44
Food waste	26	375
Yard waste	25	10.4

what is the bulk density prior to compaction? Assume that the density after compaction in the landfill cell is 575 kg/m^3. Estimate the volume reduction (expressed as percent) during compaction in the landfill.

27. Given data for the following waste sizes, calculate the arithmetic mean, the geometric mean, and the weighted mean of the particle size distribution.

	Sieve Size, mm			
Particle diameter, mm	100	75	50	25
Weight of fraction, kg	9	12	28	8
Number of particles	450	1200	2500	5250

28. The higher heating value for cellulose, $C_6H_{10}O_5$, is 32,500 kJ/kg. Determine the lower heating value.

EXERCISE: WASTE CHARACTERIZATION

File Name: Characteriz.Xls

Background

For this exercise, you will work with waste sampling data for the town of Pristine, IL, for a period of 12 months. The data are stored on a Microsoft Excel spreadsheet.

Waste trucks are brought to the town's transfer station for unloading. Once each month, a truck is randomly selected and dumps its contents on to an isolated portion of the tipping room floor. Three university students were hired to sort the wastes into designated fractions and then weigh the fractions.

At each sampling date, a subsample of the waste was fed into a micronizing mill (a small shredder) and the shredded mixture was weighed and combusted in a tabletop furnace. The ash was collected and weighed. A separate subsample was shredded and placed in a bomb calorimeter. The heat content, measured in Btu/lb, was determined.

The data for this exercise is located at www.crcpress.com/e_products/downloads/download.asp?cat_no = 3525

Tasks

1. Calculate the percentages of each waste component for each month. What is the predominant fraction in the waste?
2. Determine the average values for each component over the year.
3. Plot the data for total paper, plastics, food waste, and yard waste, over the year. What trends do you observe?
4. Plot the data for Btu and ash content at each sampling date. Are any seasonal trends observed?
5. Finally, perform a simple regression analysis of the heat content vs. ash content data. Is there a significant correlation between the data sets? What is the correlation coefficient (r^2)?

REFERENCES

ASTM (American Society for Testing and Materials). 1998. *Test Method D5231-92 (1998) Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste*. West Conshohocken, PA: ASTM.

Chesner, W.H., Collins, R.J., and Fung, T. 1994. Assessment of the potential stability of Southwest Brooklyn incinerator residue in asphaltic concrete mixes. From Hasselriis, F., Ash disposal. In *Handbook of Solid Waste Management*. Kreith, R. (Ed.). New York: McGraw-Hill.

Drobney, N.L., Hull, H.E., and Testiiu, R.F. 1971. *Recovery and Utilization of Municipal Solid Waste*. SW-10c. Washington, DC: U.S. Environmental Protection Agency.

Kaiser, E.R. 1969. Chemical analyses of refuse compounds. *Proceedings of the National Incinerator Conference*. ASME, New York.

Khan, M.Z.A. and Abu-Gharara h, Z.H. 1991. New approaches for estimating energy content in MSW. *J Environ Eng* 117, 376–380.
Kiely, G. 1997. *Environmental Engineering*. New York: McGraw-Hill.
Liu, D.H.F. and Liptak, B.G. 2000. *Hazardous Waste and Solid Waste*. Boca Raton, FL: Lewis Publishing.
Masterson, W.L., Slowinski, E.J., and Stanitski, C.L. 1981. *Chemical Principles*, 5th ed. Philadelphia, PA: Saunders College Publishing.
NDSWRA (North Dakota Solid Waste and Recycling Association). 2013. *Household Hazardous Waste – Definition*. Available from: http://www.ndswra.org/dnn/HouseholdHazardousWaste/DefinitionofHouseholdHazardousWaste.aspx
Pearl, I.A. 1964. Lignin chemistry. *Chemical Engineering News*, July 6, pp. 81–92.
Pfeffer, J.T. 1992. *Solid Waste Management Engineering*. Englewood Cliffs, NJ: Prentice-Hall.
Rhyner, C.R. 1976. Domestic solid waste and household characteristics. *Waste Age* 50, 29–50.
Rhyner, C.R. 1992. The monthly variations in solid waste generation. *Waste Manag Res* 10, 67.
Rhyner, C.R. and Green, B.D. 1988. The predictive accuracy of published solid waste generation factors. *Waste Manag Res* 6, 329–338.
Rhyner, C.R., Schwartz, L.J., Wenger, R.B., and Kohrell, M.G. 1995. *Waste Management and Resource Recovery*. Boca Raton, FL: Lewis Publishing.
Savage, G.M. 1996. Assessing waste quantities and properties: a vital requirement for successful solid waste management planning. *Warmer Bull*, *J World Resour Foun.*, High Street, Tonbridge, Kent, UK, 49, 18–22.
Sincero, A.P. and Sincero, G.A. 1996. *Environmental Engineering: A Design Approach*. Upper Saddle River, NJ: Prentice-Hall.
Singer, J.G. (Ed.). 1981. *Combustion: Fossil Power Systems*. Windsor, CT: Combustion Engineering.
Tchobanoglous, G., Theisen, H., and Vigil, S. 1993. *Integrated Solid Waste Management: Engineering Principles and Management Issues*. New York: McGraw-Hill.
USCOTA (U.S. Congress Office of Technology Assessment). 1989. *Facing America's Trash: What Next for Municipal Solid Waste?* OTA-O-424. Washington, DC: U.S. Government Printing Office.
U.S. Department of Health, Education, and Welfare. 1969. *Incinerator Guidelines*. Washington, DC: U.S. Department of Health, Education, and Welfare.
U.S. EPA (U.S. Environmental Protection Agency). 1999. *Characterization of Municipal Solid Waste in the United States: 1998 Update*, EPA530. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 2011. *Municipal Solid Waste in the United States: 2010 Facts and Figures*. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.
Vesilind, P.A., Peirce, J.J., and Weiner, R.F. 1988. *Environmental Engineering*, 2nd ed. Boston, MA: Butterworths.
Vesilind, P.A., Worrell, W.A., and Reinhart, D.A. 2002. *Solid Waste Engineering*. Pacific Grove, CA: Brooks/Cole.
Williams, P.T. 1998. *Waste Treatment and Disposal*. New York: Wiley.
Wisconsin Department of Natural Resources. 1981. *The State of Wisconsin Solid Waste Management Plan*. Madison, WI: Wisconsin Department of Natural Resources.
Yu, C. and MacLaren, V. 1995. A comparison of two waste stream quantification and characterization methodologies. *Waste Manag Res* 13, 343–361.

SUGGESTED READINGS

Burnley, S.J. 2007. A review of municipal solid waste composition in the United Kingdom. *Waste Manag* 27(10), 1274–1285.
DSM Environmental Services, Inc. 2002. *Vermont Waste Composition Study*. Ascutney, VT: Vermont Department of Environmental Conservation Solid Waste Program.
Gidarakos, E., Havas, G., and Ntzamilis, P. 2007. Municipal solid waste composition determination supporting the integrated solid waste management system in the island of Crete. *Waste Manag* 26(6), 668–679.
Miller, C. 2002. *Garbage by the Numbers*. National Solid Wastes Management Association Research Bulletin 02-02. Available from: http://www.nswma.org/General%20Issues/Garbage%20By%20The%20Numbers%202002.pdf
Ministry for the Environment. 2002. *Solid Waste Analysis Protocol*. Available from: http://www.mfe.govt.nz

Toronto, City of, n.d., Solid Waste Quantity and Composition. How much? What is it? Available from: http://www.city.toronto.on.ca/wes/techservices/involved/swm/net/pdf/presentation_March05_03.pdf

U.S. EPA (U.S. Environmental Protection Agency). 2002. *RCRA Waste Sampling Draft Technical Guidance Planning, Implementation, and Assessment,* EPA530-d-02-002. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.

5 Municipal Solid Waste Collection

What a long strange trip it's been.

The Grateful Dead, 1970

5.1 INTRODUCTION

Collection is among the first steps of a solid waste management program; therefore, proper planning and implementation of collection services can serve as a foundation for sound waste management. Waste disposal costs continue to increase across the United States, and the costs of collection actually exceed those of disposal—collection costs range between 40% and 60% of a community's solid waste management system costs (U.S. EPA 1999). Efficient collection can, therefore, ultimately hold down waste management costs.

5.2 DEVELOPING A WASTE COLLECTION SYSTEM

In the United States, collection services are provided to residents of most urban and suburban locations, as well as rural areas, by municipal governments or private haulers. Collection programs vary across communities depending on waste types collected, community characteristics, economics, and the desires of residents. In recent years, collection services have expanded in many communities to include pickup of recyclable materials, yard wastes, and even household hazardous wastes. Different collection equipment and hauling companies are used in a single community to serve different customers (e.g., single family, multifamily, commercial) or to collect specific materials (raw MSW, recyclables, and bulky waste).

Because collection and waste transfer may be difficult and cumbersome, several factors and options must be considered in their planning and design. When a community is considering the implementation of a new collection program, some of the most immediate variables to identify and address are waste types, the service area, the level of desired service, public versus private hauling, how to fund the program, creating and meeting waste reduction goals, and handling labor contracts. Some of the more salient issues for a community planning its MSW collection program are discussed in this section.

5.2.1 Characterization of Wastes

Data concerning waste sources, waste composition, and total volumes are critical for proper planning of a collection program. Accurate and current data on the characteristics of municipal wastes will not only encourage well-organized and smoothly functioning collection but also enhance recycling programs and possibly reduce the amount of waste generated, thus holding down overall waste management costs. Waste characterization has been discussed in Chapter 4.

5.2.2 Service Area and Level of Service

Block- and city-street maps should be evaluated by program planners to determine street configurations, including the number of houses, location of one-way and dead-end streets, and

traffic patterns. The ultimate goal is to formulate an efficient system where dead time (e.g., U-turns, detours, delays at railroad crossings) for vehicles and collection crews is minimized.

The level of services to the community includes specifying the materials to be collected and any requirements for separate collection (e.g., picking up recyclables in a separate vehicle). The frequency of pickup and the set-out requirements for residents must also be determined.

5.2.3 Public versus Private Collection

A municipality's waste collection system may be operated by a city department, one or more competing private firms, or a combination of public and private haulers. In municipal collection, a city or county agency, such as the local waste management office, hires its own employees and equipment to collect waste. With private collection, the municipal agency contracts with a private collection firm. Larger communities may issue multiple collection contracts, each for a different geographic area, type of customer (single family vs. multifamily units), or material collected (e.g., MSW vs. recyclables). Private collection relies on competition to set prices and establish quality of service. Some communities allow haulers to bid competitively to provide a specified level of service to residents within an area.

5.2.4 Funding the Collection System

The municipality must formulate a funding plan to generate the money necessary to pay for collection services. The three options for funding waste services are property tax revenues, flat fees, and variable-rate fees. Property taxes are the conventional means of funding solid waste collection, especially in communities where municipal employees are the waste collectors and haulers. The property tax method is preferred for its administrative simplicity—a separate system is not needed to bill and collect payments since funds are derived via the collection of personal and corporate property taxes. Unfortunately, however, funding waste collection from property taxes provides no incentive for waste reduction (U.S. EPA 2003).

In recent years, many municipalities have shifted away from the property-tax-based system and are instead instituting user fees, primarily a result of imposed caps on property tax increases. With the property tax method of payment, customers rarely see a bill and generally have no idea how much it costs to remove their wastes. User fees are a common method for funding collection in communities served by private haulers and in cities where a separate authority is used for solid waste services. As with the property tax method, flat fees provide no incentive for reducing wastes by residents.



FIGURE 5.1 Bags and stickers may be used in a "pay-as-you-throw" waste collection program.

The variable-rate fee system (also known as "pay as you throw") requires waste generators to pay in proportion to the amount of waste they set out for collection. Variable-rate systems typically require that residents purchase special bags or stickers (Figure 5.1). A range of service levels is made available to waste generators. The purchase price of bags or stickers is set sufficiently high to cover program costs. The use of bags and stickers helps citizens become more aware of how much waste they are producing; thus, there is an incentive to reduce waste volumes. In addition, by using smaller or fewer bags or fewer stickers, residents can generate savings from source reduction efforts. Another option is to charge different rates for various sizes of cans or other containers. Some communities will collect recyclables at reduced cost to residents as a financial incentive to recycle. In a study of eight U.S. communities (Miranda and Aldy 1996), significant increases in recycling tonnages were reported when a pay-as-you-throw pricing system was established. San Jose, CA, and Lansing, MI, experienced more than a doubling of recycling levels over a 2- and 3-year period, respectively. Communities in Illinois experienced recycling rate increases between 41% and 64% over 5 years. Pasadena and Santa Monica, CA experienced recycling rate increases of approximately 70% and 30%, respectively.

Many communities have chosen to combine elements of the above funding methods to form a hybrid system that is best suited to their community.

5.3 LOGISTICS OF THE COLLECTION PROGRAM

5.3.1 Storage Container Requirements

Specific waste storage containers are often required for a particular collection program. Containers should be appropriate for the collection vehicles used; for example, a community may decide to use self-loading compactor trucks. Residents must therefore place wastes in containers that fit the container-lifting devices of the trucks. Containers should also be easy to handle; durable; and resistant to corrosion, weather, and animals. In areas where waste is collected manually, standard-sized metal or plastic containers, or plastic bags, are usually specified. Many municipalities limit the size of cans to 30–35 gal or to a maximum total weight. If plastic bags are used, a minimum thickness may be required. Some programs require the use of bags because they do not have to be emptied and returned to the curb; collection is thus more rapid and efficient as compared with using cans. Many cities prohibit the use of other containers because they may be difficult to handle and increase risk of worker injury. Some municipalities also limit the total number of containers collected at a single residence. Special fees may be charged for additional containers.

5.3.2 Set-Out Requirements

To establish uniform collection, communities may formulate guidelines and enact ordinances that specify how residents are to prepare solid waste and recyclables for collection. Set-out requirements address the types of containers to be used, the segregation of recyclables or other wastes for separate collection, how frequently materials are collected, and where residents are to place containers and materials for collection.

5.3.3 Waste Separation

Many communities arrange for the separate collection of a specific solid waste component; for example, recyclable materials or yard wastes may be collected on a different day from ordinary MSW. Residents are therefore required to segregate wastes before collection; they may be expected to set aside recyclable materials such as paper, cardboard, glass, aluminum, and plastic; similarly, yard waste, bulky items, and household hazardous wastes may have to be segregated for special collection. Some communities are testing so-called wet and dry collection systems, in which "wet" organic wastes suitable for composting are collected separately from "dry" wastes, which may be sorted for recovery of recyclable material (U.S. EPA 2003).

5.3.4 Frequency of Collection

The greater the frequency of collection in a community, the more costly the collection system will be. Factors to consider when establishing collection frequency include total cost, desires of residents, storage limitations, and climate. Collection once per week is common for most U.S. municipalities. Crews collecting once per week collect more tons of waste per hour than the twice-a-week collection vehicles; however, they make fewer stops per hour. Some communities in hot, humid climates use twice-per-week service due to health and odor concerns with MSW. In one study, once-per-week systems were found to collect 25% more waste per collection hour, although serving 33% fewer homes during that period. Personnel and equipment requirements were 50% higher for once-per-week collection (U.S. EPA 1974a). In Montgomery County, MD, one part of the county received weekly MSW pickup, whereas other areas received twice-per-week pickup. Twice-per week collection was almost 70% more costly than once-per-week collection (U.S. EPA 1999).

Example 5.1

In the town of Livengood, OH, it is determined that the per capita waste generation rate is 1.4 kg (3.1 lb) per person per day. Collection is conducted once per week by the municipality. If the density of MSW in a typical trash container is 150 kg/m^3, how many 120 L (30 gal) containers would be needed for a family of four?

$$1.4 \text{ kg/person/day} \times 7 \text{ days/week} = 9.8 \text{ kg MSW}$$

$$9.8 \text{ kg lb/person} \times 4 \text{ persons} = 39.2 \text{ kg/family}$$

$$39.2 \text{ kg}/150 \text{ kg/m}^3 = 0.26 \text{ m}^3$$

$$0.26 \text{ m}^3 \times 1000 \text{ L/m}^3 = 260 \text{ L}$$

Thus, three 120-L containers are required.

Example 5.2

From the above example, collection trucks have a capacity of 11.5 m^3 (15 yd^3), which can compact the waste to a density of 420 kg/m^3. How many customers can a truck handle in a single run before departing for the transfer station?

$$11.5 \text{ m}^3 \times 420 \text{ kg/m}^3 = 4830 \text{ kg capacity}$$

$$4830 \text{ kg}/39.2 \text{ kg/household} = 123 \text{ households}$$

5.3.5 Waste Pickup Locations

In urban and suburban communities, waste is typically collected using curb-side or alley pickup. Backyard service, more common in the past, has been all but eliminated in U.S. communities. Some municipalities offer collection services to larger apartment buildings and commercial establishments. In other communities, service to these customers is provided by private collection companies. In general, wastes from such buildings are stored in dumpsters or roll-off containers.

In rural areas, residents are usually required to place containers near their mailboxes or other designated pickup points along major routes. Other municipalities require a drop-off arrangement, where wastes are brought to a facility known as a *transfer station*. A drop-off system is obviously much less expensive than a collection service but is less convenient for residents. Table 5.1 lists various waste collection methods and their advantages and disadvantages.

TABLE 5.1
Advantages and Disadvantages of Various Pickup Points for Collecting MSW

Curb-Side/Alley Collection

Residents place containers to be emptied at curb or in alley on collection day. Collection crew empties containers into collection vehicle. Resident returns containers to their storage location until the next scheduled collection time.

Advantages:

- Crew can move quickly.
- Crew does not enter private property, so fewer accidents and trespassing complaints arise.
- Less costly than backyard collection because it generally requires less time and fewer crew members.
- Adaptable to automated and semi automated collection equipment.

Disadvantages:

- On collection days, waste containers are visible from street.
- Collection days must be scheduled.
- Residents are responsible for placing containers at the proper collection point.

Drop-off at Specified Collection Point

Residents transport waste to a specified point. This point may be a transfer station or the disposal site.

Advantages:

- The least expensive method.
- Offers reasonable strategy for low population densities.
- Involves low staffing requirements.

Disadvantages:

- Residents are inconvenienced.
- Increased risk of injury to residents.
- If drop-off site is unstaffed, illegal dumping may occur.

Source: Reproduced with permission of the APWA (American Public Works Association) and Institute for Solid Wastes, *Solid Waste Collection Practice*, 4th ed., APWA, Chicago, IL, 1975.

5.3.6 Collection Equipment

A wide range of vehicle types is available for waste collection. Collection equipment is continually being redesigned to meet changing needs and incorporate advances in technology. Recent trends include increased use of computer-aided equipment, GPS units, mechanical lifting devices, and electronic controls. Some trucks are equipped with onboard computers for monitoring truck performance and collection operations.

Collection vehicles used for MSW transport in various countries include (Kiely 1997):

- Traditional compacter-type trucks taking loose and bagged waste
- Modern single-compartment trucks taking wheeled bins from single-unit dwellings, multiunit apartment buildings, and commercial establishments
- Multicompartment trucks that handle source-separated waste
- Trucks taking container loads, either closed- or open-top
- Vacuum trucks, used in areas with limited accessibility, with tube lengths up to 100 m
- Traditional open-top trucks, commonly used in low-income countries

Truck chassis and bodies are usually purchased separately and can be combined in a number of designs. When selecting chassis and bodies, municipalities must consider regulations regarding truck size and weight. Truck selection must address maximizing the amount of wastes that can be collected while remaining within legal weights for the vehicle.



FIGURE 5.2 Compactor-type truck common in urban and suburban neighborhoods.

Compactor trucks are by far the most prevalent waste collection vehicles in use (Figure 5.2). Hydraulically powered rams compact waste and later push it out of the truck at the disposal or transfer facility. Compactor trucks are classified as front-, side-, or rear-loading with capacities varying from 7.5 to 35 m^3 (10–45 yd^3).

Prior to the development of compactor trucks, open and closed noncompacting trucks were used to collect solid waste. These vehicles are inefficient for MSW collection because they carry a relatively small amount of waste, and workers must lift waste containers high to place wastes into the truck. Noncompacting trucks are still used for collecting bulky items like furniture and white goods, or other materials that are collected separately, such as recyclables and yard waste. Noncompacting trucks may also be suitable for servicing small communities and rural areas.

5.3.7 Automated Waste Collection

Waste collection is a labor-intensive business, sometimes requiring as many as three workers per vehicle to lift and dump containers. With the advent of automated lifting systems, however, collection requires fewer workers, thereby reducing labor costs and workers' compensation claims.

Semiautomated and fully automated systems are two innovative approaches to MSW collection. Both systems rely on specialized trucks with mechanical or hydraulic lifting systems and require customers to use special wheeled carts. With semiautomated vehicles, crews wheel the carts to the collection vehicle and line them up with hydraulic lifting devices mounted on the truck body, activate the lifting mechanism, and then return empty containers to the collection point. In fully automated vehicles, drivers control hydraulic arms or grippers from the vehicle cab. Unless there are problems, such as the overflow of materials, improperly prepared materials, or obstructed set-outs, the driver can service a route without leaving the collection vehicle (Figure 5.3). The benefits of automated waste collection include (U.S. EPA 1999):

- Reduced injury risk: Increased automation reduces work-related lifting injuries as well as puncture wounds and lacerations.
- Reduced vehicle needs: Fully automated collection increases (by up to 300%) the number of households served per hour. This increased productivity typically results in a smaller fleet of vehicles.
- Decreased labor needs: Automated collection reduces crew size per truck. For semiautomated collection, one- or two-person crews are typical. With fully automated systems, the driver typically works alone.



(a)



(b)

FIGURE 5.3 Automated collection vehicles for (a) residential wastes and (b) commercial wastes.

- Reduced environmental impacts: Automated collection means fewer trucks, lower fuel usage, fewer air emissions, and fewer traffic and safety impacts on community streets.
- Reduced tipping fees: Carts with lids help keep water, ice, and snow from set-outs, which helps control the weight of set-outs and decreases tipping fees.
- Improved neighborhood aesthetics: Uniform containers eliminate unsightly set-outs. Containers with lids are less likely to be tipped over or torn apart by animals, reducing litter potential.
- Reduced public health risks: Containers with lids help mitigate odor and health concerns.

Waste set-out requirements, waste quantities, and unique features of collection routes are important considerations when selecting collection vehicles. For example, suburban areas with wide streets and limited on-street parking may be ideally suited to side-loading automatic collection systems. Conversely, urban areas with narrow alleys and tight corners may require rear loaders and shorter wheelbases. For large apartment buildings and complexes and for commercial and industrial applications, hauled container systems are often used.

Table 5.2 provides criteria to consider for selecting the most appropriate collection equipment. Municipalities can use these criteria to determine the requirements that their equipment must meet. In addition, certain cost data should be compared for each truck being considered, including initial capital cost, annual maintenance and operation costs, and expected service life (U.S. EPA 2003).

If the number of households that a truck can service in a single day has been determined, the number of collection vehicles needed for a community can be estimated by the equation (Vesilind et al. 2002):

$$N = (S)\,(F)/(X)\,(W) \tag{5.1}$$

where N is the number of collection vehicles needed, S the total number of households serviced, F the number of collections per week, X the number of customers a truck can service per day, and W the number of workdays per week.

TABLE 5.2
Factors to Consider in Selecting Waste Collection Equipment

Loading Location

Compactor trucks are loaded in either the side, back, or front. Front-loading compactors are used with self-loading mechanisms and dumpsters. Rear loaders are used for both self and manual loading. Side loaders are more likely to be used for manual loading and are often considered more efficient than back-loaders when the driver does some or all of the loading.

Truck Body or Container Capacity

Compactor capacities range from 10 to 45 cubic yards. Containers associated with hauled systems generally have a capacity range of 6–50 cubic yards. To select the optimum capacity for a particular community, the best tradeoff between labor and equipment costs should be determined. Larger capacity bodies may have higher capital, operating, and maintenance costs.

Heavier trucks may increase wear and tear, and corresponding maintenance costs for residential streets and alleys.

Design Considerations:

- The loading speed of the crew and the collection method used.
- Road width and weight limits (consider weight of both waste and vehicle).
- Capacity should be related to the quantity of wastes collected on each route. Ideally, capacity should be an integral number of full loads.
- Travel time to transfer station or disposal site, and the probable life of that facility.
- Relative costs of labor and capital.

Chassis Selection

Chassis are similar for all collection bodies and materials collected.

Design Considerations:

- Size of truck body. Important for chassis to be large enough to hold truck body filled with solid waste.
- Road width and weight limitations (also need to consider waste and truck body weight).
- Air emissions control regulations.
- Desired design features to address harsh treatment (e.g., driving slowly, frequent starting and stopping, heavy traffic and heavy loads) include the following: high torque engine, balanced weight distribution, good brakes, good visibility, heavy duty transmission, and power brakes and steering.

Loading and Unloading Mechanisms

Loading mechanisms should be considered for commercial and industrial applications and for residences when municipalities wish to minimize labor costs over capital costs. A variety of unloading mechanisms are available.

Design Considerations—Loading:

- Labor costs of collection crew.
- Time required for loading.
- Interference from overhead obstructions such as telephone and power lines.
- Weight of waste containers.

Design Considerations—Unloading:

- Height of truck in unloading position. Especially important when trucks will be unloaded in a building.
- Reliability and maintenance requirements of hydraulic unloading system device.

Truck Turning Radius

Radius should be as short as possible, especially when part of route includes cul-de-sacs or alleys. Short wheelbase chassis are available when tight turning areas will be encountered.

Watertightness

Truck body must be watertight so that liquids from waste do not escape.

Safety and Comfort

Vehicles should be designed to minimize the danger to solid waste collection crews.

Design Considerations:

- Carefully designed safety devices associated with compactor should include quick-stop buttons. In addition, they should be easy to operate and convenient.
- Truck should have platforms and good handholds so that crew members can ride safely on the vehicle.
- Cabs should have room for crew members and their belongings.
- Racks for tools and other equipment should be supplied.
- Safety equipment requirements should be met.
- Trucks should include audible back-up warning device.
- Larger trucks with impeded back view should have video camera and cab-mounted monitor screen.

TABLE 5.2 (*Continued*)
Factors to Consider in Selecting Waste Collection Equipment

Loading Height

The lower the loading height, the more easily solid waste can be loaded into the truck. If the truck loading height is too high, the time required for loading and the potential of injuries to crew members will increase because of strain and fatigue.

Design Considerations:

- Weight of full solid waste containers.
- If higher loading height is being considered, an automatic loading mechanism may be preferable.

Speed

Vehicles should perform well at a wide range of speeds.

Design Considerations:

- Distance to disposal site.
- Population and traffic density of area.
- Road conditions and speed limits of routes that will be used.

Adaptability to Other Uses

Municipalities may wish to use solid waste collection equipment for other purposes such as snow removal.

Source: Reproduced with kind permission from Pferdehirt, W., Madison Solid and Hazardous Waste Education Center, University of Wisconsin, Madison, WI, 1994.

Example 5.3

From the data for the town of Livengood (Example 5.1), determine the number of collection vehicles needed if 8250 households must be serviced once per week. The trucks collect wastes 4 days per week, with 1 day for routine truck maintenance and other projects.

We will assume that an average truck can service 1.4 households per minute. The actual time spent collecting is 5 h. The total number of households served per day is

$$(1.4)/(1) = (x)/(5\ \text{h} \times 60\ \text{min}) = 420\ \text{customers per day}$$

$$N = (S)\ (F)/(X)\ (W)$$

$$N = (8250)\ (1)/(420)\ (4) = 4.9\ \text{trucks}$$

5.3.8 Developing Collection Routes

Comprehensive collection routes and schedules must be developed for the planned collection program. Efficient routing of collection vehicles hold down costs by reducing the labor expended for collection. Routing procedures usually comprise two separate components: microrouting and macrorouting (U.S. EPA 2003). *Macrorouting* consists of dividing the total collection area into routes of a size sufficient for a one-day collection for a single crew. The size of a route is a function of the amount of waste collected per stop, distance between stops, loading time, and traffic conditions. Barriers such as railroad embankments, rivers, and roads with heavy competing traffic can be used to divide route areas.

For large areas, macrorouting is best accomplished by first dividing the entire community into districts. Each district is subsequently divided into routes for individual crews. Using the results of the macrorouting analysis, *microrouting* designates the specific path that each crew and collection vehicle will follow on a given day. Results of microrouting analyses can then be used to readjust macrorouting decisions. Microrouting analyses and planning can accomplish the following (U.S. EPA 2003):

- Increase the likelihood that all streets will be serviced equally and consistently.
- Help supervisors locate crews quickly because they know the specific routes that will be followed.

- Provide potentially optimal routes that can be tested against the driver's experience to establish the best actual routes.

The method selected for microrouting must be simple enough to incorporate route adjustments; for example, seasonal variations in waste generation will require trip modification. Seasonal fluctuations can be accommodated by providing fewer, larger routes during low-generation periods (typically winter) and increasing the number of routes during high-generation periods (spring and fall).

5.3.9 Route Development

Many decades ago, the Office of Solid Waste Management Programs, U.S. EPA, developed a simple, heuristic (i.e., manual) approach to collection vehicle routing based on certain logical principles. The method was developed to promote an efficient routing layout and to minimize the number of turns and dead space encountered. This method relies on developing, recognizing, and using certain patterns that repeat in every municipality. Route planners refer to a large-scale block map showing locations of collection service garages, disposal or transfer sites, one-way streets, natural barriers, and areas of heavy traffic flow. Routes are drawn using certain practical rules, some of which are shown below:

1. Routes should not be fragmented or overlapped. Each route should be compact, consisting of street segments clustered in the same geographical area.
2. The collection route should be started as close to the garage or motor pool as possible, taking into account heavily traveled and one-way streets (see Rules 4 and 5).
3. Waste from heavily traveled streets should not be collected during rush hours.
4. In the case of one-way streets, it is best to start the route near the upper end of the street, working it through the looping process (see Figure 5.4).
5. When practical, service stops on steep hills should take place on both sides of the street while the vehicle is moving downhill, for safety, ease, speed of collection, reduction of wear on vehicle, and conservation of fuel.

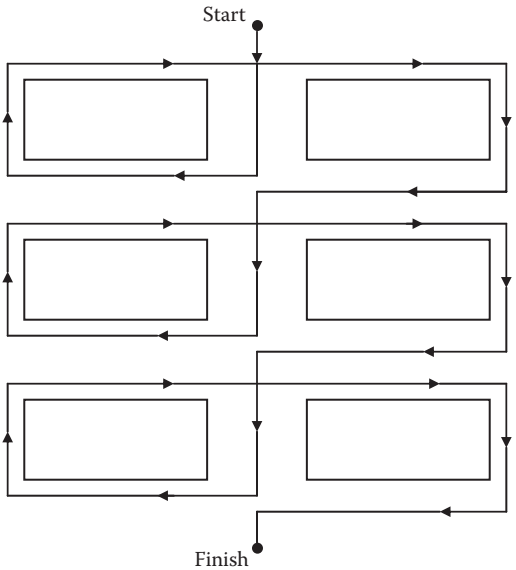


FIGURE 5.4 Routing patterns for one-way street collection. (From U.S. EPA, *Heuristic Routing for Solid Waste Collection Vehicles*, DSW/SW-1123, U.S. EPA, Washington, DC, 1974.)

6. Higher elevations should be at the start of the route.
7. For collection from one side of the street at a time, it is generally best to route with many clockwise turns around blocks.

Figures 5.5 and 5.6 are examples of heuristic tools that can be applied depending on the block patterns within a collection area.

Many computer programs are commercially available for establishing route design, especially because routes need to be adjusted periodically. Optimization of routing has been explored using a number of algorithms. Routing algorithms use a standard of measurement termed a metric (i.e., path length) to determine the optimal route or path to a specified destination. Optimal routes are determined by comparing metrics, and these metrics differ depending on the design of the routing algorithm used (Parker 2001; Karadimas et al. 2008).

Programs can be used to develop detailed microroutes or to adjust existing routes (C2Logix.com 2011). To program detailed microroutes, planners require information similar to that needed for heuristic routing, for example, block configurations, waste generation rates, distances between residences, distances between routes and disposal or transfer sites, and loading times (U.S. EPA 2003). Municipalities that have a geographic information system (GIS) database can use data for their area to facilitate computerized route balancing (RouteSmart, n.d.).

5.3.10 Waste Transfer

Waste transportation costs will be substantial if the distance between the collection zone and final destination (e.g., landfill, incinerator) is significant. In the interest of economics, many municipalities choose to transfer waste from neighborhood collection trucks to larger vehicles before transporting it to the disposal site. A transfer station may be established between the waste collection sources and the final destination to serve in this capacity.

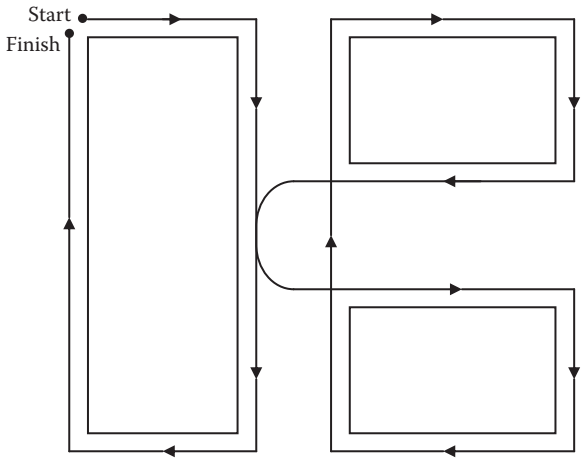
The primary purpose for using a transfer station is to reduce the traffic of smaller vehicles to the disposal site, ultimately resulting in reduced transport costs, including labor (crews spend less time traveling to the disposal site) and fuel. Transfer stations offer additional benefits, including reduced maintenance costs for collection vehicles, increased flexibility in the selection of disposal facilities, the opportunity to recover recyclable materials at the transfer site, and the opportunity to process wastes (shred or bale) prior to disposal. In determining whether a transfer station is appropriate, municipal decision-makers should compare the costs and savings associated with its construction and operation, with costs for direct shipping of the wastes from local neighborhoods to the landfill.

Transfer stations are often difficult to site and permit, particularly in urban areas. The farther the ultimate disposal site is from the collection area, the greater the savings attained from the use of a transfer station. The disposal site is typically at least 10–15 miles from the generation area before a transfer station is economically justified (see Figure 5.7). Transfer stations are sometimes used for shorter hauls to complete other duties, such as to sort wastes, or allow the shipment of wastes to more distant landfills (U.S. EPA 2003).

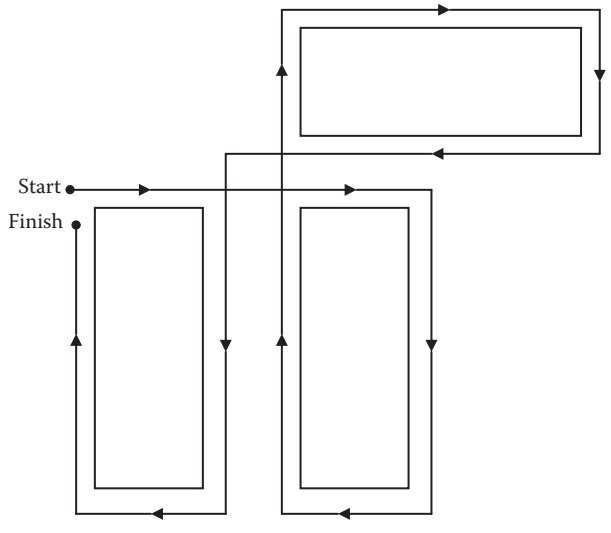
5.3.11 Types of Transfer Stations

The type of station that is most appropriate for a community depends on several design variables, for example (U.S. EPA 2003):

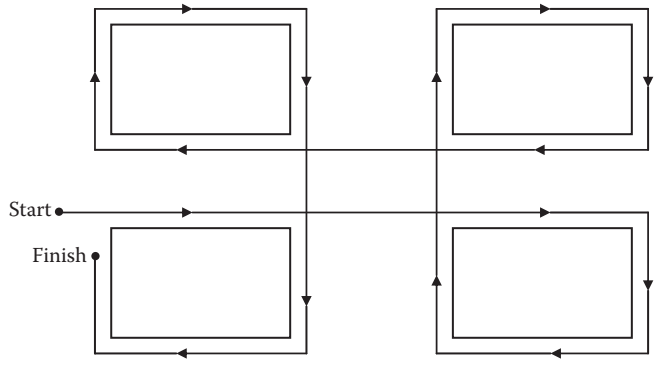
- Capacity for waste storage
- Types of wastes received
- Processes necessary to recover material from wastes
- Types of collection vehicles using the facility
- Types of transfer vehicles to be accommodated
- Site access



Three-block configuration



Variation of three-block configuration



Four-block configuration

FIGURE 5.5 Routing patterns for three- and four-block configurations. (From U.S. EPA, *Heuristic Routing for Solid Waste Collection Vehicles*, DSW/SW-1123, U.S. EPA, Washington, DC, 1974.)

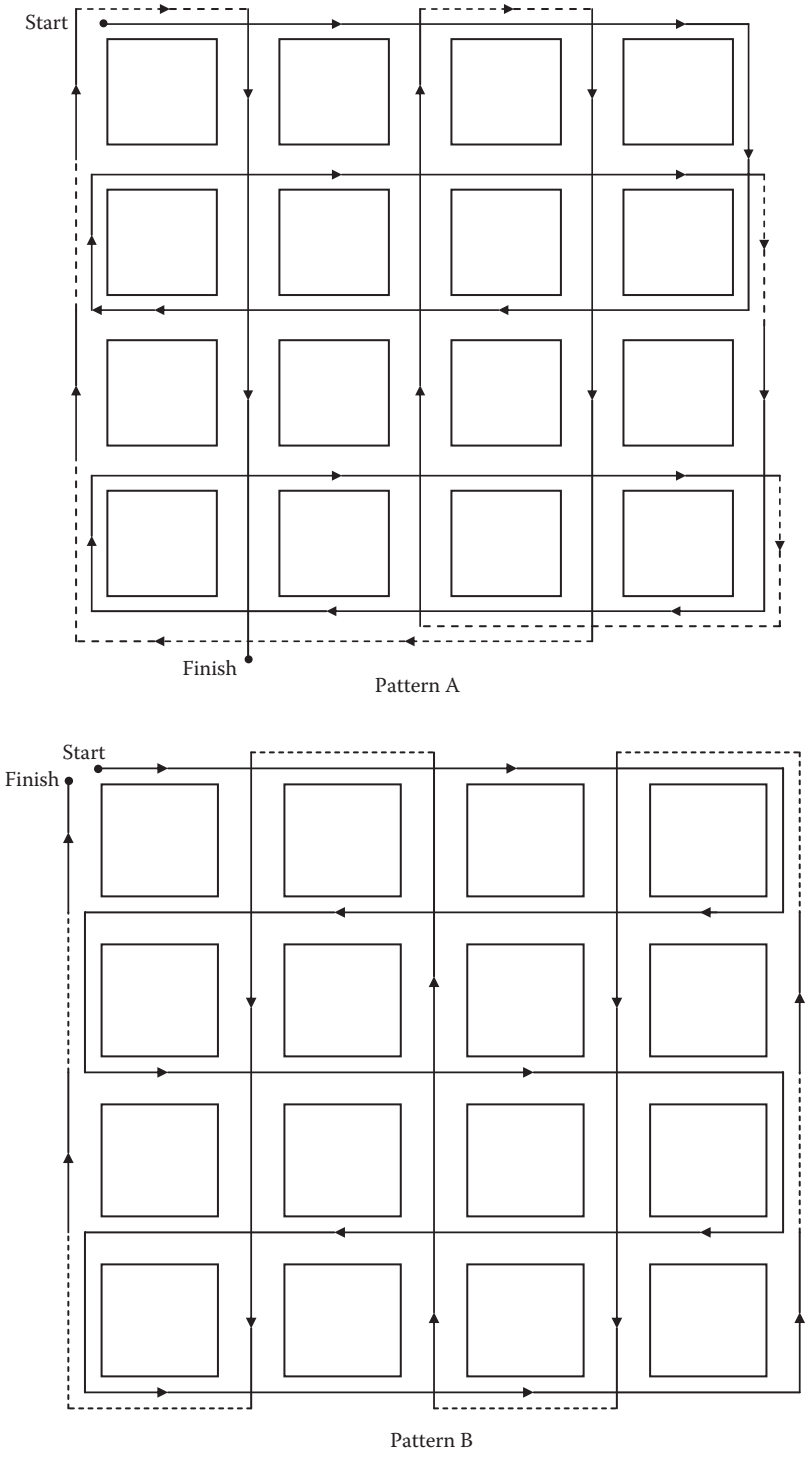


FIGURE 5.6 Routing patterns for a multiblock configuration. (From U.S. EPA, *Heuristic Routing for Solid Waste Collection Vehicles*, DSW/SW-1123, U.S. EPA, Washington, DC, 1974.)

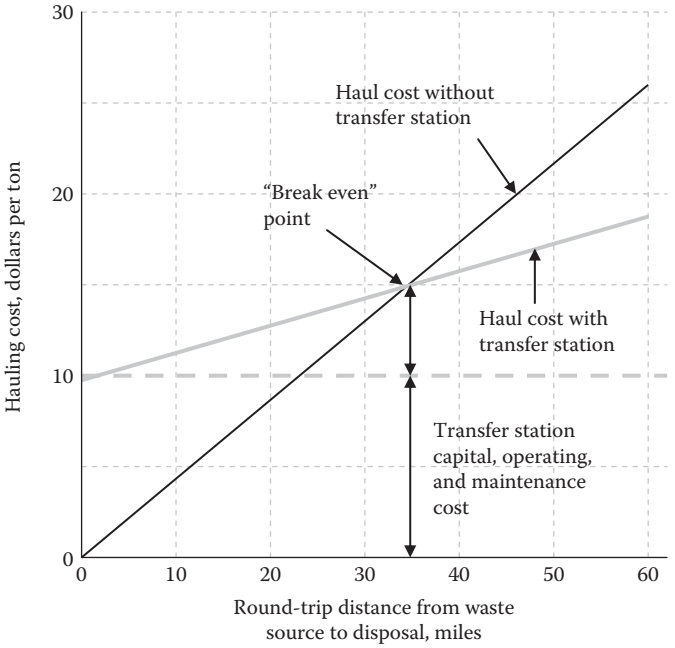


FIGURE 5.7 Comparison of waste hauling costs with and without a transfer station. (From U.S. EPA, *Waste Transfer Stations: A Manual for Decision-Making*, EPA530-R-02-002, Solid Waste and Emergency Response (5306W), U.S. EPA, Washington, DC, 2002.)

5.3.11.1 Small to Medium Transfer Stations (Capacity of Less than 100–500 Tons per Day)

Small to medium transfer stations are usually "direct-discharge" facilities that provide little area for interim waste storage. Such stations are equipped with operating areas for collection trucks and are often provided with drop-off areas for use by the public. Direct-discharge stations are often constructed with two operating floors. A compactor or open-top container is located on the lower level. Users enter the upper level and dump wastes into hoppers attached to these containers.

Some smaller transfer stations used in rural areas may use simple drop-off collection, in which a series of open-top containers is filled by users. The containers are then emptied into a larger vehicle at the station or hauled directly to the disposal site. The number and size of containers at the facility depend on the size and population density of the area served, and the frequency of collection.

5.3.11.2 Large Transfer Stations

Large transfer stations are designed for heavy commercial use by private and municipal collection vehicles. When collection vehicles arrive at the site, they are checked in for billing, weighed, and directed to the appropriate dumping area. Check-in and weighing procedures are often automated for regular users. Collection vehicles travel to the tipping area and empty wastes into a trailer or pit, or onto a platform. Transfer vehicles are weighed after loading to just under maximum legal weights; this maximizes payloads and minimizes weight violations.

Several different designs for larger transfer operations are common, depending on the transfer distance and vehicle type. Most designs fall into one of three categories: (1) direct-discharge noncompaction stations, (2) platform or pit noncompaction stations, or (3) compaction stations (U.S. EPA 2003).

1. *Direct-discharge noncompaction stations:* These stations are generally designed with two operating floors. In the transfer operation, wastes are dumped directly from collection vehicles on the top floor through a hopper and into open-top trailers on the lower floor. The trailers are



FIGURE 5.8 Pit-type noncompaction transfer station.

often positioned on scales so that dumping is halted when the maximum payload is reached. These stations are efficient because waste is handled only once. However, some provision for waste storage must be provided at peak drop-off times or during system interruptions.

2. *Platform or pit noncompaction stations:* In platform or pit stations, collection vehicles dump their wastes onto an area where wastes are temporarily stored and sorted for recyclables or unacceptable materials. The waste is then pushed into open-top trailers by front-end loaders (Figure 5.8). Platform stations are also constructed with two levels. Temporary storage is provided that can accommodate peak inflow of wastes. Construction costs may be higher with this type of station because of the increased floor space; however, the ability to temporarily store wastes results in a need for fewer trucks and trailers. Also, facility operators can haul wastes at night or during other slow traffic periods (U.S. EPA 2003).
3. *Compaction stations:* Compaction transfer stations use mechanical equipment to compact wastes before they are transferred. A hydraulically powered compactor is commonly used to compress wastes. Wastes are fed into the compactor through a chute either directly from collection trucks or after storage in a pit. The hydraulic ram pushes waste into the transfer trailer, which is mechanically linked to the compactor. Compaction stations are used when (1) wastes must be baled for shipment (e.g., rail haul) or for delivery to a so-called balefill, (2) open-top trailers cannot be used because of size restrictions such as viaduct clearances, and (3) the site layout does not accommodate a multilevel building conducive to loading open-top trailers (U.S. EPA 2003).

5.3.11.3 Transfer Station Design Considerations

The main objective in designing a transfer station should be to facilitate efficient operations. The operating program should be as simple as possible; waste handling should be minimized and the facility should be sufficiently flexible to be modified as needed. Equipment and building durability are essential to minimize maintenance costs.

1. *Site location and design:* Establishment of a transfer station can be hindered by the NIMBY syndrome. Local residents are more likely to accept a new transfer station if the site is carefully selected and buildings are designed appropriately for the site. Other factors to be addressed when considering a potential site are discussed below.
2. *Proximity to waste collection area:* Proximity to a collection area helps to maximize savings from reduced hauling time and distance. In some cases, municipalities may consider

constructing more than one transfer station. For example, two transfer stations may be economically preferable if travel time from one end of the city to the other are excessive.

3. *Accessibility of haul routes to disposal facilities:* Transfer trucks should be able to easily enter major truck routes, which reduces haul time and potential impacts on nearby homes and businesses. Planners may have to determine whether improvements to local roads are necessary. The availability of rail lines and waterways may allow the use of rail cars or barges for transfer to disposal facilities.
4. *Traffic:* Transfer stations will generate additional traffic in their immediate area, which can contribute to increased road congestion, air emissions, noise, and wear on roads. For this reason, waste transfer stations are often located in industrial areas that have ready access to major roadways. Travel routes and resulting traffic impacts typically receive significant attention during transfer station siting and design (U.S. EPA 2001).
5. *Site zoning and design requirements:* Municipalities must be certain that the proposed use meets site zoning requirements. The local site plan ordinance should also be reviewed to identify any restrictions that could affect design, such as building height and setback (U.S. EPA 2003).
6. *Availability of utilities:* A typical municipal transfer station will probably require full electricity and gas, water (for domestic use and firefighting), telephones, and sanitary and storm sewers. Designers must determine the cost of connecting to these utilities and the associated service charges.
7. *Visual impacts and aesthetics:* The transfer station should be oriented so that transfer operations and vehicle traffic are not visible to local residents. Visibility can be restricted if the site is sufficiently large. Landscaping, installation of berms, and other site improvements will greatly improve the aesthetic quality of the entire facility.
8. *Informing the community:* When initiating a siting process, education must include a community-wide outreach initiative. Components of public outreach may include (U.S. EPA 2002):
   - Public meetings
   - Interviews with local newspapers, media editorial boards, and broadcast media
   - News conferences and press releases
   - Paid advertising
   - Internet sites
   - Informational literature and direct mail
   - City council or county commission presentations
   - Presentations to civic, environmental, religious, professional, and neighborhood groups
   - Community education programs and workshops
   - Files located in public libraries or community centers
9. *Building design:* Whenever putrescible wastes are being handled, larger transfer stations should be enclosed.

   Typically, transfer station buildings are constructed of concrete, masonry, or metal. Wood is not commonly used because it is difficult to clean, is less durable, and is more susceptible to fire damage. Major considerations in building design include durability of construction, adequate size for tipping and processing, minimization of overhead obstructions to trucks, and flexibility of layout.
10. *Transfer station sizing:* The transfer station should have a sufficiently large capacity to manage the wastes that are expected to be received at the facility throughout its entire operating life. Factors to be considered in determining the appropriate size of a transfer facility include (U.S. EPA 2003):
    - Capacity of collection vehicles using the facility
    - Number of days of storage on tipping floor
    - Time required to unload collection vehicles

- Number of vehicles that will use the station and their expected days and hours of arrival (design to accommodate peak requirements)
- Waste sorting or processing to be accomplished at the facility
- Transfer trailer capacity
- Hours of station operation
- Availability of transfer trailers waiting for loading
- Time required to attach and disconnect trailers from tractors or compactors
- Time required to load trailers

Transfer stations are typically designed for one-half to two days of storage capacity. The collection vehicle unloading area usually comprises the waste storage area and a waste sorting area. When planning the unloading area, adequate space should be provided for vehicle and equipment maneuvering. To minimize the space required, the facility should be designed so that collection vehicles back into the unloading position. Adequate space must also be available for offices, employee facilities, and other facility-related activities. Formulas for determining transfer station capacity are presented below (U.S. EPA 2003).

11. *Stations with surge pits:* Based on rate at which wastes can be unloaded from collection vehicles:

$$C = P_C \times (L/W) \times (60 \times H_W/T_C) \times F \tag{5.2}$$

Based on rate at which transfer trailers are loaded:

$$C = (P_t \times N \times 60 \times H_t)/(T_t + B) \tag{5.3}$$

12. *Direct dump stations:*

$$C = N_n \times P_t \times F \times 60 \times H_W/[(P_t/P_C) \times (W/L_n) \times T_C] + B \tag{5.4}$$

13. *Hopper compaction stations:*

$$C = (N_n \times P_t \times F \times 60 \times H_W)/(P_t/P_C \times T_c) + B \tag{5.5}$$

14. *Push pit compaction stations:*

$$C = (N_p \times P_t \times F \times 60 \times H_W)/[(P_t/P_C) \times (W/L_p) \times T_C] + B_c + B \tag{5.6}$$

where C = Station capacity (tons/day)
P_C = Collection vehicle payloads (tons)
L = Total length of dumping space (feet)
W = Width of each dumping space (feet)
H_W = Hours per day that waste is delivered
T_C = Time to unload each collection vehicle (minutes)
F = Peaking factor (ratio of number of collection vehicles received during an average 30-min period to the number received during a peak 30-min period)
P_t = Transfer trailer payload (tons)
N = Number of transfer trailers loading simultaneously
H_t = Hours per day used to load trailers (empty trailers must be available)
B = Time to remove and replace each loaded trailer (minutes)
T_t = Time to load each transfer trailer (minutes)
N_n = Number of hoppers
L_n = Length of each hopper
L_p = Length of each push pit (feet)
N_p = Number of push pits
B_C = Total cycle time for clearing each push pit and compacting waste into trailer

5.3.12 Transfer Vehicles

Most transfer systems use tractor trailers for hauling wastes; however, other types of vehicles may also be used.

5.3.12.1 Trucks and Semitrailers

Trucks and semitrailers are flexible and effective because they can be adapted to serve the needs of individual communities. Truck and trailer systems should be designed to meet the following requirements:

- Wastes must be covered during transport
- The vehicles should be designed to operate safely in the traffic conditions encountered on hauling routes
- Truck capacity should be designed so that road weight limits are not exceeded
- Unloading methods should be simple and reliable
- Truck design should prevent leakage of liquids during hauling
- The materials used for trailer construction and the design of sidewalls, floors, and suspension systems should be able to withstand the MSW loads
- The number of required tractors and trailers depends on peak inflow, storage at the facility, trailer capacity, and number of hauling hours

Two types of trailers are used to haul wastes from the transfer station to the final disposal facility: compaction and noncompaction trailers. Noncompaction trailers are used with pit or direct dump stations, and compaction trailers are used with compaction stations. Noncompaction trailers can usually haul higher payloads than compaction trailers because the former do not require an ejection blade for unloading. Based on a maximum gross weight of 80,000 lb, legal payloads for compaction trailers are typically 16–20 tons, whereas legal payloads for open-top live-bottom trailers are 20–22 tons (U.S. EPA 2003).

Transfer vehicles should be able to negotiate the rough and muddy conditions of landfill access roads.

5.3.12.2 Rail Cars

Railroads carry only about 5% of transferred wastes in the United States. As the distance between sanitary landfills and urban areas increases, however, railroads become more appealing for transporting wastes to distant sites. Rail transfer stations are usually more expensive than similarly sized truck transfer stations because of costs for constructing rail lines, installing special equipment to remove and replace roofs of rail cars to load wastes, and installing special equipment to unload rail cars at the disposal facility. An 18.28-m (60-ft) boxcar can transport approximately 90 tons of waste compared with transfer trailers, which usually transport only 20–25 tons of waste (U.S. EPA 2003).

QUESTIONS

1. MSW compaction in a collection truck allows for increased volumes of waste to be transported; however, if this compacted material is brought to a materials recovery facility, there are potential disadvantages. Discuss.
2. In your community, observe the different containers used for the storage of MSW. What types of collection trucks are used for residential (single family) neighborhoods? Apartment complexes? Commercial facilities (restaurants, industrial parks, etc.)?
3. In your community, what are the major systems and equipment used for the collection of domestic and commercial solid wastes? Do programs exist for collection of source-separated wastes? For household hazardous wastes? Other?

4. In your community, is waste collected by the municipality or by a private hauler? Who collects commercial wastes?
5. What recommendations would you make regarding current waste collection in your community in order to reduce costs and improve efficiency?
6. How are yard wastes managed in your community? Are these materials collected separately from other wastes? If yard wastes are currently collected along with MSW, what changes to the collection system would be required in order to collect these wastes separately?
7. In your community, is there a program for collecting recyclable materials? If a program is in place, which materials are collected and how? Where are the recyclables shipped after collection? How much of each material (in tons) is collected per month?
8. In your community, how are household hazardous wastes transported to treatment or disposal facilities? In your opinion, is this management scheme effective, or are there problems to address?
9. If your community's wastes are collected by a municipal system, how much of the municipal budget is earmarked to cover these costs? Visit the local waste management office and determine how costs have changed over the past 10 years or more.
10. You have been hired as a consultant for a small town (population = 12,000) that wishes to begin a municipal program for solid waste collection. The community wants their wastes to be collected once per week. What type of collection vehicle would you recommend? What capacity truck would be appropriate (available truck capacities are 14, 16, and 20 yd^3)? Is once-per-week collection suitable for this community?
11. Using a map of your community, use a computer-aided design package to formulate a suitable route for waste collection vehicles. Alternatively, apply tracing paper and the U.S. EPA heuristic routing guidelines. Contact the waste hauler in your community and determine the method used to route collection vehicles.
12. Locate three sites in your area that could serve as locations for transfer stations. Justify your choices.
13. Discuss the benefits of transfer stations to a community in terms of economics, time savings, and environmental quality.
14. At your City Hall, obtain the accident records for city employees. Determine the relative accident rate for solid waste collection employees.

REFERENCES

APWA (American Public Works Association) and Institute for Solid Wastes. 1975. *Solid Waste Collection Practice*, 4th ed. Chicago, IL: APWA.

C2Logix.com. 2011. *Routing Software & Solutions for Residential Waste Collection*. Available from: http://www.c2logix.com/industries/optimize-routes-waste-collection-routing-software-route-planning

Karadimas, N.V., Doukas, N., Kolokathi, M., and Defteraiou, G. 2008. Routing optimization heuristics algorithms for urban solid waste transportation management. *WSEAS Trans Comput*, 12(7), 2022–2031.

Kiely, G. 1997. *Environmental Engineering*. New York: McGraw-Hill.

Miranda, M.L. and Aldy, J.E. 1996. *Unit pricing of Residential Municipal Solid Waste: Lessons from Nine Case Study Communities*, Report prepared for Office of Policy, Planning and Evaluation. Washington, DC: U.S. Environmental Protection Agency.

Parker, M. 2001. *Planning Land Information Technology Research Project: Efficient Recycling Collection Routing in Pictou County*. Available from: http://www.cogs.ns.ca/planning/projects/plt20014/images/research.pdf

Pferdehirt, W. 1994. Madison, WI: Madison Solid and Hazardous Waste Education Center, University of Wisconsin.

RouteSmart.com. n.d. RouteSmart for ArcGIS. Available from: http://www.routesmart.com/wp-content/uploads/2012/01/ArcGIS-RS_Brochure.pdf

U.S. EPA (U.S. Environmental Protection Agency). 1974a. *Residential Collection Systems*, *Volume* 1: *Report Summary*, SW-97c.1. Washington, DC: U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1974b. *Heuristic Routing for Solid Waste Collection Vehicles*, DSW/SW-1123. Washington, DC: U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 1999. *Collection Efficiency: Strategies for Success*, EPA530-K-99-007. Washington, DC: Solid Waste and Emergency Response (5306W), U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 2001. *Waste Transfer Stations: Involved Citizens Make the Difference*, EPA530-K-01-003. Washington, DC: Solid Waste and Emergency Response (5306W), U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 2002. *Waste Transfer Stations: A Manual for Decision-Making*, EPA530-R-02-002. Washington, DC: Solid Waste and Emergency Response (5306W), U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 2003. *Decision-Makers Guide to Solid Waste Management*, 2nd ed., EPA530-R-95-023. Washington, DC: Solid Waste and Emergency Response (5306W), U.S. EPA.
Vesilind, P.A., Worrell, W.A., and Reinhart, D.A. 2002. *Solid Waste Engineering.* Pacific Grove, CA: Brooks/Cole.

SUGGESTED READINGS

Bader, C. 2001. Where are the collection trucks going? *J Municipal Solid Waste Professionals*. Available from: http://www.forester.net/mw_0109.where.html
Blengini, G.A., Fantoni, M., Busto, M., Genon, G., and Zanetti, M.C. 2012. Participatory approach, acceptability and transparency of waste management LCAs: case studies of Torino and Cuneo. *Waste Manage*, 32(9): 1712–1721.
Bush, S. and Luken, K. 2002. Automated collection: getting the biggest bang for your buck. *J Municipal Solid Waste Professionals*. Available from: http://www.forester.net/mw_0209_automated.html
Canterbury, J. 1996. *Pay As You Throw: Lessons Learned about Unit Pricing of Municipal Solid Waste.* Chicago, IL: DIANE Publishing Company.
Central and Eastern Europe Business Information Center. 2002. *Environment Municipal Waste Management*, Market Research, May 2002.
Chatzouridis, C. and Komilis, D.A. 2012. Methodology to optimally site and design municipal solid waste transfer stations using binary programming. *Resour Conservat Recycl*, 60, 89–98.
Cutler, T. 2003. The components of comprehensive integrated waste management software systems. *J Municipal Solid Waste Professionals*. Available from: http://www.forester.net/mw_0303_componants.html
Faccio, M., Persona, A., and Zanin, G. 2011. Waste collection multi objective model with real time traceability data. *Waste Manage,* 31(12), 2391–2405.
Huang, Y.-T., Pan, T.-C., and Kao, J.-J. 2011. Performance assessment for municipal solid waste collection in Taiwan. *Waste Manage*, 92(4), 1277–1283.
Jacobsen, R., Buysse, J., and Gellynck, X. 2013. Cost comparison between private and public collection of residual household waste: Multiple case studies in the Flemish region of Belgium. *Waste Manage*, 33(1), 3–11.
Jonathan, R. and Manoor, A. 2002. *Vehicles for People or People for Vehicles? Issues in Solid Waste Collection in Low-Income Countries.* Cholchester: WEDC Publishing.
Kinhaman, T. 2003. *The Economics of Residential Solid Waste Management.* Hampshire: Ashgate.
Ludwig, C., Hellweg, S., and Stucki, S. 2003. *Municipal Solid Waste Strategies and Technology for Sustainable Solutions.* New York: Springer.
Miranda, M.L. and Aldy, J.E. 1998. Unit pricing of residential municipal solid waste: Lessons from nine case study communities. *J Environ Manag,* 52(1), 79–93.
Pasternar, S. and Yanke, S. 2003. Municipal solid waste management in Texas: A decade of change? *J Municipal Solid Waste Professionals*. Available from: www.forester.net/mw_0305_municipal.html
Teerioja, N., Moliis, K., Kuvaja, E., Ollikainen, M., Punkkinen, H., and Merta, E. 2012. Pneumatic vs. door-to-door waste collection systems in existing urban areas: A comparison of economic performance. *Waste Manage*, 32(10), 1782–1791.
U.S. EPA (U.S. Environmental Protection Agency). n.d. *Decision Makers Guide to Solid Waste Management*. Available from: http://www.epa.gov/epaoser/non-hw/muncpl/dmg2/chapter4.pdf
U.S. EPA (U.S. Environmental Protection Agency). 2000. *A Regulatory Strategy for Siting and Operating Waste Transfer Stations Response to a Recurring Environmental Circumstance: The Siting of Waste Transfer Stations in Low Income Communities and Communities of Color*, EPA 500-R-00-001. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2001. *Waste Transfer Stations: Involved Citizens Make the Difference*, EPA 530-K-01-003. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2002. *Waste Transfer Stations: A Manual for Decision Making*, EPA 530-R-02-002. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2003. *Frequently Asked Questions about Recycling and Waste Management, Municipal Solid Waste*. Available from: http://www.epa.gov/epaoswer/non-hw/muncpl/faq.htm

Vaccari, M., DiBella, V., Vitali, F., and Collivignarelli, C. 2012. From mixed to separate collection of solid waste: Benefits for the town of Zavidovići (Bosnia and Herzegovina). *Waste Manage*.

6 Recycling Solid Wastes

> We are not to throw away those things which can benefit our neighbor. Goods are called good because they can be used for good: they are instruments for good, in the hands of those who use them properly.
>
> **Clement of Alexandria (ca. 150–220 CE)**

6.1 INTRODUCTION

In an era when energy conservation, material cost and availability, and solid waste management are critical concerns to municipal administrations, scientists, and the general public, it is imperative that the importance of recycling and the value of products manufactured from scrap are appreciated. As we shall see, the benefits from waste recycling are not solely environmental, but economic and aesthetic as well.

As discussed in Chapter 1, integrated waste management embraces a hierarchy of management options to achieve maximum economic and environmental returns. Recycling was listed near the top of the hierarchy and will be addressed in this chapter.

As indicated in Chapter 2, recycling is not a new phenomenon. Animal manure, plant debris, and "night soil" have been applied to agricultural lands for millennia, and rag pickers were important recyclers in America as recently as the early twentieth century. Modern recycling can trace its roots back to the 1960s, following citizen awareness of myriad environmental and public health concerns. At that time, however, recycling programs often emphasized *segregation* of materials from the waste stream. Unfortunately, markets were not established for the purchase and reuse of separated materials. Manufacturers were reluctant to invest and participate in new processing technologies, and many were not equipped to handle these so-called "secondary materials." As a result, many separated materials found their way to the landfill. Recycling programs failed not only due to a lack of processing but also, more importantly, due to a lack of established markets for separated materials.

A new environmental awareness arose by the late 1980s, catalyzed by news of wash-ups of medical wastes, decline of landfill space, possible global warming, and atmospheric ozone depletion. At this time, sanitary landfills were closing and new ones faced substantial regulatory and grassroots opposition to permitting and siting. The cost of disposing wastes correspondingly increased. As a result, interest in recycling by the public and, significantly, by industries and government increased markedly.

In recent years, many community recycling efforts originated from efforts to reduce the waste load to the local landfill, thus saving tax dollars. Recycling drop-off centers and materials recovery facilities (MRFs) were established by municipalities as a result of public pressure. On a national and state scale, legislation has been promulgated that encourages recycling of MSW. Some regulations are aimed at waste generators, whether the individual homeowner or business; some take the form of guidelines or requirements for extending the lifetime of the local landfill. On the heels of federal mandates since 1990, most states set specific guidelines for reducing the quantities of waste entering landfills. These quotas were to be met via a combination of source reduction, recycling, and composting. Other legislation addressed the purchase of recycled materials. Some government offices, for example, are now required to

purchase paper manufactured containing a specified percentage of recycled fibers. As a result of such incentives and pressures, many industrialized nations have established innovative and proactive recycling strategies.

Two primary approaches are available for MSW segregation for eventual recycling: source separation and the MRF. Source separation includes the segregation of specific waste components by the individual homeowner and commercial establishment (i.e., *at the source*). The individual products (e.g., aluminum cans, paper, glass, plastics) are collected and transported to a facility for further processing, such as densifying and shredding. These slightly processed, clean materials are then sold to and removed by brokers or manufacturers. In contrast, the MRF is a centralized and mechanized facility that accepts either raw (*commingled*) MSW or source-separated materials. The mixed items are placed on conveyor belts where recyclables are removed at designated stations, either by hand or by a specialized mechanical device. Both source separation and MRF methods differ drastically in terms of efficiency of separation, capital costs, labor costs, energy use, and other factors. The MRF will be discussed in the next chapter.

6.2 RECYCLING TERMINOLOGY

Terms relating to recycling are often misused; in order to avoid confusion, it is important at the outset to clarify some of the relevant language.

Source separation—Removal of potentially recyclable materials from the waste stream. Conducted by the individual consumer and commercial establishment (Figure 6.1).

Reuse—Using an item for its original purpose. A common example is refilling a returnable soft drink bottle.

Recycling—Use of a material in a form similar to its original use. Newspapers are recycled into cardboard or new newspaper. Plastic is shredded and manufactured into fabric. Aluminum window frames are converted into new beverage containers.

Waste-to-energy—The conversion of MSW (preferably the organic fraction only) into energy by combustion in a controlled incinerator. Energy is recovered as heat and can be used directly; however, some facilities convert the heat energy into electrical energy.

Resource recovery—Extraction of energy or materials from wastes. This term incorporates all of the above. Thus, a waste-to-energy facility will incinerate organic wastes to generate heat energy. Glass and rubber are separated from wastes, processed, and used as road-building materials.



FIGURE 6.1 Drop-off centers are one means of segregating MSW components.

With the above terminology in mind, we can address the overall process of recycling as shown by the universal recycling symbol.



One arrow in the figure indicates source separation, that is, the removal of materials from the waste stream (e.g., setting aside aluminum cans in the homeowner's kitchen) and placement for pickup in designated bins at the curb or at a drop-off facility. The second arrow symbolizes processing of the material. Aluminum cans are collected by a waste hauler and brought to a broker or distributor, where they are compressed into large bales. Given suitable market conditions, the bales are sold and shipped off-site to an aluminum smelter. At the smelter the bales are melted, the material is drawn into sheets, and new cans are manufactured. The cans are shipped to a soft drink manufacturer and filled, and then shipped to a retail store. Finally, the consumer purchases the soft drink stored in the *recycled* cans (third arrow).

Given the above cycle, therefore, a material is not truly considered recycled until it has proceeded through all three steps and is ultimately purchased by the consumer.

Over the past several decades, the source separation component of this cycle has become disproportionately large compared with the other two. Problems with the second step have been encountered, as some industries have complained of excessive costs for retooling the equipment and facilities needed to process recycled stock. In other cases financial incentives, whether in the form of subsidies or market pricing, may still be in effect for the use of raw materials. A bottleneck has also occurred at the third arrow—there has been insufficient demand by purchasers, particularly the individual consumer, for the purchase of items manufactured from recycled products.

6.3 RECYCLING PROGRESS AND STATISTICS

According to EPA (2011), Americans generated approximately 250 million tons of MSW in 2010. A total of 34% (85 million tons) of MSW was recovered by recycling (including composting) in 2010. Over 9300 curbside recycling programs were reported in the United States in 2010, as well as about 9000 drop-off centers for recyclables (Figure 6.1) (U.S. EPA 2011a). About 630 MRFs are in operation to process the collected materials. A total of 2284 yard waste composting programs were reported in a survey by *BioCycle* (van Haaren et al. 2010).

Example 6.1

Using the data for the MSW composition of the city of Pristine, IL, in the table below, calculate the maximum contribution of source separation to the city's solid waste disposal program.

Component	Percent by Weight
Paper	31
Cardboard	5
Ferrous metals	10
Nonferrous metals	1
Glass	9

Solution

These components total 56% of the MSW stream. Of this 56%, however, not all is potentially recyclable.

Component	Expected Recovery,%	Percent by Weight of MSW
Newspaper	25	7.8
Cardboard	100	5.0
Ferrous	75	7.5
Nonferrous	50	0.5
Glass	75	6.75
Total		27.60

MSW comprises about 50% of total solid waste. As discussed in Chapter 1, the remainder is industrial, construction and demolition debris, and so on. Therefore, source separation can handle about 27.6% of 50% or:

$$27.6\% \times 50\% = 14\% \text{ of the total solid waste}$$

Unfortunately, no U.S. community has come close to attaining 100% participation in a source separation program. If we optimistically assume 50% participation, then 14% × 50% = 7% is the maximum contribution of source separation to recycling.

(Adapted from Schwarz, S.C. and Brunner, C.R., *Energy and Resource Recovery from Waste*, Noyes Data Corporation, Park Ridge, NJ, 1983.)

6.4 RECOVERY AND MARKETS FOR COMPONENTS OF THE WASTE STREAM

To understand the opportunities and challenges, and to formulate a holistic approach to waste recycling, it is useful to possess a basic understanding of the individual materials involved, manufacturing processes, and the nature of secondary material markets. Questions that recycling professionals must address include the following:

- What is the demand for reclaimed materials?
- What are the specific requirements for a raw material used by an industry?
- How can a recovered material compete, technologically and economically, with virgin feedstock?
- Are new processes or equipment necessary in order to process and work with wastes?
- What are the incentives or disincentives that affect the use of recycled materials by manufacturers?
- Can new uses be identified that will increase the demand for recycled materials?

(Adapted from Rhyner, C.R. et al., *Waste Management and Resource Recovery,* Lewis Publishing, Boca Raton, FL, 1995.)

6.5 MARKET ISSUES

Price volatility in recycling markets is inherent in the system. Prices for recycled materials follow the overall demand for manufactured goods. Supply and demand for materials are based on broader issues such as markets for raw materials, trade agreements and tariffs between countries, and so on. Handling the fluctuations in revenue helps to secure the long-term success of a recycling program. Some communities manage fluctuations by creating local manufacturing demand for recycled materials. Others negotiate contracts that include price floors.

Recycling programs that collect a wide variety of materials such as mixed paper, newspaper, cardboard, glass, metals, plastic bottles, and lead automotive batteries may be at an advantage over programs collecting only one or two items. If markets decline for a material, it can be stockpiled until the market improves; meanwhile, other more profitable materials can continue to be made available for sale.

6.6 PURITY OF MATERIALS

Processors and end-users of recovered product typically require that the materials be homogeneous and free of contamination. A small proportion of unwanted material may negatively affect the quality of a recycled product and may, in some cases, pose a hazard to workers. Some industries must comply with strict standards as to composition and will not tolerate even very low levels of contamination. Other industries routinely process materials to remove foreign articles.

There is significantly less foreign material in source-separated wastes compared with raw mixed wastes processed via a MRF. However, many citizens prefer the convenience of shipping commingled wastes to a central processing facility for sorting.

Buyers may also require that the materials be compacted or established under a specific condition (e.g., bottles are not to be broken, aluminum beverage cans must be crushed, and high-density polyethylene (HDPE) containers must be baled).

Materials that are commonly recycled or are potentially recyclable are discussed in the following sections.

6.7 PAPER

As mentioned in Chapter 4, paper products comprise the majority of the municipal solid waste stream—about 28.5% of U.S. MSW, more than double that of any other component. Paper waste has its share of environmental and economic costs, as it occupies substantial volume in collection trucks and landfills. Manufacture of paper implies that more trees must be cut in order to satisfy continued needs for new product. The massive quantities of paper waste generated, along with the associated costs for disposal, provide economic incentives for paper recycling.

6.7.1 Paper Manufacture

The Chinese developed the first known papermaking process as early as 100 C.E. A suspension of bamboo fibers served as the paper base. In the English colonies of North America, the first paper mill was constructed in 1690 near Philadelphia. Until the mid-1800s, paper was made exclusively from recycled fiber derived from cotton, linen rags, and waste paper. With an increased demand for paper and paperboard, techniques for utilizing wood fiber in papermaking were developed.

Both coniferous and deciduous wood pulp are used in modern papermaking. Hardwoods and softwoods possess very different fiber morphologies, which therefore result in different paper properties. The fibers of softwoods are longer and stronger than those of hardwoods; however, softwood fibers tend to form flocs of entangled fibers during the sheet-forming process, resulting in problems with appearance. To control this effect, softwood fibers are blended with those of hardwood to provide adequate strength and appearance.

Paper is derived from fibers originating within cells of terrestrial plants; therefore, paper does not possess a fixed chemical composition. Plant cells are mostly composed of carbohydrate polymers (polysaccharides) incorporated to some degree with lignin, a complex aromatic polymer. The quantity of lignin commonly increases with age of the plant. The carbohydrate component of the cell contains primarily the structural polysaccharide cellulose. Other lower-molecular weight nonstructural polysaccharides known as hemicelluloses occur, which play an important part in pulp and paper properties. There also occur relatively small amounts of water-soluble compounds such as alcohols, resin acids and fatty acids, and trace inorganic materials (Rhyner et al. 1995; Roberts 1996).

Essential to papermaking, whether using wood fibers or recycled fibers as the base, is that the fibers be conformable, that is, capable of being matted into a uniform sheet. They must also be capable of forming sufficiently strong bonds at the point of contact. Proper conformability and bonding begin with the pulping process, when the bonds in the wood fibers are broken.

There are three methods of pulping virgin fiber: (1) mechanical pulping, where fibers are freed by the application of mechanical energy; (2) chemical pulping, where chemicals are added to dissolve lignin and retain cellulose; and (3) semi-chemical pulping, which is a combination of methods 1 and 2.

Beyond pulping, paper manufacture operations are as follows (Smook 1982; Rhyner et al. 1995):

- *Sheet formation*. Pulp slurry (1% pulp, 99% water) is guided into a headbox.
- *Forming*. The pulp is dewatered by about 20%. The fibers are formed into a sheet.
- *Pressing*. Fibers are pressed together. Another 20% of the water is removed from the pulp.
- *Drying*. The sheet is dried to about 90–95% solids. Fibers bond together at this point.
- *Converting and finishing*. The sheet is pressed between rolls to reduce thickness and increase uniformity, and is wound on to reels (Figure 6.2).

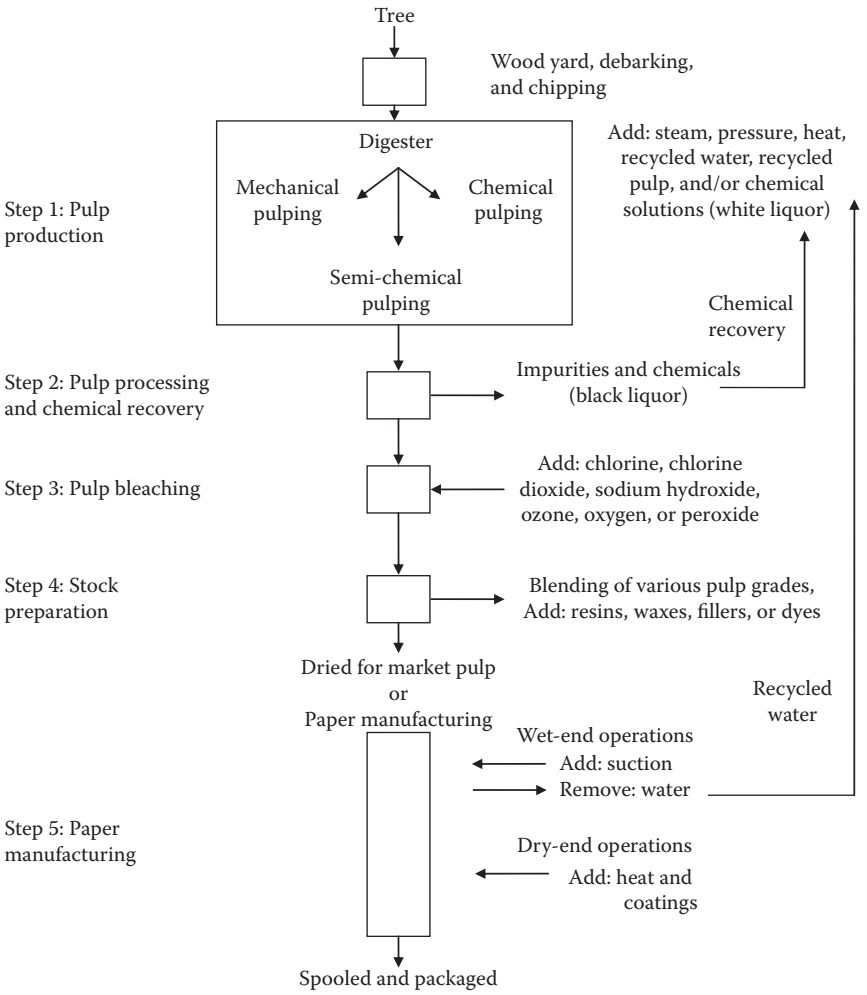


FIGURE 6.2 Papermaking process. (Reproduced with kind permission of CC Technologies Systems, *Corrosion Cost,* n.d., Available from: http://www.corrosioncost.com/pdf/pulppaper.pdf.)

6.7.2 Paper Recycling

Paper recycling has a long history. Collection drives by the Boy Scouts and other organizations were in place before World War II. Such programs increased greatly during the war.

Recovery of paper and paperboard for recycling is highest overall compared with all other MSW components. A total of 85% of all corrugated boxes was recovered for recycling in 2010 (Table 6.1) (U.S. EPA 2011a). Newspapers were recovered at 71.6% and high-grade office papers at 74.2% with lesser amounts of other papers recovered. Over recent decades, paper recycling trends continue to be robust. According to the American Forest and Paper Association, between the 1987 and 2012, the paper and paperboard recovery rate increased from 28.8% to 65.1% (Paper Recycles 2013).

The United States used more than 71 million tons of paper products but only 33% is made from recycled paper. This number compares with 69% in Western Europe. In Mexico, recycled paper, rather than wood pulp, is the principal feedstock in paper mills, accounting for about 75% of raw materials (Print Power 2010; Business News America 2012).

TABLE 6.1
Generation and Recovery of Paper Waste in the Solid Waste Stream, 2010

		Recovery		
Product Category	**Generation (Thousand of Tons)**	**Thousand of Tons**	**Percent of Generation**	**Discards (Thousand of Tons)**
Nondurable goods				
Newspapers and mechanical papers	9880	7070	71.6%	2810
Books	990			
Magazines	1590			
Office-type papers	5260			
Standard mail	4340			
Other commercial printing	2480			
Tissue paper and towels	3490			
Paper plates and cups	1350			
Other nonpackaging paper	4190			
Subtotal nondurable goods excluding newspapers and mechanical papers	23,690	10,650	45.0%	13,040
Total paper and paperboard of nondurable goods	33,570	17,720	52.8%	15,850
Containers and packaging				
Corrugated boxes	29,050	24,690	85.0%	4360
Gable top and aseptic cartons	540			
Folding cartons	5470			
Other paperboard packaging	90			
Bags and sacks	1040			
Other paper packaging	1490			
Subtotal containers and packaging excluding corrugated boxes	8630	2160	25.0%	6470
Total paper and paperboard of containers and packaging	37,680	26,850	71.3%	10,830
Total paper and paperboard	71,250	44,570	62.6%	26,680

Source: U.S. EPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States, Tables and Figures for 2010*, 2011, Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.

Waste paper is classified as bulk or high grade. The highest grade includes manila folders, hard manila cards, and similar computer-related paper products. High-grade waste paper is used as a pulp substitute. Bulk grades consist of newspapers, corrugated cardboard, and mixed paper waste (unsorted office or commercial paper waste). Bulk grades are used to make paperboards, construction paper, and other products. The Institute of Scrap Recycling Industries has established standards and practices that apply to paper stock for repulping in the United States and Canada (ISRI 2002). Common paper grades are listed in Table 6.2.

Paper manufacture from recovered paper and paperboard requires a different pulping process compared with pulping virgin fibers. A key mechanical component required for pulping waste paper fibers is the continuous pulper. In this unit, the input material is ground into a smooth

TABLE 6.2
Selected Paper Grades for Repulping and Recycling

No.	Name	Composition
1	Soft mixed paper	Mixture of various qualities of paper not limited as to type of baling or fiber content.
2	Mixed paper	Baled clean sorted mixture of various qualities of paper containing less than 10% of groundwood content.
3	—	Grade not currently in use.
4	Boxboard cuttings	Baled new cuttings of paperboard used in the manufacture of folding cartons, set-up boxes, and similar boxboard products.
5	Mill wrappers	Baled paper used as outside wrap for rolls, bundles, or skids of finished paper.
6	News	Baled newspaper as typically generated from news drives and curbside collections.
7	News, de-ink quality	Baled sorted fresh newspapers; not sunburned; containing not more than the normal percentage of rotogravure and colored sections. May contain magazines.
8	Special news de-ink quality	Baled sorted fresh newspapers, not sunburned, free from magazines, white blank, pressroom over-issues, and paper other than news, containing not more than the normal percentage of rotogravure and colored sections. This grade must be tare-free.
9	Over-issue news	Unused overrun newspapers printed on newsprint, baled or securely tied in bundles, containing not more than the normal percentage of rotogravure and colored sections.
10	Magazines	Baled coated magazines, catalogues, and similar printed materials. May contain a small percentage of uncoated news-type paper.
11	Corrugated containers	Baled corrugated containers having liners of either test liner, jute, or kraft.
12	Double-sorted corrugated	Baled double-sorted corrugated containers, generated from supermarkets, industrial or commercial facilities, or both; having liners of test liner, jute, or kraft. Material has been specially sorted to be free of boxboard, off-shore corrugated, plastic, and wax.
13	New double-lined kraft corrugated cuttings	Baled new corrugated cuttings having liners of either test liner, jute, or kraft. Treated medium or liners, insoluble adhesives, butt rolls, slabbed or hogged medium are not acceptable in this grade.
14	—	Grade not currently in use.
15	Used brown kraft	Baled used brown kraft bags free of objectionable liners and original contents.
16	Mixed kraft cuttings	Baled new brown kraft cuttings, sheets, and bag scrap free of stitched paper.
17	Carrier stock	Baled printed or unprinted, unbleached new beverage carrier sheets and cuttings. May contain wet strength additives.
18	New colored kraft	Baled new colored kraft cuttings, sheets, and bag scrap free of stitched papers.
19	Grocery bag scrap	Baled new brown kraft bag cuttings, sheets, and misprint bags. Prohibitive materials: none permitted.
20	Kraft multi wall bag scrap	New brown kraft multiwall bag cuttings, sheets, and misprint bags free of stitched papers.

Source: Reproduced with kind permission from ISRI, Washington, D.C. Copyright © 1993 The Institute of Scrap Recycling Industries, Inc.

Note: The ISRI Scrap Specifications Circular is subject to change. To find the most recent edition, go to www.isri.org.

pulp, and extraneous materials (glues, plastic, metal, clips) are removed. Recovered pulps are then de-inked by a process of chemical disintegration or chemical treatment. In some plants, a washing step is incorporated to further clean the pulp. The pulp is washed free of ink and other contaminants on a fine mesh screen. An optional flotation process may be used in which chemicals are added to the pulper to create air bubbles that separate and float ink droplets away from the pulp. The pulp may also be bleached. Apart from washing and flotation, the resultant pulp is screened and thickened. Once processed, the pulp, whether from virgin or recycled fibers, enters the paper manufacturing process.

Each time paper is recycled, some of the longer fibers are shortened, generally losing their flexibility and bonding ability. This is due to a process called *hornification*, that is, a composite of several partly irreversible physical changes. Virgin pulp is added to maintain paper strength required for efficient runnability at fast speeds, both on the paper mill and during conversion (e.g., in the printing press), as well as for the end use. Brightness also deteriorates each time paper is recycled. In summary, waste paper tends to downgrade in quality as it is recycled. However, recycled fibers possess some advantages: the twice-dried stock may drain faster than its virgin equivalent, it requires less refining, it can be co-refined with hardwood pulp or combined hardwood and softwood pulps without significant damage, and the fibers impart improved opacity (Ferguson 2001).

As with many other materials, the waste paper market is volatile and strongly influenced by region. Economic conditions continue to affect progress in paper recycling. In some locations, mixed paper waste is of little value.

One limitation on the quantity of waste paper that can be recycled annually is the capacity of paper mills. Construction or modification of such mills is capital intensive; therefore, investors must be assured that there will be an adequate supply of waste paper to the mills, and at a competitive price. Much waste paper is shipped to markets along the Pacific rim (e.g., South Korea), where timber resources are scarce. China is a major influence in the mixed waste paper market. In 2010, 39% of recovered paper from the United States was exported to overseas markets. The mixed waste paper is sorted and processed in the recipient country. The demand is expected to continue to grow.

Over the past decade, legislative programs have been developed in several countries that require a certain percentage of recycled fiber content in newspaper, office paper, and other products. Such initiatives increase the demand and the quantity of paper available for recycling. However, there may be resistance on the part of waste paper recyclers to make the large capital investments necessary to increase plant capacity.

6.7.3 Other Paper Markets

Waste paper has been adapted as a raw material for manufacturing other items. Home insulation has been prepared from old newspapers. The shredded cellulosic material is first coated with an antiflammability agent and is blown directly into wall cavities. Other applications of waste paper include insulation board, fiberboard, roofing, and siding. The molded pulp industry uses waste paper in the manufacture of plant pots, egg cartons, meat trays, and packaging materials. In agriculture, waste paper has been used as animal bedding (NAA 2002). Old newspaper bedding has replaced straw bedding in some businesses due to its availability and relatively lower price, particularly during years of weather extremes. Old newspaper bedding has been shown to not adversely affect animals, or soil where the bedding is applied as a component of manure (Rhyner et al. 1995).

Refuse-derived fuel (RDF) is a mostly carbonaceous product derived from MSW. The noncombustible components of waste such as stones, glass, and metals are removed, usually by mechanical means; the organics are shredded; and the resultant "fluff" is either used directly as a fuel or is compressed into pellets. RDF is typically burned as a co-fuel along with coal, which accrues a number of environmental and economic benefits. A detailed discussion of RDF appears in Chapter 9.

6.7.4 Benefits of Paper Recycling

Seventeen trees are required to produce one ton of paper. All Sunday newspapers in the United States require the equivalent of one-half million trees every week. When paper is manufactured from waste paper, however, trees are conserved, as are considerable amounts of energy. For one ton of paper recycled, there is a savings of approximately 4100 kWh of energy, along with 7000 gal of water and 3 yd^3 of landfill space (Liu and Liptak 2000). Paper production from recycling also requires less chemicals, including bleaches, and will therefore produce fewer toxic wastes.

6.8 GLASS

6.8.1 Glass Manufacture

The ancient Egyptians were the first to manufacture glass for containers, by first forming a sand or clay mold and then wrapping strands of molten glass around the mold. A more widespread use of glass as a container was made possible by the development of glass blowing in about 50 B.C.E. Across the Atlantic Ocean, glass manufacturing was the first known industry in pre-Colonial America, developed more than a decade before the arrival of the Pilgrims in 1620. Techniques for mass production of glass containers were developed in the nineteenth century, and the first fully automatic bottle machine, producing 1 million bottles per week, was developed in 1903. For the last decade, U.S. container glass production has been fairly constant at 270–275 million units per year (Kogel et al. 2006).

In order to manufacture new glass products, relatively inexpensive raw materials are required, including silica (SiO_2), soda ash (Na_2CO_3), and limestone ($CaCO_3$). Silica is the basic foundation of the product. Sometimes muriate of potash (KCl) is used in place of soda ash. It is common for recycled glass (*cullet*) to be added. The mixture is heated to approximately 1480°C–1570°C (2700°F–2850°F) and liquefied.

The basic structural unit of silica is a tetrahedron with a silicon atom in the center, linked symmetrically to four oxygen atoms at its corners, giving the chemical formula SiO_4. Upon quickly cooling molten silica, a randomly organized network of tetrahedra are formed, linked at their corners to give vitreous silica, an amorphous material (Pilkington 2003):

$$Na_2CO_3 + SiO_2 \xrightarrow{1500^\circ C} Na_2SiO_3 + CO_{2(g)} \tag{6.1}$$

$$Na_2SiO_3 + xSiO_2 \xrightarrow[\text{digestion}]{Na_2SO_4} (Na_2O)(SiO_2)_{(x+1)} \tag{6.2}$$

Soda ash allows the silica to melt at a lower temperature. The sodium–oxygen atoms enter the silicon–oxygen network. Limestone imparts strength to the glass; calcium enters the network structure, rendering it more complex so that during the cooling process it is more difficult for the atoms to arrange themselves via crystallization.

The molten glass is pressed into molds that form bottles and jars. Air is injected into the containers to create openings. Cooling in an annealing oven strengthens the new bottles and jars. The cooled product is checked for flaws such as bubbles. The final step is filling with food, nonfood (medicines, perfume, cosmetics, cleaning supplies), and other consumer and industrial items.

6.8.2 Glass Recycling

Glass has experienced a more rapid growth in recycling than that of any other commodity, except for aluminum beverage containers. Glass recycling has increased from 750,000 tons in 1980 to more

TABLE 6.3
Glass Waste Production and Recycling, 2010

Product Category	Generation (Thousands of Tons)	Recovery (Thousands of Tons)	Recovery (Percent of Generation)
Durable goods[a]	2,170	Neg.	Neg.
Containers and packaging			
Beer and soft drink bottles	5670	2350	41.4
Wine and liquor bottles	1700	420	24.7
Other bottles and jars	1990	360	18.1
Total glass containers	9360	3130	33.4
Total glass	11,530	3130	27.1

Source: U.S. EPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States, Tables and Figures for 2010*, 2011, Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.

Note: Neg. = less than 5000 tons or 0.05%.

[a] Glass as a component of appliances, furniture, consumer electronics, and so on.

than 3 million tons in 2010 (U.S. EPA 2012a). This growth is the result of both increased collection through curbside recycling programs and accelerated demand from glass manufacturers.

About 11.5 million tons of glass is disposed in the United States annually, which comprises about 4.6% of the total waste stream (U.S. EPA 2011a). Clear glass ("flint"), green or amber bottle, and container glass comprise 90%, and the remaining 10% is plate and other glass. A total of 6.2 million tons of glass containers were recovered for recycling in 2010. Based on 2010 glass generation rates, an estimated 33.4% of glass containers were recovered for recycling, with a 27.1% recovery rate for all glass in MSW (Table 6.3). In contrast with estimates for the United States, the European Union recycled about 70% of its total glass production (FEVE 2013).

Most recovered glass is used for the production of new containers. A smaller fraction is applied to other uses such as fiberglass, bricks, and *glassphalt*, a mixture of glass and asphalt that serves as a paving mixture for highway construction. The main purchaser of waste glass (cullet) is, however, the glass container industry.

6.8.3 Glass Recycling Process

Glass recycling begins with collection of used bottles and other containers. The glass is separated into clear, green, and amber (brown) colors by the consumer, operators of the collection vehicle, or the processing facility. At the MRF or other receiving facility, containers are crushed into small pieces (approximately 3/8 to 3/4 in. across), which are shipped to manufacturing plants.

This material is known as processed, or furnace-ready cullet. In some situations, the containers are not broken but sent directly to the manufacturer.

Manufacturers purchase whole and broken glass cullet and combine it with soda ash, limestone, and silica to create new glass products for consumer, industrial, and other applications. Recyclers in the United States utilize 10%–80% cullet in glass manufacture. This compares with 70%–90% in Switzerland and Germany (SHWEC 2012). Modern glass container manufacturing requires clean and uniform feedstock. The four requirements for cullet used in recycling include:

- Be separated by color
- Be contaminant-free
- Meet market specifications
- Be container glass

6.8.4 Color

When separating glass by color, manufacturers can ensure the desired quality and color consistency of new glass products. The preferred situation is for the consumer or business to separate glass by color at the source. This is also the optimum location for removal of contaminants such as food, labels, and dirt. Many community recycling programs will allow for collection of mixed glass. Although a convenient practice for the consumer, such mixing may actually hinder the marketability of the product.

If separation by color does not occur at the source of generation, colors and contaminants should be sorted out early during processing. At a MRF or transfer station, cullet is almost always color-sorted by hand. In some communities, intermediate processors, known as glass benefaction facilities, receive glass from recycling programs and use sophisticated optical sorting machines to separate the glass into three color types (CMI 2002). Optical sorting equipment is capital intensive; therefore, hand-picking is typically the only feasible sorting mechanism.

If the cullet is not completely color-sorted and becomes thoroughly mixed, undesired colors are difficult to remove and can ruin an entire load. Mixed cullet has a low demand and value. Glass manufacturers set limits on the amount of mixed cullet that is acceptable for manufacturing new containers. Many companies simply prefer not to buy mixed cullet. Other markets for mixed glass are available (see Sec. 6.8.8), but are limited.

6.8.5 Contamination

Contaminated cullet, probably the single greatest problem for glass manufacturers, is not suitable for the manufacture of new glass containers. Cullet can be contaminated at any point during the recycling process: at the source, and during collection, processing, or shipping. Contaminated cullet decreases quality and increases costs. Contaminants are a risk to the glass manufacturer and disrupt production, cause injury to workers, damage manufacturing equipment, and produce a poor-quality product.

Virtually all glass food and beverage containers, including food jars, soft drink bottles, juice containers, beer bottles, and wine and liquor bottles, are recyclable. However, household glass products such as light bulbs, drinking glasses, and window panes are not acceptable for producing glass containers. Such products vary significantly in chemical composition; furthermore, many possess different melting temperatures. As a result, mixing these products with container cullet may cause defects such as bubbles, cracks, or other weak points and imperfections in new containers.

Common materials that contaminate cullet include:

- Ceramic cups, plates, and pottery
- Crystal and opaque drinking glasses
- Mirrors
- Windshields and window glass
- Heat-resistant cookware (e.g., Pyrex™)
- Light bulbs
- Clay garden pots
- Laboratory glass

Other contaminants include:

- Ceramic and wire caps for beer bottles
- Metal rings from wine bottles
- Metal caps, lids, and neck rings
- Food and dirt

Glass benefaction facilities (Sec. 6.8.4) receive glass from community recycling programs and direct it through a sequence of steps to remove contaminants (stones, ceramics, metal caps). Metals are removed magnetically. Eddy current separators are used to remove nonmagnetic metal contamination from caps and lids. An air classifier removes lightweight components such as loose paper or plastic. These unit operations for waste separation are discussed in detail in Chapter 7. Some contaminants are removed manually from mixed cullet; however, this is a slow and potentially dangerous activity. The final product is a ground glass feedstock that is uniform in color, free of contaminants, and readily acceptable by container manufacturers (CMI 2002).

Preprocessors, such as glass benefaction facilities, provide a valuable market for recycling programs that do not generate the volume to justify direct delivery to a mill. A clean feedstock at the outset of processing, however, is strongly preferred by the industry.

6.8.6 Glass Markets

To be a competitive commodity, recycled glass must maintain a price that competes with raw materials. Crushed glass has a fairly strong and consistent market value compared with most postconsumer recycling materials. Based on the discussion so far in this chapter, it is obvious that the price paid for cullet will strongly depend on the color and cleanliness of the recovered product. Marketed as flint (clear), amber (brown), emerald (green), or mixed-color glass, cullet can yield up to $60 per ton delivered to the glass plant. Clean flint cullet is the most desirable form of glass scrap. Mixed-color glass contaminated with food or ceramic fragments is the least desirable grade of cullet and will bring the lowest price (Chen 2012).

6.8.7 Container Glass

Container glass is 100% recyclable, and glass containers can be recycled into new ones *ad infinitum*. There is no change in chemical or physical properties, and therefore no decline in quality with repeated recycling of cullet. According to the Glass Packaging Institute (n.d.), glass collectors, haulers, suppliers, and processors can reduce the risks and increase revenue by following some basic glass recycling guidelines:

- Contact potential buyers for their specifications and acceptance policies, ability to remove contaminants, transport preference (i.e., truck or rail car), and "furnace-ready" requirements.
- Conduct inspections regularly, especially before adding newly collected glass to stored recyclables and during loading for shipment.
- If stored outdoors, place the cullet on a concrete pad, not on the ground or asphalt, to avoid contamination from dirt or gravel during loading (Figure 6.3). Cover the cullet during inclement weather.
- When storing multiple loads of colored cullet, keep the cullet separated so that no intermingling of colors can occur.
- Prior to loading cullet shipments, wash the truck bed. Inspect the truck bed and the tarp used to cover the previous load for any residue.

6.8.8 Other Uses for Recycled Glass

In addition to serving as feedstock for manufacturing new glass containers, recycled glass is a valuable component of other products. Fiberglass, a common alternative market for cullet, is predominantly manufactured in the form of glass wool for thermal and acoustical insulation. Recycled glass used in making fiberglass now constitutes the second highest volume of postconsumer glass.



FIGURE 6.3 Cullet stored outdoors and unprotected will inevitably become contaminated.

TABLE 6.4
Other Secondary Uses for Cullet

Abrasives	Finely ground container and noncontainer glass used in sand blasting. Such abrasives contain no silica, which is the causative agent of silicosis
Aggregate substitute	Container and noncontainer glass utilized as drainage medium and backfill, or for landscaping purposes.
Bead manufacturing	Container and noncontainer glass is melted into rounded glass pellets or beads and used in reflective paint for highways.
Decorative applications	Ceramic tiles, picture frames, costume jewelry, and some household items may include recycled container and noncontainer glass.
Frictionators	Recycled glass is used to make frictionators needed for firing ammunition and lighting matches.
Fluxex and other additives	Glass powders used as lubricants, core additives, and fluxes in metal foundry work and fabrication, as well as flux or finders in the ceramics industry.

Source: Reproduced with kind permission from Glass Packaging Institute, *Glass Handling and Recycling*, n.d., Available from: http://www.gpi.org/Handling.html.

Industry standards for product quality and consistency are very high. Another promising alternative market is glassphalt, a road-paving material consisting of a mixture of crushed, low-grade, mixed-color cullet and asphalt. Some glassphalt mixtures contain ground glass, sand, gravel, and limestone. Given the comparatively low costs for road-building aggregate, however, the demand for glassphalt is modest. Cullet is also used in highway reflectors and signs, sandblasting materials, decorative glass, and drainage aggregate. Cullet has been used in the manufacture of some wastewater plumbing. As glass is a relatively inert material, it can readily withstand the corrosive agents within wastewater. Some of the more innovative uses of recycled glass are listed in Table 6.4.

6.8.9 Benefits of Glass Recycling

Although some industrial sectors have been reluctant to utilize scrap material in routine production because of concerns over retooling and excessive costs, glass recycling, particularly that of containers, is an integral component of the glass production industry. Recovered glass waste has a lower

melting point, 1370°C (2500°F), than the standard mixture of silica, soda ash, and limestone; in container manufacture, each 10% increase in cullet reduces the melting energy by about 2.5%. Reduced energy to manufacture glass products as compared with raw materials will hold down manufacturing costs. Fewer gaseous emissions result when working with cullet.

New glass containers manufactured from cullet possess the same quality and structural integrity as do containers made from raw materials only. Using recycled glass saves wear on furnaces, resulting in extended furnace life and savings on maintenance. Recycling glass also reduces the quantity of solid waste brought to landfills. Finally, recycled glass is usually closer to bottling plants than are sources of the raw materials (CMI 2002).

6.9 ALUMINUM

6.9.1 Aluminum Manufacturing

The starting material for primary aluminum manufacture is bauxite ore, a mined mineral. Dissolving powered bauxite in sodium hydroxide produces alumina, which serves as the raw material for production. The aluminum industry utilizes the Bayer process to produce alumina from bauxite. The three major stages in the Bayer process are extraction, decomposition, and calcination. During extraction, hydrated alumina is selectively removed from other insoluble oxides by transferring it into a solution of sodium hydroxide (caustic soda) (World-Aluminum 2000):

$$Al_2O_3 \cdot xH_2O + 2NaOH \rightarrow 2NaAlO_2 + (x+1)H_2O \tag{6.3}$$

This product is transferred to a heated pressure digester. Conditions within the digester (e.g., concentration, temperature, pressure) will vary according to the properties of the bauxite ore being used. Modern plants typically operate between 200°C and 240°C and involve pressures of approximately 30 atm.

After the extraction stage, the liquor, containing the dissolved Al_2O_3, is separated from the insoluble bauxite residue, purified, and filtered before it is delivered to the decomposer. The mud is thickened and washed so that the caustic soda can be removed and recycled. During the decomposition phase, crystalline alumina trihydrate is extracted from the digestion liquor by hydrolysis (World-Aluminum 2000):

$$2NaAlO_2 + 4H_2O \rightarrow Al_2O_3 \cdot 3H_2O + 2NaOH \tag{6.4}$$

The alumina trihydrate crystals are then classified into size fractions and fed into a rotary—or fluidized—bed calcination kiln. In the kiln, alumina trihydrate crystals are calcined to remove their water of crystallization and prepare the alumina for smelting.

The basis for aluminum smelting plants is the Hall–Héroult process. Alumina is dissolved in an electrolytic bath of molten cryolite (sodium aluminum fluoride) within a large carbon- or graphite-lined steel container. The bath also contains a small amount of aluminum fluoride and calcium fluoride. An electric current is passed through the electrolyte at low voltage, but very high current, typically 150,000 A. The electric current flows between a carbon anode composed of petroleum coke and pitch, and a cathode formed by the thick carbon or graphite lining of the pot. Molten aluminum is deposited at the bottom of the pot and is siphoned off periodically, taken to a holding furnace, and often alloyed with selected elements to produce the required qualities for specific end-uses such as beverage cans, sheet, transportation uses, and building and construction products.

Few U.S. companies refine bauxite into alumina. Most import alumina from Australia, Jamaica, Suriname, Guyana, and Guinea.

6.9.2 Aluminum Recycling

Aluminum waste consists of industrial scrap, which is a by-product of aluminum manufacturing processes ("new scrap"), and old scrap consisting of postconsumer items such as used aluminum beverage cans, window frames, building siding, and foil. Nearly 80% of the aluminum in MSW consists of used beverage containers (UBCs).

Nationwide, aluminum cans constitute less than 1% of MSW; in communities having established recycling programs or container deposit laws, the percentage in the local waste stream is negligible. Table 6.5 presents data on the quantity of aluminum recycled. In 1975, about 25% of aluminum cans

TABLE 6.5
Metal Disposal and Recycling, 2010

Product Category	Generation (Thousands of Tons)	Recovery (Thousands of Tons)	Recovery (Percent of Generation)
Durable Goods			
Ferrous metals[a]	14,160	3820	27.0
Aluminum[b]	1310	Neg.	Neg.
Lead[c]	1540	1480	96.1
Other nonferrous metals[d]	560	Neg.	Neg.
Total metals in durable goods	17,570	5300	30.2
Nondurable Goods			
Aluminum	200	Neg.	Neg.
Containers and Packaging			
Steel			
Cans	2300	1540	67.0
Other steel in packaging	440	350	79.5
Total steel in packaging	2740	1890	69.0
Aluminum			
Beer and soft drink cans	1370	680	49.6
Other cans	70	NA	
Foil and closures	460	NA	
Total aluminum in packaging	1900	680	35.8
Total metals in containers and packaging	4640	2570	55.4
Total metals	22,410	7870	35.1
Ferrous	16,900	5710	33.8
Aluminum	3410	680	19.9
Other nonferrous	2100	1480	70.5

Source: U.S. EPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States, Tables and Figures for 2010*, 2011, Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.

Note: Neg. = less than 5000 tons or 0.05%.

[a] Ferrous metals in appliances, furniture, tires, and miscellaneous durables.

[b] Aluminum in appliances, furniture, and miscellaneous durables.

[c] Lead in lead–acid batteries.

[d] Other nonferrous metals in appliances and miscellaneous durables.

were recycled, and this percentage remained relatively constant until about 1980. The increased rate in the latter half of the 1980s is attributable to additional collection programs and container deposit legislation. During this period, a number of states passed laws requiring deposits of $0.05–$0.10 per container, thus providing an additional incentive for recycling. Aluminum beverage containers were recovered at a rate of 49.6% of generation (0.7 million tons) in 2010, and 35.8% of all aluminum in containers and packaging was recovered for recycling. The rate of aluminum recycling has been in decline for a decade after peaking at 65% in 1992.

Numerous successful community recycling programs exist for mixed aluminum scrap and aluminum cans. These programs are generally self-sufficient and, in some municipal programs, provide an income to subsidize other recycling activities. Used aluminum cans are collected in curbside pickup programs, at buyback locations, at recycling centers, and by scrap metal dealers. A number of states have established mandatory deposits for beverage containers and have installed redemption centers at supermarkets.

Cans brought to collection centers are processed by a number of methods. Small, low-volume processors normally flatten cans and sell them to a nearby wholesaler. Larger operations will bale, densify, or shred cans for shipment to aluminum consumers (Figure 6.4). Aluminum manufacturers have established specific criteria as to how aluminum cans should be prepared. The baled or shredded aluminum is shipped by truck, railcar, or sea container to regional mills or reclamation plants.

At the reclamation plant, the bales are unloaded and cans are tested for quality and moisture content. After inspection, the bales are shredded to reduce volume. The shredded cans are conveyed to a delacquering oven to remove coatings and moisture. The hot shredded aluminum is then passed over a small screen to remove dirt and contaminants and fed directly into a reverberatory furnace. Heated to 650°C (1400°F), the cans melt and blend in with the molten metal already in the furnace. Alloying elements and primary aluminum are added as needed. A mixture of salt and potassium fluoride is added as a flux to separate any oxides (“dross”) that are skimmed off (CMI 2002).

Molten aluminum is analyzed for the appropriate chemical properties and then tapped (removed) from the furnace and poured into large molds that cast sheet ingots. These large rectangular ingots (~9100–18,200 kg or 20,000–40,000 lb each) are allowed to cool and harden. The surface of the sheet ingot is milled to a smooth surface in a process called “scalping.” The scalped ingot is then passed between two giant steel rollers in a large mill. The sheet is passed through several times until it is about 1.25 cm (~0.5 in.) thick and about 300 m (~1000 ft) long. The long sheet is then annealed to soften it and passed to a series of rollers in a finishing mill where it acquires the necessary



FIGURE 6.4 Baled aluminum UBCs ready for shipping to a container manufacturer.

hardness and thickness. The edges are trimmed in a slitter and the sheet is rolled for shipment to a can manufacturer (CMI 2002).

The finished sheet may be 3 km (2 miles) long and made from over 1.2 million recycled cans. At the container manufacturing plant, the sheets are cut into discs that are ultimately formed into cans. The cans are printed with the company label or logo and are shipped, often with the tops separate, to the filling plant (Alcoa 2013).

6.9.3 Specifications for Recovered Aluminum

Collection centers and other buyers accept cans that are free of gross contamination, such as dirt and food wastes. The buyers then compact and bale the material according to mill specifications regarding dimensions and weight. Noncontainer aluminum products purchased by scrap dealers must simply be dry and free of contamination. The Institute of Scrap Recycling Industries has developed standard specifications for a number of recycled commodities. Typical specifications for preparing aluminum beverage can scrap for sale to an aluminum recycling company are presented in Table 6.6 (ISRI 2002).

There are stringent quality requirements at U.S. mills for aluminum scrap. Aluminum UBCs must be relatively clean and free from dirt, oil, grease, and other surface contamination. Iron, aluminum foil, and other types of aluminum scrap are unacceptable if mixed in the bales. Contamination with lead, copper, brass, and other nonferrous metal may result in immediate rejection of an incoming shipment. All flammables, paper, and plastic should be removed prior to baling and cans must be relatively dry. Incoming material is tested for moisture by the receiving mills. A typical threshold of allowable moisture is 4%. Mills will accept loads with a higher moisture content but will deduct for any moisture over 2% as a penalty for wet loads (CMI 2002).

6.9.4 Benefits of Aluminum Recycling

Aluminum manufacturers such as Reynolds and Alcoa have actively promoted recycling since the mid-1960s. The aluminum industry recognized the advantages of a domestic aluminum

TABLE 6.6
Specifications for Aluminum Beverage Can Scrap

Baled UBC	Used aluminum beverage cans, magnetically separated and free from all other types of material. Average bale dimensions 30–36 in. by 36–48 in. by 60–72 in. (75–90 cm by 90–120 cm by 150–180 cm). Density 14–30 pounds per square foot. Bales should be kept dry. Most mills will allow 4% maximum H_2O content.
Densified UBC	Cans are compressed to a small block, approximately 12–16 in. by 16–24 in. by a variable thickness of 6–10 in. Density 30–50 lb per square foot. All bricks should be of the same dimensions and fairly uniform in weight. The individual bricks have slots for banding and are stacked in a uniform fashion and strapped into a bundle of 2–3000 lb with 1/2 to 3/4 in. by 0.020 in. steel strapping. This package is only made by specific machines ("Densican") designed to produce these uniform can bricks. Aluminum must be free of steel, aluminum foil, paper, wood, oil, and all types of non-UBC metals. Most mills will allow up to 4% H_2O content.
Bricked UBC	Cans compressed to a density of 45–70 lb per square foot in a high-compression press with two equal dimensions between 12 and 24 in. and one variable dimension up to 48 in. For shipment to U.S. consumers, briquettes should be stacked at least 4 ft high and strapped into bundles without the use of pallets or any support sheets or wrapping other than steel straps. It is important that the bricks be free of iron, dirt, and any other scrap since they are sometimes charged directly into a furnace.

Source: © 1993 The Institute of Scrap Recycling Industries, Inc. Reproduced with kind permission from ISRI, n.d., Washington, DC.

Note: The ISRI Scrap Specifications Circular is subject to change. To find the most recent edition, go to www.isri.org.

supply and therefore established the necessary infrastructure for transportation and processing. Although other industries have resisted recycling programs and mandatory container deposit legislation, the aluminum industry has developed collection and processing centers, a transportation network, and reclamation plants. Recycling makes economic sense to manufacturers for several reasons:

- Recycling provides a stable, domestic source of aluminum. In contrast, most of the bauxite required to produce new aluminum must be imported.
- Four pounds of bauxite are required to produce each pound of new metal.
- Aluminum recycling is profitable and well established; it requires only 5% of the electric power to remelt aluminum as it does to extract it from bauxite ore.
- Recycled cans are of uniform and known composition, and impurities are readily removed.

6.9.5 One Final Note on Aluminum

Recent reports state that more aluminum cans are littered, landfilled, or incinerated annually than are recycled. According to the Container Recycling Institute (2002), the approximately 50 billion aluminum cans wasted per year squandered the energy value equivalent to 16 million barrels of crude oil, or enough energy to supply 2.7 million American homes with electricity for a year.

6.10 FERROUS METALS

Ferrous metals are those containing iron and are used in the manufacture of industrial and consumer goods. Industrial ferrous waste may include aged tanks and silos, obsolete machine tools, retired railway locomotives, dismantled bridges, entire ships, demolished steel-framed buildings, and discarded motor vehicles. Consumer ferrous waste includes appliances ("white goods"), automobiles (about 10 million discarded each year), food, and nonfood containers.

6.10.1 Steel Manufacture

Five major activities are involved in steel manufacture: coking, sintering, iron-making, steelmaking, and final rolling and finishing (Russell and Vaughan 1976). Coking involves heating coal pyrolytically (i.e., in the absence of air) to produce a fuel high (approximately 90%) in carbon. Sintering agglomerates fine ore particles into a porous mass for charging into the blast furnace.

In the blast furnace, molten iron is produced. Workable iron ores tend to be rich in iron (III) oxide (Fe_2O_3). Recovering the iron by removing oxygen from the ore is a key processing step. Industrial iron production involves reducing iron (III) oxide in the blast furnace. Most of the iron (III) oxide is reduced using carbon monoxide:

$$Fe_2O_3 + 3CO \rightarrow 2Fe(I) + 3CO_2 \tag{6.5}$$

Not all the iron (III) oxide is reduced by carbon monoxide, however. A fraction of the iron is reduced directly using carbon as the oxidizing agent:

$$Fe_2O_3 + 3C \rightarrow 2Fe(I) + 3CO \tag{6.6}$$

In the steelmaking process, iron is converted to steel by forcing oxygen through the molten metal from the furnace. This oxidizes the impurities in the molten metal.

In steelmaking, there are three basic types of furnaces: the open hearth, the basic oxygen furnace, and the electric arc furnace. The open-hearth furnace has declined in popularity in recent years, as

it is relatively slow in preparing a batch of steel compared with the other furnace types. The primary feedstock in the basic oxygen furnace is molten pig iron, produced in a blast furnace from iron ore (hematite and magnetite), limestone, and coke. Molten pig iron can be combined with steel scrap. The electric arc furnace operates almost exclusively on steel scrap and is discussed below.

A schematic of the steelmaking process is shown in Figure 6.5.

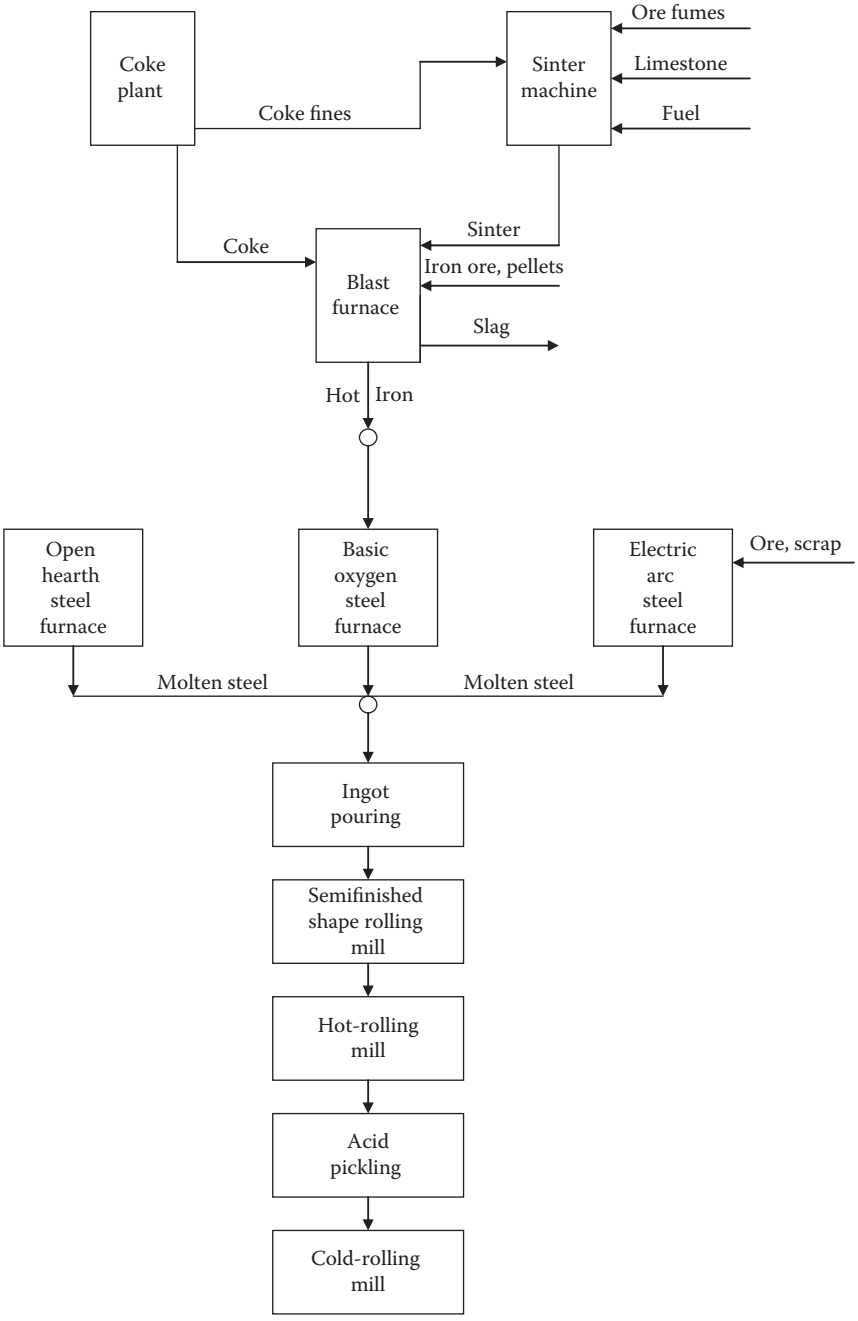


FIGURE 6.5 Schematic of the steelmaking process. (Russell, C.S., *Steel Production: Processes, Products, and Residuals*, Johns Hopkins University Press, Baltimore, MD, 1976. Reproduced with kind permission of Resources for the Future.)

6.10.2 Ferrous Recycling

Among all the materials recycled worldwide, iron and steel represent the greatest tonnages. Iron has been manufactured for thousands of years, and scrap was recycled even in the earliest times of production. Today, the scrap recycling industry processes an average of 74 million tons of scrap iron and steel annually (ISRI 2011).

Overall recovery of ferrous metals from durable goods (large and small appliances, furniture, tires) was estimated at 27% (3.8 million tons) in 2010 (Table 6.5). Steel food cans and other cans were recovered at a rate of 69% (1.9 million tons) (U.S. EPA 2011a).

Processors buy ferrous scrap from numerous sources, including municipalities, demolition operations, automobile dismantlers, shipyards, and industrial plants (Figure 6.6). Steel cans, also known as "tin cans" due to the presence of a corrosion-resistant tin coating, are recovered along with other consumer items at the curbside or a MRF. Cans are often commingled with nonferrous containers and must be separated magnetically. Afterwards, they are compacted and shipped to a detinning facility. In the detinning plant, the cans are shredded and the feed is again passed through a magnetic separator to remove aluminum, often from bimetal cans, and other nonferrous metals. The clean steel is then detinned, either by heating in a kiln to volatilize the tin, or by reaction with sodium hydroxide and an oxidizing agent. Tin is recovered by electrolysis and formed into ingots. This process allows for the production of both high-quality tin and steel. The chemically detinned steel is used for the production of new steel. Cans detinned by heating are not suitable in steelmaking, however, as the heat causes some of the tin to diffuse into the steel and occur as an impurity. In some applications, impurities from tin will not interfere with the production of new steel, and the detinning process may be skipped altogether (Rhyner et al. 1995).

White goods are large, bulky appliances such as washing machines, refrigerators, freezers, and stoves (Figure 6.7). The annual discard rate is over 12 million tons (U.S. EPA 2001). Appliances contain large amounts of ferrous, along with copper and aluminum. Before baling or shredding, such appliances must be checked for the removal of potentially useful or hazardous materials. For example, equipment manufactured prior to 1979 may contain polychlorinated biphenyls (PCBs) within electrical capacitors; similarly, chlorofluorocarbons (CFCs) may be present in compressor units in refrigerators or freezers.

Old automobiles are a major source of ferrous scrap. About 75% of an average automobile can be recycled. Ford Motor announced in 2010 that 85% of each Ford vehicle made now is recyclable. Historically, most of the recyclable materials in vehicles were ferrous; however, plastics



FIGURE 6.6 Metal processing facilities may accept ferrous waste from municipalities, demolition operations, industrial plants, and individual consumers.



FIGURE 6.7 White goods set aside for recycling.



FIGURE 6.8 Auto entering shredder. (Reproduced with kind permission of Sims Group Limited, *Cadillac Faces Shredder Jaws*, n.d. Available from: http://www/unitednotions.com.au/prjob_7.html.)

are becoming more common in auto manufacture. Prior to processing for ferrous, all hazardous materials (battery, refrigerants, used oil, antifreeze) must be removed. Auto salvage operations remove the fuel tank, tires, windshields, radiators, and other items with potential resale value. The remains are placed into an industrial shredder that converts the vehicle into small chunks (Figure 6.8); alternatively, they may be compressed in a high-capacity compactor. These packages can be fed directly into an electric arc furnace.

Larger ferrous scrap from industry is processed for reuse via cutting and baling. In dealing with industrial ferrous wastes, common machinery includes a crane, either mounted or mobile, which houses a large electromagnet (Figure 6.9); a baling press, used to densify objects such as automobiles; a hydraulic guillotine shear to slice steel I-beams and pipe; and a shredder (Figure 6.10). Several of these unit operations are discussed in more detail in the next chapter.

Industrial consumers purchase ferrous scrap directly or through a materials broker. These mills and foundries remelt the scrap and manufacture new products. Basic oxygen furnaces and electric



FIGURE 6.9 Electromagnet for moving ferrous wastes onto rail cars.



FIGURE 6.10 Shredder housing at a metal recovery facility.

arc furnaces handle most of the iron and steel scrap. In the basic oxygen furnace, molten pig iron is combined with 20%–30% steel scrap. The electric arc furnace operates almost exclusively on steel scrap. Melting is accomplished by supplying energy, either electrical or chemical, to the furnace interior. Electrical energy is furnished via graphite electrodes and is usually the largest contributor in melting operations. The scrap is charged into the furnace via a crane. The electrodes swing into place over the furnace, the roof is lowered, and then the electrodes descend to strike an arc on the scrap. The arc consists of a plasma of hot ionic gases reaching temperatures in excess of 3515°C (6000°F). Contact with the arc initiates the melting of the scrap. Once the desired steel composition and temperature are achieved in the furnace, the tap hole is opened, the furnace is tilted, and the steel pours into a ladle for transfer to the next batch operation (usually a ladle furnace or ladle station). During the tapping process, alloy additions are made based on the bath analysis and the desired steel grade (Jones 2002).

6.10.3 Benefits of Ferrous Recycling

Using ferrous waste in place of iron ore to manufacture steel has many advantages beyond cost considerations. Recycled ferrous is nearly 100% metal and is often readily available or readily

transported in bulk. In contrast, iron ore must be mined and milled free from tailings and chemical impurities, and smelted in a blast furnace before it can be converted into steel. The use of ferrous scrap in comparison with ore imparts substantial energy savings, significantly reduces the amount of water needed for processing, and generates less air pollution.

Iron and steel can be processed and remelted repeatedly for the manufacture of industrial and consumer items with absolutely no diminution of quality. Steel made from scrap is chemically and metallurgically equivalent to steel manufactured from virgin ore (ISRI 1993).

6.11 PLASTICS

Plastics possess many properties that make them desirable, if not indispensable, for the modern consumer. These synthetic polymers are shatter-resistant, waterproof, airtight, lightweight, and durable. As a result, plastics have replaced glass and a number of other materials in packaging, construction, and other uses. The United States is the largest producer and consumer of plastics in the world, which is consistent with its massive consumer-driven economy, low-cost chemical feedstocks, and well-developed petrochemical infrastructure.

Prior to 1970, plastics were generally not listed as a component of MSW. Data for 1970 show that plastics comprised about 2%–3% of the waste stream. Today, plastics occupy 30% of landfill space, although their weight percentage is approximately 17.3% (Table 6.7) (Liu and Liptak 2000; U.S. EPA 2001, 2011).

6.11.1 Plastics Manufacture

The raw materials for virtually all plastics are natural gas, petroleum, and liquified petroleum gases. Simple hydrocarbon monomers serve as the building blocks for conventional plastics.

TABLE 6.7
Recovery of Plastics from the Waste Stream, 2010

Product	Generation (Thousands of Tons)	Recovery (Thousands of Tons)	Recovery (Percent of Total)
Total plastics in durable goods	10,960	700	6.4
Total plastics in nondurable goods	6400	Neg.	Neg.
Total plastics in containers and packaging	13,680	1850	13.5
Total plastics in MSW, by resin			
PET	3980	780	19.6
HDPE	5450	570	10.5
PVC	910	Neg.	Neg.
LDPE/LLDPE	7430	420	5.7
PLA	50		
PP	7530	40	0.5
PS	2060	20	1.0
Other resins	3630	720	19.8
Total plastics in MSW	31,040	2250	8.2

Source: Adapted from U.S. EPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States, Tables and Figures for 2010*, 2011, Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.

Note: Neg. = less than 5000 tons or 0.05%. HDPE = high-density polyethylene; PET = polyethylene terephthalate; PS = polystyrene; LDPE = low-density polyethylene; PP = polypropylene; PVC = polyvinyl chloride; LLDPE = linear low-density polyethylene.

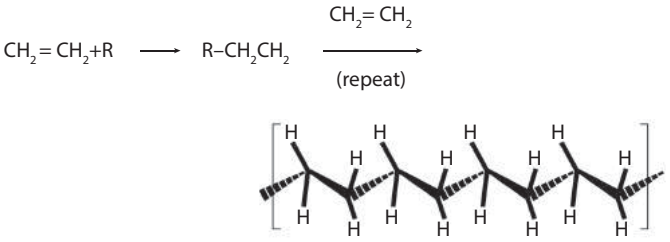


FIGURE 6.11 Ethylene monomers joining to form a polyethylene polymer.



FIGURE 6.12 Plastics numbering system. PETE = polyethylene terephthalate; HDPE = high-density polyethylene; PVC = polyvinyl chloride; LDPE = low-density polyethylene; PP = polypropylene; PS = polystyrene.

These monomers are linked together to form long chains of repeating molecules termed *polymers*. In the simplest case, gaseous ethylene monomers ($–CH_2–$) are concatenated to produce a solid polymer measuring tens of thousands of carbons in length (Figure 6.11). Hundreds of high-molecular-weight polymers are used in plastics manufacture. Each polymer possesses unique properties such that it will meet the requirements of industry and the consumer. About 80% of plastic used in consumer products is either polyethylene terepthalate (PET), also known as #1 plastic, or high-density polyethylene (HDPE) (#2 plastic). As we shall see, these are the most commonly recycled polymers as well. The plastics numbering system appears in Figure 6.12.

Two main categories of synthetic polymers exist, i.e., thermoplastics and thermosets. A thermoplastic consists of individual (nonlinked) chains of the polymer. They can be melted and reformed into the same polymer repeatedly. In contrast, thermosets consist of polymer chains linked to each other by cross-bonding (Figure 6.13). Once a product made from a thermoset polymer is melted, it cannot be reformed. Thermoplastics make up about 90% of all plastic products.

The main manufacturing processes used to transform newly formed polymers into a useful form are extrusion, blow molding, and injection molding. Most of these processes begin with plastic resins as pellets. These are subsequently subjected to heat and pressure and melted before processing.

6.11.2 Extrusion

Extrusion molding is used to convert plastics into continuous sheeting, film, tubes, rods, and filaments, and to coat wire and cable. In extrusion, dry plastic beads are loaded into a hopper and then fed into a long heating chamber through which they are transported by the action of a continuously revolving screw. At the end of the heating chamber, the molten plastic is forced through a small opening or die, with the desired shape for the finished product (Figure 6.14). As the working piece is removed from the die, it is fed onto a conveyor belt where it is cooled, typically by blowers or by immersion in water. In the production of wide film or sheeting, the plastic is extruded in the form of a tube. This tube may be split as it exits the die and is then stretched and thinned to the dimensions desired in the finished film (SPI 1999). Extruded products include plastic pipe and plastic lumber.

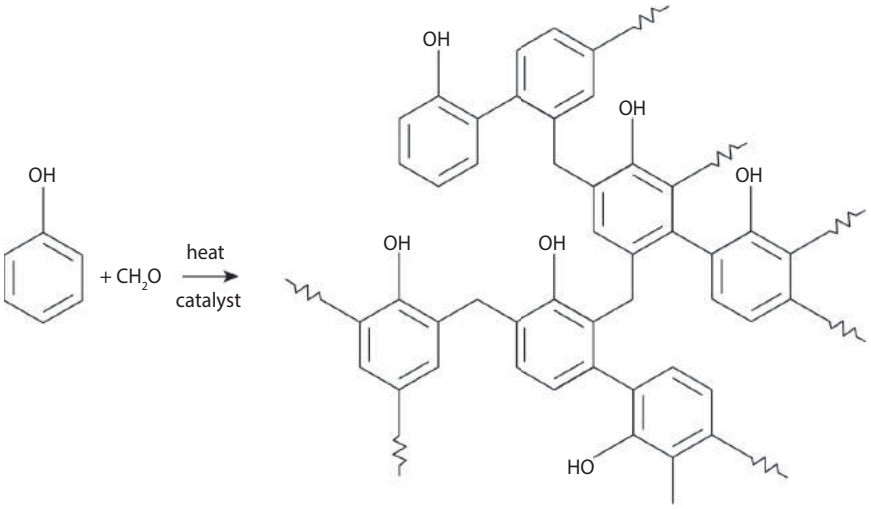


FIGURE 6.13 Thermoset polymer showing cross-links.

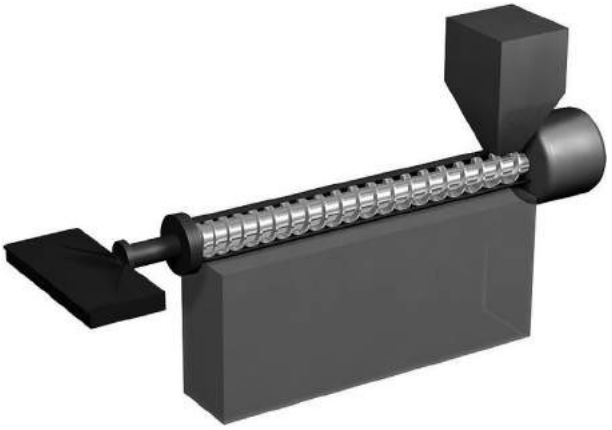


FIGURE 6.14 Plastics extruder.

6.11.3 Blow Molding

Blow molding first involves forming hollow molten tubes of thermoplastic; then, using compressed air, the tube is blown up to conform to the interior of a chilled blow mold (SPI 1999).

6.11.4 Injection Molding

In injection molding (Figure 6.15), plastic is placed into a hopper that feeds a long, heated injection unit. A reciprocating screw pushes the plastic through the heating chamber, where the material is softened to a fluid state. At the end of this chamber, a nozzle abuts firmly against an opening into a cool, closed mold. The fluid plastic is forced at high pressure through the nozzle into the mold. A system of clamps holds the mold halves shut. As soon as the plastic cools to a solid state, the mold opens and the finished plastic is ejected from the press (SPI 1999). Food tubs used for yogurt and cottage cheese are manufactured by injection molding.

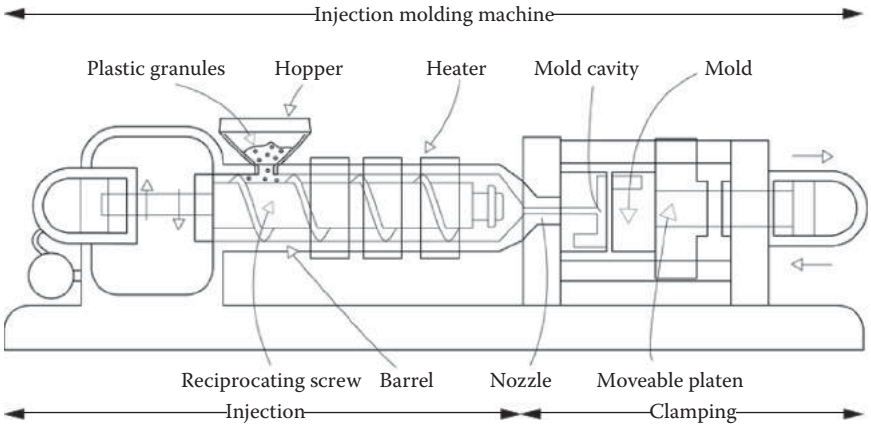


FIGURE 6.15 Injection molding apparatus. (Courtesy of Brendan Rockey, University of Alberta Industrial Design.)

6.11.5 Compression Molding

Compression molding is simply the squeezing of a material into a desired shape by the application of heat and pressure in a mold. Compression molding is used for forming thermoset products, but not for thermoplastics. Plastic molding powder, mixed with polymer feedstock and fillers such as cellulose (to strengthen or impart other qualities to the finished product), is placed directly into the open mold cavity. The mold is then closed, pressing down on the polymer and causing it to flow throughout the mold. While the heated mold is closed, the thermosetting feedstock undergoes chemical changes that permanently hardens it into the shape of the mold (SPI 1999).

Other less common methods of plastics formation include thermoforming, transfer molding, and reaction injection molding.

6.11.6 Plastics Recycling

The U.S. EPA states, "By 2005, almost 9000 curbside programs had sprouted up across the nation. As of 2005, about 500 materials recovery facilities had been established to process the collected materials" (U.S. EPA 2012b). PET and HDPE are the primary recovered polymers. In addition, thousands of grocery stores in the United States accept plastic bags (LDPE) for recycling into new trash can liners and other products.

A wide range of consumer products can be manufactured from recovered plastics; some are listed in Table 6.8. The U.S. Food and Drug Administration (FDA) regulates the use of recycled resins in food containers. The FDA has permitted only limited use of recycled polymers in food container manufacture, due to concerns about possible food contamination. Recycled containers have been used in soda bottles, tubs for butter, and detergent bottles. Recycled resins in non-food containers continue to increase in popularity (APC 2002).

Plastic lumber has become popular over the past two decades. Plastic lumber is made by extrusion and contains either single or mixed resins. Such lumber possesses physical characteristics similar to those of standard wood lumber. The advantages of plastic lumber are that it is resistant to the elements, water, and insect damage. Less maintenance (e.g., stripping, painting) is required. However, plastic lumber is relatively costly compared with its natural counterpart. There are also some concerns that plastic timbers may bend somewhat over time.

TABLE 6.8
Other Products Manufactured from Recycled Plastics

Impact barriers
Docks, decks
Fences
Scuff boards, floor boards
Boundary markers, right-of-way markers
Sign posts
Benches and picnic tables
Fiberfill for sleeping bags
Plastic lumber
Flower pots
Containers for non-food products
Mats
Strapping
Scouring pads
Toys
Compost bins
Recycling containers

6.11.7 Processing for Recycling

Postconsumer plastics can replace or supplement virgin plastic resins. Plastics recycling is difficult because each type of plastic must undergo a different process before becoming new product. There is a significant concern with contamination as well. Plastics are typically segregated by resin type and ideally by production method (e.g., extrusion vs. injection). Different resins possess differing physical characteristics including melting points, tensile strength, shatter resistance, and so on. Buyers often require that plastics are color-separated with no contamination.

Seven major types of plastics have been designated as part of a voluntary labeling system, in order to encourage recycling. Types are indicated by a recycling logo (the three chasing arrows) with a number from 1 to 7 situated in the center (Figure 6.12). As noted above, PET and HDPE are the predominantly recycled polymers. Postconsumer items made from PET and HDPE resins have developed stable markets in the United States and Asia.

Postconsumer plastics are recovered from collection centers loose in wire mesh cages, but more typically baled to reduce volume. After breaking bales, the containers are deposited along a conveyor belt for final sorting. Undesired plastics and extraneous wastes are removed manually. Plastics are also sorted by color.

Plastics can be recycled via several methods. In HDPE recycling, containers are chipped to small flakes (about 1 cm [3/8 in.] across) by a granulator designed to cut chips without causing excessive heat that might fuse particles. The flakes are washed with hot water and detergents to remove labels, adhesives and dirt and floated to remove any heavy contaminants. The HDPE is placed into a spin dryer to remove free water. Flakes are dried with hot air, reducing moisture content to about 0.5%. The dried flakes may be sold as is. More sophisticated plants reheat the flakes, add pigment, and pass them through a pelletizer, which produces small beads that are used in injection molding presses to create new products (Figure 6.16) (CMI 2002).

Resin may also be fluidized using an extruder. Flakes are fed into the extruder and compressed as they are forced forward toward the die. The combined heat from flow friction and supplemental heating causes the resin to melt. Volatile contaminants are vented from the mixture. The melted resin mixture may pass through a fine screen to remove any remaining solid impurities (Tchobanoglous et al. 1993).

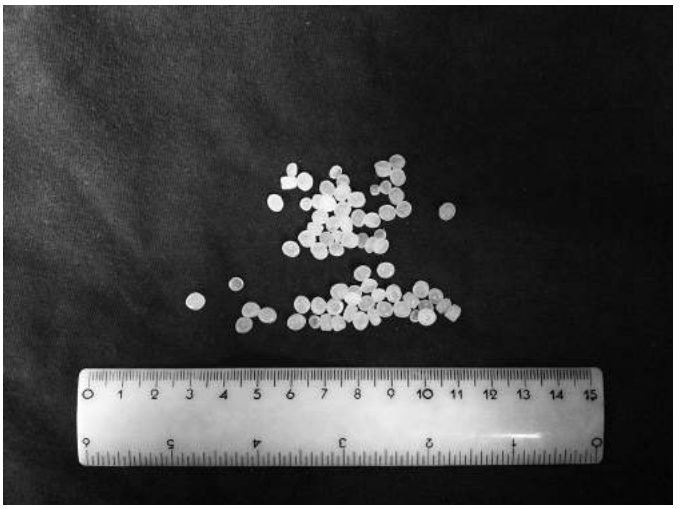


FIGURE 6.16 Recycled polyethylene beads (shown next to millimeter scale) ready for extrusion.

PET is a form of polyester that is extremely tough and versatile. Soft drink and water bottles are made from this resin as are many plastic jars and "clamshell" packages (e.g., salad containers). Recycling PET is similar to that for HDPE. Bottles may be color-sorted and are then ground and washed. Unlike polyethylene, however, PET sinks in the wash water, whereas the plastic caps and labels float off. The clean chips are dried and pelletized. PET bottles may contain aluminum caps, and granulated aluminum will contaminate PET chips. Electrostatic precipitation is used to remove the aluminum (Tchobanoglous et al. 1993). Recycled PET has many uses; well-established markets exist for this resin. The largest usage of recovered PET is in textiles. Carpet companies often use 100% recycled resin to manufacture polyester carpets in a variety of colors and textures. PET is also spun into fine filaments to make fiber filling for pillows and jackets. A substantial quantity of recycled PET returns to the bottle market (CMI 2002).

Regardless of the reassuring numbers of collection programs, the overall recovery of plastics for recycling is quite small, totaling 2.6 million tons, or 8.2% of plastics generation in 2010 (Table 6.7). However, recovery of some types of plastic containers has increased. PET soft drink bottles were recovered at a rate of 29.2% in 2010, and milk and water bottles (HDPE) at an estimated 27.5%. Significant recovery of plastics from lead–acid battery casings and other containers is also reported (APC 2002). Regardless, however, plastics recycling ranks at the bottom of all recycled materials listed. The plastics industry has launched an intensive public relations campaign and research programs to enhance the image of plastic as an easily recycled material.

6.12 YARD WASTE

This waste component embraces grass, leaves, and tree and brush trimmings from residential, institutional, and commercial sources. Limited data are available on the composition of yard waste; however, it is estimated that the average composition is about 50% grass, 25% leaves, and 25% brush on a weight basis. These numbers vary as a function of climate, region of the country, and season of the year.

Due to the huge volumes of yard wastes produced, along with concerns over diminishing landfill space, many states have enacted legislation to divert these wastes from landfills. By 2010, 24 states had enacted legislation banning or discouraging yard waste disposal in landfills (Buckner 2010). Such legislation has led to an increase in the use of mulching lawnmowers and backyard composting. Many municipalities have also established composting programs near waste transfer stations or landfills.

Over 2200 yard waste composting programs exist in the United States (van Haaren et al. 2010). These programs vary in size and sophistication, as well as in terms of quality and quantity of finished product.

Based on sampling studies at landfills and transfer stations, a total of 20.1 million tons of yard wastes were recovered for composting in 2010. The percentage of yard waste composted has more than doubled since 1992. This is a result of increased numbers of yard waste composting facilities, greater quantities of material being handled at facilities, and bans of yard waste from many landfills. Within the past few years, however, composting has increased at a slower rate, suggesting that much of the impact of the states' bans of yard waste from landfills has been realized.

Details of the composting process are discussed in Chapter 8.

6.13 FOOD WASTE

Food wastes include uneaten food and food preparation waste from residences, commercial establishments (restaurants, etc.), institutional sources (school cafeterias, hospital cafeterias), and industrial sources (factory lunchrooms). Food waste generated during the packaging of food products is not included in the EPA estimates. Food waste generation from residential and commercial sources was estimated using data from sampling studies from selected parts of the country, combined with demographic data, grocery store sales, and restaurant sales. Estimated food waste generation in 2010 was 34.8 million tons (U.S. EPA 2011a).

As mentioned in Chapter 2, a substantial portion of food waste generated during the 1940s and 1950s was fed to hogs. Today, however, "recycling" of food waste primarily refers to its incorporation into the composting process for later use as a soil conditioner or landscaping material. EPA (2011) estimates that approximately 970,000 tons of food waste are recycled (composted) annually.

6.14 TIRES AND RUBBER

It is estimated that between two and three billion tires have been disposed in the United States alone, and another 270 million tires (weighing 3.4 million tons) are added to the waste stream annually (Table 6.9) (U.S. EPA 2002). This number does not include over 30 million tires that are retreaded every year. Until recently, waste tires were simply stockpiled (Figure 6.17), landfilled, or burned. Open, uncontrolled tire fires have resulted in the generation of numerous noxious and hazardous air pollutants; such fires are difficult to extinguish, in some cases lasting months or years. Tires also serve as a breeding ground for insects such as mosquitoes and other pests.

6.14.1 Design and Manufacture

Tires are constructed from one of two distinct designs, that is, non-belted and steelbelted. The latter type dominates the tire market by virtue of its greatly enhanced lifespan, as well as improved fuel economy. A longer lifespan results in less tires ending up in landfills; unfortunately, however, steelbelted tires are more difficult to recycle and comprise about 90% of all tires in the waste stream. Tables 6.10 and 6.11 list the typical types of materials used in tire manufacture.

6.14.2 Disposal and Recycling

Many states have targeted the tire dumping problem by restricting land disposal of tires, establishing tire recycling programs, and assisting in development of markets for recovered scrap tires. Bans on disposing whole tires in landfills are in effect in 38 states (U.S. EPA 2012c), and over 30 states collect disposal fees on tires to support proper management and, in some cases, to support research and market development for tire recycling. The fate of scrap tires is outlined in Figure 6.18. The majority continues to be land-disposed (i.e., landfilled and stockpiled).

TABLE 6.9
Rubber and Leather in MSW and Recycled, 2010

Product	Generation (Thousands of Tons)	Recovery (Thousands of Tons)	Recovery (Percent of Generation)
Durable goods			
Rubber in tires[a]	3300	1170	35.5
Other durables[b]	3440	Neg.	Neg.
Total rubber and leather in durable goods	6740	1170	17.4
Nondurable goods			
Clothing and footwear	790	Neg.	Neg.
Other nondurables	250	Neg.	Neg.
Total rubber and leather in non durable goods	1040	Neg.	Neg.
Total rubber and leather	7780	1170	15.0

Source: Adapted from U.S. EPA, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States, Tables and Figures for 2010*, 2011, Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf.

Note: Details may not add to totals due to rounding. Neg. = less than 5000 tons or 0.05%.

[a] Automobile and truck tires. Does not include other materials in tires.

[b] Includes carpets and rugs and other miscellaneous durables.



FIGURE 6.17 Illegal tire dumps pose hazards from fires and insect breeding and are unsightly.

Disposal of waste tires via sanitary landfilling causes problems for operators; for example, tires tend to "float" to the surface due to their low density. Such upward migration may eventually damage the integrity of a landfill cap. Some landfill operators cut or shred tires to prevent floating behavior. Others will shred tires for use as daily landfill cover. Landfill disposal of tires is generally considered wasteful for the following reasons:

- Tires are relatively inert and may not necessarily need land disposal to limit inherent hazards.
- Tires have potential value as a recovered material.
- Tires have a potentially high economic value as a fuel.

Since the 1990s, the use of scrap tire monofills (i.e., a landfill dedicated to one only type of material) has become more common as a means to manage scrap tires. In some locations,

TABLE 6.10
Typical Chemical Composition of a Tire

Synthetic rubber
Natural rubber
Sulfur and sulfur compounds
Silica
Phenolic resin
Oil: aromatic, naphthenic, paraffinic
Fabric: polyester, nylon, etc.
Petroleum waxes
Pigments: zinc oxide, titanium dioxide, etc.
Carbon black
Fatty acids
Inert materials
Steel Wire

Source: Reproduced with kind permission from Rubber Manufacturers Association, *Scrap Tire Characteristics*, n.d., Available from: http://www.rma.org/scraptires/characteristics.html#anchor135840.

TABLE 6.11
Composition (by wt) of Passenger and Truck Tires

Material	Passenger Tire, %	Truck Tire, %
Natural rubber	14	27
Synthetic rubber	27	14
Carbon black	28	28
Steel	14–15	14–15
Fabric, fillers, accelerators, antiozonants, etc.	16–17	16–17
Average weight (lb)		
New	25	120
Scrap	20	100

Source: Reproduced with kind permission from Rubber Manufacturers Association, *Scrap Tire Characteristics*, n.d., Available from: http://www.rma.org/scraptires/characteristics.html#anchor135840.

monofills are used where no markets exist and where MSW landfills do not accept tires. In other cases, monofills are portrayed as a management system that allows long-term storage of scrap tires without the problems associated with above-ground storage. In theory, monofilled processed scrap tires can be "harvested" when markets improve. Using monofills for scrap tires is preferable to above-ground storage, especially if the latter is not well managed (Scrap Tire Management Council 1999).

Markets for waste tires recovered an estimated 86.5% in 2010 (Table 6.12). The conversion of scrap tires into fuel increases every year and is currently the largest single use of scrap tires (U.S. EPA 2012c). The use of tires as a fuel material is discussed in Chapter 9. Overall, 15% of rubber and leather in MSW was recovered in 2010 (U.S. EPA 2011a).

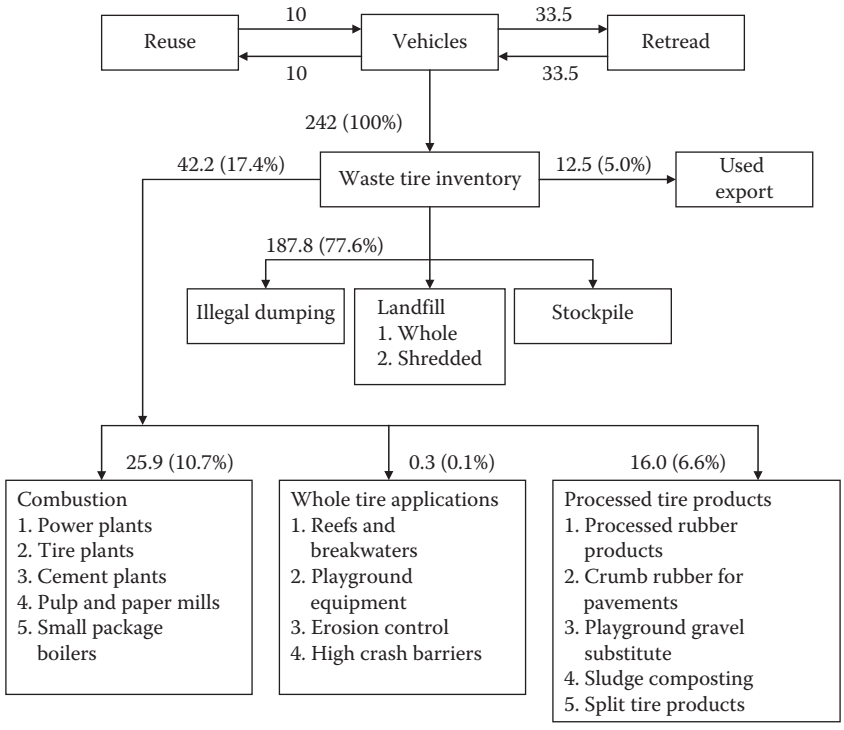


FIGURE 6.18 Destinations for scrap tires.

TABLE 6.12
Estimated Total Scrap Tire Market for 2010

Market	Thousands of Tons
Fuel	
Cement kilns	664.0
Pulp and paper mills	1075.5
Electric utilities	341.5
Industrial boilers	201.5
Dedicated TTE	203.5
Lime kilns	0.4
Ground rubber	807.5
Civil engineering	560.0
Electric arc furnace	27.1
Exported	102.1
Agricultural	5.5
Punched and stamped	1.9
Total to market	3990.5
Landfilled	730.1
Market as a percent of total generation	86.5%

Source: Blumenthal, M., *Scrap Tire Markets in the United States: An Update*, 2012, Available from: http://clu-in.org/meetings/border2012/slides/blumenthal2.pdf.

6.14.2.1 Recycling

In recent decades, many innovative uses have been found for recycled tires. For example, ground rubber is recycled into products such as rubber-modified asphalt, playground cover, and flooring material. Tire material has also been used as an alternative to pea stone in septic systems. Some facilities use scrap tires as heating fuel.

6.14.2.2 Crumb Rubber

For several recycling processes, tires are shredded to a small particle size (about 5 × 5 cm or 2 × 2 in.) for eventual processing. The steel is removed magnetically, and the particles may be shredded a second time to produce crumb rubber. The rubber is treated to restore its ability to bond with other materials. Recovered rubber may then be combined with virgin rubber or other materials to produce a quality product.

More than 227 million kg (500 million lb) of crumb rubber is used in North America annually, and the rubber manufacturing industry accounts for more than half this amount. Uses for crumb rubber include fillers in rubber compounds and asphalt modifiers, for example, in athletic tracks. Rubber adds flexibility to the surface and allows for better traction, and increases the lifetime of the material. Other useful applications exist for recovered crumb rubber (Table 6.13). Manufacturers may accrue substantial savings in material costs. Improved mixing and curing properties are additional benefits that result from use of crumb rubber.

6.14.2.3 Retreaded Tires

Approximately 70% of the cost of a new tire is in the tire body. Retreaded tires can be driven at the same legal speeds as comparable new tires with no loss in safety or performance. Retreaded truck tires are manufactured according to rigorous industry-recommended practices. Commercial aircraft retreads are approved by the Federal Aviation Administration. Retreaded passenger car tires are manufactured according to federal safety standards developed by the U.S. Department of Transportation.

Approximately 24 million retreaded tires are sold each year in the United States and Canada. Table 6.14 lists various industries using retreaded tires.

U.S. and Canadian retread tire industries used approximately 260 million kg (575 million lb) of tread rubber in 2000. There are approximately 1200 retreading plants in North America, a large percentage of which are owned and operated by independent small businesses. The remaining plants are owned and operated by new tire manufacturers and a major tread rubber supplier (TRIB 2011).

Steelbelted radials are routinely retreaded and are available with many tread patterns. Retreading greatly reduces solid waste disposal problems and conserves hundreds of millions of barrels of petroleum every year. Truck tires can often be retreaded several times (TRIB 2011).

Despite the fact that alternative uses for scrap tires exist, it is estimated that roughly 275 million scrap tires were lying in stockpiles as of 2004 (U.S. EPA 2012c). To alleviate the scrap tire problem, additional action up the product chain is encouraged. Efforts are being made by manufacturers to increase the recycled content of new tires to reduce the use of virgin materials and, at the same time, provide a significant end-market for scrap tires. Manufacturers also strive to design tires with increased durability, thus prolonging their useful life. Lastly, reuse of scrap tires via retreading gives tires a new useful life.

6.15 GOALS FOR THE NATION

The EPA goal for the United States was to recycle at least 35% of MSW by the year 2005 (compared with 1990 baseline numbers), while reducing the generation of solid waste to 1.95 kg (4.3 lb)

TABLE 6.13
Applications for Recycled Crumb Rubber

Construction/Equipment
Adhesives and sealants
Bin liners
Carpet underlay
Conveyor skirt boarding
Custom-molded goods
Dams, silos, ponds, roof liners and covers
Floor mats
Floor tiles
Foundation waterproofing
Gaskets
Hospital, industrial, and bathroom flooring
Insulation
Livestock stable mats
Non-skid surfaces
Paint
Patio bricks
Raised flooring
Roof shingles
Vibration dampers
Waterproofing compounds for roofs and walls

Geotechnical/Asphalt Applications
Drainage pipes
Fill materials for highway embankments
Porous irrigation pipes
Railroad crossings
Road building and repair
Roadway crack and joiner sealants
Rubberized asphalt for roads and driveways
Soil conditioner/ground cover
Sub-base for horse racing tracks
Subsoil drainage
Traffic cone bases
Traffic/people barricades

Automotive Industry
Belts
Brake disk pads
Brake linings
Bumpers
Car body underseal and rustproofing materials
Floor liners for trucks and vans
Floor mats for cars and trucks
Seals
Shock absorbers
Splash guards and mud guards
Tires and tire inner liners

Athletic Surfaces
Running tracks
Golf tee-off areas
Kindergarten playgrounds and recreation areas
Non-slip boat dock surfaces
School sports areas
Swimming pool borders
Walkways and garden paths
Tennis and basketball courts

Source: Adapted from Rubberecycle, *Tire Recycling*, 2001, Available from: http://www.rubberecycle.com.

per person per day. The United States recycles 34.1% and per capita generation is 2.0 kg (4.4 lb) per person per day. Economic growth results in the generation of more products and materials; therefore, there will be an increased need to expand and strengthen the U.S. recycling and composting infrastructure, purchase more recycled products, and invest in source reduction activities—such as the reuse of materials and products, and "lightweighting" of products and packaging—in order to meet these goals.

TABLE 6.14
Industries using Retreaded Tires

Eighty percent of the tires used by the commercial aviation industry are retreaded tires.
Nearly 100% of off-the-road, heavy duty vehicles
School buses and municipal vehicles
Trucking fleets and overnight delivery vehicles
Taxi fleets, race cars and industrial vehicles
Fire trucks and other emergency vehicles
Farm tractors and other agricultural equipment
Millions of passenger cars
Federal and military vehicles, including those operated by the U. S. Postal Service, use retreaded passenger, truck, and aircraft tires.

Source: Reproduced with kind permission from Tire Retread Information Bureau, *Facts about the Industry*, 2011, Available from: http://www.retread.org.

QUESTIONS

1. A material is not truly considered "recycled" until it has proceeded through several distinct steps and is ultimately purchased by the consumer. True or false? Justify your answer. List and discuss the steps.
2. Why have many community recycling programs failed over the past two decades? How could programs have been planned, operated, and financed in order to have been more successful?
3. What are the primary approaches for separation of recyclable materials from the waste stream? Which is superior in terms of producing a clean, quality product? Which method is often preferred on account of its convenience to the consumer? How do total costs differ between the different approaches?
4. How do source reduction, reuse, and recycling differ?
5. Why is price volatility in recycling markets a "given" in the industry?
6. How does purity affect the demand for a separated product? What can be accomplished (by the consumer, the municipality) in order to improve overall purity?
7. List the three major methods of pulping virgin fiber. How might each method affect the quality of recycled paper?
8. What is the major limitation on the amount of waste paper that can be recycled in a given year?
9. How many lifetimes do office paper or newsprint have before they can no longer be effectively recycled? Aluminum? Steel? Glass?
10. List some alternative recycling markets for paper, glass, and plastics.
11. Why does aluminum container manufacture from UBCs save substantially more energy and produce less pollution than manufacture using raw materials? Be specific.
12. What are the primary contamination concerns with recycled glass? Recycled aluminum?
13. "Due to the positive net value of scrap aluminum, there is virtually no waste of aluminum containers in the United States." True or false? Discuss.
14. List the main manufacturing processes used to transform raw polymers to a useful product. Are any of these processes preferable for recycling polymers?
15. What are the two most commonly recycled polymers? In what types of products, are they used?
16. The city of Pristine, IL, will develop a comprehensive waste management program in order to divert waste materials from the county landfill. The city will employ curbside collection

of glass, paper, aluminum, and PETE. What actions can the municipality undertake that will ensure the success of the recycling program? Consider legislative initiatives, educational programs, marketing, and other constructive efforts.

17. Suppose the city was to avoid working with a materials broker and instead work directly with material buyers. What agreements should be specified in a proposal from a recycled materials buyer?
18. The city is allowing a local recycling company to acquire the abandoned Hi-Jinx Chemical Company manufacturing building for use as a recycling center. List five practical issues that the company must consider before accepting the building.
19. "As of the late 1990s, recycling in the United States reached its maximum potential." True or false? Justify your answer.
20. Identify the materials that are currently being recycled in your community. What other materials could potentially be recycled?
21. If your community is engaged in a recycling or waste reduction program, is the program voluntary or mandatory? How is the public involved—for example, are educational programs available? Which agency or office is responsible for managing the program? Are there areas in which the program could be improved?
22. In your home, which waste materials do you now separate? What other components could potentially be separated for eventual recycling or reuse?
23. How does resource recovery affect the overall cost of solid waste management? Be specific. Consider storage and collection issues, and landfill lifetime.
24. At your university or place of employment, what efforts have been undertaken to reduce the volume of solid waste? Describe any resource recovery or waste reduction programs in place.

REFERENCES

Alcoa. 2013. How Aluminum Cans are Made. Available from: http://www.alcoa.com/rigid_packaging/en/about/making_cans.asp

APC (American Plastics Council). 2002. *Recycling Facts from the American Plastics Council*. Available from: http://www.plastics-resource.com/recycling/recycling_backgrounder/bk_1998.html

Blumenthal, M. 2012. *Scrap Tire Markets in the United States: An Update*, Rubber Manufacturers Association Border 2012 Meeting, Nogales, AZ. Available from: http://clu-in.org/meetings/border2012/slides/blumenthal2.pdf

Buckner, S.B. 2010. *Yard Trimmings Bans: Impact and Support*. Ronkonkoma, NY: U.S. Composting Council. Available from: http://recyclingorganizations.org/webinars/RONA-YT-Ban-impacts-and-support-8.19.pdf

Business News America. Americas staff reporters. Paper, cardboard recycling industry ranked 4th in world, Mexico. *Water & Waste, News*. Retrieved 7 May 2012. Available from: http://www.bnamericas.com/news/waterandwaste/Paper,_cardboard_recycling_industry_ranked_4th_in_world

CC Technologies Systems. n.d. *Corrosion Cost*. Available from: http://www.corrosioncost.com/pdf/pulppaper.pdf

Chen, A. 2012. *Waste Glass Finds New Life as Alternate Aggregate*. Sustainable City Network. Available from: http://www.sustainablecitynetwork.com/topic_channels/solid_waste/article_058f8a60-02a4-11e2-9c90-0019bb30f31a.html

CMI (Connecticut Metal Industries). 2002. Available from: http://www.ctmetal.com/glass.htm

Container Recycling Institute. 2002. *Trashed Cans: The Global Environmental Impacts of Aluminum Can Wasting in America*. Arlington, VA: Container Recycling Institute, p. 143.

Ferguson, L. 2001. Can Deinked Pulp Dare to Compete with Virgin Pulp? *6th Research Forum on Recycling.* Magog, QC, p. 181.

FEVE/The European Container Glass Federation. 2013. *Collection for Recycling Rates in Europe*. Available from: http://www.feve.org/FEVE-STATIS-2013/Recycling-2011.html

Glass Packaging Institute. n.d. *Glass Handling and Recycling*. Available from: http://www.gpi.org/Handling.html

ISRI (Institute of Scrap Recycling Industries). 1993. *Recycling Scrap Iron and Steel.* Washington, DC: ISRI.

ISRI (Institute of Scrap Recycling Industries). 2002. *Scrap Specifications Circular 2002. Guidelines for Nonferrous Scrap, Ferrous Scrap, Glass Cullet, Paper Stock, Plastic Scrap*, SPECS 2002-1. Washington, DC: ISRI.

ISRI (Institute of Scrap Recycling Industries). 2011. *ISRI: The Voice of the Recycling Industry*. Washington, DC: ISRI.

Jones, J.D. 2002. *Electric arc Furnace Steelmaking*. American Iron and Steel Institute, Steelworks. Available from: http://steel.org/learning/howmade/eaf.htm

Kogel, J.E., Trivedi, N.C., Barke, J.M., and Krukowski, S.T. 2006. *Industrial Minerals and Rocks: Commodities, Markets and Uses*, 7th ed. Littleton, CO: Society for Mining, Metallurgy, and Exploration.

Liu, D.H.F. and Liptak, B.G. 2000. *Hazardous Waste and Solid Waste.* Boca Raton, FL: Lewis Publishing.

McMurry, J. 1992. *Organic Chemistry*, 3rd ed. Pacific Grove, CA: Brooks/Cole.

NAA (Newspaper Association of America). 2002. *Newsprint Recovery Continues to Climb*. Available from: http://www.naa.org

Paper Recycles. 2013. *Paper and Paperboard Recovery*. Available from: http://www.paperrecycles.org/statistics/paper-paperboard-recovery

Pilkington. 2003. *The Chemistry of Glass.* St. Helens. Available from: http://www.pilkington.com/corporate/english/education/chemistry/default.htm

Print Power. 2010. *European Paper Recycling 1995–2010*. Available from: http://www.printpower.eu/de/news/p/detail/european-paper-recycling-award-ausgeschrieben

Rhyner, C.R., Schwartz, L.J., Wenger, R.B., and Kohrell, M.G. 1995. *Waste Management and Resource Recovery.* Boca Raton, FL: Lewis Publishing.

Roberts, J.C. 1996. *The Chemistry of Paper.* Cambridge: Royal Society of Chemistry.

Rubber Manufacturers Association. n.d. *Scrap Tire Characteristics*. Available from: http://www.rma.org/scraptires/characteristics.html#anchor135840

Rubberecycle. 2001. *Tire Recycling*. Available from: http://www.rubberecycle.com

Russell, C.S. and Vaughan, W.J. 1976. *Steel Production: Processes, Products, and Residuals.* Baltimore, MD: Johns Hopkins University Press.

Schwarz, S.C. and Brunner, C.R. 1983. *Energy and Resource Recovery from Waste.* Park Ridge, NJ: Noyes Data Corporation.

Scrap Tire Management Council. 1999. *Scrap Tire Use/Disposal Study: 1998–1999*. Available from: http://www.rma.org/scrap_tires/scrap_tire_markets/tire_disposal_study_exec_summary.pdf

SHWEC (Solid and Hazardous Waste Education Center). 2012. *Material Manufacturing and Recycling: Glass*. Available from: http://www4.uwm.edu/shwec/publications/cabinet/recycling/Material%20Manufacturing%20and%20Recycling-glass.pdf

Sims Group Limited. n.d. *Cadillac Faces Shredder Jaws*. Available from: http://www.unitednotions.com.au/prjob_7.html

Smook, G.A. 1982. *Handbook for Pulp and Paper Technologists*. Montreal: Canadian Pulp and Paper Association.

SPI (Society for the Plastics Industry). 1999. *Processing Methods*. Available from: http://www.socplas.org

Tchobanoglous, G., Theisen, H., and Vigil, S. 1993. *Integrated Solid Waste Management: Engineering Principles and Management Issues.* New York: McGraw-Hill.

TRIB (Tire Retread Information Bureau). 2011. *Facts about the Industry*. Available from: http://www.retread.org

U.S. EPA (U.S. Environmental Protection Agency). 2001. *Municipal Solid Waste in the United States: 1999 Facts and Figures*, EPA 530-R-01-014. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2002. *Tires. Product Stewardship*. Available from: http://www.epa.gov/epr/products/tires.html

U.S. EPA (U.S. Environmental Protection Agency). 2011. *Municipal Solid Waste Generation, Recycling, and Disposal in the United States, Tables and Figures for 2010*. Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf

U.S. EPA (U.S. Environmental Protection Agency). 2012a. *Glass*. Available from: http://www.epa.gov/osw/conserve/materials/glass.htm

U.S. EPA (U.S. Environmental Protection Agency). 2012b. *Municipal Solid Waste*. Available from: http://www.epa.gov/epawaste/nonhaz/municipal/index.htm

U.S. EPA (U.S. Environmental Protection Agency). 2012c. *Common Wastes and Materials—Scrap Tires*. Available from: http://www.epa.gov/osw/conserve/materials/tires/basic.htm

Van Haaren, R. Themelis, N., and Goldstein, N. 2010. *The State of Garbage in America*. Available from: http://www.biocycle.net/images/art/1010/bc101016_s.pdf

World-Aluminum. 2000. *Alumina Refining*. Available from: http://www.worldaluminium.org/production/refining/index.html

SUGGESTED READINGS

Ackerman, F. and Mirza, S. 2001. Waste in the inner city: Asset or assault? *Local Environ*, 6, 113–120.

Agarwal, A., Singhmar, A., Kulshrestha, M., and Mittal, A.K. 2005. Municipal solid waste recycling and associated markets in Delhi, India. *Res Conservat Recycl*, 44(1), 73–90.

Al-Salem, S.M., Lettieri, P., and Baeyens, J. 2009. Recycling and recovery routes of plastic solid waste (PSW): A review. *Waste Manage*, 29(10), 2625–2643.

Creason J. and Podolsky, M.J. 2002. Economic impacts of municipal recycling. *Rev Reg Stud*, 31, 149–164.

Derksen L. and Gartrell, J. 2000. The social context of recycling. *Am Sociol Rev*, 58, 434–442.

Donnelly, J.E. 2002. Numbers never lie, but what do they say? A comparative look at municipal solid waste recycling in the United States and Germany. *Georgetown Intl Environ Law Rev,* 15, 29–53.

Gamba R.J. and Oskamp, S. 2000. Factors influencing community residents' participation in commingled curbside recycling programs. *Environ Behav*, 26, 587–612.

RecycleHawaii. 2003. *Recycling Successes on the Big Island: Mauna Kea Resort & Hawai'i Volcanoes National Park*. Available from: http://www.recyclehawaii.org/sept99.htm

Salhofer, S. and Isaac, N.A. 2003. Importance of public relations in recycling strategies: Principles and case studies. *Environ Manage*, 30, 68–76.

U.S. EPA (U.S. Environmental Protection Agency). 2003. *Municipal Solid Waste: Recycling*. Available from: http://www.epa.gov/epaoswer/non-hw/muncpl/recycle.htm

7 Municipal Solid Waste Processing
Materials Recovery Facilities

Sooty, swarthy smiths, smattered with smoke,
Drive me to death with the din of their dents.
Such noise at night no man heard, never;
With knavish cries and clattering of knocks!
… They spit and sprawl and spill many spells;
They gnaw and gnash, they groan together
And hold their heat with their hard hammers
Heavy hammers they have that are hard-handled,
Stark strokes they strike on a steely stump.

Anonymous, ca. 1400
The Blacksmiths

7.1 INTRODUCTION

The ideal resource recovery scenario for a community would include thorough segregation of individual waste components by each homeowner, commercial establishment, industry, or municipal institution (i.e., at the *source*). Subsequently, the individual items (e.g., aluminum cans, paper, glass, and plastics) are collected on a regular basis, stored in separate bins within the collection vehicle, and transported to a facility for further processing (densifying, shredding). These slightly processed, clean materials would then be sold for reprocessing on an industry scale. The above scenario would result in a clean and highly marketable resource, thus decreasing the capital expenses for purchase of large separation equipment, energy, and labor. Since the above approach for materials separation from municipal solid waste (MSW) is often not feasible due to lack of information, lack of participation, and insufficient support from local and state governments, other approaches are necessary.

7.2 MATERIALS RECOVERY FACILITY

The materials recovery facility (MRF) is a relatively recent approach to MSW management, but its utility has become obvious and its popularity is increasing. In 1898, the first MRF was built in New York City. The facility processed the waste of over 116,000 residents and recovered up to 37% (by weight) of the wastes. More recently, the first modern MRF was established in the 1980s in Groton, CT. Despite facing a volatile market for materials, the number of MRFs has grown markedly in recent past decades. In 1991, a total of 40 projects were planned or operating. Two years later, this number had quadrupled to 166. In 1995, another doubling occurred to 307 projects. By 2010, a total of 633 MRFs were in operation (U.S. EPA 2011). Since 1995, when the implementation of curbside recycling collection programs had spread across the country, MRFs were found in nearly equal proportion by region.

The basis for the increased interest in mechanized waste processing facilities is that as MSW disposal costs rise, there is a greater incentive for recycling. As a consequence, convenient and rapid methods of separation and processing are developed. For example, in areas where landfill tipping fees are below $30–40 per ton, recycling the waste stream may not appear economically attractive to municipalities and the waste industry. However, with tipping fees in some areas exceeding $100 per ton, cities and waste management companies clearly appreciate the advantage to serious investment in recycling.

The two major configurations of MRFs are

- Facilities that handle source-separated materials (*clean MRFs*)
- Facilities that handle mixed (commingled) wastes (*dirty MRFs*)

In many parts of the United States, markets exist for most materials recovered from the waste stream. In those markets, the specifications for separated materials will vary. Some of the forms and conditions applicable to finished products are shown in Table 7.1.

7.2.1 Unit Operations

Unit operations in a centralized facility include screening, magnetic separation, shredding, and air classification. The unit operations for the separation and processing of wastes are designed to accomplish the following (Tchobanoglous et al. 1993):

- To modify the physical characteristics of the waste so that components can be removed easily
- To remove specific, useful components from the waste stream
- To remove contaminants from the waste stream
- To process and prepare the separated materials for subsequent uses

Common unit operations for MSW separation are shown in Table 7.2.

Even though many MRF systems are highly mechanized, human labor is still needed to carry out a number of duties. For example, the removal of hazardous wastes (batteries, paint cans, and pesticide containers) from MSW can only be accomplished by manual sorting. The same is true for 2-L soda bottles made from PET. In addition, nearly all MRFs that sort glass by color must rely on the human eye and hand.

7.2.2 Weigh Station

Scales of various designs are used to weigh materials delivered, recovered, and removed from the facility. Scale types vary from small units for weighing modest amounts brought in by individuals to the large platform scales that are suited to handle the heaviest collection trucks.

Trucks typically enter a weigh station immediately upon entry to the facility property. The station often consists of an office with a series of platform scales that can handle a truck of any weight (Figure 7.1). The gross weight of the truck is measured. After tipping its load at the receiving area, the truck returns to the weigh station for final weighing and calculation of the net weight of the waste. These data are used to bill the waste hauling company. Some weigh stations are equipped with magnetic card readers, and vehicles are provided with magnetic cards. Information on tonnages is thus collected and calculated automatically.

The weigh station provides other useful data, such as the rate at which waste is processed by the facility. The input tonnage is important for calculating certain facility operations, including possible requirements for additional storage space, greater equipment capacity, and size of the workforce.

The weigh station also provides data for determining total waste generation for a particular collection area. Collection trucks may be identified by route; therefore, the quantities of wastes delivered from a particular neighborhood or town can be determined. Such data are beneficial for planning improved collection routes or providing other services.

TABLE 7.1
Some Forms and Conditions Applicable to Products to Be Recycled

Paper

- Separated by grade (laser-quality white, mixed colored paper, old newspaper, corrugated, etc.)
- Baled or loose
- Dry
- Clean (or not weathered)

Ferrous Containers

- Flattened, unflattened, shredded
- Labels removed
- Clean or limited food contamination
- May not include bimetal
- Loose, baled, or densified into biscuit form

Aluminum Containers

- Flattened, shredded, baled, or densified into biscuit form
- Free of moisture, dirt, foil, plastic, glass, oil, other foreign substances

PETE and HDPE[a]

- Baled, granulated
- Separated by color or mixed
- Without caps

Glass

- Separated by color or mixed
- Size of cullet specified
- Nature and amount of allowable contamination

General

Available markets for secondary materials typically specify the means of packaging and shipping each product. The specifications depend upon location and end-use and often include the following:

- Skids or pallets
- Bundles, bins, boxes, cartons, or drums
- Trailer loads
- Roll-offs
- Rail cars

Source: U.S. EPA, *Materials Recovery Facilities for Municipal Solid Waste*, EPA/625/6-91/031, Office of Research and Development, U.S. EPA, Washington, DC, 1991.

[a] PETE = polyethylene terephthalate; HDPE = high-density polyethylene.

7.2.3 Receiving Area

After the initial weigh-in, collection vehicles transport their loads to a receiving (tipping) area for temporary storage and initial processing (Figure 7.2). The facility must be designed to create an optimum flow of collection trucks. In other words, full trucks should not interfere with the prompt exit of just-emptied vehicles from the tipping area.

7.2.4 Storage Area

Storage of MSW at a MRF is a key practical concern from the standpoint of both efficiency and safety. Storage encompasses sufficient space for the raw, incoming MSW as well as for the sorted, cleaned, baled product that is removed by a buyer.

TABLE 7.2
Common Unit Operations and Facilities for the Separation and Processing of Separated and Commingled MSW

Unit Operation	Function/Material Processed
	Shredding
Hammer mills	Size reduction
Flail mills	Size reduction, also used as bag breaker
Shear shredder	Size reduction, also used as bag breaker
Glass crushers	Size reduction
Wood grinders	Size reduction, yard trimmings, and wood wastes
Screening	Separation of over- and under sized material; trommel also used as bag breaker
Cyclone separator	Separation of light combustible materials from air stream
Air classification	Separation of light combustible materials from air stream
Magnetic separation	Separation of ferrous metal from commingled wastes
	Densification
Balers	Compaction into bales/paper, cardboard, plastics, textiles, aluminum
Can crushers	Compaction and flattening/aluminum and tin cans
	Weighing
Platform scales	Operational records
Small scales	Operational records
	Handling, Moving and Storage
Conveyor belts	Materials transport/all types of materials
Picking belts	Manual separation of waste material/source-separated and commingled MSW
Movable equipment	Materials handling and moving/all types of waste
Storage facilities	Materials storage/all types of recovered materials

Source: Data reproduced with kind permission from Tchobanoglous, G. et al., *Integrated Solid Waste Management: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1993.



FIGURE 7.1 Weigh station at a materials recovery facility.



FIGURE 7.2 Receiving area at a MRF.



FIGURE 7.3 Tipping floor of a MRF. (Reproduced with kind permission of the Portage County, Wisconsin Solid Waste Department, Available from: http://www.co.portage.wi.us/solidwaste/mrfimages/4OnToTheTipping Floor.JPG.)

A common storage system at a MRF is the tipping floor, also known as "slab storage." In this scenario, either collection trucks or front-end loaders deposit the wastes onto the floor (Figure 7.3). The waste may be stacked, if necessary, by a front-end loader to as high as 6–8.5 m (approximately 20–25 ft). The slab is partly surrounded by a "push wall," a reinforced concrete wall designed to withstand the force of large equipment pushing wastes against it. Given the physical and chemical stresses on push walls, they may be coated with polymers for long-term protection (Epoxytech 2009). Front-end loaders will later lift the wastes onto a conveyor that feeds into the processing system.

The size of the tipping floor must consider the number of trucks that will unload in a given period. Calculations for floor size should take into account surges of waste deliveries. For example, collection trucks tend to arrive at the MRF in large numbers late in the day, after the last loads are collected. Similarly, Monday deliveries may result in accumulation of substantial volumes of MSW, as there may have been no waste processing over the weekend.

Another storage system, although more common for incinerators, is the standard pit with an overhead crane. The pit may be 6–12 m (20–40 ft) deep. Waste collection trucks back up to the edge of the pit and dump their loads directly. The overhead crane is used to retrieve the waste and also to spread the waste across the pit area. The crane drops the waste into a feed chute or onto a conveyor belt. Slab storage is clearly less expensive than pit storage, especially when storage requirements are modest.

The design of storage facilities requires knowledge of materials flow; however, a means of experimentally evaluating flow rate of MSW in a storage area is also useful. The evaluation will address problems such as how quickly (or how slowly) materials move out of the tipping area. Potentially effective techniques include stereophotogrammetry, radio pills (i.e., transmitters that move with the solids in the chamber), radiological tagging, and x-ray methods. With heterogeneous materials such as MSW, the radio pill or stereophotogrammetry methods are effective (Worrell and Vesilind 2011).

The material recently processed and separated at the MRF should be stored apart from incoming wastes and vehicles. These wastes should also be protected from weather. In some facilities, storage areas for processed wastes are physically separated from those areas for incoming wastes. Such separation facilitates movement of trucks. Also, the separated wastes can be displayed for potential buyers in a clean, orderly location.

Common units for the storage of processed wastes include:

- Enclosed warehouse space
- Open-sided, roofed structures (i.e., pole barns)
- Roll-off containers
- Shipping containers

Shipping containers tend to serve as an economical storage system. The materials buyer may provide these containers. This method is popular for the shipping of various grades of paper and cardboard to overseas markets on container ships.

Example 7.1

Consider a 400 MT per day resource recovery facility. Assume that all MSW is received in 15 m^3 (20 yd^3) compactor trucks, providing an average density of 900 kg/m^3. During a routine work day, and assuming normal equipment operation, how many trucks can be accommodated per hour?

Truck capacity = (15 m^3 × 900 kg/m^3)/1000 kg/MT = 13.5 MT/truck

The facility processes MSW 12 h per day, 5 days per week.

MSW processing rate = (400 MT/day)/12 h/day = 16.7 MT/h = 16.7/5 = 3.3 truckloads/h

Waste collections that take place 5 days per week, 1 shift per day, and only about 7 h per shift are actually used for processing on the tipping floor. Therefore:

Actual receiving rate = (400 × 5 days)/(5 days × 7 h/day) = 57 MT/h

(57 MT/h)/13.5 MT/truck = 4.2 truckloads per hour

In addition to the above, it would be useful to consider hourly peaking factors and seasonal peaking factors in calculations.

(Adapted from Schwarz, S.C. and Brunner, C.R., *Energy and Resource Recovery from Waste,* Noyes Data Corporation, Park Ridge, NJ, 1983.)

7.2.5 Mobile Equipment in the MRF

Front-end loaders and forklifts are universal for routine operations of the MRF. For example, when a collection truck tips its load onto the slab, the front-end loader will promptly arrive to lift the material to a conveyor for subsequent processing (Figure 7.4). Front-end loaders also move wastes after processing. Forklifts are used to transport baled materials to storage areas and from storage areas onto trucks. Mobile equipment in a MRF typically include:

- Bins
- Containers



FIGURE 7.4 Front-end loader on the tipping floor.

- Forklift
- Front-end loader
- Manulift
- Skid steer loader
- Steam cleaner
- Vacuum or sweeper or magnetic pickup
- Yard tractor

7.2.6 Fixed Equipment in the MRF

The various types of fixed equipment typically required in a MRF are presented in Table 7.3. The equipment in use in a single facility is highly variable, and selection is based on goals for the number of commingled articles to be separated, their desired purity, the original characteristics of the waste, space considerations, the throughput capacity of the facility, and, of course, economics. The various fixed components are discussed in the following sections.

7.2.7 Conveyors

The conveyor, a system to transfer wastes from one location to another (and also for manual and mechanical removal of individual components from the waste stream), is the most common unit of equipment for handling materials in a MRF. Several designs are available, including hinge, bucket, apron, belt drag, screw, vibrating, and pneumatic (CEMA 1995). Comprehensive engineering data are available for many types of conveyors; as a result, their performance can be accurately predicted when they are used for handling materials possessing well-known characteristics.

Factors to consider in the selection of the appropriate conveyor include:

- Capacity of the belt
- Length of travel
- Lift
- Characteristics of the material to be transported
- Overall cost

Horizontal and inclined belt conveyors, where the material is carried along the surface of the belt, and drag conveyors, equipped with crossbars to drag the input wastes, are among the most commonly used conveyors for handling MSW (Figure 7.5).

TABLE 7.3
Fixed Equipment That May be Used in a Materials Recovery Facility

Size reduction equipment	Environmental control equipment
Baler	Dust collection
Shredder	Noise suppression
Vertical or horizontal hammermill	Odor control
Rotary shear	Other equipment
Flail mill	Storage bins
Can shredder	Floor scale
Can densifier	Truck scale
Can flattener	Belt scale
Glass crusher	Conveyors
Plastics granulator	Belt
Separating equipment	Screw
Magnetic separator	Apron
Eddy current device (aluminum separator)	Bucket
Trommel screen	Pneumatic
Vibrating screen	Vibrating
Air classifier	

Source: U.S. EPA, *Materials Recovery Facilities for Municipal Solid Waste*, EPA/625/6-91/031, Office of Research and Development, U.S. EPA, Washington, DC, 1991.

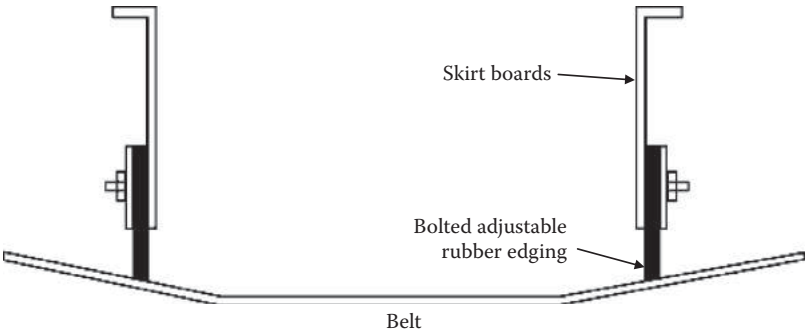
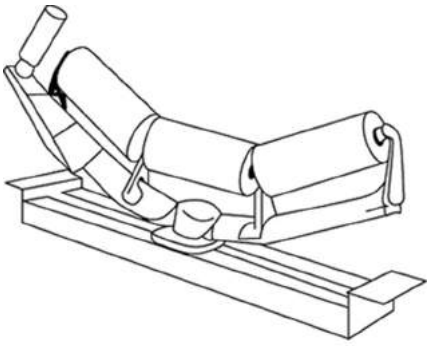


FIGURE 7.5 Cross-section of a belt conveyor. (From U.S. EPA, *Materials Recovery Facilities for Municipal Solid Waste*, EPA/625/6-91/031, Office of Research and Development, U.S. EPA, Washington, DC, 1991.)

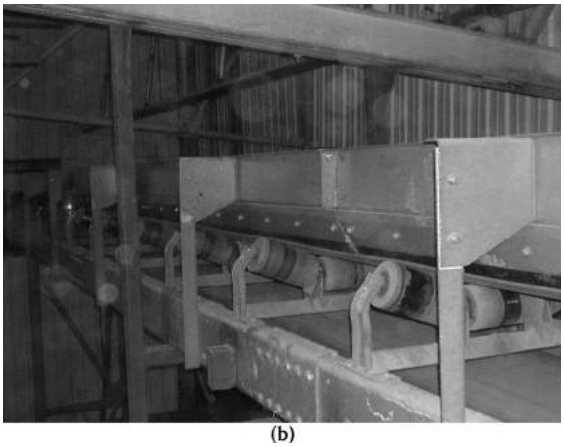
The belt conveyor can be designed with idler rolls that create a concave cross-section (Figure 7.6). Such shapes will retain lighter materials along the length of the belt, thus preventing spillage. To further minimize losses, skirt bands are used at belt transfer points. The flat belt conveyor used at many MRFs is of the slider belt design, in which the belt is supported by, and slides on, a steel-supporting surface rather than on idler rolls. When used in an inclined position, it is supplied with cleats and skirt boards over its full length in order to prevent spillage (U.S. EPA 1991).

The capacity of a conveyor belt is directly related to its cross-sectional area and belt speed. The depth of loading is limited by the height of the sidewalls, the shape of the belt, or the angle of repose of the MSW feed. The volume flow rate on the belt is calculated by (Pfeffer 1992)

$$Q = AV \tag{7.1}$$



(a)



(b)

FIGURE 7.6 Base of a conveyor belt showing rollers: (a) schematic. (Reproduced with kind permission of CEMA, *Conveyor Terms and Definitions*, CEMA No. 102-1994, CEMA, Manassas, VA, 1995); (b) photo.

where Q is the flow rate (m^3/min), A the cross-sectional area (m^2), and V the belt speed (m/min). The mass flow rate can be calculated by using the density of the MSW on the conveyor belt. The thickness of the waste on the belt is calculated using the equation

$$TW = [(LR)(1000\ kg/MT)(100\ cm/m)]/[(60\ min/h)(VDW)] \quad (7.2)$$

where TW is the thickness of the waste (cm), LR the loading rate of solid waste (MT/h), V the belt velocity (m/min), D the waste density on belt (kg/m^3), and W the belt width (m).

Waste thickness is an especially practical consideration for hand-picking operations at a MRF.

Example 7.2

Calculate the waste thickness for a conveyor belt measuring 1.1 m with an average belt speed of 17.5 m/min. Waste loading rate is 28 MT per hour and the average density of the waste on the belt is 120 kg/m^3.

$$TW = [(28\ MT/h) \times (1000\ kg/MT) \times (100\ cm/m)]/$$

$$[(60\ min/h) \times (17.5\ m/min) \times (120\ kg/m^3) \times (1.1\ m)]$$

$$= 20.2\ cm$$

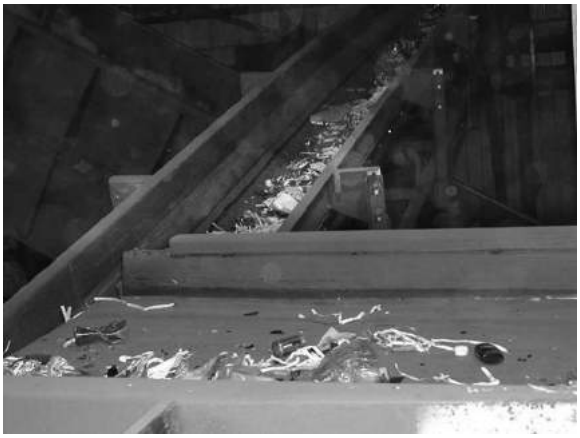


FIGURE 7.7 Transfer point along a conveyor belt. Wastes sometimes fall away from the belts during transfer to another belt.

The pneumatic conveyor is sometimes used to transport shredded, lightweight materials such as newspaper, plastic, or refuse-derived fuel. Pneumatic conveying systems consist of a fan, a feed device, piping, and a discharge device, typically a cyclone separator. Systems are operated under positive pressure (i.e., blowing air) or negative pressure (suction).

The utilization of conveyors for MSW transport has not been without problems. Wastes that are too heavy or extremely sharp can be dropped on the belt, thus damaging the belt, pulleys, or other components; wastes may fall off the belts at transfer points, that is, where one belt empties onto another (Figure 7.7); and wires and string within the wastes can become tangled around pulleys and other equipment.

7.2.8 Scales

Scales are included inside the MRF. These are typically small models that are used to weigh objects such as bales of metal or paper, or cages of product (Figure 7.8).



FIGURE 7.8 Small scale for weighing bales and other small- and medium-sized objects.

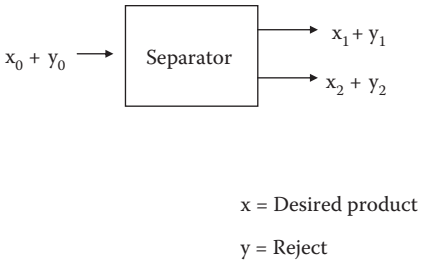


FIGURE 7.9 A binary separator receiving a mixed feed of x_0.

7.3 MATERIALS RECOVERY AT MRF UNIT OPERATIONS

In a hypothetical situation where one material is to be segregated from a mixture, the separation process is termed *binary*, as two outputs result from the operation. A binary separator receiving a mixed feed of x_0 and y_0 is shown in Figure 7.9. The goal of the unit operation is to separate the x fraction in as pure a form as possible and with the greatest total recovery possible.

One exit stream will contain the x component, the desired material, also designated the *product* or *extract*. Separation will not be perfect, however, so there will inevitably be contamination as y_1. A second stream, containing mostly the y, is termed the *reject*. Note that this stream will contain some of the product x. The recovery of x can be expressed as (Hasselriis 1984)

$$R(x_1) = (x_1/x_0) \times 100 \tag{7.3}$$

where $R(x_1)$ is the recovery of x in the first output stream (%).

This equation, however, does not take into account purity of the product. If the separation device is not operational, then all the input (both the desired product as well as the reject) will pass through. In other words, $x_0 = x_1$ with the result that $R_{(x1)} = 100\%$. A second requirement, the purity of the product, is therefore necessary. The purity of the extract stream is defined as

$$P(x_1) = (x_1)/(x_1 + y_1) \times 100 \tag{7.4}$$

There are, however, difficulties with using purity alone as a descriptor of separator performance. For an example, it might be possible to extract a small amount of x in a pure state, but the recovery ($R(x_1)$) will be very small. It is therefore necessary to describe the operation of a materials separation device by incorporating both the recovery and purity. Binary separator efficiency can be determined as (Rietema 1981)

$$E_{(x,y)} = (x_1/x_0) \times (y_1/y_0) \times 100 \tag{7.5}$$

Example 7.3

An eddy current separator (described below) is to separate aluminum product from an input stream of shredded MSW. The feed rate to the separator is 1500 kg/h. The feed is known to contain 55 kg of aluminum and 1445 kg of reject. After operating for 1 h, a total of 65 kg of material is collected in the product stream. On close inspection, it is found that 46 kg of product is aluminum. Calculate the percent recovery of aluminum product, the purity of the product, and the overall efficiency of the separator.

$$R(x_1) = x_1/x_0 \times 100 = 46/55 \times 100 = 83.6\%$$

$$P_{(x1)} = x_1/(x_1+y_1) \times 100 = 46/65 \times 100 = 70.8\%$$

$$E_{(x,y)} = (x_1/x_0) \times (y_1/y_0) \times 100 = 46/55 \times [(1500 - 65) - (55 - 46)]/1445 \times 100 = 82.5\%$$

7.4 MATERIALS SEPARATION AND PROCESSING AT THE MRF

7.4.1 Hand-Sorting

The simplest method for the separation of materials from MSW is hand-sorting. Workers assume positions along a conveyor belt, either on one or both sides (Figure 7.10). Sorting takes place after bags have been opened in a trommel screen or simple shredder. At a clean MRF, the material may arrive already in loose form.

At the MRF, picking may occur at several points along the waste transit route. Workers have two primary functions: first, to recover any items of potential value that do not need to be processed. Items such as metal and PET bottles are deposited in bins or chutes. Their second responsibility is to remove those items that are detrimental to workers downstream; to the quality of the final, separated products; or to system equipment. This could include removing toxic and potentially explosive items. Material along the conveyor is recognized visually ("coding") by such properties as color, reflectivity, and opacity; and removed (separated) by hand-picking (Worrell and Vesilind 2011).

Important factors in the design of the manual picking area are the width of the belt, belt speed, and average thickness of material placed on the belt for picking. A picking belt usually measures no more than 60 cm (24 in.) wide for one-sided picking or 120 cm (48 in.) wide for pickers on both sides. Belt speeds vary from 450 to 2700 cm/min (15–90 ft/min) depending on the material to be processed and the extent of any preprocessing. The belt should not move faster than about 900 cm/min (30–40 ft/min) depending on the number of pickers (Engdahl 1969; Worrell and Vesilind 2011). The average thickness of wastes on the belt for effective picking is about 6 in. (Tchobanoglous et al. 1993).

The picking operation is best performed under natural lighting. Artificial light, for example, from fluorescent bulbs, emits only a narrow band of light that makes identification (coding) of certain components difficult.

At those facilities where waste is not preprocessed, sorting is inefficient. Pickers can salvage about 450 kg (1000 lb)/person/h depending on the material density (Worrell and Vesilind 2011).



FIGURE 7.10 Hand-sorting along a conveyor belt. Note that workers are not wearing eye, respiratory, or hearing protection.

For example, a worker removing metallic objects will remove more material by weight than would a picker removing lightweight plastic containers.

Hand-picking is dirty and dangerous work. Dust generation may be significant, and the wastes being handled are odoriferous. Wastes may be hazardous to workers by being sharp-edged, explosive, flammable, or infected with pathogenic microorganisms. Noise from equipment can be extreme in some facilities. Heavy equipment may be routinely moving across the facility floor, and the unit operations themselves are noisy. Appropriate worker safety including protection of eyes, skin, and hearing, as mandated under Occupational Safety and Health Administration (OSHA) statutes, is essential in a MRF.

7.4.2 Screening

Screening is a unit operation designed for the separation of waste input into *oversize* and *undersize* fractions. In many MRFs, the oversize materials consist primarily of old corrugated cardboard (OCC) and newspaper. Screening is carried out either wet or dry, although dry separation is most common. Screens are classified as primary, secondary, or tertiary, depending on where they are situated in the sequence of separation steps. The primary applications of screening during MSW processing include:

- Removal of oversized material
- Removal of undersized material
- Recovery of paper and plastics for recycling or as refuse-derived fuel (RDF)
- Separation of soil, glass, and grit from combustible materials

Screens have a long history in various industries for particle separation by size. Rotary (trommel) screens have been used in the mineral industry for many years for the removal of potentially valuable metals from coarse ores, gravel, and rock.

As discussed in Chapter 4, different components of MSW possess characteristic size ranges. If screen size is properly selected, it is possible to create a fairly enriched stream of a particular waste component. Of course, due to the variability of sizes of a single waste component, only partial separation is possible; additional processing is still required for further purification of the product.

Three major modes of screening are used in materials recovery: trommel screening, disk screening, and vibrating shaker screening.

7.4.2.1 Trommel Screens

Of the major methods of MSW screening, the *trommel* is the most popular. Trommel screening is *primary* screening, designated as such because it is usually placed before all other separation units in a MRF.

The trommel is a rotating perforated cylinder with a diameter ranging between 0.6 and 3 m (2 and 10 ft) with a screening surface consisting of a perforated plate or wire mesh (Figure 7.11). Some are equipped with spikes, usually positioned within initial volume of the drum to break open plastic trash bags. The drum is inclined at a slight angle. A motor is attached to one end which rotates the drum at a rate of about 10–15 rpm. The waste is introduced at the elevated end via a conveyor belt. As the drum rotates, waste particles are carried up the side until they reach a desired height and then fall to the bottom. The waste which falls through the openings is collected by a conveyor or a hopper and the fraction retained within the trommel is collected on a separate belt.

A typical trommel screen is depicted in Figure 7.12. The length and diameter of the drum have a direct relationship to the efficiency of separation by the trommel. The longer the drum, the longer the MSW will remain in contact with the screen, and the greater the diameter, the more effective the trommel will be in breaking up large objects such as trash bags. Large trommels



FIGURE 7.11 Trommel screen.

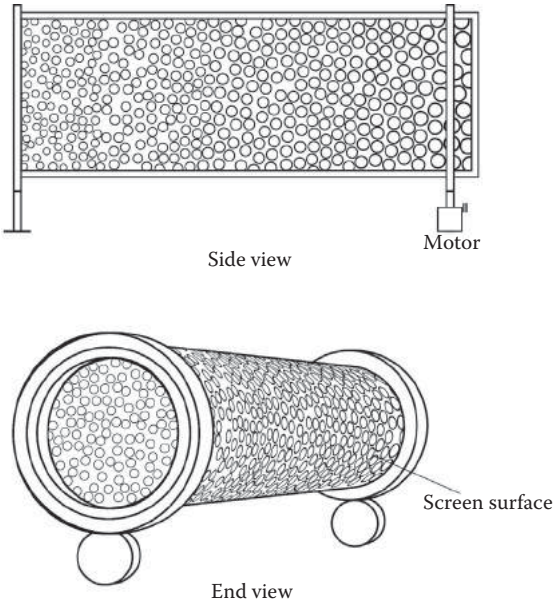


FIGURE 7.12 Schematic of a trommel screen. (From U.S. EPA, *Materials Recovery Facilities for Municipal Solid Waste*, EPA/625/6-91/031, Office of Research and Development, U.S. EPA, Washington, DC, 1991.)

(2.5–3 m, or 8–10 ft in diameter, up to 15 m long) have been used to separate large OCC and newsprint from smaller office paper and commingled containers (particularly glass). Small trommels (0.3–0.6 m in diameter by 0.6–1.2 m long) have been used to separate labels and caps from crushed glass. These small units are used in conjunction with an air stream to aid in separation (U.S. EPA 1991).

Two-stage or compound trommels are also used in waste processing. In two-stage trommels, the first section is set with small openings (e.g., 2–3 cm diameter) which permit soil, broken glass, and other small fragments to fall through and be collected. This material is largely nonrecyclable and will probably be landfilled. The second stage is provided with larger apertures (e.g., 12–15 cm), which allow glass, aluminum, and plastic containers to be removed from the waste stream.

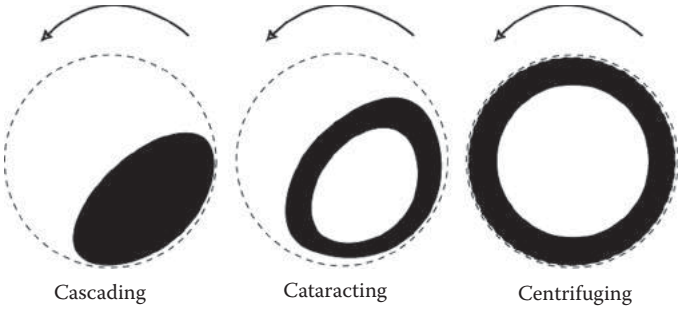


FIGURE 7.13 Cascading, cataracting, and centrifuging of waste input in a trommel screen. (Reproduced with kind permission from Stessel, R.I., *Recycling and Resource Recovery Engineering*, Springer, Berlin, 1996.)

Trommel screens separate waste materials based on size and do not identify the material by any other property. As a result, trommels are used as a classification step before true separation of materials. For example, smaller particles such as grit and broken glass can be removed early in the processing scheme to produce better quality (i.e., greater purity) recyclables such as paper, aluminum, and glass containers. Removal of coarse or abrasive components early in the process will reduce the load on a shredder (see below) which therefore reduces shredder maintenance.

Waste behaves within the trommel in distinctly different patterns depending on the speed of rotation. Waste rotating very slowly within the cylinder will travel only slightly up the sides and will immediately slide back, thus missing most openings. This behavior is termed *cascading* (Figure 7.13). Waste that is rotated more rapidly within the cylinder will rise up farther and then tumble and slide back. This *cataracting* motion results in substantial turbulence of the waste. At even higher speeds, the material may adhere to the inside of the trommel and will not effectively tumble or fall by gravity through the screens—that is, it tends to *centrifuge*. The so-called "critical speed," that is, the frequency of rotation at which the force of the trommel on the waste holds it against the wall throughout a complete revolution, is given by the equation (Vesilind et al. 1988)

$$N_c = (g/4\pi^2 r)^{1/2} \tag{7.6}$$

where N_c is the critical speed (rotations/s), g the acceleration due to gravity (cm/s^2), and r the radius of the trommel (cm).

The ideal trommel rotation speed is that immediately *prior* to the point where the waste starts to centrifuge; in other words, it climbs the side of the trommel and then falls upon reaching the zenith of rotation, which is the upper limit of the cataracting type of motion. This creates the greatest opportunity for waste particles to fall through the screen openings.

Example 7.4

Calculate the critical speed for a trommel screen having a diameter of 3.2 m.

$$N_c = (g/4\ \pi^2\ r)^{1/2}$$

$$N_c = (980/[4\ (3.14)^2\ (320/2)])^{1/2}$$

$$= 0.39 \text{ rotations per second}$$

Some trommels are equipped with horizontal lifter bars along the inside which help to carry waste part-way up the side of the drum. Any additional upward motion depends on the rotational speed of the drum (Pfeffer 1992).

Separation efficiency with trommel screens

The speed of rotation plays a role in the trommel's separation efficiency via agitating the waste input. The tumbling action of waste within the trommel induces separation of individual items that have adhered to each other, or of one material contained within another. The more cycles of rising and dropping, the greater the separation efficiency. At the same time, however, the rate of throughput must be considered, so there is a limit as to how long a waste charge should remain in the trommel.

The following equation was developed for calculating trommel throughput (Sullivan et al. 1992):

$$D = [11.36\ Qm/(d_b\ F\ K_v\ g^{0.5} \tan a)]^{0.4} \tag{7.7}$$

where D = trommel diameter, m
Qm = trommel throughput, kg/s
d_b = bulk specific weight of MSW, kg/m^3
α = angle of trommel from base frame, degrees
K_v = velocity correction factor (K_v = 1.35 when α = 3°, and K_v = 1.85 when α = 5°)
F = fillage factor (a typical range is between 0.25 and 0.33)
g = 9.81 m/s^2

Using data such as that shown in Figure 7.14, separation efficiency at a particular screen size can be estimated. For example, in a trommel with an aperture of 10 cm, about 90% of metals and glass will fall through and be captured as undersize material. Concurrently, about 30%–35% of the paper and plastics will also fall through and thus contaminate the metal or glass fraction.

A number of factors influence separation efficiency of a trommel, including:

- Characteristics of the incoming materials (dense, loose, fragile, wet)
- Quantity of the incoming materials (feed rate)
- Size ranges of the cylinder screen
- Incline angle of the cylinder
- Rotational speed
- Size and number of screen openings

The primary factor influencing separation is, ultimately, retention time of the waste within the trommel. The average waste retention time in trommels ranges from 25 to 60 s for raw waste prior to shredding, to about 10 s for shredded, air-classified light materials. Long trommels are desirable because they achieve a more thorough screening. Optimal trommel performance was found to occur

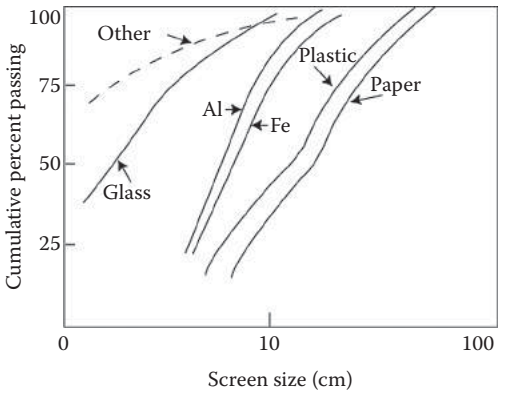


FIGURE 7.14 Hypothetical particle size distribution as relates to screening MSW. (Reproduced with kind permission from Diaz, L.F. et al., *Resource Recovery from Municipal Solid Wastes*, Vols. 1 and 2, CRC Press, Boca Raton, FL, 1982. Copyright Lewis Publishing, an imprint of CRC Press.)

with a solids retention time of 30–60 s, with the waste charge making 5–6 revolutions within the drum (Worrell and Vesilind 2011).

A practical advantage with waste separation in trommels is its avoidance of clogging. Some material may attach to the interior of the drum, but, with the continued tumbling motion and impaction by other materials, the attached items will eventually fall out and be removed.

7.4.2.2 Disk Screens

A *disk screen* is not a "screen" in the conventional sense; rather, it occurs as a series of rounded or lobed-shaped disks mounted on shafts (Figures 7.15 and 7.16). The disks are parallel and interlocked. The shafts rotate in one direction, carrying the waste charge along in a fashion analogous



FIGURE 7.15 Disk screen.

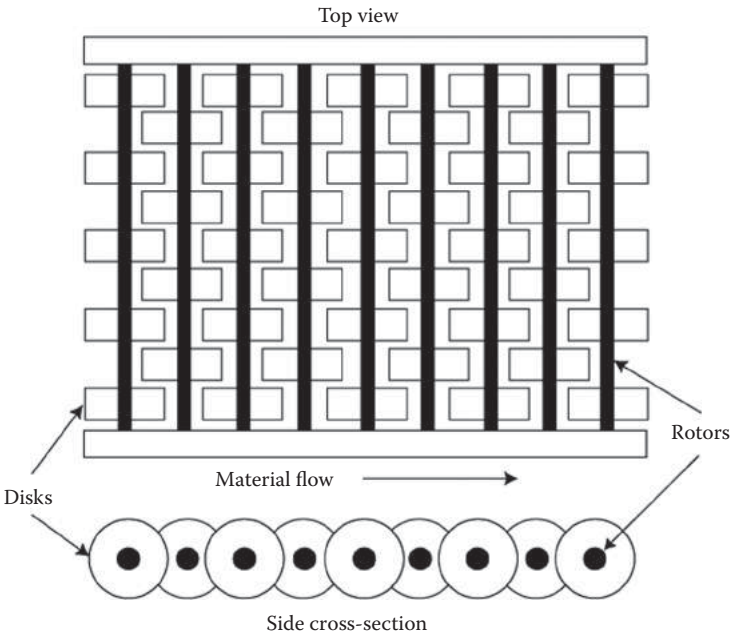


FIGURE 7.16 Schematic of a disk screen. (Reproduced with kind permission from Stessel, R.I., *Recycling and Resource Recovery Engineering*, Springer, Berlin, 1996.)

to a conveyor belt. Due to turbulence and the irregular shape of the disks, however, undersized materials fall between the spaces in the disks and are collected in one hopper while the larger components are carried along the top to be deposited in a second hopper.

The spacing between the outer diameter of the shafts and the spacing of the disks on the shaft determine the size of separation. Particles having two dimensions less than these spacings can fall through. Most particles have a tendency to orient such that the two larger dimensions are situated horizontally; therefore, size separation is usually based on these two larger dimensions (Pfeffer 1992). Varying the spacings of the disks on the drive shaft will change the desired particle size ranges.

In the event of blockage, an electronic sensor will signal for the shafts to rotate in the opposite direction in order to clear any materials.

7.4.2.3 Vibrating Screens

Another variation of screening is the so-called *vibrating screen*, which consists of a mounted flat screen that undergoes a reciprocating or gyrating motion. Such flat screens are typically not used to process mixed MSW, however—they are most successful in purifying more concentrated fractions of waste that have previously been processed into a relatively fine particle size. Examples include glass, metals, and wood chips. Flat screening may be applied to remove impurities (e.g., broken glass, ceramics, and stones) from compost feedstock (Rhyner et al. 1995).

7.4.3 Size Reduction

Size reduction, a unit operation that can also be considered volume reduction, is important for certain treatment and disposal practices (e.g., composting and incineration) as well as for cost-effective transportation of materials.

A wide range of size reduction methods are available, and many types of size reduction equipment are employed at a MRF, many of which had originated in other industries. Such equipment is employed to reduce particle size or increase the density of material in order to meet market specifications or to reduce the cost of storage and transportation. Either incoming MSW or separated and outgoing components can undergo size reduction.

7.4.3.1 Compactors

Compactors became popular in the 1960s in response to increased waste hauling and disposal costs. The earliest stationary compactors compressed wastes into roll-off boxes, that is, large metal containers usually measuring $2.5 \times 2.5 \times 6.5$ m. When the box was sufficiently loaded, a transporter removed it for shipment to a sanitary landfill. This system was ideal for dry wastes. Some businesses and industries, however, such as restaurants and hospitals, disposed of liquid as well as solid wastes. Because the compactor was separate from the container, liquid wastes and residues were spilled, which left odors and attracted pests. In response to this practical problem, the self-contained compactor was developed. These units comprise a compactor and roll-off box housed within the same unit. For hauling, the electrical power unit is separate from the assembly. Self-contained units typically include a liquid collection area situated directly beneath the compactor to contain any spillage (Ely 1993).

7.4.3.2 Balers

A baler (Figure 7.17) is one of the more common components of the MRF waste processing system. Balers are used for producing bales of corrugated cardboard, newspaper, high-grade paper, mixed paper, aluminum cans, and plastic containers (Figure 7.18). Balers are available with a wide range of horsepower and levels of sophistication. Some balers have fully automated operation, whereas others require significant input by an operator. As previously discussed, many industrial buyers have specific requirements for secondary materials being purchased; therefore, the market specifications for a particular product should be determined before a baler is selected (U.S. EPA 1991).



FIGURE 7.17 Baler at a MRF.



FIGURE 7.18 Bales of OCC awaiting shipment to a recycling facility.

Most balers are of sufficiently low force that, once released, the baled product will simply rebound to its original form. Hence, bales must be tied, either with steel wire, high-tension nylon string, or similar durable material. However, some high-power balers apply sufficient force such that a bale will maintain its shape even after the force is removed. Such balers tend to be more expensive and maintenance intensive than the low-force models. The original waste input material will also influence the need for tying a bale. Bales of aluminum or other metal will hold their form better than would bales of HDPE containers or old newspaper, for example.

The performance of baling and compaction equipment is measured by calculating the percentage volume reduction and the compaction ratio. Percentage volume reduction is calculated by the equation

$$\text{Volume reduction } (\%) = (V_i - V_f)/V_i \times 100 \tag{7.8}$$

where V_i = initial volume of wastes before compaction, m^3
V_f = final volume of compacted wastes, m^3

The compaction ratio is calculated as

$$\text{Compaction ratio} = V_i/V_f \tag{7.9}$$

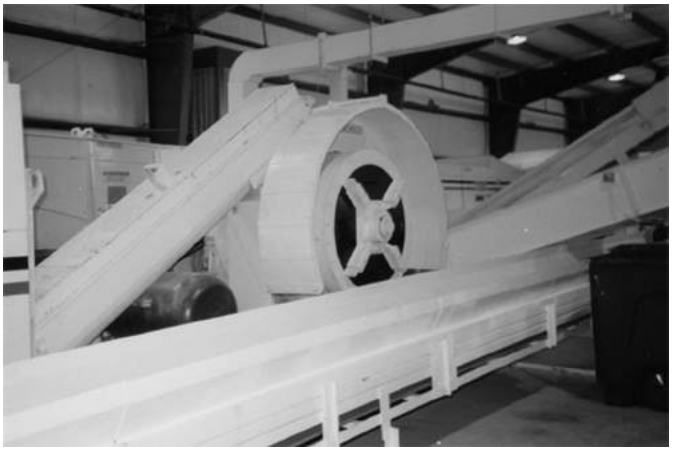


FIGURE 7.19 Pelletizer (densifier) for shredded organic wastes in the manufacture of RDF.

7.4.3.3 Densifiers

The purpose of a densifier is to enhance the storability or transportability of waste components that are to be used as fuel. This includes RDF, which will be discussed in Chapter 9. Essentially, RDF is composed of the light organic fraction of MSW, including paper, plastics, and some food waste.

Densification results in increased energy value per unit volume (e.g., kJ/kg or Btu/lb) of waste fuel. Densifiers are located at the end of the process line before the storage and retrieval system. Equipment types that densify RDF include pelletizers, briquetters, cubetters, and extruders (Figure 7.19).

7.4.3.4 Shredders

Shredders were originally developed for the crushing of stone and ores. The shredder's versatility has resulted in its application in other areas. In a MRF, shredding is designed primarily for size reduction of raw MSW; however, shredders can be applied to specific items including scrap metal, plastic, aluminum, wood, and paper products. Shredders serve in construction and demolition activities for breaking up concrete, steel, and other building materials.

The shredding process includes four modes of action: crushing, impaction, shearing, and grinding. *Crushing* involves the reduction of particles by pounding, *impaction* is the result of an item being thrust against a stationary structure with great force, *shearing* involves forcing two parts of an item in different directions, and *grinding* is friction applied to the surface of an object. All shredding units use two or more of these actions simultaneously.

Shredding imparts a number of benefits to waste. Shredded wastes are more amenable to sanitary landfilling by virtue of decreased odor and therefore fewer rodents and insects; it also provides for greater ease of movement of landfill equipment. Shredding is extremely useful for production of RDF, as it increases the surface area of fuel particles.

Shredding can process demolition debris and yard wastes. However, the most important application of shredders is for materials recovery. Shredded MSW offers several advantages to recycling and waste-to-energy systems:

- Waste volume is significantly reduced
- Waste becomes more homogenous
- Waste separation processes (e.g., iron, paper) are facilitated

- Separation of noncombustibles from combustibles is enhanced
- RDF is sized for convenient burning in power plant boilers

In a MRF, shredders can be installed in one or more positions within the processing scheme. Primary shredders are used to reduce incoming raw MSW, whereas secondary shredders further reduce the size of the output from the primary shredder.

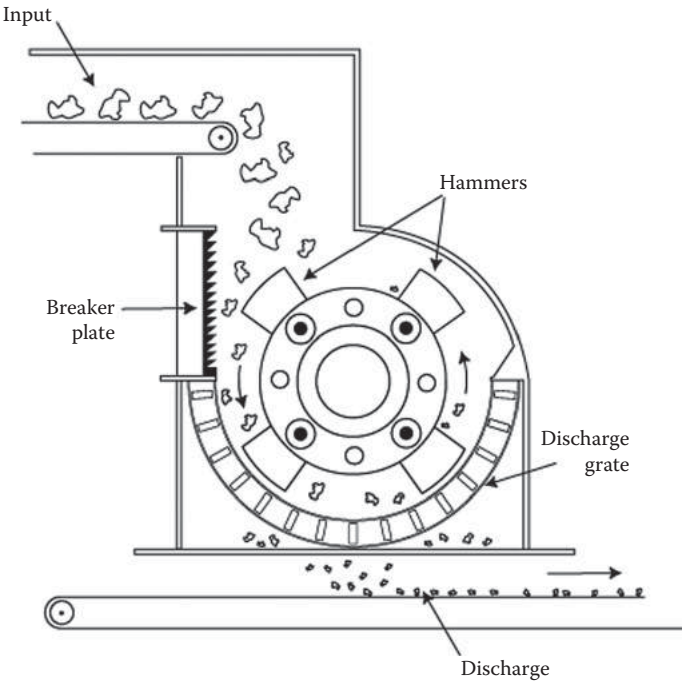
Shredders are available in a variety of shapes and sizes, from portable paper shredders to huge units that shred flattened automobiles at the rate of 1/min. The three most common types of shredding units used for size reduction of MSW are the hammermill, the flail mill, and the rotary shear (Figure 7.20). The tub grinder is also used; however, this device is primarily devoted to the processing of yard wastes or construction and demolition debris (Figure 7.21).

7.4.3.5 Hammermills

The most common shredder type is the *hammermill*, which is a large cylindrical or tapered unit equipped with a central rotor. A series of rapidly rotating hammers is attached (Figures 7.20a and 7.22). Hammers are either fixed or swing on the rotating shaft to allow for movement over bulky or very dense waste components. The rotor and hammers are enclosed within a heavy-duty housing. The housing interior may be lined with stationary breaker plates or mounted cutter bars. Shredding relies on heavy force breakage of particles by the rapidly swinging hammers in the enclosed vessel. Size reduction occurs by the combined actions of impaction and shearing.

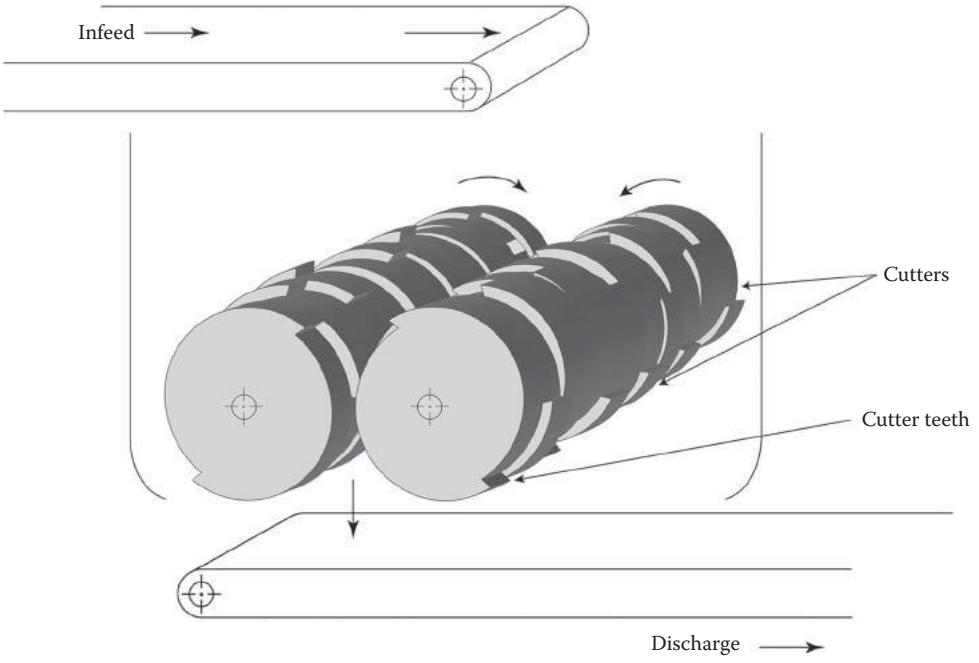
Feedstock can be commingled or sorted MSW; in other applications, however, entire automobiles or steel I-beams are processed for shredding.

A shredder used for MSW processing usually has a width:diameter ratio greater than 1.0, a hammer weight of 70 kg (150 lb), a hammer tip speed of 4260 m/min (14,000 ft/min), and four rows of

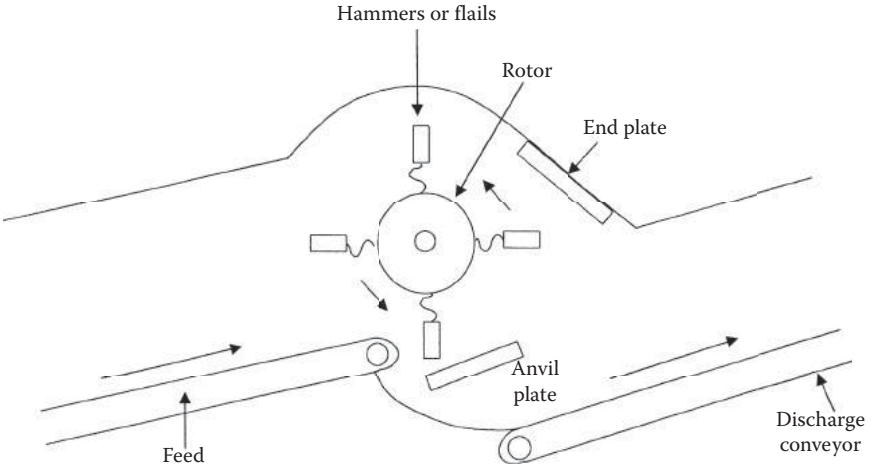


(a)

FIGURE 7.20 Three major types of shredders: (a) hammermill; (b) rotary shear; (c) flail mill.



(b)



(c)

FIGURE 7.20 (*Continued*) Three major types of shredders: (a) hammermill; (b) rotary shear; (c) flail mill.

hammers (Worrell and Vesilind 2011). Rotational speed ranges from about 700 to over 3000 r/min with power set at approximately 500–700 kW. Hammermills vary drastically in terms of horsepower, electrical needs, and type of acceptable input. For high-speed shredders, rotational speeds are usually set between 1000 and 3500 r/min. A high-speed shredder relies on brute force and is noisy. High-horsepower motors, 50 Hp and higher, are necessary. As a result, electrical costs can be substantial for high-speed shredders.



FIGURE 7.21 Tub grinder for yard wastes.



FIGURE 7.22 A new hammer for a horizontal hammermill.

7.4.3.6 Horizontal-Shaft Hammermills

In shedders, the hammer shaft can be oriented in either the horizontal or the vertical direction. In the horizontal configuration, input is from the top; materials flow through by gravity and exit the bottom through a grate. Most horizontal hammermills have a grate positioned across the outlet under the swinging hammers. The grate, possessing specific-size openings, may be changed depending on the desired size of the final product. The hammers pound the material until it is small enough to pass through the grate openings. The size of the output material in horizontal-shaft hammermills is therefore ultimately controlled by the size of the openings in the grate.

A disadvantage of the horizontal-shaft unit is that if a durable waste such as an engine block is introduced, it will remain there until it is shattered to smaller fragments. This results in considerable wear on the hammers; furthermore, excessive heat and sparks create a fire or explosion risk. Rejection portals are used in cases of difficult feed materials.

7.4.3.7 Vertical-Shaft Hammermills

Vertical-shaft hammermills (Figure 7.23) are designed with the shaft mounted vertically. The unit was originally designed in the United Kingdom for MSW processing. Large steel hammers rotate at high speeds within a large steel housing. The input enters at the top and flows downward

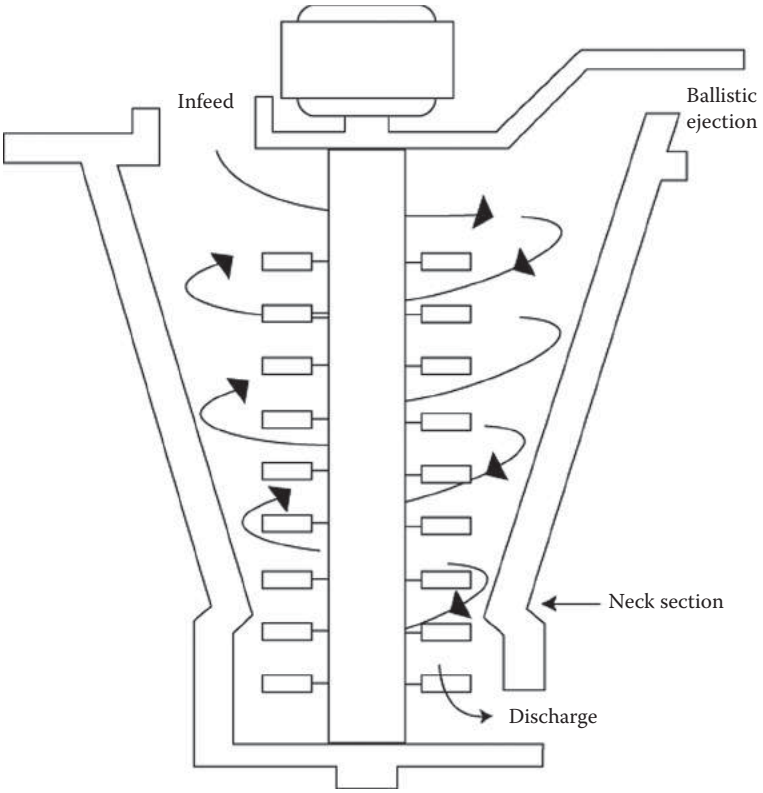


FIGURE 7.23 Vertical hammermill. (From U.S. EPA, *Fine Shredding of Municipal Solid Waste*, EPA-600/2-76-208, Environmental Protection Technology Series, Industrial Environmental Research Laboratory, Research Triangle Park, NC, 1976.)

by gravity. The housing is cone-shaped and tapers down to a narrow throat section. The rotating hammers create a vortex or fan effect that, in addition to gravity, pulls wastes downward into the unit. Some size reduction occurs as the waste is milled in the upper portion. Farther down the rotor shaft are more hammers; once the feed passes the throat section, it is further reduced by the action of the lower hammers and the breaker bars on the housing walls. Adjusting the spacing between the hammers and the walls controls particle size. It is in the lower region that most of the size reduction occurs. When the input waste reaches the bottom, it has been sufficiently reduced in size such that a grate is not needed. The final shredded product is forced out through the discharge chute.

If the input material is difficult to break, for example, a steel I-beam, the continued impact of the hammers will impart a centrifugal motion that will eventually direct the difficult item to an ejection portal. Such items will normally be ejected rather than remain in the mill and damage the hammers (Pfeffer 1992).

The primary factors affecting particle size in the vertical-shaft hammermill include retention time in the mill and the number of impacts by the hammer. The clearance between hammers and wall of the housing in both the upper and lower portions of the unit regulates passage through the mill. By changing the number and position of the hammers, the particle size is changed.

An advantage of the vertical-shaft hammermill is the ability to achieve a high degree of size reduction. Energy consumption per ton of waste processed is less for the vertical-shaft hammermill than for the horizontal-shaft model. Primary disadvantages include high-energy costs and high maintenance. Operational problems encountered with the vertical-shaft unit include internal jamming and explosions.

A common waste processing problem when using a hammermill is contamination of organic materials with inorganics. For example, paper wastes become impregnated with shards of glass when the high-speed hammer shatters glass containers. The best course to pursue, therefore, is separation of potential contaminants from feedstock prior to introduction into the mill.

7.4.3.8 Rotary Shear

The rotary shear, or shear shredder, contains two parallel counter-rotating shafts with a series of disks mounted perpendicularly that act as cutters, working in a scissor-like fashion (Figure 7.20b). Rotary shears are low-speed devices (60–190 rpm) compared with hammermills. The input to be shredded is directed to the center of the rotating shafts. The size of the input is reduced by the shearing or tearing action of the cutter disks. The shredded materials fall through or are pulled through the disks. The orientation of the shafts and the spacing between shafts control the particle size of the product. Particle sizes range from as low as 2.5–25 cm (approximately 1–10 in.). Shutdown is not typical; even large bulky objects like railroad ties can be processed. Most are driven by hydraulic motors that can be reversed automatically in the event of an obstruction.

Advantages of the rotary shear include slower speeds and the consequent lack of brute, destructive force. These changes help in preventing contamination of organic wastes by broken glass—any glass containers or other small input can simply fall between the shears, given adequate spacing of the shafts. In addition, lower speeds imply lower energy costs and also less maintenance of moving parts. As was the case for other shredders, large steel and other durable objects pose a problem for the rotary shear and should be removed prior to feeding the device.

7.4.3.9 Flail Mill

The flail mill (Figure 7.20c) is similar to the hammermill in that a rotary shaft is secured with a number of rotating metallic appendages; however, this provides only coarse shredding since the hammers are spaced farther apart. In some units, chains or knives replace the hammers. As the waste passes through the mill, the hammers strike the MSW and thrust it against the anvil plate. If the particle is sufficiently small, it will pass through the mill without size reduction. Flail mills tend to be single-pass devices whereas in the hammermill, wastes may be retained until they are small enough to pass through the gratings at the base of the unit.

Advantages of the flail mill include low power requirements and low maintenance. The major disadvantage is the limited capability for size reduction.

7.4.3.10 Hammer Wear

Due to the abrasive nature of high-speed shredding of extremely heterogeneous wastes, hammers, grates, and housing walls are all subject to excessive wear. Both high- and low-speed shredders are maintenance intensive due to their violent mode of action.

Hammer damage and wear is the major maintenance issue related to MSW shredders (Figure 7.24). As hammers wear, their effectiveness in shredding waste decreases due to blunting of hammer tips and increased clearance between hammers and the housing or grates. Hammer wear occurs primarily along its outer edge, since this is the area of impact as the material is crushed against the grate. Wear is mostly due to abrasion, although severe impact with very hard objects is another source of damage and wear. Maintenance involves periodically turning the hammers, which are double sided. Once both sides are worn down, however, they must either be replaced, retipped, or resurfaced. Resurfacing involves rewelding a work surface on the hammers followed by resharpening to a cutting edge (Stessel 1996). After a number of retippings, the entire hammer must be replaced.

Hammer wear is reduced by using special hardened facings with abrasion-resistant alloys (for example, tungsten plus titanium) (DSMAC 2012) and by slowing the speed of shredding. Shredding after removal of metals, concrete, glass, and ceramics greatly extends hammer lifetime.



FIGURE 7.24 Old hammer. Compare with Figure 7.22.

7.4.3.11 Safety Issues Related to Size Reduction

A number of hazards are possible during the operation of high-speed shredders. First, because waste materials are so heavily pulverized, dust concentrations can become sufficiently high, both in the shredder housing and in the shredder room, to cause an explosion. If a hammer strikes a metallic object and produces a spark, the dust in the atmosphere could ignite. This hazard is magnified by the fact that the frictional action of the hammers and shafts produces excessive heat.

A significant danger is the inadvertent shredding of containers storing volatile or explosive compounds such as solvents, which create explosive atmospheres. A logical protection against such a hazard is a comprehensive inspection program to detect and remove explosive or flammable materials from entering the unit. Recent regulations governing disposal of organic liquid wastes should reduce the quantities of such materials entering a MRF. A single empty solvent container is not sufficient to cause a significant explosion; however, a full solvent container could cause a problem if vapors are allowed to accumulate. Dust is the most likely cause of explosions in shredders, however (Iron Mountain 2012).

Electrical switches, controls, and lighting should be installed in explosion-proof housing and conduit to avoid sparking. Shredders should be installed in structurally isolated rooms separate from other processing areas. In some facilities, the MSW is conveyed to a shredder that is operated by remote control. In the event of an explosion, worker safety is enhanced by their physical separation from the mill. Keeping the MSW moist via a fine mist of water adds protection against dust hazards. Wetting will cause problems with liquid accumulation, treatment, and removal. However, water applied to wastes will also be beneficial in the manufacture of RDF. A good quality ventilation system will draw dust-free, filtered air into the shredder and will greatly improve the safety of the local atmosphere (Eckhoff 2009).

Explosion suppression devices are available, which serve to reduce the force of an explosion. Sensors, designed to detect the pressure change from an explosion, are installed within the shredder housing. In response to a sudden pressure increase, an inert gas such as nitrogen or carbon dioxide is immediately forced into the chamber, thus displacing oxygen and limiting propagation of a flame. This system works for most types of explosions, but is not fast enough for supersonic releases (detonations) as occurs with TNT and similar high explosives. All shredders possess outlets for pressure buildup. Blast doors are situated in the roof above a shredder, and a blast duct is used to direct the force of the blast upward through the blast doors.

The blockage of materials due to jamming between rotor and shredder housing is a frequent cause of operational problems. Should a high-speed shredder encounter an object that it cannot cut

through, there is no reverse or overload setting. Either the problem material or the revolving shaft will have to give way. Preferably, the machine will simply jam up, although shafts have been known to break. In the event of a simple jam, it is necessary to open the machine and remove the object. There may be substantial down time in order to remove jammed articles and repair hammers. A hazard exists for workers entering the hammermill, as there may be a buildup of pressure on the rotor and hammers caused by the obstruction.

Problems with flying objects and noise are also encountered in MSW shredding. Since raw MSW is contaminated, any dust produced contains a broad range of microorganisms, and the atmosphere in the vicinity of the shredder may become a potential health hazard to facility personnel.

7.4.4 Magnetic Separation

Magnetic separation is a relatively simple unit process designed to recover magnetic material, primarily ferrous metals, from mixed MSW. Two critical reasons for removing ferrous metals in a MRF are to recover a saleable product and to increase the heat content of RDF. On average, there is approximately 6.8% ferrous metal in the incoming MSW (U.S. EPA 2011). Furthermore, metal removal reduces wear on subsequent processing and handling equipment and also reduces the amount of ash generated if the waste is to be incinerated. Magnetic recovery systems have also been used at landfill sites to recover product for recycling.

Magnetic separators are available in three primary configurations, that is, drum, magnetic head pulley, and magnetic belt pulley (Figures 7.25–7.27). Either permanent or electromagnets are used. Magnets may be composed of exotic (e.g., rare earth) metals that tend to be expensive.

The principle of a single-drum-type magnetic separator is shown in Figure 7.25. The drum is positioned under the lead pulley of a conveyor belt carrying mixed, shredded MSW. A stationary magnet is located inside the revolving drum. The ferrous metal within the MSW is attracted to the magnet against the force of gravity and is conveyed around the drum circumference until it exits the magnetic field and is discharged. The drum magnet assembly can be installed for either overfeed or underfeed, and it directs the ferrous along a trajectory other than that taken by the nonferrous material.

The single-drum magnet tends to entrap pieces of paper and plastic. To minimize this problem, a design using two-drum magnets with an intermediate belt conveyor is used (Figure 7.28). The first drum is suspended above the end of the MSW feed conveyor and rotates in the direction of the material flow. Ferrous materials are picked up and directed forward to the intermediate belt conveyor. Most of the nonmagnetic materials fall to a conveyor located below the first drum.

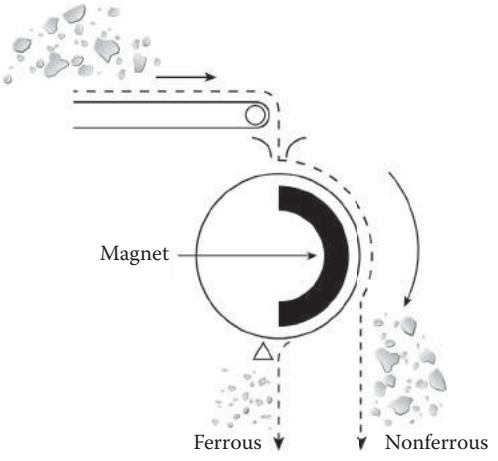


FIGURE 7.25 Drum magnet.

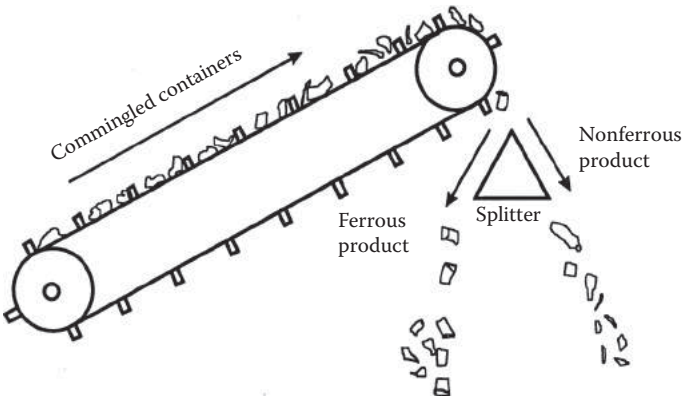


FIGURE 7.26 Magnetic head pulley. (From U.S. EPA, *Materials Recovery Facilities for Municipal Solid Waste*, EPA/625/6-91/031, Office of Research and Development, U.S. EPA, Washington, DC, 1991.)

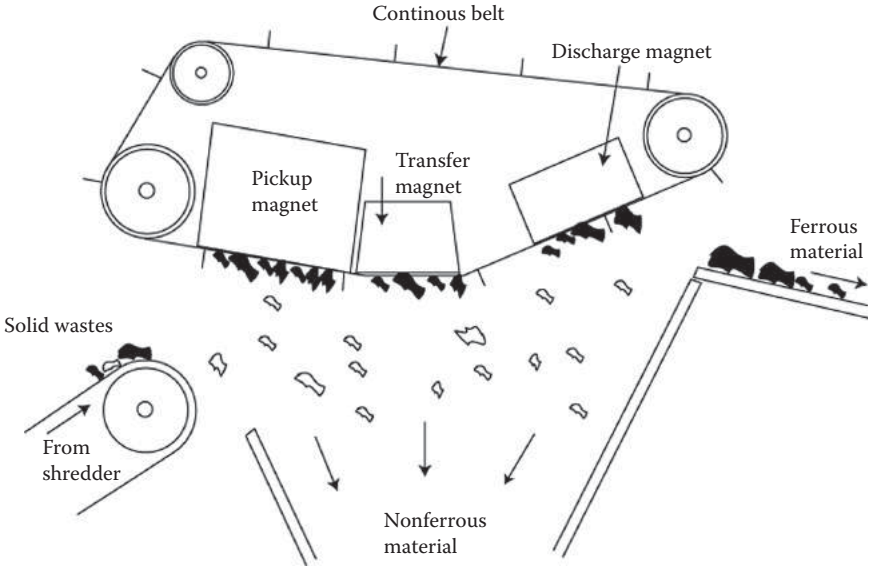


FIGURE 7.27 Magnetic belt pulley. (From U.S. EPA, *Processing Equipment for Resource Recovery Systems. Vol. II: Magnetic Separators, Air Classifier and Ambient Air emissions Tests,* EPA-600 2-80-007b, Municipal Environmental Research Laboratory, Cincinnati, OH, 1980.)

The second drum, which can be smaller than the first because of less material flow, is positioned over the discharge end of the intermediate conveyor, and rotates in the direction opposite to material flow to avoid bridging or jamming. The ferrous metal is carried over the top of the drum and released onto a conveyor or bin on the far end.

The magnetic head pulley (Figure 7.26) conveyor is designed so that material passes over the pulley, such that nonferrous material will fall along a different trajectory than will the ferrous material. A separator ("splitter") is positioned over the discharge end of the feed belt. The magnetic head pulley is the simplest of the magnetic separation devices described in this chapter; unfortunately, there is a tendency of contamination by nonferrous components.

The overhead belt magnet is the most common magnet in MSW processing systems (Figure 7.27) (Stessel 1996). The magnetic belt, in its simplest form, consists of a single magnet mounted between two pulleys that support a cleated conveyor belt (Figure 7.29). In placing the

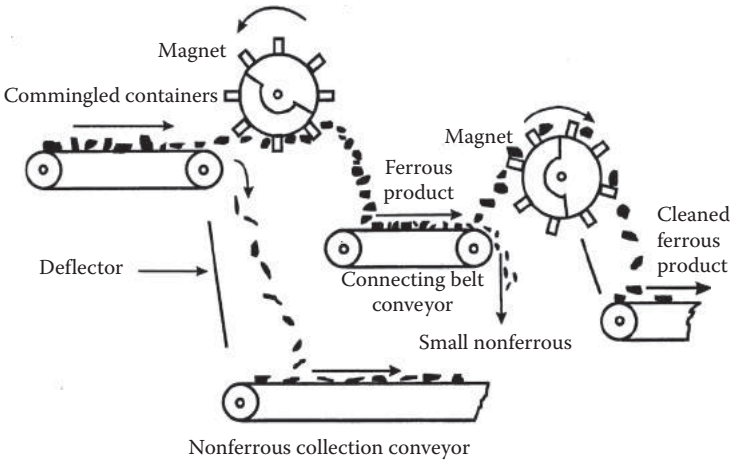
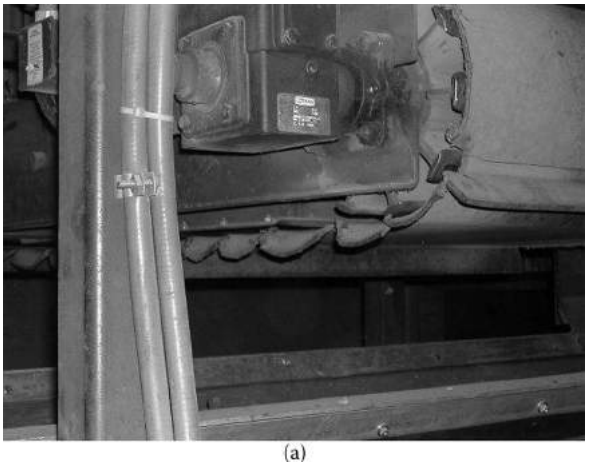


FIGURE 7.28 Two-drum magnet configuration. (From U.S. EPA, *Materials Recovery Facilities for Municipal Solid Waste*, EPA/625/6-91/031, Office of Research and Development, U.S. EPA, Washington, DC, 1991.)


(a)

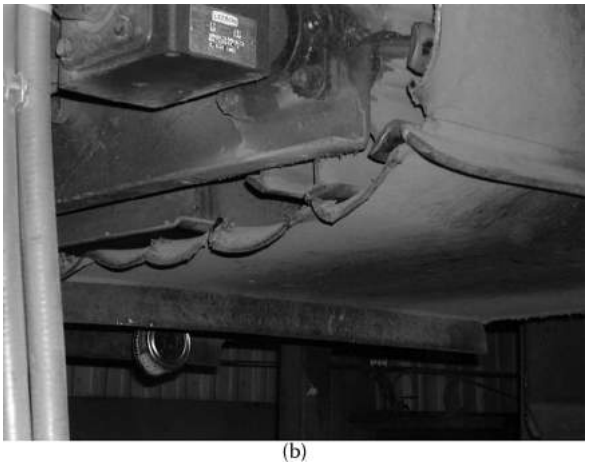

(b)

FIGURE 7.29 Overhead belt magnet in operation. (a) Belt in motion; (b) ferrous waste is attached.

belt around the magnet, ferrous materials will rise up to the belt and nonferrous materials will fall out of the stream by the action of gravity. The gap between the belt and the magnet permits an interval where entrained nonferrous materials can fall back onto the feed belt.

The depth of the waste stream affects the efficiency of magnetic separation. For more complete removal of ferrous product, a secondary magnet is added to the processing train. In order to limit interferences, conveyor and hopper components in the vicinity of the magnetic field should be constructed of nonmagnetic materials.

Entrainment of nonferrous particles with the ferrous product is a common problem. One solution is to use a dual-sequential magnet system. More commonly, an air classifier is included to clean the input stream (Stessel 1996).

In order to improve ferrous recovery, a more sophisticated belt magnet has been devised. A belt is suspended above a standard conveyor belt that is transporting processed MSW. The upper belt covers a strong electromagnet that can recover relatively heavy pieces of ferrous metal. As the ferrous is transported to the electromagnet, the polarity of the magnetic field is reversed, causing the metal to rotate. As the polarity changes, the metal falls a very small distance from the belt and rotates 180°. This movement allows entrapped nonferrous wastes to be released from the belt (Pfeffer 1992).

Although magnetic separators have been used for numerous industrial applications, their use with MSW presents some problems. There is a tendency for nonmagnetic materials, such as paper and plastic, to be entrapped with the ferrous metal, thereby reducing the purity of the recovered metal product. Furthermore, sharp edges on metals shorten the life of rubber belts. Although the resale value of ferrous scrap is low, it is advantageous to remove most ferrous materials from the waste stream early on. As noted earlier, metals will cause problems for other parts of the MRF processing train.

The effectiveness of magnetic separation depends on several variables, including:

- *Height of magnet above conveyor belt carrying the MSW.* The closer the magnet is to the MSW input, the more effective is the ferrous removal (Figure 7.30) (Worrell and Vesilind 2011).

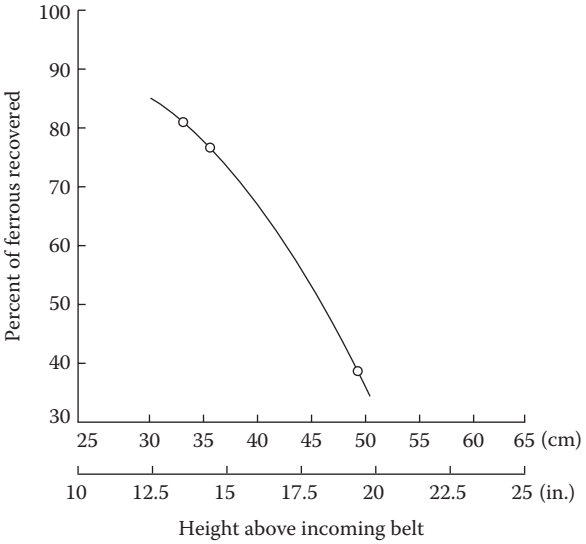


FIGURE 7.30 The height of a magnet above the waste stream affects the efficiency of ferrous recovery. (Reproduced with kind permission from Parker, B.L., Magnetic separation of ferrous metals from shredded refuse, M.S. thesis, Duke University, Durham, NC.)

- *Magnetic force*. The greater the magnetic force applied, the greater the recovery of the ferrous fraction (Parker 1983).
- *Speed of the conveyor*. Higher speeds will experience reduced recovery due to insufficient contact of ferrous materials with the magnet.
- *Depth of feed on conveyor*. The deeper the waste on the belt, the lower the recovery of ferrous.
- *Material density*. Dense wastes such as steel containers will sink below other wastes on a conveyor. Such settling increases with increased time on the conveyor belt.

7.4.5 Eddy Current Device

The eddy current unit operation separates nonferrous metals, particularly aluminum, from the waste stream. The device uses either a permanent magnetic or electromagnetic field to generate an electrical current (eddy), which causes nonferrous metals to be ejected. Eddy current separation is based on the use of a magnetic rotor with alternating polarity, spinning rapidly inside a nonmetallic drum driven by a conveyor belt. Eddy current separation is based on Faraday's law of electromagnetic induction:

$$-dB/dt = V/A \tag{7.10}$$

where B is the magnitude of magnetic flux density (T), V the voltage, and A the cross-sectional area normal to magnetic field (m^2).

As nonferrous metals pass over the drum, the alternating magnetic field creates eddy currents in the particles, repelling the material away from the conveyor. Although other materials drop off at the end of the conveyor, the nonferrous metals are propelled over a splitter for separation (Figure 7.31) (Walker Magnets, 2013).

A time-varying field can be created, either by rapidly reversing the voltage on an electromagnet (i.e., using alternating current), or by using strips of permanent magnets with alternating polarities.

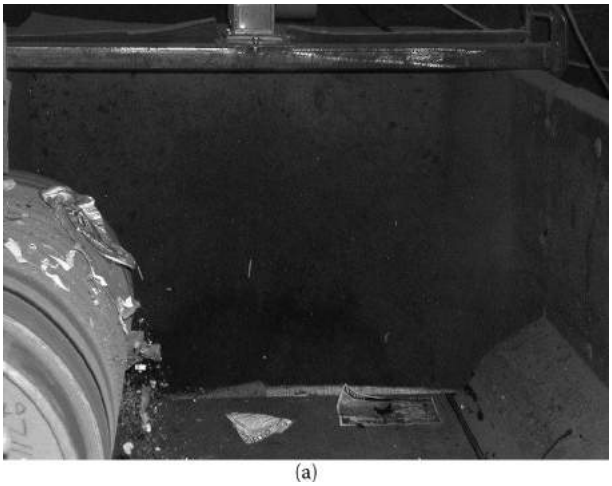
7.4.6 Air Classifier

Air classification is a unit operation designed to separate the lightest waste components, such as paper and plastic, from heavier materials based on their differential behaviors when subjected to a stream of air. When a waste mixture is fed into an air stream of sufficient velocity, lightweight materials will be carried with the air stream, whereas the heavier components fall by gravity.

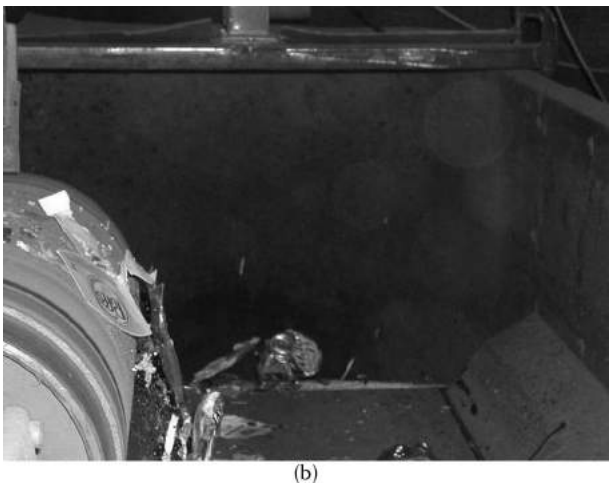
Air classification has been used by industry for decades for the separation of various components in mixtures. Air classifiers are used in waste-to-energy processing lines to segregate the MSW stream into two fractions—one consists of light materials (paper, plastic, wood, dust), and the other of heavy materials (metals, glass, stones). In most MSW, the light fraction constitutes 60%–75% of the total mass (see Chapter 4). Air classification concentrates the combustible components into the light fraction as a fuel product. Metals and glass can be separated as the heavy fraction and sold in secondary markets. In the processing scheme, an air classifier is often situated after the magnetic separator and upstream of a secondary shredder.

Separation is optimized through the proper design of the separation chamber, airflow rate, and material feed rate. Specific variables of the input waste feed will affect material separation by air classification. Variables include:

- Particle density
- Particle size
- Particle surface area



(a)



(b)

FIGURE 7.31 An eddy current separator in operation. (a) Wastes entering separator; (b) aluminum UBCs being ejected.

Air classifiers may be configured in several designs of varying capacity and efficiency of separation. A schematic diagram of a typical air classifier is provided in Figure 7.32. The vertical, straight type is one of the most common configurations of air classifiers. Shredded MSW is dropped into the chute. An upward stream of air, fed by blowers, lifts lightweight materials upward for subsequent capture in a cyclone or other receptacle. There is little breakage of aggregated particles. Airflow direction is fairly uniform, and the airflow rate is held constant. Variations to the simple vertical design include installation of baffles along the length. Such appendages may be angular, thus creating turbulence within the housing and causing some of the aggregated particles to separate.

A second type of air classifier consists of a vertical column having a zig-zag internal configuration, through which a rapid stream of air is drawn up at a constant rate. Shredded wastes are introduced at either the top or middle of the column, and air is introduced at the base. A rotary airlock mechanism is necessary to introduce the shredded wastes into the classifier housing. The zig-zag classifiers use gravitational force and the impact upon the sides of the housing to break up aggregates and minimize entrapped "lights." The shape of the structure creates a vortex effect (Figure 7.33) that causes the waste to tumble and thus enhances separation of clumps. Lighter particles will

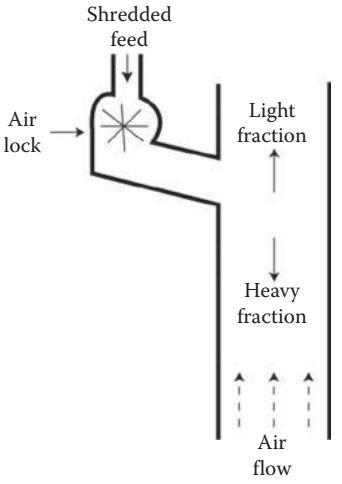


FIGURE 7.32 Schematic of a typical air classifier. (Reproduced with kind permission from Rhyner, C.R. et al., *Waste Management and Resource Recovery*, Lewis Publishing, Boca Raton, FL, 1995. Copyright Lewis Publishing, an imprint of CRC Press.)

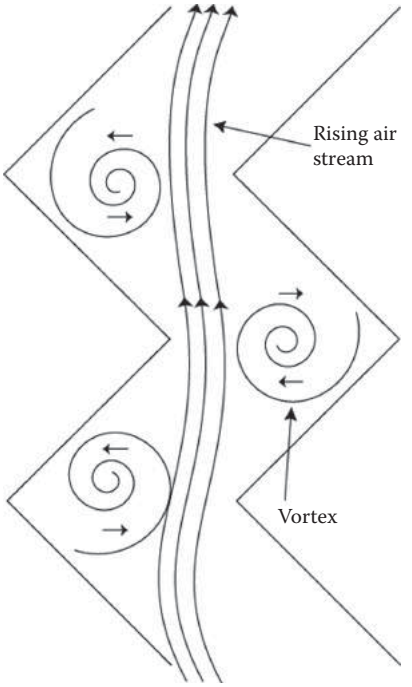


FIGURE 7.33 Vortex effect occurring within an air classifier. (Reproduced with kind permission from Stessel, R.I., *Recycling and Resource Recovery Engineering,* Springer, Berlin, 1996.)

follow the air stream up and heavier components fall. Although the zig-zag shape of the housing has been shown empirically to enhance separation, the shape is also known to enhance blockage of input wastes (Stessel 1996).

In a third configuration, the pulsed air classifier uses a varying airflow velocity. Airflow to the column is varied with a louver valve. The pulsed airflow unit achieves better discrimination

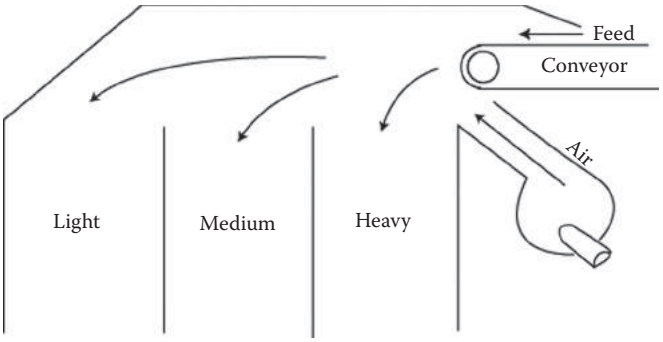


FIGURE 7.34 Horizontal air classifier. (From National Aeronautics and Space Administration, *Energy Recovery from Solid Waste,* Vol. 2 – Technical Report NASA CR-2526, Washington, DC, 1975.)

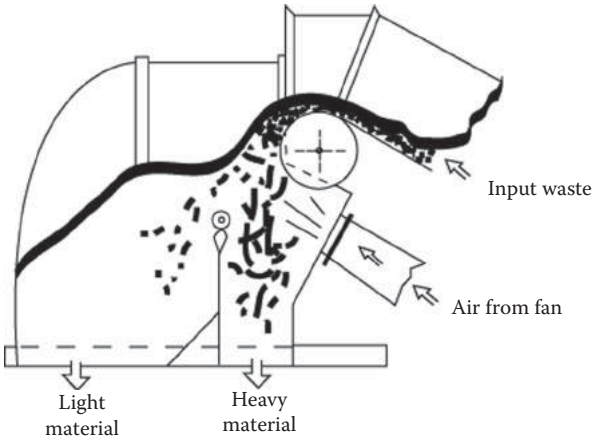


FIGURE 7.35 Air knife. (From Pfeffer, J.T., *Solid Waste Management Engineering*, Prentice Hall, Englewood Cliffs, NJ, 1992. Reproduced with kind permission of Pearson Education, Inc., Upper Saddle River, NJ.)

between materials. Velocity of a falling object is a function of time until its terminal velocity has been attained. Varying the velocity of the air stream has the effect of keeping the falling particles in a velocity range, such that particles with similar terminal velocities are more completely separated (Tchobanoglous et al. 1993). A pulsed system can use a simple, straight throat, as was the case for the vertical air classifier.

Horizontal air classifiers are also in use in MRFs (Figure 7.34). In the horizontal system, both light and heavy waste components are entrained with the air stream in one direction. The waste and air enter at one end of the shaft and are forced toward the other end. Separation occurs when heavier components that have hugged the bottom of the shaft fall through an opening and are collected, whereas the light fraction is forced beyond the opening to a separate collection area (Rhyner et al. 1995).

A similar concept to the standard air classifier is the air knife (Figure 7.35). This relatively simple separation device has been compared with throwing leaves and twigs upward into an autumn breeze. In the air knife, the airflow is forced horizontally through a vertically falling input. Lighter particles are carried with the air stream, whereas the heavier ones quickly drop. Another use of the air knife has been to prevent contamination by lightweight particles during magnetic separation. Air is blown opposite the direction of travel of the metal under a magnet. The air flow helps in

separating the lights from the metals, thus keeping them from being carried over to the metals conveyor (Worrell and Vesilind 2011).

All air classifiers use one of two types of air transport to aid in separation. A positive-pressure air transport system will push MSW feed through the system. This process is accomplished by attaching a blower to the air classifier housing and creating a higher pressure within the system relative to the ambient environment. The other method, a negative-pressure air transport system, pulls the MSW through. An exhaust fan is placed at the end of the system, creating a lower pressure within the system.

The extracted materials must be removed from the air stream once they are separated. A cyclone separator often follows the air classifier and is used to separate the collected light fraction from the conveying air. In the cyclone (Figure 7.36), the air is either pushed or pulled. Particles and air enter the chamber at a tangent, setting up a high velocity rotational air movement within the chamber. The solid particles, having greater mass, move outward toward the wall, decrease velocity on contact, and eventually drop out of the bottom of the chamber under the force of gravity. Before being discharged to the outer atmosphere, the conveying air is passed through a dust collection system, typically a baghouse. The air, free of solids, exits the unit. Alternatively, the discharge air can be recycled back to the air classifier. The light fraction is stored in bins or conveyed to another shredder for further size reduction before storage or utilization as a fuel or compost feedstock.

7.4.7 Efficiency of Separation in an Air Classifier

As it may be obvious from discussions of the various unit operations in a MRF, complete separation of one material from all others is not possible. In the case of air classification, the recovery of organics is complicated by two factors (Vesilind et al. 1988):

- Not all organics are aerodynamically light, and some inorganics (e.g., aluminum foil) are not aerodynamically heavy.

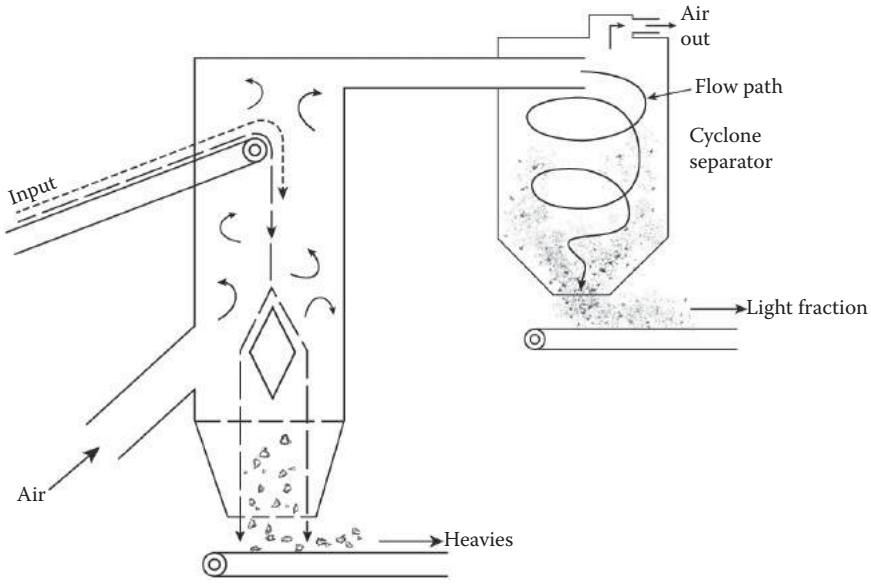


FIGURE 7.36 Complete air classification system including cyclone.

- Perfect separation of heavy and light materials is difficult because of the stochastic (i.e., any phenomenon obeying the laws of probability) nature of material movement within the classifier.

In Figure 7.37, terminal settling velocity (i.e., air velocity at which the particle will just begin to rise with the air stream) is plotted against percentage of particles of selected materials. Regardless of the air velocity chosen, there will never be a complete separation of the lighter organics (paper and plastic) from the heavier inorganics (metal, glass, stone). Figure 7.38 shows the efficiency of separation of fractions versus feed rate to the air classifier. With a greater loading of solids, an increasing proportion of light particles will fall into the underflow stream rather than be separated as desired.

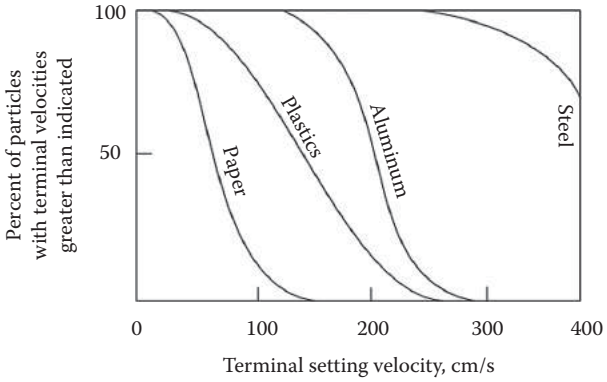


FIGURE 7.37 Terminal settling velocities of MSW components. (From Vesilind, P.A. et al., *Environmental Engineering*, 2nd ed., Butterworths, Boston, MA, 1988. Reproduced with kind permission of Elsevier, Oxford, U.K.)

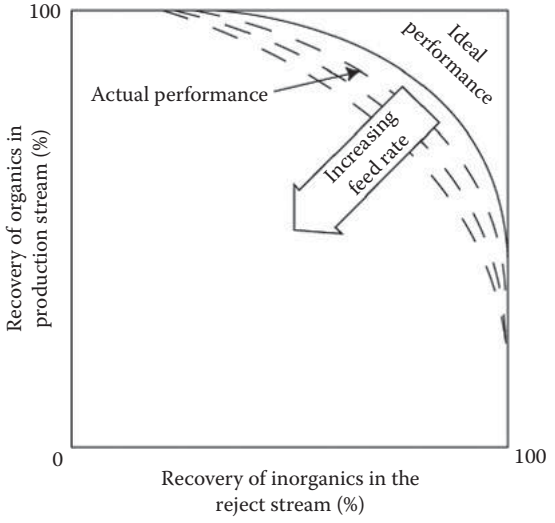


FIGURE 7.38 Actual and ideal performance of air classifiers. (From Vesilind, P.A. et al., *Environmental Engineering*, 2nd ed., Butterworths, Boston, MA, 1988. Reproduced with kind permission of Elsevier, Oxford, U.K.)

The effectiveness of air classification can be estimated using published data (Figure 7.37). As air velocity is increased from zero, the first material to float upwards and collect in the extract is paper. At a velocity of 500 cm/s (1000 ft/min), all of the paper occurs in the extract. However, at this velocity, about 50% of the plastic is also entrained. If we increase the air velocity beyond 500 cm/s, some aluminum will start to become entrained with the extract. At an airflow of 1010 cm/s (2000 ft/min), all of the paper and plastic will be collected in the extract; however, this will be contaminated by 50% of the aluminum. The steel component would not become entrained until the air velocity exceeded 1010 cm/s. At 1525 cm/s (3000 ft/min) virtually all of the input feed would become entrained. From the data in Figure 7.37, then, if the goal of a MRF is to produce high-quality feedstock for RDF, the air velocity is best maintained under 500 cm/s.

Example 7.5

Shredded MSW containing equal proportions of paper, plastic, aluminum, and steel is fed into an air classifier operating with an air velocity of 175 cm/s. Calculate the recovery of the organic product and the purity of the product. Use the terminal settling curves of the individual waste components shown in Figure 7.37.

Based on the figure, at 175 cm/s the fractions of the components that are captured as product are

Paper	98%
Plastics	75%
Aluminum	20%
Steel	0%

The total organics (paper + plastic) in the product is

$$98\ (1/4) + (75)\ (1/4) = 43\%\ \text{of feed}$$

The total aluminum + steel in the product is

$$(20)\ (1/4) + (0)\ (1/4) = 5\%\ \text{of the feed}$$

Using equations 7.3–7.5, the recovery of organics is calculated as

$$R_{org} = 43/(25 + 25) \times 100 = 86\%$$

And the purity is

$$P_{product} = 43/(43 + 5) \times 100 = 90\%$$

7.4.8 Miscellaneous Processing

7.4.8.1 Dryers

In waste-to-energy systems, dryers reduce the moisture content of MSW, thereby increasing its heat (Btu) value. Moisture reduction also results in improved storability, possibly improved air classification, and reduction in populations of potentially pathogenic microorganisms. The dryer is typically installed just before or just after the air classifier.

A drying system is equipped with (1) a blower to circulate heat and to force the MSW charge forward, (2) a rotary drum with a variable speed motor, and (3) a cyclone separator that isolates the MSW from the air stream. The MSW inlet is positioned directly in front of the rotary drum. The waste and hot air stream flow through the drum in multiple stages, typically passing the length of the drum several times before exiting to the cyclone separator. As the drum is constantly rotating, the waste is agitated and greater surface area is exposed to the heat (Bendersky 1982).

7.5 MATERIALS FLOW IN THE MRF

A number of designs are available for unit operations in a MRF. As mentioned earlier, MRFs can be "clean" or "dirty." The former style handles materials that have already been source-separated into desired fractions. The latter accepts bags of commingled wastes collected directly from curbside. Considerations as to clean versus dirty modes and equipment to use will vary according to factors such as initial capital costs and funding available, political pressures, and convenience to the consumer. A simplified waste separation scheme is depicted in Figure 7.39.

Placement of unit operations in the MRF varies depending on the materials desired for separation and the purity desired. For example, placement of a trommel screen upstream of a shredder will result in removal of stones and other small abrasive debris. This placement will lengthen the lifetime of a hammermill shredder by reducing hammer wear. In addition, trommels will extract a large proportion of glass containers. If not removed, glass will shatter in the shredder and become embedded in paper and other potentially recyclable materials. If this paper product is combusted as fuel, there are implications for handling larger volumes of ash.

In some communities, source-separated wastes are collected in transparent bags that are placed in the same truck along with mixed MSW. A typical process flow diagram for a MRF using separation, manual combined with mechanical, from commingled MSW and source-separated waste, is illustrated in Figure 7.39. Commingled MSW is discharged in the receiving area. Hazardous items are removed immediately by hand. Recyclable and oversized materials such as lumber, white goods, and furniture are also removed in this *first-stage* operation. Source-separated materials in see-through bags are segregated from the commingled MSW.

The commingled waste is loaded onto an inclined conveyor. Additional cardboard and large items are removed manually from the conveyor at the second presorting station. The next step involves breaking open trash bags, either manually or mechanically at a bag-breaking station. In some facilities, a short, enclosed trommel equipped with protruding blades is used as a bag breaker. Flail mills, shear shredders, and screw augers have also been used as bag breakers.

After the presorting steps, the materials typically removed include paper, cardboard, glass, metals, and several types of plastic. In some operations, different types of plastic (e.g., PETE and HDPE) are separated simultaneously. Material remaining on the conveyor is discharged into a trommel or disc screen for size separation. The oversized material is sorted manually a second time (*second-stage sorting*). The undersized materials from trommel screening and that remaining after second-stage sorting are processed further and combusted, used to produce compost for daily landfill cover, or hauled away for landfill disposal.

Mixed source-separated materials are further purified using the second-stage sorting line. Source-separated mixed paper and cardboard are processed separately.

7.6 CONTAMINATION ISSUE

Depending on the design of the MRF, the quality of the separated product will vary significantly. Mixed MSW received at the facility poses the greatest challenge to ensuring separation of clean, quality product. For this reason, it is advantageous to require some initial separation, ideally by

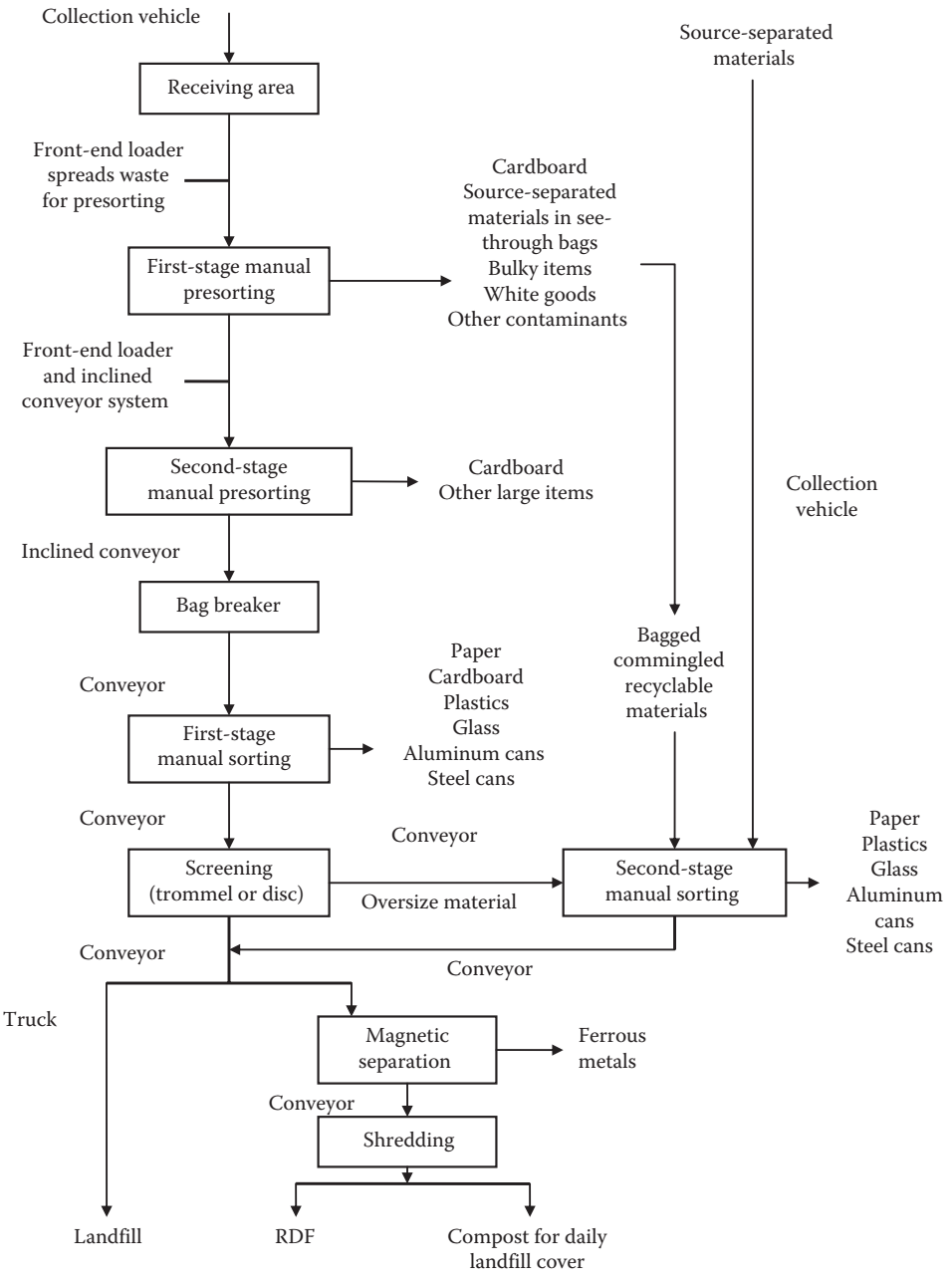


FIGURE 7.39 MRF flow scheme for a dirty MRF. (Reproduced with kind permission from Tchobangoious. G. et al., *Integrated Solid Waste Management: Engineering Principles and Management Issues,* McGraw-Hill, New York, 1993.)

the waste generator, well in advance of collection. Having recyclables picked up separately from the nonrecyclable wastes best ensures adequate separation.

The success of recovery at the MRF is variable depending on the processes used, but recovery (and purity) from a dirty MRF is obviously much less than we would expect for a source-separated system (Figure 7.40).

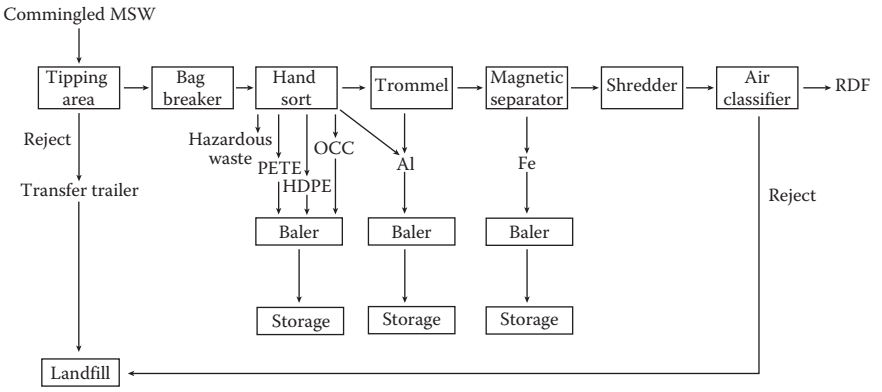


FIGURE 7.40 A second materials flow plan, dirty MRF.

7.7 ENVIRONMENTAL CONTROL

To protect the health and safety of facility employees, as well as to meet environmental requirements of the local community, it may be necessary to install additional equipment. Title 29 of the Code of Federal Regulations, part 1910, provides the OSHA standards for adequate worker protection. Local codes often address the environmental responsibilities of a facility. In the planning and design phase of the MRF, those operations likely to cause problems for either workers or the community should be identified in order to determine how to best eliminate or minimize them.

7.7.1 Dust Collection

MSW brought to the tipping room floor is laden with soil and dust. In addition, shredding, crushing, baling, screening, and conveying are dust-producing operations. Dust poses several problems: it can be a vector for the transmission of pathogenic microorganisms, it can impart a detrimental effect on the respiratory system, and it can explode.

OSHA standards presently limit dust inhalation to 15 mg/m^3 of total dust over an 8-h day period. Studies of dust production at several resource recovery facilities have shown that dust levels are 7–13 times higher than the OSHA standard. This finding dictates the use of respirators while working.

Air quality studies at shredding operations have indicated that total bacterial counts during shredder operation are as much as 20 times greater than the ambient, which contains about 880 organisms/m^3 of air. In resource recovery facilities where shredders are used, coliform counts can increase from 0 to 135 per m^3, and fecal streptococci from 0 to over 975 per m^3 (Diaz et al. 1976; Worrell and Vesilind 2011). These data show the potential danger of disease transmission during shredding of MSW.

The degree of dust collection is a function of the types and volumes of wastes handled, unit operations, and local climate. Effective systems can vary from the installation of individual dust collection units at each operation along the line, to one or two centralized dust collection units. Systems include fans, ducts, cyclones, and baghouses. The plant worker may be required to wear a simple dust mask during operations.

7.7.2 Odors and Their Control

Odors can be significant in MRFs, especially dirty MRFs, where raw MSW is brought to the facility, stored, and processed. Odors are reduced by minimizing storage time of raw materials and product, followed by frequent wash-down of tipping floors.

Some of the most effective odor control techniques involve applying negative pressure (suction) within an enclosed MRF and treating the exhaust gases. The gases can be incinerated, passed through granular activated carbon filters, or chemically (catalytically) oxidized. They can also be scrubbed by passage through a gravity spray tower, that is, an enclosed chamber containing a fine mist of water or other absorbing solution. There has been some work on biofiltering exhaust gases, i.e., forcing them through a mixture of soil and gravel. Indigenous microorganisms will act upon and oxidize a wide range of gases, using them as substrates. In the interest of speed and cost, odors can simply be masked—a disinfectant spray can be released in the working area. Its purpose, however, is primarily to coat the nostrils of workers, thereby blocking the malodorous MSW gases—it does not eliminate noxious gases. In situations with severe odors, multiple technologies may be required.

7.7.3 Noise Suppression

Much of the equipment used in MRFs generate noise: conveyor belts, crushers, pumps, front-end loaders, and so on. The noise levels around a 3 ton/h hammermill range from 95 to 100 dBA, with much of the noise produced being low frequency. The unit "dBA" is a standard method of noise



(a)



(b)

FIGURE 7.41 The exterior of the MRF (a and b) should be aesthetically appealing in order to limit NIMBY attitudes.

measurement and indicates decibels on the A scale of the sound-level meter. This scale is an attempt to duplicate the hearing efficiency of the human ear. In addition to a high constant noise level, materials recovery facilities processing MSW produce considerable impact noise that is difficult to measure, and whose effect on human beings is poorly understood. The existing OSHA standard limits noise to 90 dBA over an 8-h working day. The corresponding limit set by the EPA is 85 dBA. Shredder operators must wear ear protection (Worrell and Vesilind 2011).

Engineering controls for noise are difficult to establish in many situations. Sound muffling equipment and soundproofing at unit operations may be installed throughout a building or specific pieces of equipment can be isolated, although this is often impractical.

7.7.4 Aesthetics

Practical issues to be addressed in the design of MRFs include aesthetics and public health. In order to be a good neighbor to the community, it is important for a MRF to be designed, constructed, and landscaped to blend in with an area zoned for commercial or industrial use. Berms and attractive vegetation may be established at the perimeter of the property. Blowing litter should be prevented, or at least quickly removed from facility grounds. Attractive signs should be posted at the entrance (Figure 7.41).

Odors of decomposing wastes will saturate the MRF and readily migrate beyond facility boundaries if proper precautions are not taken. Rodents and insects may be a problem. Spontaneous combustion can occur in MSW piles. A rule of thumb is that 2 days of storage is a safe maximum, with a week being dangerous. A waste fire is difficult to extinguish, and the newly formed wet wastes following extinguishing pose new disposal problems.

QUESTIONS

1. The number of MRFs in the United States has increased dramatically over the past two decades. Explain the reasons for this increase based on factors such as economics, NIMBY, and environmental consciousness.
2. Where in the MRF is human labor essential (i.e., a machine cannot adequately perform the job)?
3. What factors influence separation efficiency of a trommel screen?
4. What is the *most critical* parameter for efficient MSW separation by a trommel screen?
5. To avoid carryover of glass fines in an air classifier, what device or unit operation may wastes be first passed through?
6. What are the advantages in using a shredder for MSW processing in a MRF? What are the disadvantages?
7. Plastic wastes can be sorted optically or mechanically using "color screening" (true/false). Explain.
8. What is the ideal trommel rotation speed? Consider cascading, cataracting, and centrifuging of feed.
9. List and discuss some of the major safety hazards associated with shredding MSW.
10. All other factors being equal, are there any practical advantages to horizontal hammermills over vertical models? Consider efficiency of shredding, energy requirements, noise generation, and jamming by rigid articles.
11. Using mechanical equipment for separation of mixed MSW, it is not possible to achieve 100% separation efficiency. Explain and provide an example.
12. During air classification, recovery of organics is complicated by what factors?
13. What factors influence the effectiveness of magnetic separation?
14. Calculate the waste thickness for a conveyor belt measuring 1.0 m wide with an average belt speed of 20 m/min. The waste loading rate is 25.5 MT per hour and the average density of the waste on the belt is 105 kg/m^3.

15. A trommel screen measuring 9 m long and 3 m diameter is rotating at 2.5 rpm. The feed rate is 12 MT of raw MSW per hour. Calculate the critical speed. At the above speed, would the waste input be cascading, cataracting, or centrifuging?
16. If the trommel screen in Question 15 were to be adjusted to a steeper angle, how would separation efficiency be affected?
17. A magnetic separator is used at a MRF for ferrous recovery from commingled MSW. The feed rate to the separator is 1255 kg/h. The feed contains 4.2% ferrous. A total of 40 kg is collected in the product stream and 32 kg is actually ferrous. Calculate the recovery, purity, and efficiency of the unit operation.
18. List the key components of the receiving area of an MSW processing facility.
19. In terms of separation of potentially recyclable components, what is a detrimental effect of shredding raw MSW to a fine particle size?
20. Contact your local waste management authority and determine the fraction of materials recovered for recycling collected via drop-off centers versus curbside pickup programs or MRFs.
21. Diagram a sequence of unit operations for a mechanized waste separation system. The input waste includes paper products, food waste, glass, plastic (PET, HDPE, and others), metals (ferrous and nonferrous), and household hazardous wastes. List all the equipment required for adequate separation. Include at least one shredder.
22. Hazardous materials can be removed from the commingled wastes arriving at a MRF via: (a) magnetic separation, (b) manual hunt-and-pick, (c) air knife, (d) froth flotation.
23. Waste paper should be removed: (a) using an air classifier, (b) after ferrous removal, (c) after shredding the waste stream, (d) after trommel screening, (e) all of the above.
24. Suppose your community has decided to develop a waste management program with a goal of substantially greater waste recycling and materials recovery. The three major alternatives are source separation, a dirty MRF, and a clean MRF. Discuss the key factors to consider in order to identify the optimum alternative. Consider short-term and long-term economics, public acceptance, environmental impacts, aesthetics, and convenience to local citizens.

REFERENCES

Bendersky, D. 1982. *Resource Recovery Processing Equipment*. Park Ridge, NJ: Noyes Data Corporation.

CEMA (Conveyor Equipment Manufacturers Association). 1995. *Conveyor Terms and Definitions*, CEMA No. 102-1994. Manassas, VA: CEMA.

Diaz, L.F., Riley, L., Savage, G., and Trezek, G.J. 1976. Health considerations associated with resource recovery. *Compost Sci* 17, 18–24.

Diaz, L.F., Savage, G., and Golueke, C.G. 1982. *Resource Recovery from Municipal Solid Wastes*, Vols. 1 and 2. Boca Raton, FL: CRC Press.

DSMAC (Dingsheng Machinery). 2012. *Crusher Hammer Mill Parts Composition*. Dingsheng Machinery. Available from: http://crusher-spare-parts.com/news/Crusher-hammer-mill-parts-composition.html

Eckhoff, R.K. 2009. Dust explosion prevention and mitigation, status and developments in basic knowledge and in practical application. *Int J Chem Eng* 2009, 12.

Ely, K., Jr. 1993. Processing equipment. In *The McGraw-Hill Recycling Handbook.* Lund, H.F. (Ed.). New York: McGraw-Hill, 28.1–28.23.

Engdahl, R.B. 1969. *Solid Waste Processing.* Washington, DC: EPA OSMP.

Epoxytech. 2009. *Epoxytec Featured Projects. Infrastructure Rehabilitation & Protection*. Available from: http://epoxytec.blogspot.co.uk/2009/08/solid-waste-tipping-floor-push-walls.html

Hasselriis, F. 1984. *Refuse-Derived Fuel Processing*. Boston, MA: Butterworths.

Hering, R. and Greeley, S.A. 1921. *Collection and Disposal of Municipal Refuse*, 1st ed. New York: McGraw-Hill.

Iron Mountain. 2012. *The Dangers of In-House Shredding*. US-SS-EXT-FL-062712-001. Boston, MA: Iron Mountain.

Montgomery County, MD. 2006. *Solid Waste Transfer Station.* Available from: http://www6.montgomerycountymd.gov/swstmpl.asp?url=/content/dep/solidwaste/facilities/tours/transfer_tour2.asp

National Aeronautics and Space Administration (NASA). 1975. *Energy Recovery from Solid Waste*. Volume 2 – Technical Report NASA CR-2526. Washington, DC.
Naval Civil Engineering Laboratory. 1986. *Comparison of shear shredder with hammermill for size reduction of Navy solid waste*. AD-A168 202. Port Hueneme CA.
Parker, B.L. 1983. Magnetic separation of ferrous metals from shredded refuse. M.S. thesis, Duke University, Durham, NC.
Pfeffer, J.T. 1992. *Solid Waste Management Engineering.* Englewood Cliffs, NJ: Prentice Hall.
Rhyner, C.R., Schwartz, L.J., Wenger, R.B., and Kohrell, M.G. 1995. *Waste Management and Resource Recovery.* Boca Raton, FL: Lewis Publishing.
Rietema, K. 1981. On the efficiency of separating mixtures of two components. *Chem Eng Sci* 7, 89.
Schwarz, S.C. and Brunner, C.R. 1983. *Energy and Resource Recovery from Waste.* Park Ridge, NJ: Noyes Data Corporation.
Stessel, R.I. 1996. *Recycling and Resource Recovery Engineering.* Berlin: Springer-Verlag.
Sullivan, J.W., Hill, R.M., and Sullivan, J.F. 1992. The place of the trommel in resource Recovery. *Proceedings of the Waste Processing Conference.* New York: American Society of Mechanical Engineers.
Tchobanoglous, G., Theisen, H., and Vigil, S. 1993. *Integrated Solid Waste Management: Engineering Principles and Management Issues.* New York: McGraw-Hill.
U.S. EPA (U.S. Environmental Protection Agency). 1976. *Fine Shredding of Municipal Solid Waste*. EPA-600/2-76-208. Environmental Protection Technology Series. Research Triangle Park, NC: Industrial Environmental Research Laboratory.
U.S. EPA (U.S. Environmental Protection Agency). 1980. *Processing Equipment for Resource Recovery Systems. Vol. II: Magnetic Separators, Air Classifier and Ambient Air emissions Tests*. EPA-600 2-80-007b. Cincinnati, OH: Municipal Environmental Research Laboratory.
U.S. EPA (U.S. Environmental Protection Agency). 1991. *Materials Recovery Facilities for Municipal Solid Waste*, EPA/625/6-91/031. Washington, DC: Office of Research and Development, U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 2011. *Municipal Solid Waste in the United States: 2010 Facts and Figures.* Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.
Vesilind, P.A., Peirce, J.J., and Weiner, R.F. 1988. *Environmental Engineering*, 2nd ed. Boston, MA: Butterworths.
Walker Magnets. 2013. Eddy current separation equipment. Available from: http://www.walkermagnet.com/separation-eddy-current-separators.htm
Worrell, W.A. and Vesilind, A. 2011. *Solid Waste Engineering*, 2nd ed. Stamford, CT: Cengage Learning.

SUGGESTED READINGS

Barnes Reports. 2009. 2009 U.S. Materials Recovery Facilities Industry Report. Available from: http://www.researchandmarkets.com/reports/836479/2009_u_s_materials_recovery_facilities_industry
Biddle, D. 2005. Single stream success: Blue Mountain Recycling Finds Success with its Single-Stream MRF in Philadelphia. *Recycling Today*. Available from: https://www.recyclingtoday.com/Article.aspx?article_id = 19840
Chang, N.-B., Davila, E., Dyson, B., and Brown, R. 2005. Optimal design for sustainable development of a material recovery facility in a fast-growing urban setting. *Waste Manag* 25(8), 833–846.
Chang, Y.H. and Chang, N.B. 2003. Compatibility analysis of material and energy recovery in a regional solid waste management system. *J Air Waste Manage Assoc* 53, 32–40.
Dubanowitz, A.J. 2000. Design of a Materials Recovery Facility (MRF) for processing the recyclable materials of New York City's Municipal Solid Waste. M.S. thesis, Columbia University, New York.
Hooper, R., Potter, A.K.N., and Singh, M.M. 2001. Diversion from landfill: Mechanical recycling of plastics from materials recovery facilities and from shredder residue. *Green Chem* 3, 57–60.
Kang, H.-Y. and Schoenung, J.M. 2006. Economic analysis of electronic waste recycling: Modeling the cost and revenue of a materials recovery facility in California. *Environ Sci Technol* 40(5), 1672–1680.

8 Composting MSW

Drive my dead thoughts over the universe
Like withered leaves to quicken a new birth!

Percy Bysshe Shelley (1792–1822)
Ode to the West Wind

8.1 INTRODUCTION

Organic materials comprise the majority of municipal solid waste (MSW) generated in the United States, accounting for about 139 million tons (56%) of the waste stream (U.S. EPA 2011a). Certain organics such as newspaper, office paper, and corrugated cardboard are recovered extensively for recycling. Other potentially useful materials (e.g., yard waste, food scraps, mixed paper), however, may be lost from the recycling loop and become landfilled.

The organic fraction of MSW can circumvent land disposal and undergo various other fates, including direct conversion into fuels, fermentation as a biofuel, pyrolysis, and composting. Composting has been documented in ancient societies predating the Roman Empire, and the method has since been streamlined in terms of efficiency, time of completion, health impacts, and area requirements. The composting of MSW, agricultural wastes (plant residues, animal manures), food factory waste, and municipal wastewater treatment solids (biosolids) is increasingly used worldwide as a means of waste management. It is estimated that about 33.4 million tons of yard waste and 34.8 million tons of food waste are available for composting (see Table 1.3). This data do not include the millions of tons of paper that are not recycled.

Numerous programs divert organic materials from landfills to create beneficial uses. These include:

- Mixed waste composting at centralized processing facilities that accept MSW for separation into composting, recycling, and disposal streams
- Residential source-separated systems using organic materials separated by the generator, set out for collection, and processed at a centralized facility
- Commercial composting operations that utilize materials generated by commercial and industrial establishments
- Yard waste composting at centralized facilities
- Backyard composting of food and yard waste

8.2 BENEFITS OF COMPOSTING

Composting is defined as a controlled, aerobic, biological conversion of organic wastes into a complex, stable material. The final product has a number of beneficial uses, most commonly for agriculture and landscaping.

If shredded, raw MSW were introduced directly into a soil to be used for agriculture, the organic component would undergo rapid transformation by soil microorganisms. A number of adverse effects would result:

- *Undesirable reactions.* Anaerobic transformations will generate ammonia (NH_3), hydrogen sulfide (H_2S), and methane (CH_4) gas. Such gaseous products are toxic to plants and will additionally cause odor problems.

- *Competition for plant nutrients.* The most important nutrient to most crop plants is nitrogen. With application of raw waste to soil, microorganisms attack the carbon (an energy source), and will simultaneously require large quantities of nitrogen for manufacturing cell biomass. Being opportunistic and fast-growing, microorganisms can incorporate and render unavailable virtually all plant-available soil N, such that plants cannot obtain sufficient quantities. This phenomenon is termed "nitrogen depression."
- *Leaching.* Potentially toxic materials (e.g., salts, metals, acids, microbial cells) are released from raw waste into soil and water.

In contrast, composting transforms the organic feedstock via:

- Mineralizing the simple, easily assimilable substances, that is, protein, cellulose, sugars, and lipids, to CO_2 and simple N compounds (e.g., nitrate).
- Humifying more complex compounds, such as lignin, to produce a relatively homogeneous and stable organic product.

The final humus-like product is hygienically safer, more aesthetically appealing, and substantially lower in odor than raw MSW. The finished organic product has several potential applications.

A primary application of compost is for agriculture—compost serves as a soil conditioner (i.e., an organic resource that improves water-holding capacity, increases aeration, and improves drainage), and it supplies nutrients, particularly N, P, and S, all of which occur primarily in the organic form. Compost also provides a number of micronutrients, including Cu, Fe, Zn, and Ni. Many such trace nutrients will occur as organic chelates and complexes that are relatively plant available. Finally, because composts are often circumneutral in pH, they moderate pH extremes of the recipient soil.

Compost is also used in landfill operations as a daily cover material, for landscaping applications and for remediation of contaminated sites and mined lands (U.S. EPA 1997b, 1998).

8.3 OVERVIEW OF THE COMPOSTING PROCESS

Composting on the commercial scale occurs in three major phases. Initial processing includes size reduction to enhance microbial reactions. First, separation of inert materials (glass, plastic, metals, etc.) from the organic fraction is necessary. Size reduction (shredding) and chemical or biological conditioning are important at the outset if the finished product is to be used in agriculture. Next, microorganisms decompose the raw feedstock into simpler compounds, producing heat as a result of metabolic activity. The volume of the compost pile is reduced during this stage, and the heat generated destroys many pathogens. In the final stage, the compost product is "cured."

Microorganisms deplete the supply of available nutrients in the pile, which, in turn, slows their activity. As a result, heat generation diminishes and the compost mass dries. When curing is complete, the compost is considered *stabilized* or *mature*. Any further microbial decomposition occurs only very slowly. Figure 8.1 provides the overall steps involved in the aerobic composting of the organic fraction of MSW.

8.4 ROLE OF MICROORGANISMS IN COMPOSTING

Composting is an aerobic biological process; a diverse consortium of microorganisms acting concurrently controls the process. The most active players in composting are bacteria, actinomycetes, fungi, and protozoa. These organisms are naturally present in most organic materials, including food waste, soil, leaves, grass clippings, and other organics.

Composting is also dependent upon a *succession* of microbial communities and activities, whereby the environment created by one group of microorganisms ultimately promotes the activity of successor groups. Different types of microorganisms are active during different phases of the

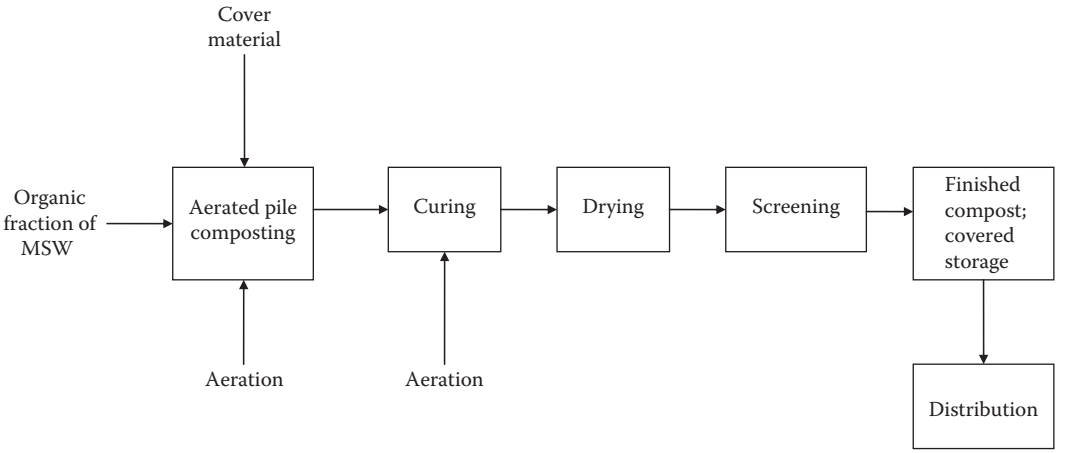


FIGURE 8.1 Flow chart showing the steps involved in the aerobic composting process.

TABLE 8.1
Microbial Populations during Aerobic Composting

	Number per Wet Gram of Compost			
Microbe	**Mesophilic Initial Temp (40°C)**	**Thermophilic (40–70°C)**	**Mesophilic (70°C to Cooler)**	**Species Identified**
		Bacteria		
Mesophilic	10^8	10^6	10^{11}	6
Thermophilic	10^4	10^9	10^7	1
		Actinomycetes		
Thermophilic	10^4	10^8	10^5	14
		Fungi		
Mesophilic	10^6	10^3	10^5	18
Thermophilic	10^3	10^7	10^6	16

Source: Reproduced with kind permission of Haug, R.T., *The Practical Handbook of Compost Engineering*, Lewis Publishing, Boca Raton, FL, 1993. Copyright Lewis Publishing, an imprint of CRC Press.

composting process. Bacteria have the most significant effect on decomposition—they are the first to become established in the pile, processing readily decomposable substrates (e.g., proteins, carbohydrates, sugars) faster than any other group. Table 8.1 lists some of the major microbial types involved in composting. Commercial products are available that claim to speed the composting process via the introduction of selected strains of bacteria. However, contradictory results have been described by different authors (Faure and Deschamps 1991; Elorrieta et al. 2002; Gaind et al. 2005) regarding the use of inoculants to speed the composting process or to obtain better final compost.

Fungi play an important role in composting as the pile dries since fungi can tolerate low-moisture environments better than bacteria. Some fungi also have lower nitrogen requirements than bacteria and, therefore, are able to decompose lignin and cellulose materials, which bacteria cannot.

Because fungi are numerous in composting, concern has arisen over the growth of genera such as *Aspergillus*, which pose a potential human health hazard.

The actinomycetes are often considered a middle group between bacteria and fungi. Most genera of actinomycetes produce slender, branched filaments that develop into a mycelium. Actinomycetes are

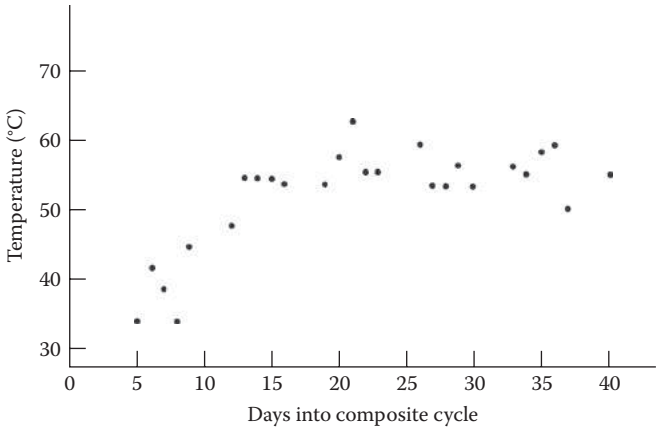


FIGURE 8.2 Temperature trends in the early stages of composting. (From U.S. EPA, *Windrow and Static Pile Composting of Municipal Sewage Sludges,* Project Summary, EPA-600-S2-84-122, Engineering Research Laboratory, Cincinnati, OH, 1984.)

widely distributed in soil, compost piles, river sediments, and other environments. Actinomycetes decompose aromatics, steroids, phenols, and other complex organic molecules (Eweis et al. 1998).

Macroorganisms also play a role in composting. Rotifers, nematodes, mites, springtails, sowbugs, beetles, and earthworms reduce the size of the compost feedstock by foraging, burrowing within the pile, and breaking up particles of the feedstock. These actions physically break down the organics, creating greater surface area and additional sites for microbes to attach and metabolize (U.S. EPA 1994).

The bacteria and fungi important in decomposing MSW feedstock can be classified by optimal temperature regime as mesophilic or thermophilic. Mesophilic microorganisms experience the most rapid growth at temperatures between 25 and 45°C (77–113°F). They are dominant within the pile early in the process when temperatures are nearly ambient. The mesophiles use oxygen within the interstices (pores) to oxidize carbon and thus acquire energy. End-products of the reactions include carbon dioxide (CO_2) and water. Heat is also generated, as chemical bonds in the substrate are broken during metabolism.

If the pile is insulated from the local environment with no aeration or turning, most of the heat generated is trapped within the pile. In the insulated center, when temperatures of the mass rise to about 45°C (112°F), the mesophiles die or are inactivated. At this time, thermophilic microorganisms, that is, those that prefer temperatures between 45 and 70°C (112 and 158°F), are activated. These microorganisms multiply and metabolize substrates, and replace the mesophiles in most sections of the pile.

Thermophiles generate even greater quantities of heat than do mesophiles. The temperatures reached during this phase of the process are sufficiently high to kill most pathogens and weed seeds. Many composting facilities maintain a temperature of 55°C (131°F) in the interior of the pile for 72 h to ensure pathogen destruction and to inactivate seeds.

The thermophiles continue decomposing the feedstock as long as nutrient and energy sources are available. As the substrates become depleted, the thermophiles die and the pile temperature falls. Mesophiles are again activated and decompose the remaining substrate until all available energy sources are exhausted (U.S. EPA 1994). Figure 8.2 provides a typical temperature pattern for the composting process, and Table 8.1 shows the density of microorganisms as a function of temperature during composting.

8.5 FACTORS AFFECTING THE COMPOSTING PROCESS

Composting is strongly influenced by several environmental factors; as a result, much research into system design and environmental controls has been conducted in attempts to optimize the process.

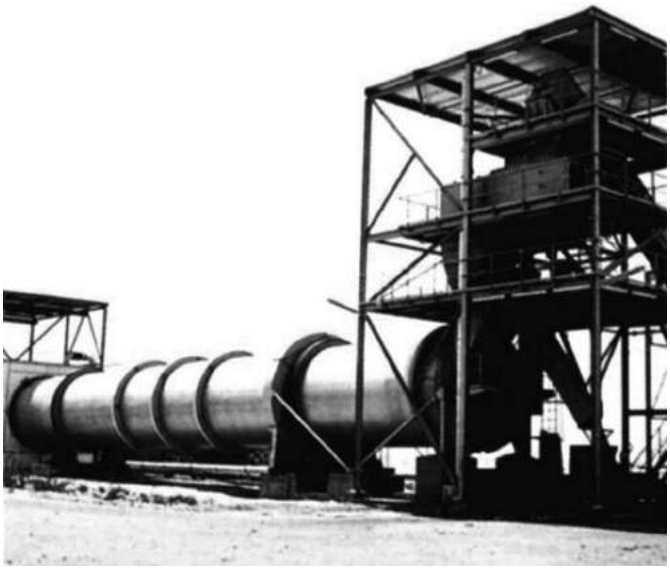


FIGURE 8.3 Biological compost reactor. (Reproduced with kind permission of Cornell Waste Management Institute, Available from: http:// cwmi.css.cornell.edu/composting.htm.)

8.5.1 Preprocessing of the Feedstock

The preparation of the organic component of MSW for composting can be carried out in two ways:

- *Mechanical*. Composting a mixed waste material, that is, organics commingled with inerts such as plastic and metal, is fraught with hazards and complications and should be avoided. Inerts (nonreactives) may benefit the process by acting as a *bulking agent* and promoting aeration of the mass; however, they end up as useless and sometimes hazardous components of the finished material. Mechanical processing involves size reduction by shredding, followed by separation of inert materials by screening, magnetic separation, and other unit operations (see Chapter 7). The resulting material possesses a higher surface area for reaction and a more available substrate for microbes.
- *Biological and mechanical*. In combined biological and mechanical pretreatment, waste is physically processed, as described above, and then transferred to biological reactors (Figure 8.3) for 1–3 days. The reactors are rotating heated cylinders mounted on a slight incline. Biological activity increases immediately and significantly after introduction to the reactor, and degradation of organics occurs concurrently. After preliminary treatment in the reactor, the feedstock is transferred to a compost pile.

8.5.2 Environmental Factors

Microorganisms are clearly central to successful composting; therefore, those factors that affect their proliferation and activity will determine the rate and extent of composting. The principal environmental factors regulating the speed and degree of decomposition include nutrient levels, nutrient balance (e.g., carbon to nitrogen ratio), aeration, moisture, temperature, pH, and particle size of the feedstock material. Any shift in these factors is interdependent—a shift in one parameter often results in changes in others. The closer these variables collectively approach optimum levels, the more rapid is the rate of composting. The chemical and physical nature of the substrate, and the degree of aeration, are especially important in process design.

8.5.3 Nutrients

The organic fraction of the MSW feedstock contains a range of microbial substrates, including proteins, lipids, sugars, starch, amino sugars, chitin, cellulose, lignin, crude fiber, and other compounds (see Chapter 4) that vary in terms of nutrient content, energy content, and availability to microbes. N, P, K, Mg, S, Fe, Ca, Mn, Zn, Cu, Co, and Mo are integral to the protoplasmic structure of the microbial cell. These nutrients, along with C, H, and O, are essential for proper cell synthesis. Most are present in raw compost.

Nutrients obviously must be present in sufficient concentrations in a substrate; however, they must also occur in a form that can be readily assimilated by the microbial cell. Availability is partly a function of enzyme production by the microbe. Certain microbes possess enzymes that permit them to attack and utilize the organic matter within raw feedstock, whereas others can utilize only intermediate products.

Another aspect of nutrient availability in composting is that certain organic molecules are resistant to microbial attack, even to those that possess the required enzyme systems. Such *refractory* materials are broken down slowly, even with all other environmental conditions set at an optimum level. Common examples are lignin (from wood) and chitin (in exoskeletons). Cellulose C is unavailable to most bacteria, although it is utilized by certain fungi. Nitrogen is readily metabolized when in the amino acid form, whereas N present in chitin is relatively unavailable. Many sugars and starches are rapidly decomposed, and many fats and fatty acids are likewise relatively available to microorganisms.

The availability of nutrients is also influenced by pH of the feedstock. In the circumneutral pH range, trace metals (e.g., Cu, Ni, Zn) are typically soluble and, therefore, available in sufficient quantities. In contrast, excess quantities, for example under acidic pH regimes, will prove toxic and inhibitory. Also, at neutral pH, phosphorus is maximally available. A pH of 5.5–8, therefore, is generally considered optimal for composting (see Sec. 8.5.8).

8.5.4 C:N Ratio

The ratio of carbon to nitrogen content in feedstock strongly affects the rate of microbial activity. With few exceptions, all other nutrients are present in organic MSW in adequate amounts and ratios. A large percentage of the carbon substrate is oxidized to CO_2 during metabolic activities. The remaining carbon is converted into cell wall or membrane, protoplasm, and storage products. The principal use of nitrogen is in the synthesis of protoplasm (e.g., proteins, amino acids, nucleic acids). Significantly more carbon than nitrogen is required for adequate microbial growth and activity.

After much empirical research, the optimum C:N ratio for soil and compost microorganisms has been established at approximately 25:1. A ratio much higher will slow decomposition; if the initial ratio is over 35, the microbial consortium must pass through many life cycles, oxidizing the excess carbon to CO_2 until a more suitable ratio is attained. On the other hand, if the C:N ratio is lower than about 20:1, composting is inhibited due to low energy supplies, and nitrogen is lost both by leaching as nitrate (NO_3^-) and volatilization as ammonia ($NH_{3(g)}$). A low C:N ratio in composts is typically rare, however. Of course, these ratios may vary widely depending on the type of carbonaceous materials initially present.

If the initial C:N ratio of a waste is too high, adding a nitrogenous waste (e.g., blood meal) can bring it to acceptable levels. If the ratio is too low, a carbonaceous waste (straw, wood shavings, sawdust, shredded paper) can be added. The nitrogen contents and C: N ratios of various wastes and other materials are listed in Table 8.2.

8.5.5 Aeration

The atmosphere within the interstices of the composting mass will shift significantly during decomposition. When the organic feedstock is delivered to the compost site, the oxygen supply to microbes

TABLE 8.2
Carbon:Nitrogen Ratios of Various Wastes and Materials

Material	C:N
Sawdust	200–500:1
Wheat straw	125–150:1
Grass clippings	12–20:1
Corn stalks	60:1
Humus	10:1
Activated sludge	6:1
Cow manure	18:1
Horse manure	25:1
Poultry manure	15:1
Food scraps	15:1
Mixed MSW	50–60:1

Source: Adapted from Diaz, L.F. et al., *Composting and Recycling Municipal Solid Waste,* Lewis Publishing, Boca Raton, FL, 1994.

is present in air originally trapped within the voids and via limited diffusion of ambient air. The rate of diffusion of air into the mass is limited, however; hence, the initial interstitial air is the primary source of oxygen.

At the outset, the composition of air in voids is similar to that of ambient air (i.e., approximately 20.9% O_2 and 0.03% CO_2, v/v). Within a short time (hours to days), however, heterotrophic pioneer communities become activated and begin decomposition of the raw organic substrates with the concurrent increase in CO_2 concentration and decrease in O_2 level. With a closely monitored composting system, the O_2 content can be varied from 15% to 20% and CO_2 from 0.5% to 5% for the process to be successful.

During aerobic respiration, organic compounds are oxidized to carbon dioxide and water or other end-products using molecular oxygen as the terminal electron acceptor. The reaction for the aerobic oxidation of a glucose molecule is

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy} \tag{8.1}$$

If the O_2 concentration falls below approximately 15%, facultative anaerobic microorganisms are activated and rapidly become dominant. Fermentation and anaerobic respiration reactions take over. Undesirable products such as acetic acid, ethanol, methane, and ethane will form. These are odoriferous and may inactivate beneficial compost microorganisms:

$$\underset{\text{glucose}}{C_6H_{12}O_6} \rightarrow \underset{\text{ethanol}}{2C_2H_5OH} + 6CO_2 + 6H_2O \tag{8.2}$$

Additional reactions occurring under anaerobic conditions are discussed later.

The decomposition of organic materials is significantly faster and more complete in the presence of oxygen. The energy available in Equation 8.1 is approximately 14 times greater than that for anaerobic decomposition of glucose (Equation 8.2) (Zubay 1983).

The oxygen level of the pile can be measured using a simple portable O_2 meter (Figure 8.4). Oxygen requirements during aerobic composting can also be determined based on the composition



FIGURE 8.4 Portable O_2 meter.

of feed substrate and final product. This method is applied when small, pilot-scale composting studies are conducted and final product composition is determined. Degradability of the feed substrate is thus assessed as well. Rich (1963) formulated the following stoichiometric equation:

$$C_aH_bO_cN_d + 0.5(ny + 2s + r - c)O_2 = nC_wH_xO_yN_z + sCO_2 + rH_2O + (d - nz)\,NH_3 \qquad (8.3)$$

where $r = 0.5[b\text{-}nx\text{-}3(d\text{-}nz)]$

$s = a\text{-}nw$

The formulae $C_aH_bO_cN_c$ and $C_wH_xO_yN_z$ represent the compositions of feed substrate and final product, respectively. An elemental analysis is necessary in order to establish the subscripts.

Example 8.1

Pilot-scale aerobic composting was conducted on 1000 kg (dry solids) of MSW feedstock determined to have an initial composition $C_{35}H_{67}O_{31}N$. By completion of composting (60 days), the initial 1000 kg of feedstock was reduced to 180 kg dry solids. The final product composition was determined to be $C_{14}H_{20}O_9N$. Determine the stoichiometric oxygen requirement per 1000 kg of feedstock.

Solution

1. The molecular weight of the substrate is

Carbon	35(12) = 420
Hydrogen	67(1) = 67
Oxygen	31(16) = 496
Nitrogen	1(14) = 14
Total	997

The kg-mol of organic feedstock at the start of the process = 1000/997 = 1.00

2. Molecular weight of the compost product is

Carbon	14(12) = 168
Hydrogen	20(1) = 20
Oxygen	9(16) = 144
Nitrogen	1(14) = 14
Total	346

The kg-mole of finished compost per kg-mol at the start of the process = n = 180/(1.00)(346) = 0.52

3. The following values are to be used in the calculations:

a = 35	w = 14
b = 67	x = 20
c = 31	y = 9
d = 1	z = 1

The values r and s are determined as

$$r = 0.5\{67 - 0.52\ (20) - 3[1 - 0.52(1)]\} = 27.58$$

$$s = 35 - 0.52\ (14) = 27.7$$

4. From Equation 8.3, the quantity of oxygen required to complete the composting process is:

$$W = 0.5\ [0.52(9) + 2(27.7) + 27.58 - 31]\ (1.00)(32) = 906.6\ \text{kg}$$

5. The above data can be checked with a materials balance.

Inputs		
Substrate	1000	
Oxygen	907	
Total input	1907 kg	
Outputs		
Compost		180
CO_2	1.00(27.7)(44)	1218.8
H_2O	1.00(27.58)(18)	496.44
NH_3	[1 − 0.52(1)](1.00)(17)	8.16
Total out		1903 kg

Note: Since air (not O_2) is being applied to the pile, the air required is 907/0.232 = 3909 kg. This value is equivalent to 3909/1000 = 3.909 kg air/kg substrate.

8.5.6 Moisture Content

The preferred moisture content and oxygen availability for composting are closely interrelated. The interstices in the waste feedstock will contain either water or air, so the presence of one will directly affect the quantity of the other. The optimal moisture content for successful composting varies depending on the physical state and size of the particles and on the composting system used. Regular monitoring of the chemical and physical properties of the pile, previous experience with MSW composting, along with a review of the literature should serve as a practical guide to optimum moisture content.

Less moisture in the pile will result in dehydration, which slows biological processes. Water is required for numerous cellular processes and properties, including nutrient transport, waste removal, turgidity, and as a component in innumerable biochemical reactions. Excess water interferes with aeration by clogging pores. If the moisture content of the mass is so high as to displace most of the air from the interstices, anaerobic conditions develop. Therefore, the maximum acceptable moisture content is a level at which no nuisance conditions (e.g., anaerobiosis) develop and at which microbial reactions will proceed satisfactorily.

Moisture content of the pile can be measured in the field by using analytical equipment ranging from gypsum blocks to tensiometers. Alternatively, a sample can be taken to the laboratory and measured field-moist and oven-dry (i.e., after 48 h in an oven at 105°C). These data are used to calculate the gravimetric moisture content.

Moisture is rapidly depleted from an active compost pile and must be replaced by regular additions of water or, in some cases, application of wastewater sludge (which is also a rich source of heterotrophic microorganisms). The optimum amount of water to be applied to a compost pile can be calculated from a mass balance equation (Vesilind et al. 2002)

$$M_p = (M_s X_s + 100\ X_w)/(X_w + X_s) \tag{8.4}$$

where M_p is the moisture content of the compost pile at the start of composting (%); M_s the moisture content of the solids, for example, shredded MSW (%); X_s the mass of solids (wet metric tons); and X_w the mass of water, wastewater, or other source of water (metric tons).

Example 8.2

At a municipal waste-handling facility, a mixture of approximately 25 metric tons of food waste, yard waste, and paper waste is to be composted. The moisture content of this feedstock measures 9.5%. It has been previously determined that an ideal moisture content for the compost pile should be about 55%. Calculate the metric tons of water to be added to the solids to achieve optimum moisture content.

Solution

$$M_p = (M_s X_s + 100\ X_w)/(X_w + X_s) = [(25 \times 9.5) + (100 \times X_w)]/(25 + X_w)$$

$$X_s = 25.3\ \text{MT}\ H_2O \text{ to apply to the pile.}$$

8.5.7 Temperature

A direct relationship exists between microbial activity and temperature of the pile. High temperatures result from biological activity, that is, heat liberated from microbial respiration and the resultant breaking of chemical bonds of substrate compounds. Heat builds up within the pile; dispersal of this heat is limited due to the insulating effects of the pile.

Thermophilic versus mesophilic temperature ranges have their own advantages and disadvantages with respect to composting. The temperatures that enhance microbial activity are in

the range of 28–55°C (48–131°F). The highest O_2 consumption also occurs within this range. High temperatures are considered necessary conditions for effective composting. Excessively high temperatures, however, inhibit growth of most microorganisms, thus slowing the decomposition of feedstock. When the temperature rises beyond approximately 65–70°C (150–160°F), the tendency is for spore formers (e.g., *Bacillus* and *Clostridium*) to convert to spores. This transition is undesirable because the spore is a resting stage; therefore, the rate of decomposition is reduced. Moreover, microbes incapable of forming spores are strongly inhibited or killed at those temperatures. Consequently, maximum temperature should not exceed about 65°C (150°F).

The temperature distribution within a composting mass is affected by the surrounding climatic conditions and by the method of aeration. In static piles (see below), the highest temperatures develop at the center of the mass and the lowest temperatures occur at the edges of the pile. These temperature gradients promote a small degree of convection (i.e., natural airflow). The degree of air movement is influenced by ambient conditions as well as porosity of the composting mass. The problem of temperature control is best solved, however, either by periodically turning the pile or using forced ventilation.

8.5.8 pH

The optimum pH range in composting is so broad that difficulties due to an excessively high or low pH level are rarely encountered. Organic feedstock having a pH range from 3 to 11 can be composted. Optimum values, however, fall between 5.5 and 8. Recall from above that bacteria are the key catalysts in organic matter transformations, and typically prefer a near-neutral pH. In contrast, fungi develop better in an acidic environment.

During the early stages of composting, the pH level normally decreases (perhaps to as low as 5.0) because of the production of organic acids (e.g., formic, acetic, and pyruvic). These acids serve as substrates for succeeding microbial populations. As the acids are decomposed, pH rises and often stabilizes at approximately neutral. In some cases, compost pH may reach as high as 8.5.

Because it is unlikely that pH will decline to inhibitory levels, there is no need to buffer the feedstock by adding liming materials (e.g., limestone, calcium hydroxide). In fact, the addition of lime should be avoided because it can lead to excessive losses of ammonia nitrogen. Lime does, however, promote the formation of aggregates, which, in turn, improves air and water movement.

8.6 COMPOSTING STAGE

After MSW feedstock is preprocessed, indigenous microorganisms actively transform it; most of the physical and chemical changes to the compost mass occur during this stage. The actual compost process can be established in a number of environments, from simple outdoor piles to sophisticated reaction vessels with controlled temperature, airflow, and humidity. Some popular composting methods include:

Open systems
- Turned piles
- Turned windrows
- Static piles using air blowing or suction

Closed systems
- Rotating drums
- Tanks

All of the above systems are designed and operated to establish optimum conditions for composting. These conditions directly influence the growth and metabolism of the microorganisms responsible for the process. The factor that can be most influenced by technology, around which composting designs are developed, is the availability of oxygen.

8.6.1 Turned Piles

Turned piles are a widely used method for composting MSW, due to their simplicity of operation. As the name implies, the feedstock is mixed periodically using a front-end loader or similar equipment. Turning of the feedstock maintains oxygen, moisture, and temperature at adequate levels for microbes. The outer layers are incorporated into the pile, where they are exposed to higher temperatures and more intensive microbial activity. Frequent turning allows for the introduction of oxygen and also releases excess heat from the center of the pile. Turning, therefore, promotes uniform decomposition of materials. Using the turned pile method, the composting process is completed in approximately 2 months to 1 year.

Turned piles are constructed outdoors; however, piles can also be situated under shelters. A roof will prevent saturation and consequent development of anaerobic conditions, as well as leachate generation. Leachate problems are further addressed by constructing piles on firm surfaces (preferably paved) surrounded by berms or trenches to collect runoff. This issue is discussed below.

Turning frequencies range from twice per week to once or twice per year. The more frequently that piles are turned, the faster the composting process is completed. Where odor control and composting speed are high priority, oxygen-monitoring equipment can be installed to alert operators when O_2 levels fall below 10%–15%, which is the minimum oxygen concentration required for aerobic decomposition and for limiting odor problems (Richard 1992). Simple portable oxygen meters and long-stem thermometers can be inserted within the pile to assess O_2 level and pile temperature.

8.6.2 Turned Windrows

Turned windrows are elongated compost piles that are mixed frequently to maintain aerobic conditions (Figure 8.5). Constructing windrows of the appropriate size helps to maintain the desired temperature and oxygen levels. Windrows operate most effectively at a height of 1.5–1.8 m (5–6 ft) (CRS 1989). This height allows the feedstock to be insulated but prevents the buildup of excessive heat. Windrow heights vary, however, based on the feedstock (e.g., tendency to compact), season,

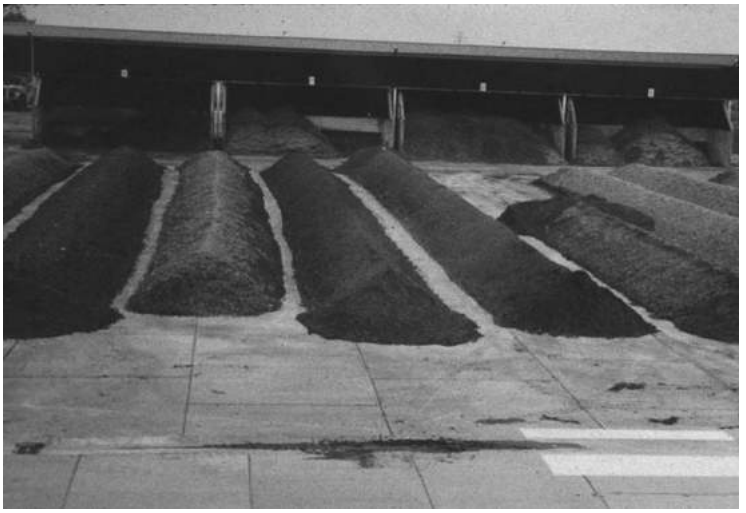


FIGURE 8.5 Composting of MSW by using the windrow system.

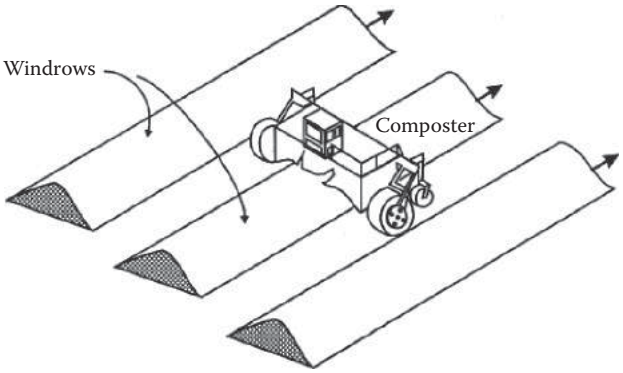


FIGURE 8.6 Schematic of windrow composting showing scarab compost turner. (From U.S. EPA, *Windrow and Static Pile Composting of Municipal Sewage Sludges,* Project Summary, EPA-600-S2-84-122, Engineering Research Laboratory, Cincinnati, OH, 1984.)

local climate, and turning equipment used. Windrow widths generally are twice the height of the piles. Land availability, operating convenience, type of turning equipment, and desired end-product quality also affect windrow width (U.S. EPA 1994).

If the windrow resembles a triangular shape, the volume can be determined by the equation:

$$\tfrac{1}{2}\,(WHL) \tag{8.5}$$

where W = average width at bottom
H = average height of pile
L = length of windrow

For a trapezoidal shape, volume is determined by

$$\tfrac{1}{2}\,(W_1 + W_2)HL \tag{8.6}$$

where W_1 = average width at bottom
W_2 = average width at top

Pile-turning equipment determines the size, shape, and space between the windrows. Front-end loaders are common in smaller operations. Windrow turners, also known as scarab composters, straddle windrows and thoroughly mix materials as it moves over the pile. These machines are either self-propelled or mounted to front-end loaders (Figure 8.6). Self-propelled windrow turners minimize the required space between windrows.

8.6.3 Aerated Static Piles

In terms of operation, aerated static piles are somewhat more complicated than turned piles. This approach is effective when space is limited and the composting process must be completed relatively rapidly. A series of perforated pipes is situated within or below a pile (or windrow). Air can be supplied via a negative pressure (suction) system or a positive pressure (blower) system. Fans or blowers force air through the pipes, which is then drawn through the feedstock (Figure 8.7). Air movement through the pipes maintains aeration within the pile, thus eliminating the need for turning.

Static piles are built to approximately 3–3.7 m (10–12 ft) in height. Topping off the pile with a layer of finished compost protects the surface from drying, insulates it from heat loss, discourages pests, and filters odors generated within the pile (Rynk 1992). The compost is finished within 3–6 months.

To ensure that decomposition proceeds at optimal rates within aerated static piles, oxygen levels and temperature must be closely monitored and maintained. Aeration management essentially depends on how the blower is controlled. The blower can be run continuously or intermittently.

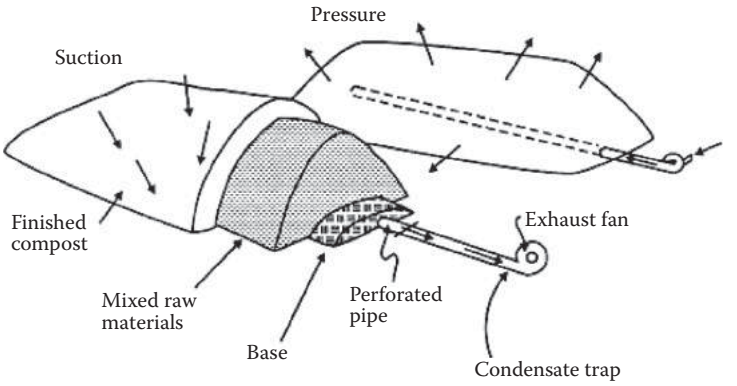


FIGURE 8.7 The aerated static pile. (From Rynk, R. Ed., *On-Farm Composting Handbook*, NRAES-54, Cooperative Extension, Ithaca, NY, 1992.)

Continuous operation permits lower airflow rates because oxygen and cooling are supplied constantly. Intermittent operation of the blower is achieved with a timer or temperature feedback device.

8.6.4 In-Vessel Systems

In-vessel systems are relatively sophisticated units in which composting is conducted within a fully enclosed chamber. Environmental conditions are mechanically controlled and usually automated.

An in-vessel system may be suitable for MSW composting if:

- The process must be finished rapidly.
- Odor and leachate control are a significant concern.
- Space is limited.

In-vessel technologies range from simple to complex. Two categories of in-vessel technologies include rotating drums and tank systems. Rotating drums rely on a tumbling action to mix feedstock materials continuously. Figure 8.8 illustrates a rotating drum composter. The drums typically are long cylinders, approximately 3 m (10 ft) in diameter, which are rotated slowly, usually at less than 10 rpm (CRS 1989). Oxygen is forced into the drums through nozzles from air pumps. The tumbling action allows oxygen to be maintained at uniform levels throughout the drum.

Tank systems are available as horizontal or vertical configurations. Tanks are long vessels in which aeration is accomplished through the use of external pumps that force air through the perforated bottom of the tank. Mixing is accomplished by mechanically turning a moving belt, paddle wheel, or flail-covered drum through the feedstock. The agitation breaks up clumps and maintains porosity. Solids are retained in this system for 6–28 days and then cured in windrows for 1–2 months (U.S. EPA 1994).

8.7 CURING STAGE

Once the organic feedstock is chemically stable, it must be cured. Measurement of O_2 uptake and CO_2 evolution indicate the degree of compost maturity. Another method to measure pile maturity is to monitor the internal temperature of the compost pile after it is turned. If reheating of the pile occurs, then the material is not yet ready for curing.

During the curing stage, compost is stabilized as microorganisms metabolize the remaining available nutrients. For the duration of the curing stage, microbial activity diminishes as available

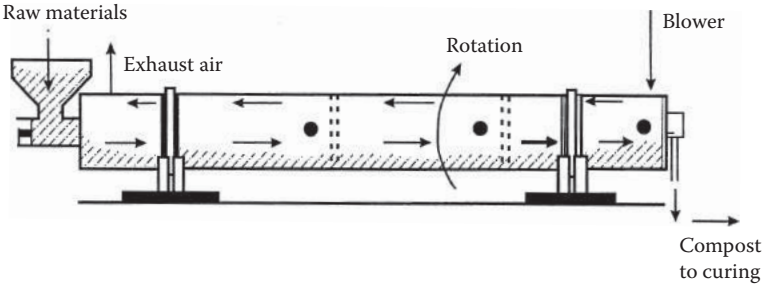


FIGURE 8.8 A drum composter. (From Rynk, R. Ed., *On-Farm Composting Handbook*, NRAES-54, Cooperative Extension, Ithaca, NY, 1992.)



FIGURE 8.9 A cured pile ready to go to market.

nutrients are depleted. Curing is a relatively passive process compared with the primary composting operation, so less intensive actions are required. In general, materials are formed into piles or windrows and left until the specified curing period has ended (Figure 8.9).

Since curing piles undergo slow decomposition, monitoring is important so that piles do not become anaerobic. The curing piles should be small enough to permit adequate natural air exchange. A maximum pile height of 2.4 m (8 ft) is suggested. If compost is intended for high-quality uses, piles should be limited to 1.8 m (6 ft) height and 4.8–6.1 m (15–20 ft) width (Rynk 1992).

The C:N ratio of finished compost should not exceed 20:1. As mentioned earlier, C:N ratios that are too low can result in production of phytotoxins within the pile, which are dispersed into the recipient soil when the compost is land-applied. For example, nitrogen-based toxins are generated when microorganisms are not capable of utilizing excess nitrogen. The free nitrogen is biologically transformed, resulting in release of NH_3 and other compounds that are toxic to plant roots and inhibit growth.

8.8 ENVIRONMENTAL CONCERNS DURING COMPOSTING

Composting at the municipal level involves the treatment of tons of potentially odoriferous and wet material containing a wide range of microorganisms. Homes and businesses may be located near the facility. Therefore, it is essential to carefully control the composting process at all times in order to limit environmental concerns, such as air and water pollution, odor, noise, vectors, fires, and litter. These concerns can be minimized through proper design of the facility and conscientious daily operations.

8.8.1 Air Quality

Air pollution is typically not a major concern at composting facilities, with the exception of natural odor problems. Dust can be a problem, particularly in the dry summer months. Dust is generated from dry, uncontained organic material, especially during screening and shredding operations and from vehicular traffic. Dust carries bacteria and fungi that may adversely affect facility workers and possibly facility neighbors. Dust may also clog equipment and filters.

8.8.2 Odor

Most stages of the composting process can release odors. The feedstock itself will contain malodorous compounds; odors are generated during collection, transport, and storage of the feedstock. Improper composting procedures, for example, not providing adequate O_2 and allowing anaerobiosis, will encourage the formation of undesirable products (Kissel et al. 1992). Anaerobic conditions encourage generation of organic acids, mercaptans, alcohols, amines, hydrogen sulfide gas, and other sulfur compounds (Diaz 1987; Williams and Miller 1992). Ammonia is released under anaerobic conditions and infrequently during aerobic conditions (for example, if the C:N ratio is less than 20:1) (Kissel et al. 1992). The compounds commonly linked to odor production at composting facilities are listed in Table 8.3.

Hellman and Small (1973) formulated the odor index (OI) to measure the potential of a chemical compound to become an odor problem. The OI is defined as (Haug 1993)

$$\text{Odor index} = \text{OI} = \text{vapor pressure/odor recognition threshold (100\%) (ppm)} \tag{8.7}$$

The OI is a measure of the potential of a particular odorant to cause odor problems under conditions that promote evaporation. The OI takes into account the vapor pressure of a compound, that is, the measure of its potential to occur in the gas phase, and the odor recognition threshold,

TABLE 8.3
Threshold Odor Concentrations and Boiling Points for Selected Odorous Compounds

	TOC (ppmv)		
Compound	**Detect**	**Recognition**	**Boiling Point (°C)**
Ammonia	0.037	47	−33
Hydrogen sulfide	0.00047	0.0047	−62
1-Butene	0.069		−6
Methyl mercaptan	0.0011	0.0021	8
Ethylamine	0.026	0.83	17
Dimethyl amine	0.047	0.047	
Acetaldehyde	0.004	0.21	20
Ethyl mercaptan	0.002		
1-Pentene	0.0021		30
Dimethyl sulfide	0.001	0.001	36
Dimethyl disulfide	0.001	0.0056	
Diethyl sulfide	0.0008	0.005	88
Butyl mercaptan	0.0005		65
Acetic acid	0.008	0.2	63
α-Pinene, oil of pine	0.011		37

Source: Reproduced with kind permission of Haug, R.T., *The Practical Handbook of Compost Engineering*, Lewis Publishing, Boca Raton, FL, 1993. Copyright Lewis Publishing, an imprint of CRC Press.

which is a measure of the strength of the odorant. The boiling points of ammonia, hydrogen sulfide, ethyl mercaptan, dimethyl sulfide, and acetaldehyde are all lower than the temperatures associated with composting. Thus, these compounds will "boil off" into the vapor phase if they are generated during composting. Other compounds have boiling points near or above the temperatures common to composting. Nevertheless, they may possess significant vapor pressures and can volatilize into the vapor phase. Such volatilization is enhanced by the substantial airflow rates used in many composting systems (Haug 1993).

8.8.3 Noise

Noise is generated by trucks entering and leaving the facility and by equipment used in composting operations. Hammermills and other shredding machines are the noisiest of this equipment, generating about 90 dB at the source. Many states have mandated controls to limit noise at the property line. Measures that can reduce noise emanating from the facility include (U.S. EPA 1994):

- Providing a sufficient buffer zone around the facility by using plenty of trees.
- Including noise reduction features in facility design, such as noise hoods, when procuring equipment.
- Properly maintaining mufflers and other noise-reducing equipment.
- Coordinating hours of operations with adjacent land uses.
- Limiting traffic to and from the facility.

8.8.4 Toxins within the Pile

Many lawns, golf courses, farm fields, and other vegetated areas receive copious quantities of herbicides, pesticides, and other biocides. Some have been found to persist after composting. The ten most commonly used agricultural pesticides in the United States include six herbicides and four fumigants (Table 8.4) (U.S. EPA 2011b). Herbicides are also commonly used for residential and commercial or industrial applications.

TABLE 8.4
Pesticides Most Commonly Applied in the United States by Agricultural, Residential, and Commercial Users, 2007 (Based on Active Ingredient)

Rank	Agriculture Common Name	Type
1	Glyphosate	H
2	Atrazine	H
3	Metam sodium	SF
4	Metolachlor-S	H
5	Acetochlor	H
6	Dichloropropene	SF
7	2,4-D	H
8	Methyl bromide	SF
9	Chloropicrin	SF
10	Pendimethalin	H

Source: U.S. EPA, *Pesticides Industry Sales and Usage, 2006 and 2007 Market Estimates*, 2011, Available from: http://www.epa.gov/opp00001/pestsales/07pestsales/market_estimates2007.pdf.

Note: F = fungicide, H = herbicide, I = insecticide, SF = soil fumigant.

TABLE 8.5
Pesticides Monitored in Yard Waste and Compost in Illinois Study

	Pesticide	Average Levels in Yard Waste (ppm)	Average Levels in Finished Compost (ppm)	MAT[a] (ppm)
Herbicides	2,3,4-T	0.788	1.15	
	2,4-D	1.04	0.268	300
	Alachlor	0.749	0.304	3
	Atrazine	4.61	3.03	15
	Dichlobenil	0.0144	0.0133	0.15
	Metolachlor	1.06	0.972	30
	Trifluralin	0.142	0.156	2
Organochlorine insecticides	Chlordane	0.526	0.4	
	DDD	0.0641	0.0505	
	DDE	0.0516	0.0807	
	Dieldrin	0.00992	0.00834	
	Heptachlor	0.00942	ND	
	Heptachlor epoxides	0.0216	0.0151	
	Lindane	0.495	0.314	7
	Methoxychlor	0.314	0.507	100
Organophosphate insecticides	Chlorpyrifos	0.00996	0.0077	15
	Diazinon	0.991	0.587	40
	Fonofos	0.0112	0.00538	
	Malathion	0.313	0.169	135
	Parathion	0.235	0.104	5
Carbamate insecticides	Carbaryl	22.5	11.0	100

Source: Miller, T.L. et al., *Selected Metal and Pesticide Content of Raw and Mature Compost Samples from Eleven Illinois* Facilities, Illinois Department of Energy and Natural Resources, Springfield, IL, 1992.

Note: ND = not detected; NA = not available.

[a] Maximum Allowable Tolerance for Raw Agricultural Commodities (U.S. EPA 40 CFR).

A study conducted in Illinois tested for the presence of 21 pesticides in yard waste and compost from 11 landscape composting facilities (Table 8.5) (Miller et al. 1992). Concentrations of all pesticides detected in feedstocks and compost samples were below the Maximum Allowable Tolerance for Raw Agricultural Commodities. In a study from Portland, OR, a total of 19 pesticides were monitored in yard waste compost (Gurkewitz 1989). Only four pesticides were found, all at extremely low levels. The testing program was expanded to include 27 pesticides. Low concentrations of pentachlorophenol and chlordane were consistently measured in yard waste compost. Dieldrin, DDT, DDE, toxaphene, aldrin, chlorpyrifos, and dinoseb were detected in only a limited number of samples. In leaf compost in Westchester County, NY, 200 pesticides were tested for (Richard and Chadsey 1989). Chlordane, lindane, captan, and 2,4-D were identified. Mean concentrations of all pesticides, except chlordane, were well below the minimum USDA tolerance level for food.

The Washington State University (WSU) composting facility and the Spokane Regional Compost Facility discovered traces of persistent herbicides, including clopyralid and picloram in their composts (Bezdicek et al. 2001). In both cases, the compost damaged sensitive plants in gardens and nurseries. Clopyralid contamination since has been reported in other facilities in Washington, Maine (Maine DEP, n.d.), Pennsylvania, and New Zealand. Rose and Mercer (1968) investigated the fate of pesticides during composting of fruit and vegetable processing wastes. DDT, dieldrin,

parathion, and diazinon were applied to a mixture of processing residues and rice hulls, and the mixture was composted using either a batch system with minimal turning, or a system with frequent turning that maintained thermophilic temperatures. Over 120 days, all pesticides, except dieldrin, degraded faster in the thermophilic system.

Most herbicides decompose rapidly after application. Buyuksonmez et al. (1999, 2000) reported that herbicides generally break down during normal composting. However, some in the pyridine carboxylic acid group, such as clopyralid, decompose very slowly, including during composting (Bezdicek et al. 2001). Monitoring incoming feedstock to remove pesticide containers and other foreign materials can help to reduce the occurrence of synthetic chemicals in compost.

8.8.5 Leachate

Leachate is produced in uncovered piles exposed to excessive precipitation. Leachate released from the pile may contain elevated biochemical oxygen demand (BOD) and phenols resulting from dissolution and decomposition of organics. Nitrates are also generated by composting grass clippings and leaves. Leachate composition from a compost pile is shown in Table 8.6.

Leachate can also contain potentially toxic synthetic compounds, including pesticides, chlorinated organics from treated wood, polycyclic aromatic hydrocarbons (PAHs), and combustion products of gasoline, oil, and coal. Chlorinated organics and PAHs are resistant to biodegradation and tend to persist after composting (Gillett 1992). Microorganisms can partly degrade some PAHs

TABLE 8.6
Croton Point, NY, Yard Waste Compost Leachate Composition

	Compost Leachate (16 Samples)	
	Average (mg/L)	**Standard Deviation (mg/L)**
Cd	ND	
Cu	ND	
Ni	ND	
Cr	ND	
Zn	0.11	0.13
Al	0.33	0.38
Fe	0.57	0.78
Pb	0.01	0.02
K	2.70	0.99
NH_4-N	0.44	0.35
NO_3-N	0.96	1.00
NO_2-N	0.02	0.02
Phosphorus	0.07	0.08
Phenols (total)	0.18	0.45
COD	56.33	371.22
BOD	>41[a]	>60
pH	7.75	0.36
Color	ND	
Odor	ND	

Source: Richard, T. and Chadsey, M., *BioCycle* 31, 42–46, 1990. Reproduced with permission of The J.G. Press.

Note: ND = not determined; COD = chemical oxygen demand; BOD = biochemical oxygen demand.

[a] Includes three samples above detection limit of 50 mg/L.

during composting; however, the resultant compounds can be more toxic than the original PAHs (Menzer 1991; Chaney and Ryan 1992).

The age of the pile will also affect leachate composition. In a mature pile, microorganisms have decomposed complex compounds and released or consumed substantial carbon and nitrogen. If the C:N ratio is maintained within the desired range, little excess N will leach from the pile, since it is rapidly utilized by microorganisms for growth (U.S. EPA 1994).

Leachate generation can be reduced or prevented by monitoring and correcting the moisture levels in the composting pile. In some facilities, windrows or piles are installed under a roof to limit excessive moisture levels arising from precipitation. If the compost feedstock contains excess moisture, leachate is released during the first few days of composting regardless of any rainfall event. Following this initial release, the volume of leachate generated will decrease as the compost product matures and humifies, thus improving its water-holding capacity.

The installation of a concrete pad for a compost base is useful for collection and control of any leachate produced. A simple method for managing leachate is to collect all liquids from the pad and reintroduce them into the pile. Such leachate recycling should not be conducted once the compost pile has completed the high-temperature phase, as any pathogenic microorganisms that were inactivated by the high heat may be reintroduced with the leachate (CC 1991). Leachate can also be transported to a municipal wastewater treatment plant. If contaminant levels within the leachate are excessive, beyond regulatory limits, or both, an on-site wastewater pretreatment system could be installed.

Measures to control leachate include:

- Diverting from the compost curing and storage areas to a leachate-holding area
- Installing liner systems composed of low-permeability materials such as clay or synthetic geomembranes
- Using drain pipes to collect leachate for treatment
- Curing and storing compost indoors to eliminate infiltration of leachate into the ground (Wirth 1989)

8.8.6 Runoff

Operations that compost MSW and yard waste can produce runoff containing measurable quantities of inorganic nutrients and other pollutants. Runoff may be caused by heavy precipitation, by the presence of wet components within the feedstock, and by practices at the facility that use water. For example, water used to wash trucks may contribute to runoff. Polluted water can be spilled in the tipping area of composting facilities when packer trucks from restaurants, grocery stores, and food processors are emptied.

For both yard waste and MSW composting facilities, water that has come into contact with incoming raw materials, partially processed materials, or compost should not be allowed to run off the site. Figure 8.10 shows several options for diverting water from composting piles and for containing runoff. Provisions for isolating, collecting, treating, or disposing of water that has come in contact with the composting feedstock can include (U.S. EPA 1994):

- Maintaining sealed paved surfaces in all areas
- Grading facility areas (1%–2% grade) where contaminated water will be collected
- Installing containment barriers to prevent contaminated water from contacting adjacent land and waterways
- Covering compost beds and cured piles
- Percolating contaminated water through soil to adsorb and decompose organic compounds
- Building retention ponds to prevent discharge of runoff to surface water

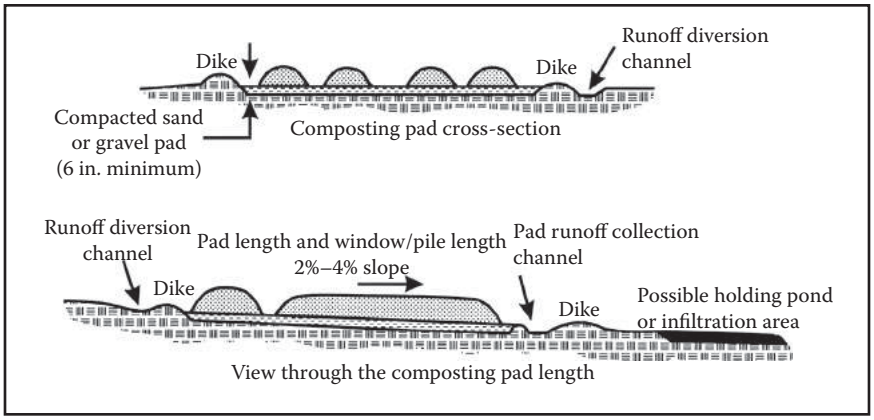


FIGURE 8.10 Methods to divert runoff water from a compost pile for eventual collection. (From Rynk, R. Ed., *On-Farm Composting Handbook*, NRAES-54, Cooperative Extension, Ithaca, NY, 1992. With permission.)

8.8.7 Vectors

Vectors are small animals or insects that carry disease. Mice, rats, flies, and mosquitoes may occur at composting facilities. Rodents may be attracted by the food and shelter available and can be difficult to eradicate. Flies, which can transmit salmonella and other food-borne diseases, are often carried in with the incoming material and are attracted to piles that have become anaerobic. All life stages of the housefly are killed by the temperatures attained in the compost pile (Golueke 1977). Mosquitoes, which can also transmit disease, breed in standing water. Keeping the processing area tidy can control insects; also, maintaining aerobic conditions and proper temperatures in the piles and grading the area properly to prevent ponding will limit mosquito breeding.

8.8.8 Fires

If the compost material dries and becomes too hot, spontaneous combustion may occur in the pile (Figure 8.11). Organic material can ignite spontaneously at a moisture content between 25% and 45%. Combustion is unlikely, however, unless the feedstock reaches temperatures exceeding 93°C (199°F).

Key conditions that lead to spontaneous combustion are biological activity, relatively dry materials or dry pockets, large well-insulated piles, limited airflow, and sufficient time for the temperature to build up. Other contributing factors include short circuiting of airflow, a nonuniform mix of materials, poor moisture distribution, and inadequate monitoring of temperature and other variables. These conditions tend to be more common within large undisturbed piles containing raw feedstocks, curing compost, and finished compost, than in the active compost pile. Piles and vessels containing active compost tend to be monitored and controlled for temperature, moisture, and aeration, whereas storage and curing piles may be neglected (Rynk 2000).

The facility must be designed for access by firefighting equipment, including clear aisles between piles or windrows, and must have an adequate water supply (Richard et al. 1990).

8.8.9 Litter

Although not a hazard per se, litter from the facility is an aesthetic problem and a possible source of complaints from nearby residents. Litter originates from MSW brought into the facility, plastic and



(a)



(b)

FIGURE 8.11 Compost fire presumably initiated by spontaneous combustion. (© 2009 The Saginaw News/MLive.com. All rights reserved. Used with kind permission of The Saginaw News/MLive.com.)

paper blowing from piles, and rejects (such as plastic) blowing away during screening. Litter can be controlled by (Wirth 1989; U.S. EPA 1994):

- Requiring loads of incoming material to be covered.
- Using moveable fencing or chain link fences along the site perimeter as windbreaks and to facilitate collection of litter.
- Enclosing receiving, processing, and finishing operations.
- Collecting litter as soon as possible before it scatters off-site.
- Removing plastic bags before windrowing.
- Collecting leaves and woody materials in paper bags, plastic bins, or in bulk.

8.9 OCCUPATIONAL HEALTH AND SAFETY CONCERNS DURING COMPOSTING

Potential health and safety problems at composting facilities include accidents with heavy equipment, exposure to excessive noise, and exposure to bioaerosols and potentially toxic chemicals. Proper siting, design, operation of the facility, and adequate worker training can minimize these problems.

8.9.1 Bioaerosols

A variety of biological aerosols (bioaerosols) may be generated during composting. Bioaerosols are suspensions of particles in air consisting partially or entirely of microorganisms. These aggregates may remain suspended in air for long periods, retaining their viability (infectious nature).

The bioaerosols of concern during composting include actinomycetes, bacteria, viruses, molds, and fungi. For example, *Aspergillus fumigatus* is a common fungus that is naturally present in decaying organic matter. Fungal spores can be inhaled or enter the body through cuts and abrasions in the skin. The fungus is not considered a hazard to healthy individuals (U.S. EPA 1994). *A. fumigatus* is freely dispersed from dry compost piles during and after mechanical turning. Levels of *A. fumigatus* decrease rapidly a short distance from the pile or a short time after composting activity ceases (Epstein and Epstein 1989).

Endotoxins are another concern at composting facilities; these are toxins produced within a microbial cell and are released upon cell destruction. Many endotoxins are carried by airborne dust particles. The level of endotoxins in air at one yard waste composting facility ranged from 0.001 to 0.014 mg/m^3 (Roderique and Roderique 1990).

Because both bioaerosols and endotoxins are carried with dust, it is necessary to control dust at all times at the facility. Steps to minimize dust generation may include (U.S. EPA 1994):

- Keeping feedstock and compost piles moist.
- Moistening compost during the final pile teardown and before being loaded onto vehicles, taking care not to over-wet the material (which may produce leachate or runoff).
- If the facility is enclosed, proper ventilation is required via engineering controls such as collection hoods, negative air pressure at dust generation points, and the use of baghouse filtration.

Workers should also be informed that disease-producing microorganisms are present in the work environment. Precautions should be followed for personal protection and include (U.S. EPA 1994):

- Wear dust masks or respirators under dry and dusty conditions, especially when the compost is being turned.
- Cuts should receive prompt attention to prevent contact with incoming loads or feedstock.
- Individuals with asthma, diabetes, or suppressed immune systems should be advised not to work at a composting facility because of the greater risk of infection.

8.9.2 Potentially Toxic Chemicals

Compounds such as benzene, chloroform, and trichloroethylene present potential risks to workers at MSW composting facilities (Gillett 1992). Certain solvents, paints, and cleaners contain volatile organic carbon compounds (VOCs). The combination of forced aeration (or periodic turning in the case of windrow systems) and elevated temperatures serves to release VOCs from the compost pile into the local atmosphere.

To avoid worker exposure to VOCs, adequate ventilation is needed. Control technologies developed for odor control also apply to VOC control. The best method of controlling VOC emissions, however, is to limit their presence in the feedstock. Limiting MSW composting to residential and high-quality commercial feedstocks, instituting source separation, and implementing effective household hazardous waste collection programs will minimize the presence of VOCs in MSW.

8.10 FACILITY SITING

Compost feedstock is originally derived from MSW and therefore is odoriferous. It is thus logical and practical to locate a composting facility in proximity to a solid waste transfer station, landfill, wastewater treatment plant, or similar waste management operation in an area zoned for industry or commercial use. Some of the major factors in facility siting include (U.S. EPA 1994):

- Location to minimize hauling distances
- Adequate buffer between the facility and nearby residents

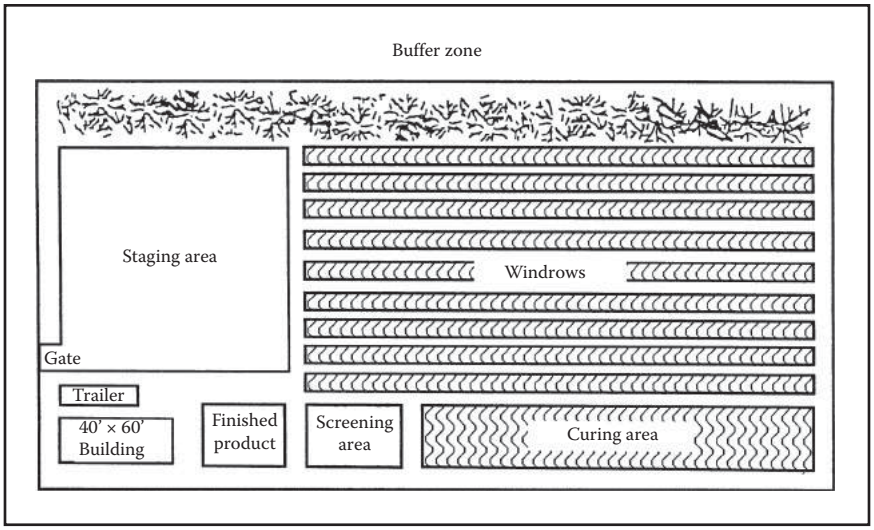


FIGURE 8.12 Suggested layout of a compost facility. (From Appelhoff, M. and McNelly, J., *Yard Waste Composting, Guidebook for Michigan Communities,* Michigan Department of Natural Resources, Lansing, MI, 1988.)

- Suitable site topography and soil characteristics
- Sufficient land area for the volume of material to be processed

Current federal guidelines prohibit siting any solid waste facility, including composting facilities, within 10,000 ft of an airport. This guideline is to prevent birds, which could be attracted by potential food sources, from interfering with airplanes (see Chapter 10).

Local residents may be concerned about potential odors and other nuisance conditions. Locating a facility with an extensive natural buffer zone, planted with trees and shrubs, is an effective way to reduce such concerns. Visual screens such as berms or landscaping can be installed to maintain the aesthetic values of the surroundings. Figure 8.12 shows a suggested field plan for a large-scale composting facility.

8.10.1 Topography

The composting site should be graded to avoid standing water, runoff, and erosion. The land surface should be sloped at least 1% and ideally 2%–4% (Rynk 1992). The type and structure of the local soil should be assessed to control run-on and runoff. A firm base is preferred in order to capture and control liquids and prevent groundwater contamination.

If the site is unpaved, the soil should be sufficiently permeable to ensure that excess water is absorbed during periods of heavy precipitation and that the upper layers of the soil do not become waterlogged. If the soil is impermeable or the site is paved, drainage systems are necessary to divert precipitation from the composting pad and storage areas. Proximity to water sources should also be considered. Floodplains, wetlands, surface water, and groundwater all must be protected from runoff or leachate from the site. The water table should be no closer than 60 cm (24 in.) below the surface. Otherwise, leachate from the compost may percolate downward and contaminate groundwater (Richard et al. 1990).

8.10.2 Land Area Requirements

To operate efficiently, a composting facility must allot sufficient space to the preprocessing, processing, and postprocessing compost stages, as well as to the surrounding buffer zone.

8.10.3 Other Factors Affecting Siting Decisions

Other factors to consider when siting a composting facility include:

- *The existing infrastructure.* The presence of utility hookups, storage space, and paved access-roads.
- *Zoning issues.* The construction of composting facilities is permitted in locations as directed by local zoning laws.
- *Nearby land users.* Sites near public parks, schools, or residential areas could cause objections from citizens concerned about odor and noise (U.S. EPA 1994).

8.11 DESIGN

The following items must be incorporated in the design of a large-scale composting facility:

- Preprocessing area
- Processing area
- Postprocessing area
- Buffer zone
- Access and on-site roads
- Site facilities and security

While designing the facility, the possibility for future expansion should be considered.

8.11.1 Preprocessing Area

A preprocessing area provides space to receive feedstock and to sort and separate materials. Receiving materials in a preprocessing area eliminates the need for delivery trucks to unload directly into piles in inclement weather. The size and design of the preprocessing area depends on the amount of incoming material and how the materials are collected and sorted. The tipping area is often under a roof to avoid the effects of severe weather.

8.11.2 Processing Area

The processing area includes the composting pad and the curing area. The pad surface should be paved to prevent infiltration. Adequate drainage is also essential. Precipitation collected on the pads can be diverted through the drains. Poor drainage will result in ponding of water, saturated compost materials, muddy and unsightly conditions, odor production, and excessive runoff and leachate from the site (Rynk 1992).

Proper ventilation is required in enclosed preprocessing and processing areas because the air within the structure can be a source of bioaerosols, odors, dust, and excess moisture. Filters can be installed to clean the exhaust air; biofilters may be used to absorb odor-producing compounds. Vents can be situated over preprocessing equipment (e.g., conveyor belts, trommels) to reduce dust and odors.

A curing area is used to store the compost for the final phase of the process, to allow the material to stabilize. The material should be fairly stable and therefore runoff, groundwater contamination, and other siting issues should be of less concern. The curing area needs less space—about one quarter of the area of the compost pad (University of Connecticut 1989; Richard et al. 1990).

8.11.3 Buffer Zone

The larger the buffer zone, the greater the acceptance of the facility among residents. The size depends on the type of feedstock being composted and the level of technology (i.e., monitoring and odor control) employed. State and local regulations frequently require minimum buffer zone sizes or specify the distances that composting operations must be from property lines, residences, or adjacent businesses and from surface water or water supplies.

The buffer zone must be larger than the composting pad, particularly when the operation is adjacent to residential areas or businesses. Enclosed facilities may function adequately with a smaller buffer zone since operations are more closely controlled.

When designing the facility, prevailing wind direction should be considered. The buffer zone should be extended in this direction. This will help in minimizing the transport of odor and bioaerosols downwind of the facility.

8.11.4 Site Facilities and Security

Composting operations may require several buildings to house various site functions, from maintenance and administrative work to personnel facilities. Access to the site must be controlled to prevent vandalism, especially arson and illegal dumping. At a minimum, access roads must be secured with a fence, cable, locked gate, or similar barrier.

8.12 MSW COMPOSTING BY ANAEROBIC PROCESSES

Anaerobic digestion of low-solids (4%–10%) wastewater has been carried out for decades at publicly owned treatment works and industrial facilities. A number of waste management facilities in the United States and Europe, however, now use so-called high-solids reactors, containing up to 30% or greater solids content. This technology allows for the anaerobic digestion of high-solids MSW, specifically the organic fraction.

Anaerobic digestion is described by the following equation:

$$\text{Organic MSW} + H_2O \rightarrow CO_2 + CH_4 + NH_3 + H_2S + \text{mixed solids} + \text{new cell biomass} \quad (8.8)$$

The desired end-products include methane and sludge water. Other products are carbon dioxide and trace quantities of ammonia and hydrogen sulfide. The sludge water is dewatered to produce a filter cake and supernatant. The filter cake serves as a soil conditioner. The supernatant can be mixed with new organic MSW to create a slurry feedstock, or it can be fed directly to the digester. The liquids can also be used as fertilizer. A simple schematic of anaerobic digestion of MSW appears in Figure 8.13.

High-solids anaerobic digestion (HSAD) of the MSW organic fraction occurs in three phases:

1. *Hydrolysis.* High-molecular-weight compounds are converted to low-molecular-weight molecules by microbial action (e.g., hydrolyzing bacteria); for example, polysaccharides are hydrolyzed to monosaccharides, lipids to fatty acids, proteins to amino acids, and nucleic acids to purines and pyrimidines. These products subsequently serve as substrate for new populations of microorganisms.
2. *Acid generation*. The low-molecular-weight amino acids, fatty acids, and monosaccharides are converted to smaller, intermediate compounds by the action of non-methanogenic, acetogenic bacteria, also known as acid formers. Acidogens are facultative and obligate anaerobes. Products include carbon dioxide and hydrogen and a number of organic acids and alcohols, including acetic acid (CH_3COOH), propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), and ethanol (C_2H_5OH).

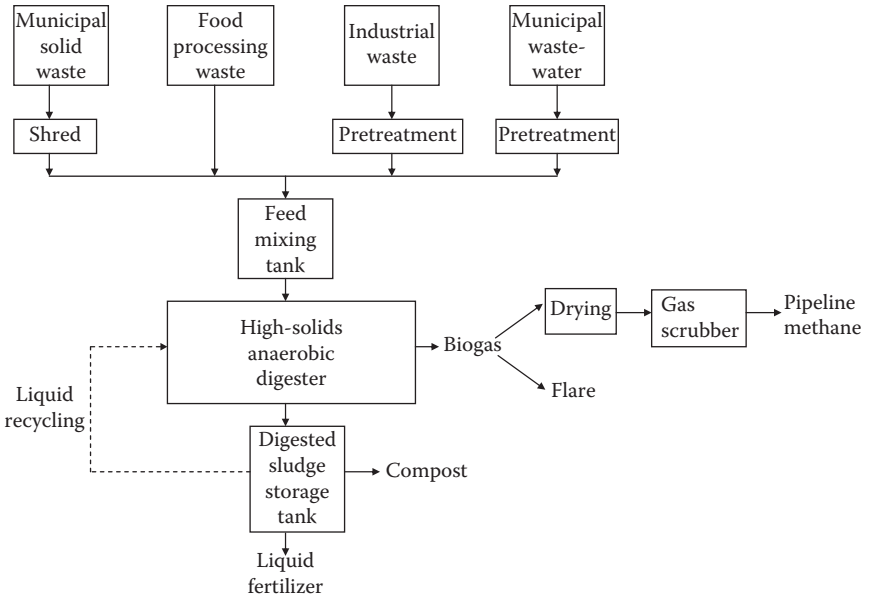


FIGURE 8.13 Schematic for a high-solids anaerobic digestion facility.

An example of an acid-forming reaction is shown below:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2 \tag{8.9}$$

3. *Methanogenesis*. The acids and alcohols produced in Phase 2 are converted to methane and carbon dioxide by the action of methanogenic bacteria, which are strict anaerobes. Methanogenesis reactions include:

$$CH_3COOH \rightarrow CH_4 + CO_2 \tag{8.10}$$

$$2C_2H_5OH + CO_2 \rightarrow CH_4 + 2CH_3COOH \tag{8.11}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{8.12}$$

As we shall see in Chapter 10, these identical reactions occur within the sanitary landfill, with the potential for production of enormous volumes of methane gas.

8.12.1 Process Description

Four basic steps are involved in high-solids anaerobic digestion of MSW to produce methane:

1. Initial processing. Commingled MSW is sorted to obtain the organic fraction and then shredded.
2. Preparation and conditioning. Water and nutrients are added, the input is blended, pH is adjusted to near-neutral, and the slurry mix is heated to between 55°C and 60°C. Moisture and nutrients are added to the wastes in the form of wastewater sludge or animal manure. Additional nutrients may also be required, depending on the chemical composition of the added wastewater or manure. Anaerobic digestion is typically conducted in

a continuous-flow reactor whose contents are thoroughly mixed. In some operations, a series of batch reactors is used. Foaming and the formation of surface crusts have caused problems in MSW digestion; therefore, adequate mixing is critical for successful system operation.
3. Recovery, storage, and separation of the gas components.
4. Dewatering and disposal (or application) of the digested sludge.

8.12.2 Subsystems

Several subsystems have been developed to treat MSW anaerobically. Categories include (Chiang Mai University 1998):

Batch versus continuous

- Batch—The reactor vessel is loaded with raw feedstock and inoculated with digestate from another reactor. It is sealed and allowed to react until degradation is complete. The digester is emptied, and a new organic mixture is added.
- Continuous—The reactor vessel is fed continuously with digestate material. Fully degraded material is continuously removed from the bottom of the reactor.

Single step versus multistep

- Single step—All digestion processes occur in one reactor vessel.
- Multistep—Several reactors operate simultaneously. In some cases, the acid-forming stage is separated from the methane-forming stage. This results in increased efficiency as the two microbial communities are separated in terms of nutrient needs, growth capacity, and ability to cope with environmental stress. Some multistage systems also use a preliminary aerobic stage to raise the temperature and increase degradation of organic material. In other systems, the reactors are separated into mesophilic and thermophilic stages (Chiang Mai University 1998).

Co-digestion with animal manure. The organic fraction of the MSW is mixed with animal manure and the two are co-digested. Such mixing improves the carbon-to-nitrogen ratio and enhances gas production.

Systems in use. A number of HSAD systems are in use either commercially or at the pilot scale. The Dranco (Dry Anaerobic Composting) system was developed in Gent, Belgium. Feed is introduced into the top of the reactor while digested materials are removed from the base. A portion of the digestate is recycled as an inoculum and the remainder is dewatered, resulting in a compost product. No mixing occurs within the reactor. Solids content ranges from about 15%–40%. Retention time in the reactor varies between 15 and 30 days, and the operating temperature ranges between 50°C and 58°C. The Dranco system can yield between 100 and 200 m^3 of gas per ton of MSW input. The gas content is 55% CH_4 (Six and DeBaere 1992).

The Valorga system, developed in France, combines four mesophilic HSAD reactors. Mixing of feed within the reactor is carried out by circulation of a portion of the biogas under pressure. The biogas product contains about 55%–60% CH_4. The process operates with a solids content of 25%–50%, with residence times ranging between 18 and 25 days.

The BIOCEL process is a mesophilic dry anaerobic batch digestion system (ten Brummeler 2000). Net energy production is achieved by converting biogas into heat. The first full-scale plant started in Lelystad, The Netherlands, in 1997. This plant processes 50,000 tons of MSW per year. Anaerobic digestion using the BIOCEL process has been found to inactivate several important groups of plant and animal pathogens. The mechanism that causes the inactivation is not yet fully understood but may be related to the relatively high volatile fatty acid concentration during the first 2 weeks of digestion.

The Kompogas system is a thermophilic digestion system developed in Switzerland (Wellinger et al., 1993). The reaction vessel is a horizontal cylinder where feed is introduced daily and movement through the cylinder is accomplished via horizontal plug-flow. An agitator is installed within the cylinder to mix the material intermittently. Digested material is removed from the end of the cylinder after about 20 days. The digestate is dewatered and some of the press water is either used as an inoculum or sent to a wastewater treatment facility to produce more biogas (University of Southampton 2002).

The Wabio process was developed by Ecotechnology of Finland (Chhabria, n.d.). Two Wabio process plants are in operation. A plant at Vaasa, Finland, has been in operation since 1991, and another facility has been operating in Bottrop, Germany, since 1995. The Wabio process is a single stage process operating in the mesophilic temperature range. Feed preparation tanks receive the screened material, and a slurry of 15% solids concentration is prepared. The slurry is then pumped to bioreactors. Digestion occurs at 30°C, and the retention time of the material is 15–20 days. The process can also be operated in the thermophilic range at 55°C. The supernatant liquid is recirculated to make more slurry. Biogas is stored in a gas holder and a portion is used for mixing the contents in the bioreactors. From the gas holder, the gas is transferred to engines to produce electricity. The digested slurry is pasteurized at ~7°C for 30 min to produce a material that is safe for spreading on agricultural land.

The feasibility of applying anaerobic digestion for stabilization of solid wastes generated during space missions was investigated (Chynoweth et al. 2003). High-solids leach bed anaerobic digestion involves solid-phase fermentation with leachate recycling and removal of volatile organic acids during startup. Anaerobic biochemical methane potential assays were run on several waste feedstocks expected during space missions. The methane yields ranged from 0.23 to 0.30 L/g of volatile solids added.

QUESTIONS

1. It is undesirable to land-apply raw solid wastes to soil because undesirable reactions may occur, which could inhibit plant growth. Explain.
2. When a waste possessing a high C:N ratio (200:1) is land-applied: (a) microbial growth is relatively unchanged, (b) agricultural plants cannot compete with soil microbes for soil N, (c) N is converted into ammonia gas (NH_3) and lost to the atmosphere, (d) nitrogen is converted to N_2 gas.
3. During the composting of MSW, a series of complex N transformations, including immobilization, nitrification, mineralization, and others occur. Explain how the C:N ratio declines during composting. What are the fates of N and C? Provide specific reactions.
4. Microbial succession is important to bring the composting process to completion. Explain.
5. Explain how fire could be generated in an actively composting pile. How could such a scenario be prevented?
6. Compare the dynamics of microbial populations, oxygen levels, and temperature over time with the turned pile method of composting versus aerated static piles.
7. Discuss the pH requirements for optimizing composting. Why, from a biochemical or microbiological perspective, is this pH range most effective?
8. Composting of sewage sludge poses different management concerns compared with composting of MSW. Describe how the process may differ in terms of pathogen control, odor control, leachate control, and aeration.
9. Explain how anaerobic reactions may occur in a compost pile that contains 15%-20% oxygen in the interstitial spaces.
10. What is the relationship between pile temperature and microbial growth and activity? What is an ideal compost temperature range? Why is this range considered optimal?

11. The city of Pristine, IL, in developing their comprehensive waste management program, will establish a composting facility adjacent to the transfer station. What attributes should be considered when screening potential locations for a composting site? Consider size of area, soils, drainage and slope, land-use compatibility, and controls for run-on and runoff.
12. The land area of the selected compost site is smaller than optimum. Based on practical issues, the following compost method should be used: (a) turned pile, (b) static pile with forced aeration, (c) sheet composting, (d) on-the-shelf heated bins, (e) avoid composting altogether and land-apply the organic component of the wastes and directly to soils. Explain your choice.
13. Is there a large-scale MSW composting program operating in your community? What are the feedstock materials? Where is the facility located; for example, adjacent to the transfer station or landfill? On privately owned land? How are odors and leachate production managed?
14. List and discuss the possible uses for finished compost. What are the benefits of MSW composting in a community integrated waste management program? Given the time, space requirements, energy and labor requirements, is composting economically justified for a community?
15. For decades, the market value of compost has been quite low. However, many communities continue to support yard waste composting programs. Explain why this is so.
16. Bench scale tests of aerobic composting were conducted on a feedstock with the starting empirical formula $C_{28}H_{46}O_{22}N$. Pilot tests indicated that 1000 kg dry solids of the feedstock decreased to 245 kg dry solids by completion. The final product empirical formula was determined to be $C_{12}H_{16}O_6N$. Determine the stoichiometric oxygen required to complete the aerobic decomposition per 1000 kg of feed.
17. At a waste-handling facility, a mixture of approximately 70 metric tons of food waste and yard waste is to be composted. The moisture content of the feedstock measures 5.5%. It has been previously determined that an ideal moisture content for the compost pile should be about 58%. Calculate the metric tons of water to be added to the solids to achieve the optimum moisture content.

EXERCISE: SOIL AND GROUNDWATER QUALITY AT A COMPOSTING FACILITY

File Names: Compost _ Soil.Xls, Compost _ Gw.Xls

The Situation

A municipality in the eastern United States installed an MSW and food waste composting facility. A local farmer leases some of his property for the facility. Surface soils are silt loam or silty clay loam texture. At a depth of approximately 40 cm (16 in.) below ground surface, loam is the predominant texture, and beyond this horizon there are occasional lenses of coarse sand and gravel. Three small streams occur within 0.5–3 miles of the facility. There were no siting regulations at the time of the installation (early 1990s), and therefore no concrete pad was installed during construction. Rainfall ranges from 42 to 48 in. per year.

MSW arrives at the compost site from two municipalities (“MSW1” and “MSW2”); both have previously processed their wastes via shredding and magnetic separation. A third facility tips significant quantities of vegetable processing wastes, including plant scraps and washings. These three wastes are being composted separately for a research project (below).

MSW1 contained large proportions of yard waste, whereas MSW2 did not. In addition, MSW2 contained a significantly higher proportion of inerts such as glass, stone, and some metals.

Research plots were established on the property (see map) to test the possible effects of the composts on soil and groundwater properties. Maize, soybeans, and pasture hay were grown. Plot setups are shown below.

The materials applied at the East Fork site:

Material	Plot Designation
MSW1	1A, 1B, 1C
MSW2	2A, 2B, 2C
Inorganic fertilizer	3A, 3B, 3C
Food-processing waste	4A, 4B
No treatments	Control

For the Powder Creek site:

Material	Plot Designation
MSW1	5A, 5B, 5C
MSW2	6A, 6B, 6C
Inorganic fertilizer	7A, 7B, 7C
Food-processing waste	8A, 8B
No treatments	Control

The data for this exercise is located at www.crcpress.com/e_products/downloads/download.asp?cat_no = 3525

Tasks

1. Determine the direction of groundwater flow and draw directional arrows.
2. Observe the data for groundwater quality in the site wells. Are there any constituents that are in excess of maximum contaminant levels (see Table 10.1, also the Code of Federal Regulations)?
3. Based on groundwater data, can you suggest the plots and waste types that may be contributing to the highest levels of contamination?
4. Do you observe any correlation between concentrations of any of the contaminants in groundwater?
5. In the groundwater, does the EC correlate with data for any elements or compounds?
6. As mentioned above, MSW2 contained relatively higher concentrations of metals compared with other feedstocks. Why were these metals detected only at very low levels in the soil or groundwater?
7. If we were to assume that the soils were similar from both sites, which compost feedstock results in the lowest NO_3^- concentrations in groundwater? The highest concentrations?
8. From the data, what is the general relationship between soil data for NO_3^- and groundwater data for NO_3^-? For NH_4^+? For metals?
9. This study was not a strictly scientific one; however, conduct an Analysis of Variance (ANOVA) on soil data and determine whether any of the treatments is significantly different in terms of NO_3^- content, P, or K levels.
10. Conduct an ANOVA on groundwater data and determine whether any of the treatments is significantly different in terms of NO_3^- contamination of groundwater.
11. What corrective measures would you propose in order to control the excess leaching of nutrients from any of these sites?

REFERENCES

Appelhoff, M. and McNelly, J. 1988. *Yard Waste Composting, Guidebook for Michigan Communities*. Lansing, MI: Michigan Department of Natural Resources.

Bezdicek, D., Fauci, M., Caldwell, D., Finch, R., and Lang, J. 2001. One year later: Persistent herbicides in compost. *BioCycle* 25. Available from: http://www.jgpress.com/BCArticles/2001/070125.html

Buyuksonmez, F., Rynk, R., Hess, T.F., and Bechinski, E. 1999. Occurrence, degradation and fate of pesticides during composting, part I. *Compost Sci Util* 7, 66–82.

Buyuksonmez, F., Rynk, R., Hess, T. F., and Bechinski, E. 2000. Occurrence, degradation and fate of pesticides during composting, part II. *Compost Sci Util* 8, 61–81.

CC (Composting Council). 1991. *Compost Facility Planning Guide*. Washington, DC: CC.

Chaney, R.L. and Ryan, J.A. 1992. Heavy metals and toxic organic pollutants in MSW composts: Research results on phytoavailability, bioavailability, fate, etc. As cited in Hoitink, H.A.J. et al. (Eds.) Columbus, OH. *Proceedings of the International Composting Research Symposium*, 1992, p. 451.

Chhabria, N.D. n.d. *Wabio Anaerobic Digestion Process to Produce Energy from Garbage*. United Nations Development Programme. Available from: http://www.undp.org.in/Programme/GEF/september/page16-20.htm

Chiang Mai University. 1998. *Review of Current Status of Anaerobic Digestion Technology for Treatment of Municipal Solid Waste*. Regional Information Service Center for South East Asia on Appropriate Technology, Institute of Science and Technology Research and Development. Available from: http://www.ist.cmu.ac.th/riseat/documents/adreview.pdf

Chynoweth, D.P., Haley, P., Owens, J., Teixeira, A., and Welt, B. 2003. *Anaerobic Composting for Regenerative Stabilization of Wastes during Space Missions*. Bioastronautics Investigators' Workshop. January 13–15, Galveston, TX. Available from: http://www.dsls.usra.edu/dsls/meetings/bio2003/pdf/Environmental/2198Chynoweth.pdf

Diaz, L.F. 1987. Air emissions from compost. *BioCycle* 28, 52–53.

Diaz, L.F., Savage, G.M., Eggerth, L.L., and Golueke, C.G. 1994. *Composting and Recycling Municipal Solid Waste*. Boca Raton, FL: Lewis Publishing.

Elorrieta, M.A., López, M.J., Suárez-Estrella, F.F., Vargas-García, M.C., and Moreno, J. 2002. Composting of different horticultural wastes: Effect of fungal inoculation. In *Microbiology of Composting*. Insam, H., Riddech, N., and Klammer, S. (Eds.). Berlin: Springer, 119–132.

Epstein, E. and Epstein, J.I. 1989. Public health issues and composting. *BioCycle* 30, 50–53.

Eweis, J.B., Ergas, S.J., Chang, D.P.Y., and Schroeder, E.D. 1998. *Bioremediation Principles*. Boston, MA: McGraw-Hill.

Faure, D., and Deschamps, A.M. 1991. The effect of bacterial inoculation on the initiation of composting of grape pulps. *Bioresour Technol* 37, 235–238.

Gaind, S., Pandey, A.K., and Lata. 2005. Biodegradation study of crop residues as affected by exogenous inorganic nitrogen and fungal inoculants. *J Basic Microbiol* 4, 301–311.

Gillett, J.W. 1992. Issues in risk assessment of compost from municipal solid waste: Occupational health and safety, public health, and environmental concerns. *Biomass Bioenergy* 3, 145–162.

Golueke, C.G. 1977. *Biological Reclamation of Solid Wastes*. Emmaus, PA: Rodale Press.

Gurkewitz, S. 1989. Yard debris compost testing. *Biocycle* 30, 58–59.

Haug, R.T. 1993. *The Practical Handbook of Compost Engineering*. Boca Raton, FL: Lewis Publishing.

Hellman, T.M. and Small, F.H. 1973. Characterization of petrochemical odors. *Chem Eng Progr* 69, 75–77.

Kissel, J.C., Henry, C.H., and Harrison, R.B. 1992. Potential emissions of volatile and odorous organic compounds from municipal solid waste composting facilities. *Biomass Bioenergy* 3, 181–194.

Maine Department of Environmental Protection. n.d. *Persistent Herbicides in Leaf & Yard Compost*. Available from: http://www.state.me.us/dep/rwm/compost_herbicides.htm

Menzer, R.E. 1991. Water and soil pollutants. In *Casarett and Doull's Toxicology The Basic Science of Poisons*, 4th ed. Amdur, M.O., Doull, J., and Klaassen, C.D. (Eds.). New York: Pergamon Press, 872–902.

Miller, T.L., Swager, R.R., and Adkins, A.D. 1992. *Selected Metal and Pesticide Content of Raw and Mature Compost Samples from Eleven Illinois Facilities*. Springfield, IL: Illinois Department of Energy and Natural Resources.

Rich, L.G. 1963. *Unit Processes of Sanitary Engineering*. New York: Wiley.

Richard, T. and Chadsey, M. 1989. *Croton Point Compost Site Environmental Monitoring Program*. White Plains, NY: Westchester County Solid Waste Division.

Richard, T. and Chadsey, M. 1990. Environmental impact of yard waste composting. *BioCycle* 31, 42–46.

Richard, T., Dickson, N., and Rowland, S. 1990. *Yard Waste Management, A Planning Guide for New York State*. Albany, NY: New York State Energy Research and Development Authority, Cornell Cooperative Extension, New York State of Environmental Conservation.
Richard, T.L. 1992. Municipal solid waste composting. Physical and biological processing. *Biomass Bioenergy* 3, 195–211.
Roderique, J.O. and Roderique, D.S. 1990. *The Environmental Impacts of Yard Waste Composting*. Falls Church, VA: Gershman, Brickner and Bratton.
Rose, W.W. and Mercer, W.A. 1968. *Fate of Insecticides in Composting Agricultural Wastes*. Washington, DC: National Canners Association.
Rynk, R. (Ed.). 1992. *On-Farm Composting Handbook*. NRAES-54. Ithaca, NY: Cooperative Extension.
Rynk, R. 2000. Fires at composting facilities: Causes and conditions. *BioCycle* 41. Available from: http://www.environmental-expert.com/magazine/biocycle/january2000/article4.htm
Six, W. and DeBaere, L. 1992. Dry anaerobic conversion of municipal solid waste by means of the Dranco process at Brecht, Belgium. *Proceedings of International Symposium on Anaerobic Digestion of Solid Waste, Venice.* April 14–17. Cecchi, F., Mata-Alvarez, J., and Pohland, F.G. (Eds.). *Int Assoc Wat Poll Res Control*, pp. 525–528.
ten Brummeler, E. 2000. Full scale experience with the BIOCEL process. *Water Sci Technol* 41, 299–304.
University of Connecticut. 1989. *Leaf Composting: A Guide for Municipalities*. Hartford, CT: University of Connecticut Cooperative Extension Service; State of Connecticut Department of Environmental Protection, Local Assistance and Program Coordination Unit, Recycling Program.
University of Southampton. 2002. *Anaerobic Digestion*. Environment Division, Civil and Environmental Engineering. Available from: http://www.soton.ac.uk/~env/research/wastemanage/anaerobic.htm#plants 4organic MSW
U.S. EPA (U.S. Environmental Protection Agency). 1984. *Windrow and Static Pile Composting of Municipal Sewage Sludges*. Project Summary, EPA-600-S2-84-122. Cincinnati, OH: Engineering Research Laboratory, U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 1994. *Composting Yard Trimmings and Municipal Solid Waste,* EPA 530-R-94-003. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 1997. *Innovative Uses of Compost for Erosion Control, Turf Remediation, and Landscaping*, EPA530-F-97-043. Washington, DC: Office of Solid Waste and Emergency Response, (5306W), U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 1998. *An Analysis of Composting as an Environmental Remediation Technology,* EPA530-B-98-001. Washington, DC: Office of Solid Waste and Emergency Response, (5306W), U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 2011a. *Municipal Solid Waste Generation, Recycling, and Disposal in the United States Tables and Figures for 2010*. Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf
U.S. EPA (U.S. Environmental Protection Agency). 2011b. *Pesticides Industry Sales and Usage, 2006 and 2007 Market Estimates*. Available from: http://www.epa.gov/opp00001/pestsales/07pestsales/market_estimates2007.pdf
Vesilind, P.A., Worrell, W., and Reinhart, D. 2002. *Solid Waste Engineering*. Pacific Grove, CA: Brooks/Cole.
Wellinger, A., Wyder, K., and Metzler, A.E. 1993. Kompogas – a new system for the anaerobic treatment of source separated waste. *Water Science and Technol* 27(2), 153–158.
Williams, T.O. and Miller, F.C. 1992. Odor control using biofilters, part I. *BioCycle* 33, 72–77.
Wirth, R. 1989. *Introduction to Composting*. St. Paul, MN: Minnesota Pollution Control Agency.
Zubay, G. 1983. *Biochemistry*. Reading, MA: Addison-Wesley.

SUGGESTED READINGS

Araújo, A.S.F. and Monteiro, R.T.R. 2005. Plant bioassays to assess toxicity of textile sludge compost. *Scientia Agricola* 62, 286–290.
Araújo, A.S.F., Monteiro, R.T.R., and Abarkeli, R.B. 2003. Effect of glyphosate on the microbial activity of two Brazilian soils. *Chemosphere* 52, 799–804.
Benito, M., Masaguer, A., Moliner, A., Arrigo, N., and Palma, R.S. 2003. Chemical and microbiological parameters for the characterization of the stabilizing and maturing of pruning waste compost. *Biol Fertil Soils* 37, 184–189.

Bernal, M.P., Albuquereque, J.A., and Moral, R. 2008. Composting of animal manures and chemical criteria for compost maturity assessment: a review. *Bioresour Technol* 99, 3372–3380.

Bhattacharyya, P., Pal, R., Chakraborty, A., and Chakrabarti, K. 2001. Microbial biomass and its activities of a laterite soil amended with municipal solid waste compost. *J Agron Crop Sci* 187, 207–211.

Butler, T.A., Sikora, L.J., Steinhilber, P.M., and Douglass, L.W. 2001. Compost age and sample storage effects on maturity indicators of biosolids compost. *J Environ Qual* 30, 2141–2148.

Garcıa-Gil, J.C., Plaza, C., Soler-Rovira, P., and Polo, A. 2000. Longterm effects of municipal solid waste compost application on soil enzyme activities and microbial biomass. *Soil Biol Biochem* 32, 1907–1913.

Goyal, S., Dhull, S.K., and Kapoor, K.K. 2005. Chemical and biological changes during composting of different organic wastes and assessment of compost maturity. *Biores Technol* 96, 1584–1591.

Larney, F.J. and Hao, X. 2007. A review of composting as a management alternative for beef cattle feedlot manure in southern Alberta, Canada. *Biores Technol* 98, 3221–3227.

Pedra, F., Polo, A., Ribeiro, A., and Domingues, H. 2007. Effects of municipal solid waste compost and sewage sludge on mineralization of soil organic matter. *Soil Biol Biochem* 39, 1375–1382.

Roca-Perez, L., Martinez, C., Marcilia, P., and Boluda, R. 2009. Composting rice straw with sewage sludge and compost effects on the soil-plant system. *Chemosphere* 75, 781–787.

Selivanovskaya, S.Y. and Latypova, V.Z. 2006. Effects of composted sewage sludge on microbial biomass, activity and pine seedlings in nursery forest. *Waste Manag* 26, 1253–1258.

Singh, R.P. and Agrawal, M. 2008. Potential benefits and risks of land application of sewage sludge. *Waste Manag* 28, 347–358.

9 Incineration of MSW

Such myriads of flames I saw shine through
the gloom of the eighth abyss when I arrived
at the rim from which its bed comes into view.

Dante Alighieri (ca. 1265–1321)
Inferno, Canto XXVI

9.1 INTRODUCTION

Incineration is defined as the controlled burning of solid, liquid, or gaseous wastes. The term *controlled* is emphasized in order to distinguish the technology from simple, open burning or other similarly unsound processes. Controlled conditions typically include an oxygen-enriched combustion zone under elevated temperatures, the use of auxiliary fuel, vigorous agitation of incoming waste, and the use of a forced air system.

The primary purpose of MSW incineration is volume reduction, with the ultimate result of extending the lifetime of the land disposal facility. It has been reported that reductions of 80%–90% of the total MSW volume are possible through incineration, although reductions of 50%–60% are more realistic. Reductions of up to 95%–99% of the combustible fraction (paper products, plastics, food waste, and yard waste) have been reported. Compaction of the ash residue will result in additional volume reduction, and recovery of metals from the residue will further reduce volume. Therefore, MSW processed in a municipal incinerator and subsequently compacted in a landfill may occupy only 25% of its original volume. It is estimated that incineration in combination with sanitary landfilling can double the life span of a disposal facility.

A second purpose of incineration is termed *waste to energy*, that is, the recovery of heat energy for water heating, space heating, or electricity generation. A third, albeit unintended benefit of incineration is detoxification—the destruction of microbial and other pathogenic organisms—of the waste.

As shown in Chapter 4, MSW is extremely heterogeneous in composition; therefore, a wide assortment of residues is generated that require additional processing and disposal. Residues include:

- Acid-forming gases such as SO_2, NOx, and HCl
- Trace gases (e.g., chlorinated dibenzodioxins) that are hazardous at very low concentrations
- Particulate matter. Also known as *fly ash* and soot, this takes the form of solids or liquids suspended in the gas stream.
- Incinerator residue (*bottom ash*)
- Process water

9.2 COMBUSTION CONCEPTS

Incineration is almost exclusively carried out as an aerobic thermal destruction process. Aerobic combustion results in the most complete transformation of solid waste to ash, gases, and heat. In order to achieve efficient combustion while releasing minimal quantities of air pollutants, however, several requirements must be addressed during system design. For example, the correct amount of air must be available to the combustion chamber. This *stoichiometric air* is needed to bring

combustion reactions to completion and avoid generation of any products of incomplete combustion (PICs; see below).

In the combustion of an organic component of MSW, the general reaction is

$$(HC)_x + O_2 \rightarrow CO_2 + H_2O + \text{heat} \tag{9.1}$$

The process is much more complex, however, since not all the hydrocarbons are converted to carbon dioxide and water, and other components of the waste such as sulfur and nitrogen are also oxidized (see below).

Example 9.1

Determine the stoichiometric air required to combust: (a) char, C; and (b) methane, CH_4.

Solution

(a) First, we calculate the O_2 required for complete combustion.

	$C +$	$O_2 \rightarrow$	$CO_2 + 2H_2O$
Grams	12	32	

The stoichiometric O_2 required for complete combustion is 32/16 = 2 g O_2/g C.

We will assume that the O_2 concentration in the incinerator is about equivalent to dry air concentrations (~23.5%), although many incinerators will operate with elevated O_2 levels.

The stoichiometric air requirement will be:

$$2 \text{ g}/0.235$$

$$= 8.5 \text{ g air/g C}$$

(b) For methane, the equation is

	$CH_4 +$	$2O_2 \rightarrow$	$CO_2 + 2H_2O$
Grams	16	64	

The stoichiometric O_2 required for complete combustion is 64/16 = 4 g O_2/g CH_4.

The stoichiometric air requirement will be:

$$4/0.235$$

$$= 17.0 \text{ g air/g } CH_4$$

We can represent the aerobic decomposition of carbonaceous materials in MSW by the reaction:

$$C_aH_bO_cCl_dF_eN_fS_g + [a + b/4 - (c + d + e - f)/2 + g]\ O_2 \rightarrow aCO_2 + [(b - d - e)/2]\ H_2O + d\ HCl + eHF + fNO + gSO_2$$

Fluorine, chlorine, and sulfur are typically present in small amounts in MSW and are, therefore, omitted from calculations.

Example 9.2

A carbonaceous waste given by the empirical formula $C_{65.5}$ $H_{102.3}$ $O_{40.8}N_{1.1}$ is to be incinerated. Proximate and elemental analyses of the waste are as follows:

Proximate Analysis	Percent	Elemental Analysis	Percent
Moisture	4.8	Carbon	47.36
Noncombustibles	6.2	Hydrogen	6.25
		Oxygen	39.25
		Nitrogen	0.85
		Sulfur	0.19
		Ash	6.10

Calculate the following: (a) The gross heat value and net heat value of this waste as received, and (b) the volume of air needed for complete combustion of 1000 kg (i.e., one metric ton) of input material.

Solution

(a) The higher heat value (HHV) and lower heat value (LHV) of the waste can be calculated using Equations 4.6 and 4.7:

$$HHV = 0.339\ (C) + 1.44\ (H) - 0.139\ (O) + 0.105\ (S)\ MJ/kg$$

$$HHV = 0.339\ (47.36) + 1.44\ (6.25) - 0.139\ (39.25) + 0.105\ (0.19)\ MJ/kg,$$

$$HHV = 19.61\ MJ/kg$$

$$LHV = HHV\ (\text{in MJ/kg}) - 0.0244\ (W + 9H)\ MJ/kg$$

$$LHV = 19.61\ MJ/kg - 0.0244\ (4.8 + 9\ (6.25))\ MJ/kg$$

$$LHV = 18.12\ MJ/kg$$

(b) When computing the oxygen requirement, the chlorine and sulfur components may be neglected. Given that a = 65.5, b = 102.3, c = 40.8, d = 0, e = 0, f = 0.85, g = 0, the combustion equation is as follows:

$$C_{65.5}H_{102.3}O_{40.8}M_{0.85} + 71.1\ O_2 \rightarrow 65.5\ CO_2 + 51.2\ H_2O + 1.1\ NO$$

The formula mass of the waste is then calculated:

Carbon	12 × 65.5 = 786
Hydrogen	1 × 102.3 = 102.3
Oxygen	16 × 40.8 = 652.8
Nitrogen	14 × 0.85 = 11.9
Total	1553

Therefore, the molar mass of the material is 1553 or 1.55 kg.

Of the 1000 kg of the material, 890 kg (i.e., 1000 kg minus 48 kg moisture and 62 kg inert material) is combustible. This quantity corresponds to 890 kg/1553 kg/mole = 573 moles.

From the equation, we see that one mole of the material requires 71.1 moles of O_2. So 573 moles of material require 573 × 71.1 = 40,746 moles of O_2.

At standard temperature and pressure (STP) (0°C and 1 atm), one mole of a gas occupies 22.4×10^{-3} m^3. Consequently,
Volume = 40,746 moles of $O_2 \times 22.4 \times 10^{-3}$ m^3/mole of O_2
Volume = 913 m^3 of O_2

Air contains about 21% oxygen; therefore, 4348 m^3 of air is required to supply this volume of oxygen. This converts to 4.35 m^3 of air per kg of dry combustible material.

Other formulas have been devised to calculate the air required for waste combustion. For example, Dvirka (1986) established:

$$W_a = 0.0431\ [2.667C + 8H + S - O]\ \text{kg of air/kg of waste} \tag{9.2}$$

where W_a is the mass of dry stoichiometric air (at STP) required to burn 1 kg of combustible waste, and C, H, S, and O are the mass percent of carbon, hydrogen, sulfur, and oxygen, respectively, of the moisture- and ash-free material.

Other critical factors influencing the completeness of combustion are temperature, time, and turbulence, known as the "three T's of combustion." Each combustible substance has a minimum ignition temperature that must be attained in the presence of oxygen for combustion to be sustained. Above the ignition temperature, heat is generated at a higher rate than it loses to the surroundings, which makes it possible to maintain the elevated temperatures necessary for sustained combustion. The residence time of the input wastes in the high-temperature region of the combustion zone should exceed the time required for combustion to take place. Such a requirement will affect the size and shape of the furnace. Turbulence (i.e., the thorough mixing of MSW as it passes through the combustion chamber) will expose particle surfaces to oxygen and high temperatures, and will speed evaporation of carbonaceous liquids for combustion in the vapor phase. Inadequate mixing of combustible gases and air in the furnace will lead to the generation of PICs, even from a unit containing excess oxygen.

9.3 MASS-BURN INCINERATOR

Mass burning is the most straightforward incineration technology, involving combustion of MSW as received from the collection vehicle. The only processing involved is the simple mixing of wastes and the removal of large, bulky items such as white goods (stoves and washing machines), bulky, combustible items (mattresses, furniture, etc.), and hazardous materials. The crane operator often accomplishes the removal in the waste storage pit. Therefore, a major benefit of mass-burn systems, beyond its relative simplicity, is the avoidance of capital and operating costs associated with extensive waste processing. Some incinerators use shredding equipment for reducing bulky items to workable sizes. As will become apparent, the convenience of mass burn is countered by a number of significant health and environmental concerns.

The major components of the mass-burn incinerator include:

- Tipping area or receiving floor
- Storage pit
- Equipment for charging (loading) the waste into the incinerator hopper. This equipment is often a crane or front-end loader
- Combustion chamber
- Energy recovery system
- Pollution control equipment
- Flue

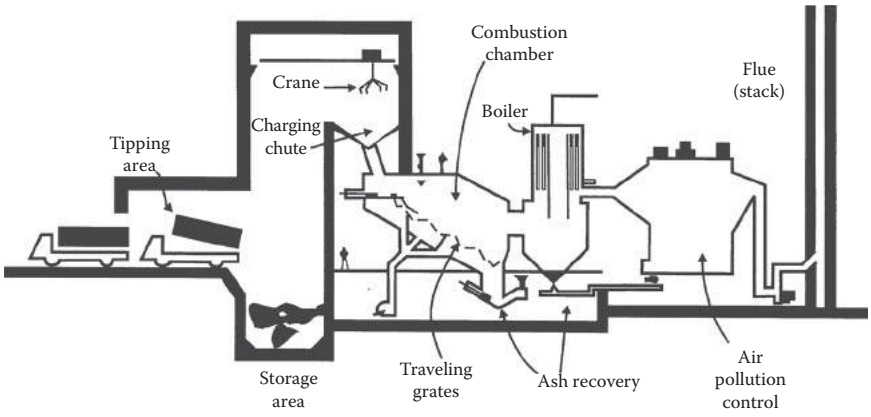


FIGURE 9.1 Cross-section of a typical mass-burn incinerator. (From Holmes, J.R., *Refuse Recycling and Recovery*, Wiley, New York, 1981. Copyright John Wiley & Sons. Reproduced with permission.)

A typical mass-burn system is shown in Figure 9.1.

Mass-burn incineration can be divided into four broad areas (Hickman 1984):

- Incineration without energy recovery
- Incineration using modular furnaces
- Incineration using refractory furnaces with heat recovery boilers
- Incineration using waterwall furnaces

All four methods are in use in the United States as well as Europe; however, waterwall incinerators have proven to be the superior means of recovering energy from MSW (Hickman 1984).

MSW is tipped by the collection vehicle directly into a storage pit. The pit must allow for storage of sufficient volumes of waste for steady, uniform operation and should provide for a 24 h a day, 7 days a week operation. The MSW charge is next transferred into loading hoppers by crane, which is then transported into the furnace by a grate system. The temperature of the combustion zone will vary with furnace type and is usually maintained between 815°C and 1095°C (1500°F and 2000°F). Within this temperature range, combustion is optimized and the production of odoriferous compounds is minimized. These temperatures are also suitable for protecting the refractory linings of the combustion chamber. The waste is conveyed through the firebox by a system of agitating grates. A limited number of grate types are in use (Figure 9.2), all designed for transporting waste, agitation, and conducting *underfire air* upwards. The rocking or turning action of the grate agitates MSW for more complete combustion. Openings in the grates allow for large ash particles to fall through into a collection bin. This residue is the so-called *bottom ash*. Additional unburned residue is carried to the end of the grates and is collected and combined with other bottom ash.

During mass burn of MSW, the charge is spread several inches thick on the grate surface. As the waste is agitated, it mixes with air that is pumped over the grates (*overfire air*). The overfire air assists in completing combustion of the fuel gas and any MSW-generated gases and particulate matter rising from the grates. Air is also directed under the grates. This underfire air (about 40%–60% of the total air entering the furnace) feeds the combustion process and cools the grates. If there is too low a flow of underfire air, grate temperatures will increase and ash will soften and clog the grates, resulting in damage to the grates and nonoptimal combustion.

The combustion gases transfer heat to boilers or waterwalls. Boilers are defined as enclosed units whose primary purpose is the recovery and export of thermal energy in the form of hot water, saturated steam, or superheated steam. The principal components of a boiler are a burner, a firebox, a heat exchanger, and a means of creating and directing gas flow through the unit. The boiler combustion

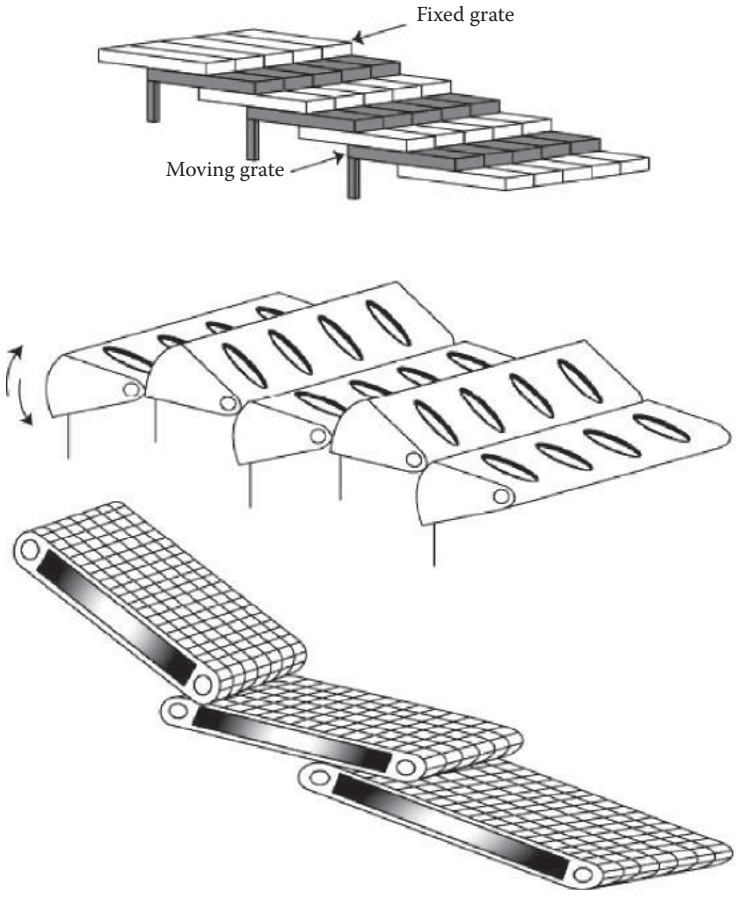


FIGURE 9.2 Common grate types for an MSW combustor. Underfire air is forced upwards through the grates, and overfire air is passed over the top of the burning MSW. (From U.S. EPA, n.d., Lesson 14, Municipal Incinerators, Available from: http://yosemite.epa.gov/oaqps/EOGtrain.nsf/12f4a7ba1594b00d85256b450052f92a/be2e374ff50cf6f485256b88004e4c06/$FILE/si431-lesson14.pdf.)

chamber and primary energy recovery sections are usually of *integral design*; i.e., the combustion chamber and the primary energy recovery sections (waterwalls and superheaters) are manufactured as a single unit (U.S. EPA 2002). Figure 9.3 illustrates a cross-section of a typical boiler.

MSW can be combusted for the production of steam, which is useful for driving turbines and generating electricity. The remaining steam has little industrial use, however, unless it is produced sufficiently close to other buildings and used for space and water heating. Often, the residual steam is condensed to liquid water that is either cooled and used again in the power plant, or released to the local environment. Boiler water is typically treated and reused because it is too expensive to be used only once. Small amounts, less than 10%, are *blowdown* (i.e., fresh water added to the system) to minimize the concentration of dissolved solids (Worrell and Vesilind 2011).

If hot water is discharged directly into a body of surface water, it will create adverse impacts in streams, rivers, and estuaries; as a result, heat discharges are regulated by federal and state codes. The typical limit is that the temperature of the receiving water must not rise by more than 1°C. Given this requirement, the heated water must be cooled prior to discharge. Various technologies are used for dissipating this energy, including large shallow ponds and cooling towers. A cutaway drawing of a typical cooling tower is shown in Figure 9.4.

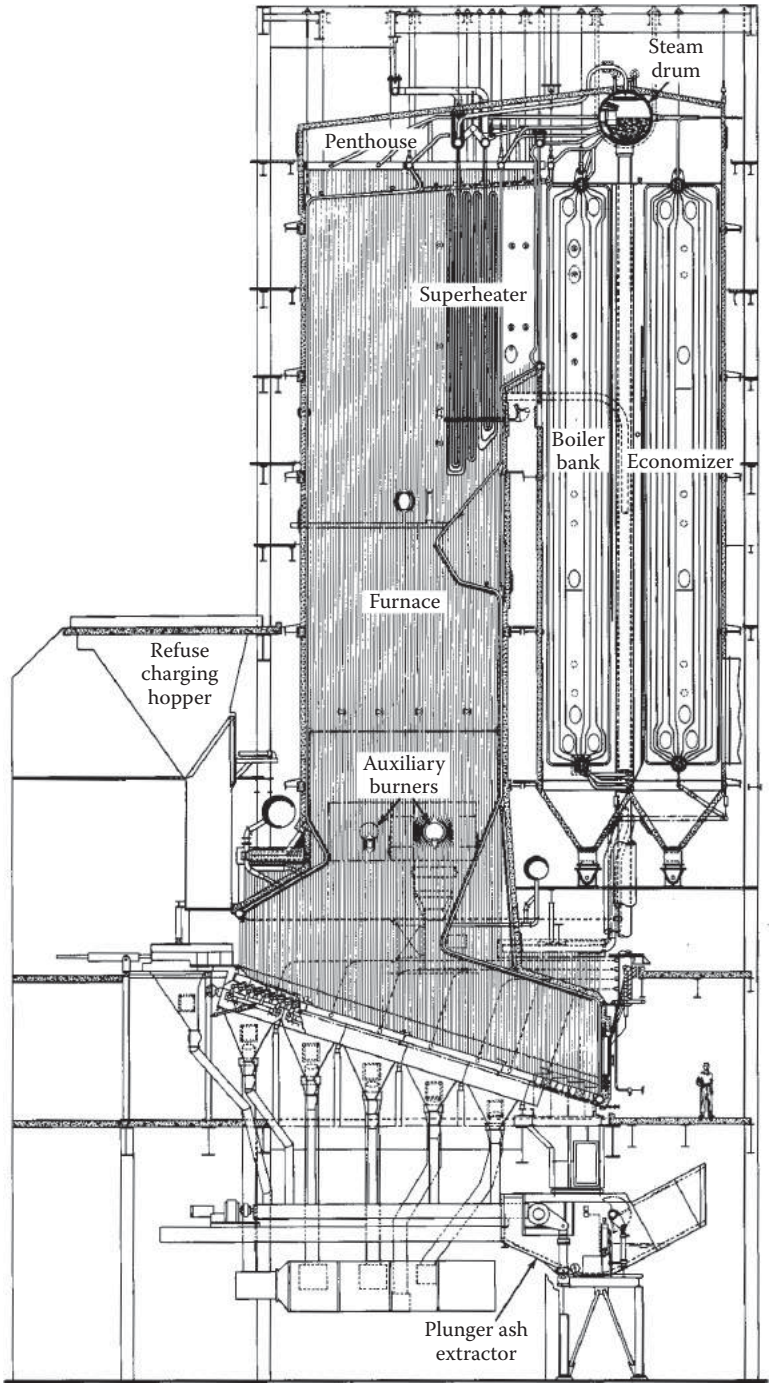


FIGURE 9.3 Boiler system used in a mass-burn incinerator (Reproduced with kind permission from Gittinger, J.S. and Arvan, W.J., *Steam: Its Generation and Use,* Barberton, OH, Babcock & Wilcox, 1998.)

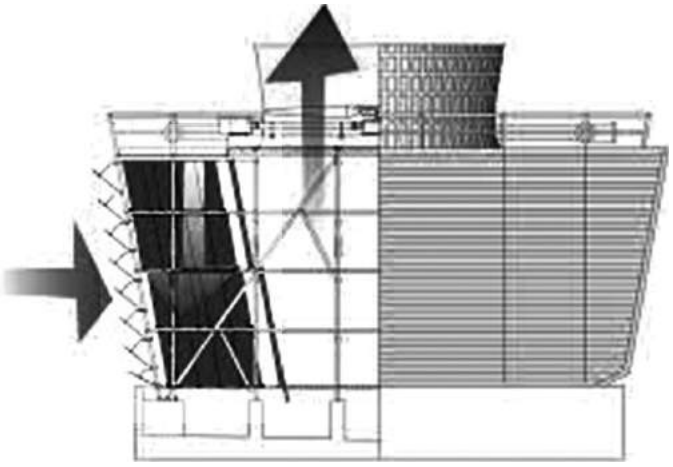


FIGURE 9.4 Cooling tower for cooling exhaust gases from an MSW incinerator. (Reproduced with kind permission of Midwest Towers, Inc., Chickasha, OK, Available from: http://www.midwesttowers.com/crossflow-cooling-towers/.)

After passage through the boiler area, the combustion gases are freed of particulates and acid gases by a number of technologies (ranging from simple to sophisticated in design), including electrostatic precipitators, baghouses, and mist separators (discussed below), and then discharged to the atmosphere via the flue.

9.4 ENVIRONMENTAL CONSIDERATIONS OF MASS BURN

Mass burn is a simple and rather crude method of waste destruction. As a result, a number of undesirable end-products, hazardous end-products, or both are inevitably generated.

9.4.1 Fuel Quality

If energy is to be recovered from mass-burn incineration, raw MSW is considered a rather poor quality fuel. The calorific value of raw, unprocessed MSW is estimated at approximately 11,650 kJ/kg (5000 Btu/lb). Of this, it is estimated that about 40%–45% is released as waste heat to the atmosphere via the flue. The moisture content of raw MSW may range from 20%–50%, and the percentage of combustible materials may comprise only 50% of the entire mass (see Tables 4.16 through 4.19).

9.4.2 Resource Recovery

No opportunities are available for materials recovery in mass burn, except for magnetic removal of ferrous metals from the ash. This removal is known as *back-end recovery* (i.e., after combustion), as opposed to *front-end* (separation before combustion). The recovered metal is worth less than front-end metal and is often unsuitable for sale. Degradation of the ferrous component of MSW will occur as a result of oxidation and contamination by other metals and nonmetals as the mixed waste passes through the burning zones of the incinerator.

9.4.3 Air Quality

Flue gases escaping the combustion chamber contain an array of inorganic and organic substances. The Law of Conservation of Mass is still being observed during incineration; the matter occurring

within the original waste is simply converted either into a gaseous form or to ash. Under ideal conditions, carbonaceous wastes are converted into innocuous products such as CO_2 and H_2O, along with release of heat energy. The actual composition of flue gases, however, is highly complex and is based upon the composition of the original MSW, furnace design, and combustion conditions. Many of the substances emitted from incinerator flue gases are known to negatively impact human health. The air pollutants of concern arising from MSW combustion are primarily particulates, acid gases, and trace gases.

9.4.4 Particulates

Particulates, also known as *fly ash*, occur as either solid particles or liquid droplets composed of organic or inorganic substances. A number of terms are used to describe atmospheric particles; the more important of these are summarized in Table 9.1. Particulate matter makes up the most visible form of air pollution.

Atmospheric aerosols are solid or liquid particles smaller than 100 μm in diameter. Particles in the 0.001–10 μm range are commonly suspended in the air near pollution sources. Aerosols consist primarily of carbonaceous material, metal oxides, glass, dissolved ionic species (electrolytes), and ionic solids. The predominant constituents are carbon, water, sulfate, nitrate, ammonium, and silicon. The composition of aerosol particles varies significantly with size. Smaller particles tend to be acidic and often originate from gases, for example, from the conversion of SO_2 to H_2SO_4. Larger particles tend to consist of materials generated mechanically (Manahan 2009).

Particulates are a public health concern because those occurring in the respirable fraction (approximately 15 μm in diameter) are commonly emitted from MSW incinerators in large quantities. In addition, heavy metals, chlorinated dibenzodioxins, and other trace elements become attached to fly ash. The rates of particulate emissions from a mass-burn incinerator depend on:

- Ash content, that is, the percentage of noncombustible materials in the waste. If particle size is sufficiently small, particulates become entrained in the gases passing through the system.
- Furnace design. Some systems create greater agitation of waste, thus releasing particles. Entrainment of particulates can result from air being forced through. Optimal use of overfire and underfire air is important to limit particulate emissions.

TABLE 9.1
Terminology Associated with Atmospheric Particles

Term	Definition
Aerosol	Colloidal-sized atmospheric particle
Condensation aerosol	Formed by condensation of vapors or reactions of gases
Dispersion aerosol	Formed by grinding of solids, atomization of liquids, or dispersion of dusts
Fog	Term denoting high level of water droplets
Haze	Denotes decreased visibility due to the presence of particles
Mists	Liquid particles
Smoke	Particles formed by incomplete combustion of fuel

Source: Reproduced with kind permission from Manahan, S.E., *Environmental Chemistry*, 9th ed., CRC Press, Boca Raton, FL, 2009. Copyright Lewis Publishing, an imprint of CRC Press.

- Temperature. A low-temperature zone occurring in the combustion chamber can result in the formation of incompletely burned residuals that are often lightweight and easily transportable.

9.4.5 Acid Gases

As shown in Equation 9.1, the combustion of a carbonaceous material results in the generation of carbon dioxide, water, and other components. With mixed MSW, however, gases such as SOx, NOx, and HCl may be produced by incinerators at rates of several pounds per ton of waste charged. These are collectively termed *acid gases* because they dissolve readily in water to yield the corresponding strong acids.

Sulfur occurs in tires, wallboard, and plant tissue (yard waste). During combustion, sulfur is converted to the corresponding oxides. Sulfur dioxide is a primary pollutant, as it is emitted directly from MSW burning and concurrent sulfur oxidation,

$$S + O_2 \rightarrow SO_2 \tag{9.3}$$

SO_2 can cause direct respiratory irritation and damage materials such as stone and metal. Sulfur emissions are converted to a secondary pollutant when sulfur dioxide reacts with water vapor and oxygen in the atmosphere, producing sulfur trioxide,

$$2SO_2 + O_2 \rightarrow 2SO_3 \tag{9.4}$$

The SO_3 combines with water to form sulfuric acid,

$$SO_3 + H_2O \rightarrow H_2SO_4 \tag{9.5}$$

This product is corrosive to skin and mucosa and is linked with several respiratory ailments. Sulfuric acid is the primary component of acid rain. It will damage concrete, metal, and other materials and is hazardous to biota. A wide range of values of SO_2 has been measured in stack emissions. As much as 0.68–1.4 kg (1.5–3 lb) of SO_2 has been measured per ton of MSW charged, which can substantially alter the pH of local precipitation. Natural, uncontaminated rain has a pH of about 5.6–5.7, but the pH of acid rain can be as low as 2.0. The deposition of atmospheric acid on freshwater aquatic systems prompted EPA to recommend a limit of emissions of 10–20 kg SO_4^{2-}/ha/year.

Nitrogen (N) also occurs in food and yard waste. The product of N combustion is nitrogen oxides, NOx,

$$N_2 + O_2 \rightarrow 2NO \tag{9.6}$$

$$2NO + O_2 \rightarrow 2NO_2 \tag{9.7}$$

Nitrogen dioxide is an important component of photochemical smog. The formation of smog begins with the production of nitrogen oxides originating from automobiles, industrial facilities, or MSW combustion. Hydrocarbons are also emitted into the atmosphere from sources such as motor vehicles and industry (including incineration). The constituents react with sunlight to yield ozone (O_3), a secondary pollutant, which, in turn, reacts with hydrocarbons to form a toxic suite of compounds, including aldehydes and organic acids. Table 9.2 lists some of the major reactions involved in the formation of photochemical smog.

TABLE 9.2
Overview of reactions involved in the formation of photochemical smog.

$NO + h\upsilon$	→	$NO + O$
$O + O_2$	→	O_3
$NO + O_3$	→	$NO_2 + O_2$
$R\text{-}C + O$	→	$R\text{-}CO + O_2 \rightarrow R\text{-}CO_3$
$R\text{-}CO_3 + O_2$	→	$R\text{-}CO_2 + O_3$
$R\text{-}CO_3 + NO + \rightarrow R\text{-}CO_2 + NO_2$	→	peroxyacetyl nitrates

Where R = a hydrocarbon compound.

The concentrations of NO_2 generated from incineration, however, are often low, due to the relatively low temperatures at which incineration occurs. Nitrogen can also be converted to HNO_3, another component of acid rain, by a series of reactions abbreviated below:

$$2NO_2 + ½\ H_2O \rightarrow \rightarrow 2HNO_3 \tag{9.8}$$

Chlorine occurs in MSW in paints, dyes, polyvinylchloride (PVC)-based products, and bleached paper. During combustion, gaseous hydrogen chloride, HCl, is generated, which condenses with water to form the corresponding hydrochloric acid. This corrosive liquid affects eyes, skin, and mucosa and also is linked with acid rain.

$$HCl(g) + H_2O \rightarrow HCl(aq) \tag{9.9}$$

9.4.6 Trace Gases

Comprising this category are gases that may occur at levels of a few parts per million (ppm), yet that may still exert a hazardous effect on living systems. Polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) (Figure 9.5), some of which are highly toxic, are now known to form during the combustion of chlorine-containing wastes. Seventy five isomers of PCDD and 135 of PCDF have been identified (Lisk 1988). The 2,3,7,8-tetrachlorodibenzodioxin isomer (2,3,7,8-TCDD) (Figure 9.5) is an animal teratogen and by far the most toxic; however, its toxicity varies over 5000-fold among species.

A World Health Organization (WHO) report confirmed that exposure to PCDDs, even at extremely low levels, can cause severe reproductive and developmental problems and that PCDDs can cause immune system damage and interfere with regulatory hormones (WHO 2013). The International Agency for Research on Cancer of WHO declared in 1997 that 2,3,7,8-TCDD is a Class 1 carcinogen; that is, it is a known human carcinogen. The U.S. National Toxicology Program has listed TCDD as a known human carcinogen since 2001 (NTP 2005).

Various isomers of PCDD and PCDF have been detected at parts per billion (ppb) levels in fly ash and at ng/m^3 concentrations in incinerator emissions in several countries. The concentrations of selected isomers of PCDD and PCDF in fly ash samples from MSW incinerators are shown in Table 9.3. Three possibilities have been proposed to account for the presence of PCDDs and PCDFs in MSW incinerator emissions (Hutzinger et al. 1985; Lisk 1988):

- They are already present in the incoming refuse and are not completely destroyed during incineration.
- They are produced from chlorinated precursors such as PCBs, chlorophenols, and chlorobenzenes contained in the refuse.

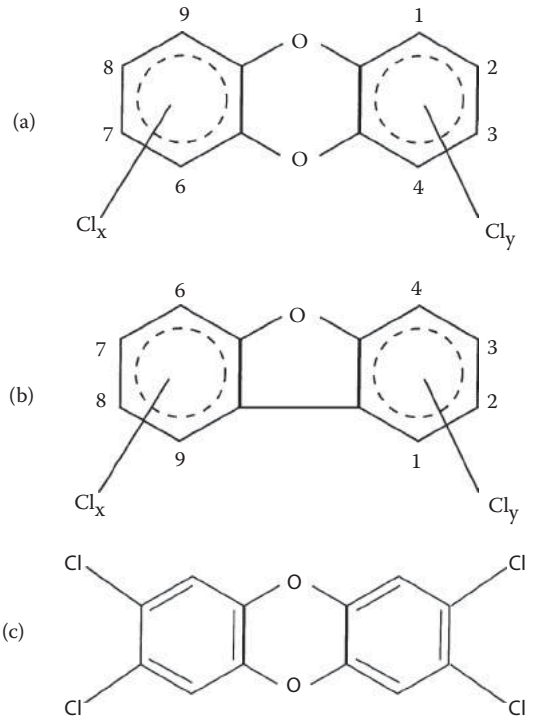


FIGURE 9.5 Structures of (a) a generic PCDD molecule, (b) a generic PDCF molecule, and (c) 2,3,7,8-tetrachlorodibenzodioxin.

TABLE 9.3
Concentrations of Tetrachloro through Octachloro Group Isomers of PCDD and PCDF in Fly Ashes from Five North American MSW Incinerators

Incinerator	Cl^4	Cl^5	Cl^6	Cl^7	Cl^8
			PCDD (ng g^{-1})		
1	85	213	354	184	97
2[a]					
3	2.7	6.6	11.6	5.7	3.5
4	12.9	37.5	75.6	41.9	35.2
5	2.4	7.9	9.7	9.1	2.1
			PCDF (ng g^{-1})		
1	209	549	1082	499	24
2[a]					
3	7.0	17.8	32.1	10.9	0.7
4	8.2	19.8	38.7	20.6	4.0
5	4.4	21.0	21.6	16.6	

Source: Reprinted from *Sci Total Environ*, 74, Lisk, D.J., Environmental implications of incineration of municipal solid waste and ash disposal, 39–66, Copyright 1988, with permission from Elsevier.

Note: PCDD = polychlorinated dibenzodioxin; PCDF = polychlorinated dibenzofurans; MSW = municipal solid waste.

[a] < 0.5 ng g^{-1}.

- They result from the cracking of complex organic substances (such as lignin to produce phenol) and are subsequently synthesized in the presence of chlorine at high temperatures, perhaps catalyzed by metal ions. Formation from chemically unrelated chlorinated organics such as PVC during pyrolysis is also possible.

PCDDs form in incinerators at temperatures of approximately 500°C and are destroyed at a minimum of 900°C. PCDD and PCDF formation and persistence are favored by low combustion temperature, wet MSW, insufficient or excess oxygen, and inadequate residence time (Lisk 1988). High temperatures and well-oxygenated multistage combustion zones are incorporated in modern furnace designs to optimize conditions for destruction of PCDDs and PCDFs. Some newer incineration facilities use auxiliary burners employing fossil fuels to maintain the temperature in the combustion zone sufficiently high at critical times, for example, when burning wet MSW or when starting up and shutting down operations. EPA has issued guidelines for MSW incinerator emissions, and optimum operational parameters to meet emission standards have been published. Degradation of PCDDs and PCDFs requires sufficient oxygen, ample turbulence in the combustion zone to avoid quench zones, and adequate residence time of the compounds in the combustion zone. About 7%–10% oxygen or 50%–100% excess air and a residence time of at least 1 s are estimated to be required for adequate destruction (McKay 2002).

Early theories of PCDD formation from MSW incineration centered on the content of PVC, which typically accounts for 50% of the chlorine content of the original waste; however, subsequent studies found that if temperature, oxygen, turbulence, and residence time parameters are optimized for the destruction of PCDDs and its precursors, the quantities of PCDDs emitted in the flue gas are independent of the PVC content of the original MSW. PCDDs are known to form during wood burning, so the chlorine content of wood is apparently sufficient to combine with precursors (e.g., phenols) released during combustion (Choudry et al. 1982; Olie et al. 1983). Removing PVC from MSW before incineration in order to reduce PCDD emissions, therefore, may be of questionable benefit.

It has been hypothesized that PCDDs and PCDFs form in pollution control devices, in the cooling gases as they exit the flue, or both. These compounds may be produced by chlorination of precursor molecules adsorbed to fly ash. Since PCDDs and PCDFs are strongly sorbed to fly ash particles beyond the combustion zone, they may be removed by conventional particulate removal technologies. For example, electrostatic precipitators (see below) efficiently trap large fly ash particulates; however, they do not consistently remove fine particles (<2 μm in diameter) unless sophisticated components are incorporated (Lisk 1988). Baghouses (fabric filters; see Sec. 9.5.2) are also highly efficient for particulate removal from the flue gas stream.

Measurement of PCDDs during waste combustion is difficult and expensive. The emissions of PCDDs from a stack can be roughly estimated by measuring the emission of carbon monoxide. According to Hasselriis (1987), generation of PCDDs is proportional to the CO concentration as

$$\text{PCDDs} = (\text{CO}/\text{A})^2 \tag{9.10}$$

where CO is the concentration of carbon monoxide in the flue gas as percent of total gas, and A is a constant, a function of the operating system. PCDD concentrations in the off-gases are expressed as ng/m^3.

The emission of PCDDs rises with increasing CO emissions, both of which are regulated by the amount of excess air used and the combustion temperature. From empirical evidence, several quantitative relationships have been developed that are good predictors of PCDD and PCDF formation (Worrell and Vesilind 2011).

For modular incinerators:

$$\text{PCDDs} + \text{PCDFs} = 2670.2 - 1.37\ T + 100.06\ CO \tag{9.11}$$

For waterwall incinerators:

$$\text{PCDDs} + \text{PCDFs} = 4754.6 - 5.14\ T + 103.41\ CO \tag{9.12}$$

where T (°C) is the temperature in the secondary chamber for modular combustors and the furnace temperature in waterwall incinerators, respectively.

PCDDs and PCDFs may be generated, albeit in extremely low quantities, during incineration of other solids, that is, not only MSW. Formation has been reported during combustion of paper, wood, vegetable wastes, chlorophenols, and polychlorinated biphenyls (PCBs) and from coal- and gasoline-powered engines (Lisk 1988).

Berlincioni and di Domenico (1987) monitored vapor and smoke emissions from an MSW incinerator for PCDDs and PCDFs and found that the fraction of compounds associated with fly ash accounted for less than 10% of the total emitted. They also sampled soils up to 1 km in several directions from the incinerator and found a maximum PCDD concentration of 7×10^4 ng/m^2 of soil surface. These compounds were not confined to the top 5 cm of soil and may have reached deeper layers by leaching or plowing. The more highly chlorinated isomers accumulated to the greatest degree. The authors postulated that the less chlorinated isomers were less persistent, owing to their higher vapor pressure and reactivity with light (*photolability*).

Other chlorinated and nonchlorinated organic compounds arising from MSW combustion include PCBs and polycyclic aromatic hydrocarbons (PAHs) (WSL 1992; Dyke 2003). Compounds in the latter category include pyrene, benzo[*a*]pyrene, and chrysene, among others (Figure 9.6). PAHs such as benzo[*a*]pyrene are known carcinogens. As with PCDDs, PAHs are

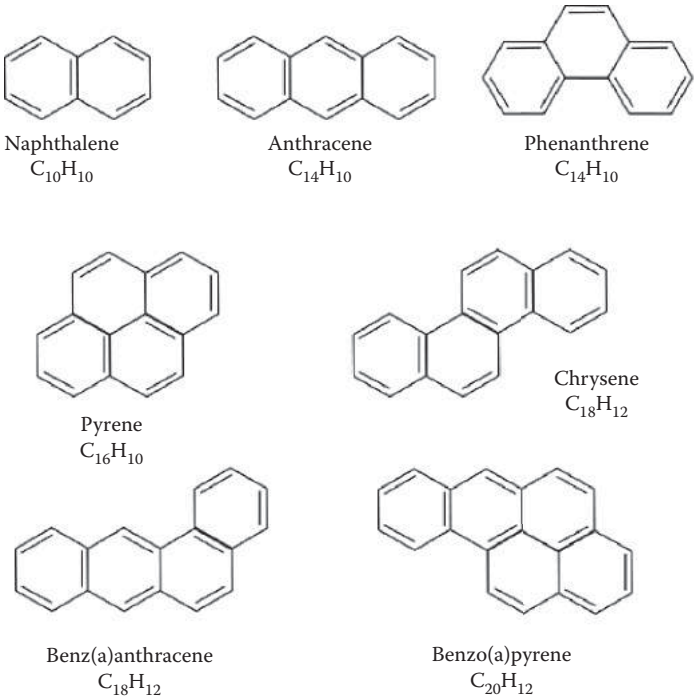


FIGURE 9.6 Structures of some common polycyclic aromatic hydrocarbons.

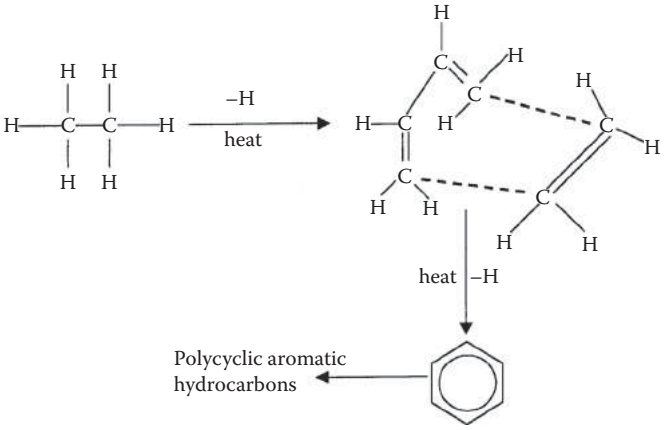


FIGURE 9.7 Formation of a PAH molecule from a simple aliphatic compound. (From Manahan, S.E., *Environmental Chemistry*, 9th ed., CRC Press, Boca Raton, FL, 2009. Copyright Lewis Publishing, an imprint of CRC Press.)

produced as a result of incomplete combustion and have been reported in gaseous emissions and fly ash from MSW incinerators. For example, incomplete combustion of saturated hydrocarbons form PAHs. At temperatures exceeding about 500°C (950°F), carbon–hydrogen and carbon–carbon bonds are broken, resulting in the formation of free radicals. The radicals are dehydrogenated and combine to form aromatic rings that are resistant to thermal degradation (Figure 9.7) (Manahan 2009).

Concentrations of PAHs on fly ash from an MSW incinerator were found to vary markedly from day to day, and the variations were consistent with those of the total concentrations of organic compounds on fly ash (Eiceman et al. 1981). Colmsjö et al. (1986) found that the concentration of PAHs in stack gases from an MSW incinerator increased by more than 1000-fold during cold start-up of the plant. Large PAH molecules were strongly adsorbed to fly ash particles. Pierce and Katz (1975) found the highest concentrations of PAHs on the smallest particulates, those <5 μm in diameter, and therefore in the respirable range. Davies et al. (1976) reported that PAHs in the stack gases from a MSW incinerator were primarily the more volatile compounds and that an electrostatic precipitator and a spray tower were capable of removing them. Incinerators operating under conditions for optimum destruction of PCDDs and PCDFs should also markedly reduce PAH emissions. Concentrations of 21 PAH compounds from the gaseous and particulate phases in incinerator flue gas are shown in Table 9.4.

PAHs are also produced in other combustion processes, including wood burning, operation of gasoline engines, sewage sludge incineration, and coal burning.

9.4.7 Toxic Metals

The escape of heavy metals with emission gases is a significant concern with combustion of MSW. Mercury, cadmium, and lead have been the most studied, represent the metals of most urgent health concern, and are regulated under the Clean Air Act.

Mercury as an atmospheric pollutant is especially difficult to control because it readily volatilizes and escapes with incinerator flue gases. Furthermore, different species of mercury possess different physical and chemical properties and thus, behave quite differently in air pollution control equipment and in the atmosphere. Emissions of mercury from waste incinerators are approximately 10%–20% elemental mercury (Hg°) and 75%–85% divalent mercury (Hg^{2+}), which may be predominantly $HgCl_2$. In comparison, emissions of mercury from coal combustion sources are approximately

TABLE 9.4
Concentrations of 21 PAH Compounds from the Gaseous Phase and Particulate Phase in Incinerator Flue Gas

Compound	Gaseous Phase (μg/nm³)	Particulate Phase (μg/nm³)	Total (μg/nm³)
Naphthalene	1086	3.61	1090
Acenaphthylene	111	0.689	112
Acenaphthene	3.96	0.228	4.19
Fluorene	4.39	0.079	4.47
Phenanthrene	25.0	0.203	25.4
Anthracene	23.7	0.66	24.4
Fluoranthene	3.77	0.53	4.27
Pyrene	1.42	1.29	2.71
Cyclopenta[*c,d*]pyrene	0.003	0.006	0.009
Benz[*a*]anthracene	0.402	4.65	5.05
Chrysene	0.075	0.544	0.618
Benzo[*b*]fluoranthene	0.070	0.920	0.989
Benzo[*k*]fluoranthene	0.170	1.47	1.64
Benzo[*e*]pyrene	0.684	3.03	3.71
Benzo[*a*]pyrene	0.754	2.53	3.28
Perylene	0.944	1.85	2.79
Ideno[1,2,3,-*c,d*]pyrene	0.024	0.055	0.79
Dibenzo[*a,h*]anthracene	0.306	1.24	1.54
Benzo[*b*]chrysene	0.069	0.163	0.232
Benzo[*ghi*]perylene	0.119	0.991	1.11
Coronene	0.461	2.35	2.81
Total PAHs	1260	27.1	1290

Source: Reprinted from *Atmos Environ*, 36, Lee, W.-J. et al., Emission of polycyclic aromatic hydrocarbons from medical waste incinerators, 781–790, Copyright 2002, with permission from Elsevier.

20%–50% Hg° and 50%–80% divalent mercury (Carpi 1997). The emission of mercury from combustion facilities depends not only on input composition but also on the species in the exhaust stream and type of air pollution control equipment in use. The partitioning of mercury in flue gas between the elemental and divalent forms may be dependent on the concentrations of particulate carbon, HCl, and other pollutants in stack emissions. In a study by Nishitani et al. (1999), the proportion of $HgCl_2$ (i.e., $HgCl_2$/total Hg) increased with increasing HCl concentration.

A number of elaborate technologies are in use for removal of Hg from stack gases; however, all are very expensive. Air pollution control equipment for mercury removal includes activated carbon injection, sodium sulfide injection, and wet lime or limestone flue gas desulfurization. Although Hg^{2+} is water soluble and may be removed from the atmosphere by wet and dry deposition close to combustion sources, the combination of a high vapor pressure and low water solubility facilitates long-range transport of Hg^{o} in the atmosphere. Elemental mercury is eventually removed from the atmosphere by dry deposition onto surfaces and by wet deposition after oxidation to divalent mercury (Carpi 1997). Changes in mercury speciation upon passing through a dust collector were investigated by Nishitani et al. (1999). A portion of Hg° was converted to $HgCl_2$ when flue gas passed through a fabric filter. Clearly, however, the preferred solution to reduce quantities of Hg in incinerator flue gas is to prevent its entry into the waste stream. Household battery collection programs and the virtual elimination of mercury from batteries, thermometers, and thermostats in the 1990s have resulted in a substantial decrease in atmospheric mercury emissions.

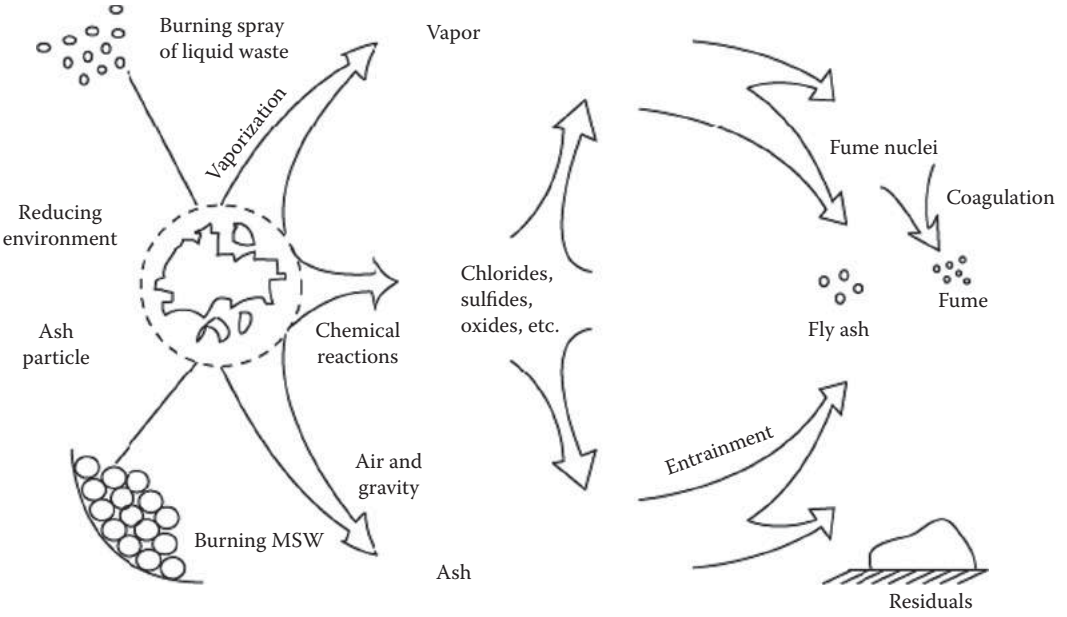


FIGURE 9.8 Transformations of inorganics during combustion of MSW. (From U.S. EPA, *Operational Parameters for Hazardous Waste Combustion Devices*, EPA/625/R-93/008, Office of Research and development, Cincinnati, OH, 1993.)

Cadmium is another toxic metal that may be volatilized and therefore mobilized in a mass-burn incinerator. In a study by Zhang et al. (2001), average Cd losses from a laboratory-scale system combusting assorted waste types were 69% and 74% at 850°C and 1000°C, respectively. Twenty other metals were additionally lost to the atmosphere. At 500°C, Sn was emitted; at 850°C, K, Mg, Na, Bi, Cr, Ge, Li, Pb, Sn, Tl, and Zn were released; and nine more metals, Al, Be, Cs, Nb, Sb, Sr, Th, Y, and Zr were lost at 1000°C. It was speculated that the released metals were transferred to the combustion flue gas, mainly in the forms of metallic chloride compounds, for example, $CdCl_2$, $SnCl_4$, $SnCl_2$, $ZnCl_2$, and $PbCl_2$. No significant losses for Ca, Fe, Ag, Ba, Co, Cu, Ga, Hf, Mn, Mo, Ni, Rb, Sc, Ta, Ti, U, V, and W were reported. Transformations of inorganic substances during MSW combustion are depicted in Figure 9.8.

Several studies have been conducted on the effects of atmospheric emissions from MSW incinerators on soil and plants. For example, Morselli et al. (2002) found that heavy metal (Hg, Cd, Pb, Cr, Mn, Cu, Zn) concentrations in soil and vegetation showed a clear dependence on sampling year; a dependence on the distance from the incinerator was also apparent. Kukkonen and Raunemma (1984) found that the concentrations of Br, Ca, Cl, Cr, Fe, Ni, Pb, Si, Ti, V, and Zn on birch leaves showed a strong inverse correlation with distance from an MSW incinerator in Finland.

9.4.8 Aesthetics

Noise is inevitable during MSW incineration. Waste collection vehicles, processing equipment, the combustion process itself, air pollution control (e.g., operation of pumps), and production of steam or other energy all produce noise. Therefore, worker safety must be addressed and the facility should be sited such that local populations are considered.

MSW is odoriferous. Organics generated by decomposition of putrescibles can be detected at low concentrations, in ambient air, and over substantial distances. The most significant sources

of odor are the tipping floor, storage pits, and shredders. Sometimes the gases will carry a strong odor. The extent of odor production and dispersal (and therefore effects on workers and local populations) is related to air temperature, barometric pressure, humidity, wind direction, and wind speed.

The ideal odor control scenario is to contain them within the facility boundary. One possible solution is to apply negative air pressure (suction) within the tipping area and recycle the collected air back into the incinerator. The gases can also be passed through a charcoal filter system that will capture foul-smelling organic vapors. An additional precaution to reduce odor production is to require collection vehicles to keep compartments closed except only when tipping wastes. One of the best preventative actions for odor impact, however, involves proper siting of the facility. Residential neighborhoods and other sensitive areas must be avoided. The facility is best sited in an area zoned for heavy industry.

9.5 AIR POLLUTION CONTROL

There is a wide range of incinerator air pollution control devices available, ranging from a series of simple baffles to trap particulates, to scrubbers designed to remove certain acid gases. Many of these technologies, although high in capital cost, are extremely effective in removing specific pollutants. The proper choice of equipment depends not only on desired emission quality and quantity but also on conditions outside the incineration system. For example, a lack of local water supply will restrict the use of wet scrubbers.

9.5.1 Electrostatic Precipitator

Many large municipal incinerators use the electrostatic precipitator (ESP) for flue gas cleaning, specifically for the removal of particulate matter (Figure 9.9). The ESP can remove particles down to fractions of a micron and are about 99% effective.

The stream of "dirty" gas passes through a series of discharge electrodes (Figure 9.10) that are negatively charged, usually in the range of 1000–6000 V. At this voltage, a *corona*, or cloud of charge, is generated. Most particles passing through this corona, regardless of the initial composition, will acquire a negative charge. A grounded (positive) surface, or collector electrode, is situated near the discharge electrode. The negatively charged particulates will be attracted to and collect on the grounded surface. The particulate matter is removed from the collector surface by cutting off the voltage to each electrode and then striking them with rappers at regular intervals or by wetting the plates. In some cases, particulates may physically or chemically resist changing charge. These will pass through the ESP without being captured.

The advantages of using the ESP for flue gas cleaning include:

- Highly efficient removal of particulates.
- Relatively insensitive to high effluent gas temperatures.
- No wastewater treatment requirements.

Disadvantages include:

- High capital costs (a simple model may cost several million dollars).
- Large space requirements.
- The ESP is often sensitive to the chemical composition of flue gas. Acid gases will corrode metallic components.
- Equipment is needed for the collection of captured particulate matter.
- Extensive electrical equipment is needed.

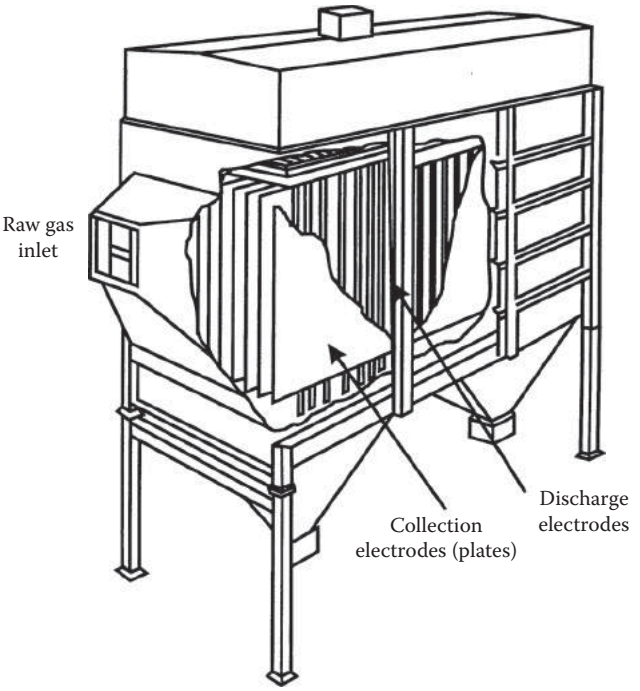


FIGURE 9.9 Electrostatic precipitator. (From U.S. EPA, *Air Pollution Engineering Manual*, 2nd ed., AP-40, NTIS PB-225132, Office of Air Quality Planning and Standards, U.S. EPA, Research Triangle Park, NC, 1973.)

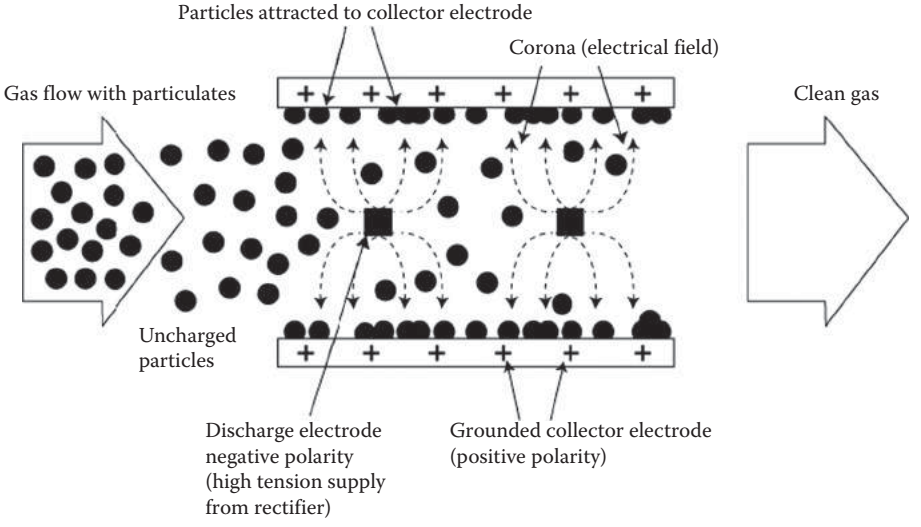


FIGURE 9.10 Electrodes within the ESP. (From Williams, T., *Waste Treatment and Disposal*, McGraw-Hill, New York, 1998. Reproduced with kind permission of John Wiley & Sons.)

9.5.2 Fabric Filters (Baghouses)

The baghouse is one of the oldest, simplest, and most efficient methods for removing solid particulate contaminants from gas streams, by using simple filtration through fabric media. The baghouse is constructed as a series of permeable bags that capture particulate matter but allow passage of gases (Figure 9.11). The filter fabric is composed of heat-resistant material ranging from cotton to

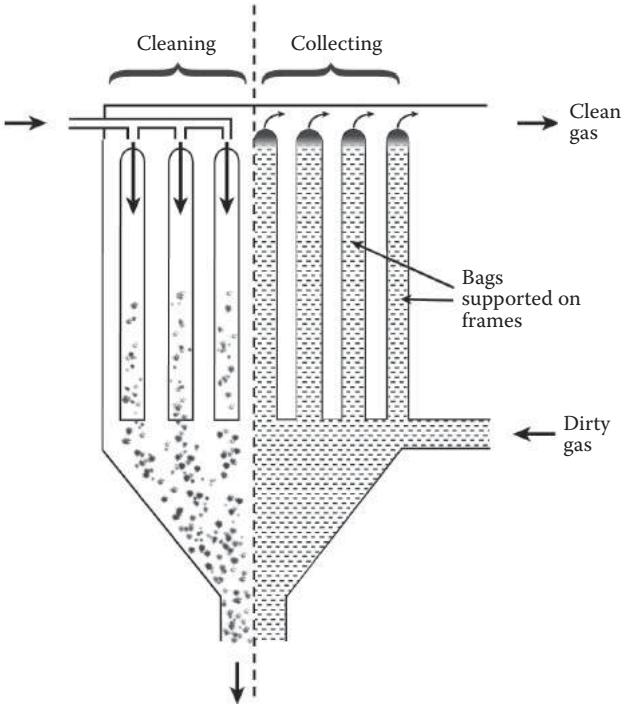


FIGURE 9.11 Schematic of a baghouse for particulate removal. (Adapted from Williams, T., *Waste Treatment and Disposal*, McGraw-Hill, New York, 1998. Reproduced with kind permission of John Wiley & Sons.)

TABLE 9.5
Baghouse Fabric Ratings

		Chemical Resistance	
Fabric	**Recommended Maximum Temperature, °C**	**Acid**	**Alkali**
Cotton	81	Poor	Fair
Wool	103	Good	Poor
Nylon	103	Good	Poor
Dacron	134	Excellent	Good
Glass	285	Excellent	Excellent

nylon to glass fibers (Table 9.5). The choice of the fabric is determined by the operating temperature range, chemical composition of the flue gas, moisture, and the physical and chemical properties of the particles being collected.

The filter bags are usually tubular or flat. The structure in which the bags hang is the baghouse, and the number of bags may vary from less than ten to several thousand. The baghouse system can be operated continuously, with airflow to some bags turned off for cleaning and maintenance. In bottom-feed units, flue gases are introduced through the baghouse hopper at the base and then to the interior of the bag (Figure 9.11).

The baghouse filter fabric is typically woven with relatively large spaces, about 50 μm across. However, these filters are capable of capturing particulates measuring <1 μm; obviously, processes beyond simple sieving are taking place. Capture of particulates apparently occurs as a result of electrostatic attraction, as well as entrapment within the fabric weaving.

Within the woven fabric, a dust cake eventually forms, which, in turn, acts as an effective sieving mechanism. When felted fabrics are used, this dust cake is minimal or nonexistent, and the primary filtering mechanisms are a combination of inertial forces and impingement (Vesilind et al. 2002).

As particles are collected, the pressure decreases across the fabric filtering media; therefore, the filter must be cleaned at predetermined intervals. Dust is removed from the fabric by gravity or mechanical means. When large numbers of bags are involved, the baghouse is compartmentalized so that one compartment may be cleaned while others are still in service.

The efficiency of baghouses for fly ash removal can be improved by use of a dry scrubber upstream. It is suggested that scrubbers, which remove acidic constituents by introduction of alkaline (e.g., lime) slurry into the flue gas, increase agglomeration of fly ash particles, thus further improving collection efficiency.

Example 9.3

A baghouse from a mass-burn incinerator unit holds a total of 50 bags for particulate removal. A single bag is cylindrical in shape and measures 25 cm diameter and 6 m length. What is the filtering area of the bag?

If the baghouse unit (50 bags) is to treat 15,000 m^3/h of flue gas, calculate the effective filtration velocity in meters per minute and the mass of particles collected daily if the inlet loading is 120 g/m^3 and the unit operates at 99.99+% collection efficiency. Note that 1 kg of collected residue is ~15,430 grains.

Solution

The total area of the bag is calculated as (Reynolds et al. 2002)

$$A = A_{\text{curved surface}} + A_{\text{flat top}} \tag{9.13}$$

$$= \pi Dh + \pi D^2/4$$

$$= \pi \times [(25\text{ cm}/100) \times (6\text{ m}) + \pi \times (25\text{ cm})^2/100]/4$$

$$= 4.76\ m^2$$

where D = bag diameter

The combined area for the 50 bags is

$$A = (50)\ (4.76) = 238\ m^2$$

The filter velocity is then

$$V = qG/A \tag{9.14}$$

$$= [15{,}000\ m^3/60)]/238$$

$$= 1.05\ m/min$$

If we assume 100% collection efficiency, the mass collected daily is

$$\text{Mass collected} = q_G C_i = (15{,}000)(24)(120)/15{,}430$$

$$= 2800\ kg/day$$

The advantages of a baghouse for cleaning flue gas include:

- High particle removal efficiencies over a wide range of particle sizes.
- Variations in loading and flow rates do not affect removal efficiency.
- Corrosion and rusting are minimized because the bags are manufactured from resistant materials.
- Simple operation and maintenance.
- Flexible designs are possible.

Disadvantages include:

- The adhesion and accretion of hygroscopic material. These accretions will block filter pores and waste energy.
- High temperatures, acids, and alkalis within the flue gas tend to shorten fabric life.
- There is the potential for fire and explosion if oxidizable particulates accumulate.
- Gases are not removed.

9.5.3 Gas Washing

Wet scrubbers have become popular for cleaning contaminated gas streams because of their ability to remove effectively both particulate and gaseous pollutants. Wet scrubbing involves bringing a contaminated gas stream into intimate contact with a liquid introduced as a finely atomized mist. The most common low-energy scrubbers are gravity spray towers in which liquid droplets, often simply cold water or a dilute alkaline solution, fall through rising exhaust gases and is drained at the base of the chamber into a wastewater collector (Figures 9.12 and 9.13). The droplets are usually formed by liquid atomized in an array of spray nozzles. The hot flue gas enters from the bottom of the unit and rises. The vertical gas velocity ranges from 75 to 150 cm/s (2 to 5 ft/s). For higher velocities, a mist eliminator should be installed at the top of the tower (Figure 9.12). Particulate matter is wetted immediately upon entering the chamber and falls out by gravity. Gases such as H_2SO_4, HNO_3, and HCl readily dissolve in the mist, forming the corresponding aqueous acids that also fall out by gravity. The spray water continuously washes the walls of the chamber.

Sulfur dioxide is one of the most common gaseous pollutants from MSW combustion, as well as from other sources such as coal combustion. For decades, coal-burning utilities and other significant emitters of SO_2 have condensed SO_2 to sulfuric acid as the primary means for removal from stack gas. SO_2 is relatively soluble in water; once dissolved, the acidic liquid is collected and treated for disposal. The reactions for SO_2 capture are identical to those for acid rain formation, given earlier:

$$SO_2 + ½\ O_2 \rightarrow SO_3 \tag{9.15}$$

$$SO_3 + H_2O \rightarrow H_2SO_{4(aq)} \tag{9.16}$$

A quicklime or limestone solution can also be prepared to absorb the SO_2. The reaction with quicklime is

$$SO_2 + CaO \rightarrow CaSO_{3(s)} \tag{9.17}$$

The reaction with limestone is

$$SO_2 + CaCO_3 \rightarrow CaSO_{4(s)} + CO_2 \tag{9.18}$$

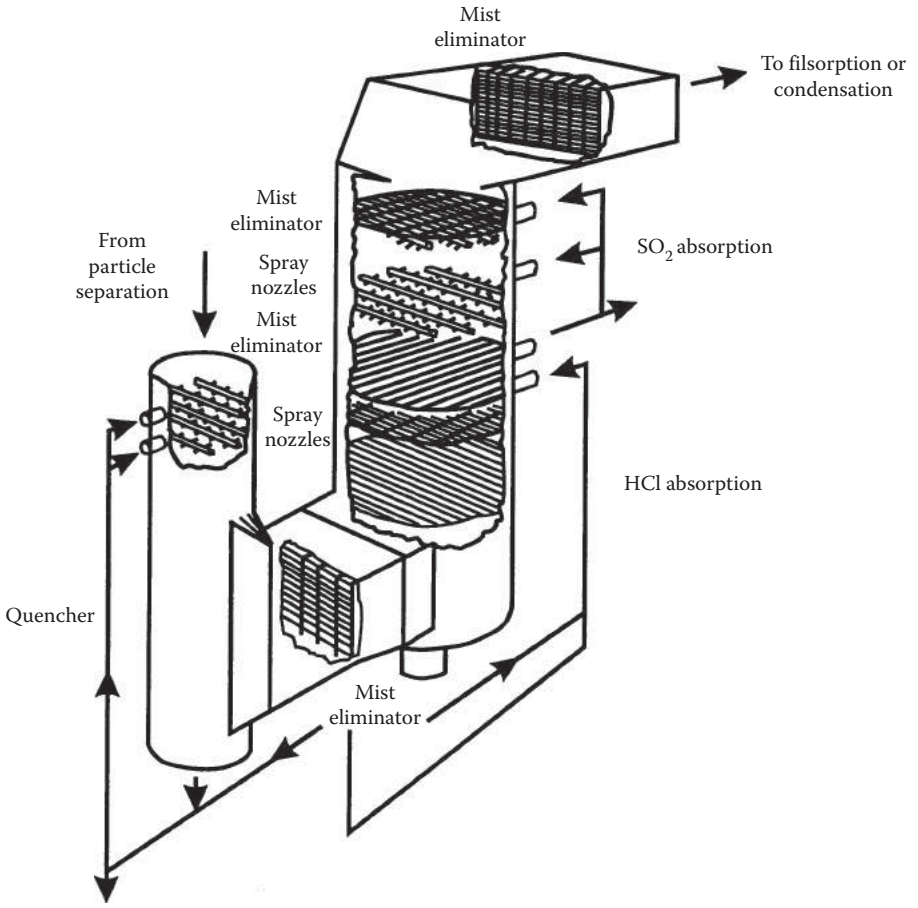


FIGURE 9.12 Scrubber (packed tower) for washing acid gases. (From U.S. EPA, *Operation and Maintenance of Hospital Medical Waste Incinerators*, EPA/625/6-89/024, Center for Environmental Research Information, Cincinnati, OH, 1990.)

Lime materials can be injected directly into the scrubber or added to the combustion chamber. If limestone is injected into the furnace, it quickly reacts to form quicklime:

$$CaCO_3 \rightarrow CaO + CO_2 \tag{9.19}$$

Both calcium sulfite ($CaSO_3$) and calcium sulfate ($CaSO_4$) are solids of low solubility that can be separated in gravity settling tanks. The calcium salts formed create a new problem, i.e., the disposal of enormous quantities of solid waste, actually a high water content slurry. In some facilities, the flue gas desulfurization sludge is simply stored in ponds on company property. There is much ongoing research regarding beneficial use of this sludge. Possible applications include use as an agricultural amendment (Sakai et al. 2004), reclamation of coal mine spoils (Kost et al. 2005), low-permeability liners (Cheng et al. 2007), roadway construction (Friend et al. 2004), and incorporation in building panels (drywall). Based on the discussions above, flue gas may contain heavy metals and other inorganic contaminants; treatment of the scrubbing effluent must address these as well. At an MSW incinerator in Germany, Reimann (1995) used a combination of lime and trimercaptotriazine in a two-stage process to remove mercury, other heavy metals, and salts from the scrubbing medium. The treated effluent met Germany's stringent discharge requirements.

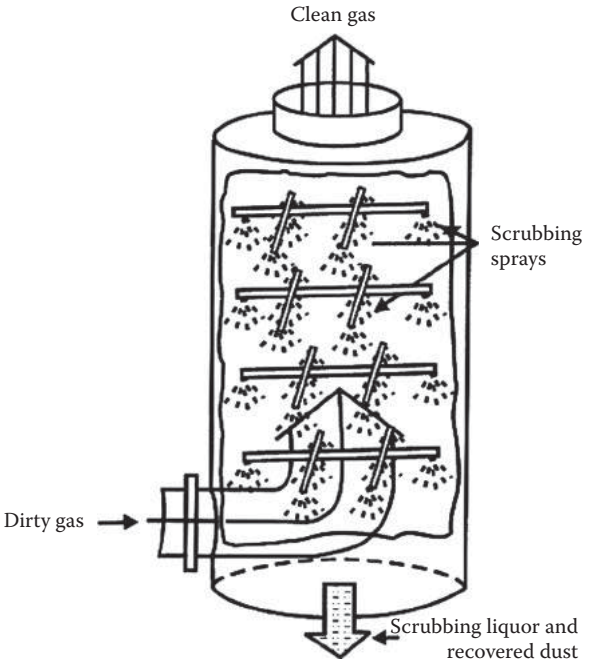


FIGURE 9.13 Gravity spray tower scrubber for washing acid gases. (From U.S. EPA, *Operation and Maintenance of Hospital Medical Waste Incinerators*, EPA/625/6-89/024, Center for Environmental Research Information, Cincinnati, OH, 1990.)

Advantages of gas washing include:

- Simultaneous removal of acid gases as well as particulates. It is recommended, however, that particulates be removed first (e.g., using a baghouse). Early particulate removal promotes more efficient gas scrubbing.
- The system, fed by a liquid mist, accommodates high-temperature flue gas streams.
- The scrubbing medium can be modified to increase removal efficiencies. For example, a dilute NaOH solution can be used in place of water for the treatment of especially acidic flue gases.

Disadvantages:

- A high input of energy is required, primarily to pump liquids into and out of the system.
- A constant supply of water is necessary.
- Since aqueous acids and alkalis are formed, equipment corrosion is inevitable. Maintenance costs therefore may be substantial.
- Large quantities of wastewater are produced. This liquid must be treated prior to discharge into a receiving body of water.

9.6 ASH QUALITY FROM MASS BURN

Incinerator residues consist of noncombustible materials such as metal, glass and stones, and also incompletely burned combustibles. MSW incinerators produce two types of ash: (1) bottom ash, i.e., the large, dense debris that falls through grates by gravity and collects at the base of the combustion chamber; and (2) fly ash, the fine particles transported out of the combustion chamber with the air stream, which are removed by air pollution control devices. Most facilities combine the two ash types for disposal.

Incinerator fly ash and bottom ash pose hazards to public health and the environment. If preprocessing of MSW does not occur, a number of concerns exist regarding the generation, storage, and ultimate disposal of MSW ash. These are outlined in the following sections.

The composition of a typical MSW ash sample is shown in Table 4.14. The predominant health and environmental concern with incinerator ash is its content of heavy metals. Table 9.6 lists a representative array of heavy metals found in combined fly ash and bottom ash from an MSW waste-to-energy unit.

TABLE 9.6
Concentration Ranges of Elements in MSW and Bottom Ash, Fly Ash, and Suspended Particulates from MSW Incineration

Element	MSW (Combustible Fraction)	Bottom Ash	Fly Ash	Suspended Particulates	Possible Carcinogens
Ag	<3–7		52–220	84–2000	
Al (%)	0.54–1.17	2.6–14.2	9.0–14.2	0.58–4.8	
As			9.4–74	81–510	X
Ba	47–447	80–9000	1600–360	40–1700	
Be	<2				X
Bi	<15–30				
C (%)		1.0–28.7	1.7–7.4	1.8–2.2	
Ca (%)	0.59–1.65	3.6–11.2	3.3–8.6	0.66–5.3	
Cd	4–22	3.8–442	<1–477	520–2100	X
Cl		0.2–1.0	0.12–1.12	9.29	
Co	<3–5		25–54	3.8–28	
Cr	22–96		730–1900	122–1800	X
Cu	79–877	630–4281	69–2000	3000	
F	140–200	130–250	1500–3100	990–6800	
Fe (%)	0.10–0.35	2.1–32	2.4–8.7	0.17–1.8	
Hg	1–4.4	0.03–3.5	0.09–25	20–2000	
K (%)	0.09–0.21	0.42–2.41			
Mg (%)	0.09–0.21	0.04–0.86	0.5–2.1	0.31–2.8	
Mn (%)	0.005–0.02	0.08–39	0.20–0.85	0.03–0.57	
Mo					
N (%)		0–0.35	0		
Na (%)	0.18–0.74	2.3–14.2	1.12–1.94	5.1–9.8	
Ni	9–90	110–210	38.6–960	65–440	X
P (%)		0.04–0.83			
Pb (%)	0.01–0.15	0.04–0.80	0.06–0.54	2.5–15.5	X
S (%)		0.27–1.0	1.9–3.6	0.001–0.01	
Sb	20		139–760	610–12000	
Se			1.4–13	7.0–122	
Si (%)		4.7–9.4			
Sn (%)	<0.002–0.004	0.01–0.1	0.12–0.26	0.4–1.51	
Sr	11–35		110–220		
Ti (%)	0.14–.31	0.04–0.90	2.5–4.2	0.13–1.29	
Tl				150	
V			110–166	6–60	
Zn (%)	0.02–0.25	0.35–3.61	0.08–2.6	4.7–24	

Source: Reprinted from *Sci Total Environ*, 74, Lisk, D.J., Environmental implications of incineration of municipal solid waste and ash disposal, 39–66, Copyright 1988, with permission from Elsevier.

Based on chemical composition and leachability of certain components, MSW ash may technically be classified as a hazardous waste by EPA. As discussed below and in Chapter 11, the Toxicity Characteristic Leaching Procedure (TCLP) is an extraction procedure used to determine whether a solid waste may be designated hazardous. If fly ash alone is tested, its constituents often fail the test, i.e., it is designated hazardous. Combined with the bottom ash, however, the mixture often meets the requirements for a nonhazardous waste (Worrell and Vesilind 2011).

9.6.1 Metals

Ash may contain high concentrations of a number of toxic metals, including Cd, Pb, As, Be, V, and Hg, and other comparatively less toxic metals such as Cu, Zn, Fe, and Al (Table 9.6). Fly ash contains several thousand times more lead and cadmium than bottom ash; however, the concentrations in bottom ash still greatly exceed the amounts measured in uncontaminated soils. These elements are concentrated in the ash via the incineration process. Incineration destroys the matrix materials, such as paper and plastics that contained the metals and had restricted their release to the biosphere. Once in the form of ash, metals become much more bioavailable. Metals such as lead and cadmium are readily leachable from ash at levels that frequently exceed federal limits for defining a hazardous waste.

Many consumer products contribute toxic metals to the municipal waste stream. Arsenic may originate in paint, ceramics, and obsolete insecticides. Chromium may originate from metal plating and occurs in plastics, inks, and paints. Mercury occurs in batteries, fungicides, newspapers, paints, and plastics. Batteries, plastics, and various pigment formulations contribute lead and cadmium to MSW. Recycling of batteries via specialized collection systems and prohibition on disposal are practical approaches to reducing the quantity of toxic metals in the waste stream. Such approaches are more difficult to implement for plastics and pigments, however.

9.6.2 Health Effects of Metals in Incinerator Ash

Ash may be dispersed into the workplace or the local environment at all stages of ash management, including during on-site handling and storage, transport, and handling at the disposal site. At each step, the potential exists for airborne and waterborne dispersal of ash. Most metals of concern can be adsorbed by soils and sediments and many accumulate in living tissue; therefore, heavy metals persist in the biosphere. Thus, long-term releases, even at low levels, can substantially increase metal levels in the environment. Figure 9.14 presents possible exposure routes for air emissions from MSW incinerators and incinerator ash.

Many heavy metals have well-defined health effects. Several are carcinogenic; however, they also exert neurological, hepatic, renal, hematopoietic, and other adverse effects, both in humans and in other biota. As, Cd, Be, and Pb are carcinogenic; As, Pb, V, Cd, and Hg are neurotoxins; Zn, Cu, and Hg are acutely toxic to aquatic life. More detailed effects of these and other metals are discussed in several excellent works (see Suggested Readings). Total metal concentrations provide only a partial picture of the relative risk associated with heavy metals, however. Other methods are necessary to better understand the behavior of metals in the biosphere, for example, in a landfill, surface impoundment, or as fine dust attached to plant tissue.

9.6.3 Leachability of Metals in Incinerator Ash

In the high-temperature zone of the incinerator, many metals are vaporized. For example, cadmium and mercury boil at 765°C (1412°F) and 355°C (674°F), respectively. As combustion gases cool, metals condense onto the surface of fly ash particles. The concentrations of these condensed metals increase with decreasing ash particle size.

If ash containing metal-coated particulates comes into contact with ambient moisture, for example, leachate within a landfill, some metals will become mobilized. The small particle size of ash increases

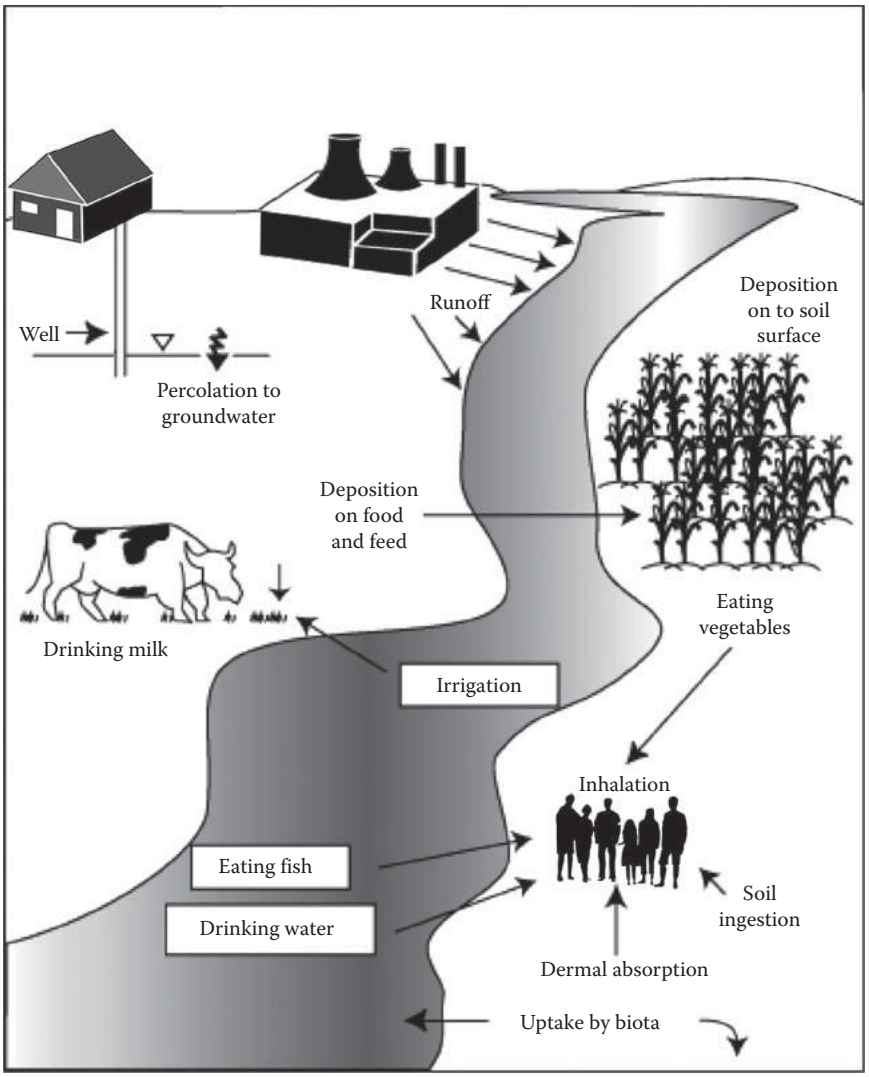


FIGURE 9.14 Exposure pathways for emissions from an MSW incinerator. (From U.S. EPA, *Methodology for the Assessment of Health Risks Associated with Multiple Pathway Exposure to Municipal Waste Combustor Emissions,* Office of Air Quality Planning and Standards, U.S. EPA, Research Triangle Park, NC, 1986.)

the surface area exposed to leaching, and the presence of metals at or near the particle surface further enhances leachability. An additional factor contributing to metal leachability involves conversion to soluble salts. MSW contains significant amounts of chlorine from plastics, bleached paper, and other sources. During incineration, the chloride ion combines with metals to form metal chlorides:

$$M^{2+} + 2Cl^- \rightarrow MCl_{2\,(aq)} \tag{9.20}$$

where M^{2+} is cationic metal species.

These salts tend to be significantly more soluble in water than in the uncharged metallic form.

Leachability of metals in incinerator ash is one estimate of hazard and relates specifically to the potential for groundwater or surface water contamination. Under federal law (40 CFR part 261), leachability is assessed using the TCLP. To perform the test, a sample of ash is exposed to a dilute

acid solution for 18 ± 2h. The concentrations of eight metals, which may have leached into solution, are measured. If a minimum permissible limit of a metal in solution is exceeded, the ash (or other test material) must be managed as a hazardous waste.

The slightly acidic conditions of the TCLP are designed to simulate conditions encountered in a typical sanitary landfill. Incinerator ash is often disposed in landfills along with raw MSW. As will be seen in Chapter 10, landfill leachate can become quite acidic as a result of microbial decomposition processes. Most metals become more soluble under conditions of increasing acidity, so metals in intimate contact with leachate will become solubilized to some extent.

The leachability of metals in incinerator ash is a function of numerous variables, for example, species of the metal. Lead occurring as $PbCl_2$ is more soluble in water than are PbO or $Pb(OH)_2$, for example (see Appendix). As mentioned above, a smaller ash particle size results in a corresponding larger particle surface area. Metal occurring on the exterior of many fine particles will more rapidly solubilize than would the same metal occurring as a single, large granule. The most important variable affecting metal mobility in ash, however, is pH of the solution in which the metal is exposed. In leaching tests of ash from several U.S. incinerators, lead and cadmium leached at high levels, often in excess of regulatory standards defining a hazardous waste (Niessen 2002).

Large volumes of incinerator ash are managed by minimally controlled means such as use as landfill cover, fill material in marshy areas, and deicing grit on winter roads. Under these management conditions, ash is susceptible to leaching.

9.6.4 Ash Management

MSW incinerator ash is hazardous because it contains high levels of toxic metals and may also contain chlorinated organics and PAHs. Ash mobility and toxicity concerns focus primarily on leachability of selected constituents from ash; in other words, how quickly will a toxic component leach and enter groundwater or some other environmental receptor? Some have questioned so-called leachability methods, however, for being incomplete in terms of assessing toxicity. Total concentrations of metals, PCDDs, and PAHs must also be considered in assessing ash toxicity, because exposure occurs via many routes. For example, humans can inhale ash particles into the lungs, after which adsorbed toxins are transported to living tissue. Ash particles may also be ingested, either directly or through contaminated food or water. Because these exposure routes can be highly significant, a full assessment of the hazards posed by ash must include data of its *total* chemical composition as well as its content of *leachable* toxins.

Reducing the hazard relating to toxins in ash requires several actions:

- Keeping toxic metals out of products that may enter the waste stream
- Keeping metal-containing materials out of incinerators
- Chemically or physically treating ash prior to disposal (e.g., mixing with Portland cement and allowing to set)
- Disposing all ash in secure facilities that do not contain other types of waste (this practice is termed *monofilling*)
- Compacting the ash prior to or during landfilling

Noncompacted MSW ash may have a density of 900 kg/m^3 (1500 lb/yd^3). If ash is compacted the density increases to as high as 1980 kg/m^3 (3300 lb/yd^3). At this density ash is highly impermeable—permeability may be as low as 1×10^{-9} cm/s (Worrell and Vesilind 2011). As more ash is being generated and landfill space is becoming increasingly scarce, alternative uses for ash are being sought. Some practical uses for ash include:

- Road base material
- Structural fill
- Gravel drainage ditches

- Capping strip mines
- Mixing with cement to make building (construction) blocks

9.7 MSW INCINERATION IN THE UNITED STATES: THE FUTURE

A number of influences are at work to sustain or expand the use of incineration in managing MSW. These include (Denison and Rustin 1990):

- Diminishing landfill capacity, especially in heavily urbanized areas of the Northeast, along with rising landfill costs and difficulties with siting.
- An aggressive marketing campaign conducted by incinerator vendors.
- A public perception that waste-to-energy is cleaner and more conserving of resources than is landfilling.
- A perception that the convenience that incineration provides is preferred (albeit more expensive) to implement than are municipal-level recycling programs.

However, a number of arguments persist regarding the nonsuitability of incineration. Factors restricting development include:

- Intense public opposition
- Unresolved risk issues relating to air emissions and ash residues
- Uncertainty over regulatory requirements
- Major long-term economic risks
- Initial high capital costs and frequent cost overruns
- Concern over the effect that a long-term commitment to incineration may have on recycling and other conservation efforts (will incineration simply support a "throw-it-away" mindset?)

9.8 REFUSE-DERIVED FUEL

During mass burning of MSW, no processing or separation of the fuel occurs other than simple mixing by the tipping vehicle. In contrast, refuse-derived fuel (RDF) technology uses a two-stage production–incineration system. Wastes are processed to produce a higher quality and more homogeneous fuel product compared with raw MSW. The input waste is usually shredded to reduce particle size. Ferrous metals are recovered using magnetic separators. Glass, stones, and soil may be removed by trommel screening. In some RDF plants, additional equipment is used to eliminate additional noncombustible materials. Final stages of processing may involve air classification to remove the lightest fractions of the charge followed by, in some cases, densification to produce fuel in pellet or briquette form. Ideally, the separated, mostly organic fraction is composed of paper products and nonhalogenated plastics; however, PVC, food waste, and yard wastes also occur. The RDF is either marketed to external customers or is burned on-site in a dedicated furnace.

The practice of selling a solid fuel derived from physical processing of MSW dates only to the early 1970s. Since then, a number of processes have evolved for RDF production and utilization. Several RDF combustion plants are in operation in both the United States and Europe. RDF facilities represent the smallest portion of the various waste-to-energy plants. The RDF-only facility came on line in 1975 and gradually increased in number through 1991. Since its peak, (29 plants), their numbers have since declined—a total of 15 were still operating as of 2008 (Psomopoulos et al. 2008). In addition to combusting RDF only, however, many more plants burn RDF as a co-fuel, that is, in a mixture with other solid fuels such as coal. Co-firing with coal in a ratio of approximately 75:25 coal:RDF is a fairly typical ratio.

Benefits of RDF utilization include diverting potentially useful organic materials from landfills; energy recovery from solid waste; and, when used as a co-fuel, reduction in a number of gaseous pollutants compared with combustion of coal alone.

9.8.1 Overview of RDF Preparation

Although other methods have been tested, so-called "dry separation" of RDF from municipal waste is by far the most common method of initial preparation. The method may be adapted to produce various qualities of fuel, depending primarily on the extent of separation of inorganic and putrescible components from paper and plastics. Because waste may undergo processing for other reasons, such as extraction of potentially recyclable metals, dry separation is a logical fit for fuel production.

In order to separate the organic fraction from metals, glass, and other dense components, it is first necessary to pass the waste through a trommel screen. The incorporation of a screen early in waste flow is used to remove stones, dirt, and putrescibles before air classification. Screening may be followed by pulverization in a hammermill or other shredding device. Separation of ferrous metals via magnetic extraction is a next logical step (see Chapter 7). Most systems for RDF production include an air classifier to divert the heavy inorganic components from the largely organic RDF. Most RDF systems in the United States incorporate all organics into the fuel, whereas many in Europe segregate mainly paper and plastics.

9.8.2 Grades of RDF

Different grades of RDF can be produced from MSW. The higher the fuel quality, the lower is the total yield of fuel. For example, if a materials recovery facility simply shreds the incoming waste and passes it under a magnetic separator to remove the ferrous component, the fuel yield may be 90%–95%, whereas the average Btu value may approximate that of raw MSW. Conversely, producing a pelletized fuel of paper and plastic may yield 50% fuel based on the total incoming waste. However, the heating value may be as much as 14,000–15,650 kJ/kg (6500–7000 Btu/lb), which is approximately two-thirds the heat value of many Midwest bituminous coal samples. Industry-wide specifications for RDF do not exist, but RDF has been classified according to the type and degree of processing and the form of fuel produced. The properties of RDF to consider and incorporate into supply contracts include the proximate analysis (moisture content, ash content, volatiles, and fixed carbon); ultimate analysis (C, H, N, O, S, and ash percentage); HHV; and content of chlorine, fluorine, lead, cadmium, and mercury (Liu and Liptak 2000).

The types of RDF produced are based upon equipment design, sequence of separation steps, and operation. The RDF forms fall into the following broad groups: coarse RDF, fluff RDF, powder RDF, and densified RDF (d-RDF). Details of the various RDF categories are provided in Table 9.7. A photograph of d-RDF is shown in Figure 9.15.

9.8.3 Properties of RDF

Chemical analysis of RDF samples provides an indication of the combustion performance that might be expected. Heat content (Btu/lb) is obviously one of the top priorities in RDF production. Total sulfur, nitrogen, and chlorine contents are a guide to possible gaseous emissions problems. Similarly, concentrations of heavy metals help to predict the chemical properties of the resultant ash. Total ash content will guide ash-handling protocols and may also help forecast particulate generation rates. Moisture content provides an indication of burnability, as well as ease of handling and shipping. Variations in physical and chemical properties of RDF due to differing sources, time of year, and methods of waste sorting make it difficult to present average analysis values; however, Table 9.8 provides a comparison between RDF and coal as fuels.

RDF has a calorific value of 50%–60% and a bulk density of 65%–75% that of bituminous coal (Table 9.8). As a consequence, considerably larger quantities of RDF must be burned to obtain performance similar to that obtained with coal. Optimization of fuel feeding and firing parameters must also be determined. The higher ash content of RDF and lower ash fusion temperatures may require modifications to ash storage and removal procedures.

TABLE 9.7
Major Categories of RDF

RDF-1 (MSW)	Raw MSW with minimal processing to remove oversize bulky waste.
RDF-2 (coarse RDF, c-RDF)	MSW processed to a coarse particle size with or without ferrous metal separation such that 95% by weight passes through a 6 in. square mesh screen.
RDF-3 (fluff RDF)	Shredded fuel derived from MSW processed for the removal of metal, glass, and other entrained inorganics; particle size of this material is such that 95% by weight passes through a 2 in. square mesh screen.
RDF-4 (powder RDF, p-RDF)	Combustible waste fraction processed into powdered form such that 95% by weight passes through a 10 mesh screen (0.035 in. square).
RDF-5 (densified RDF)	Combustible waste fraction extruded (densified or compressed) into pellets, cubettes, briquettes or similar forms. This form has become increasingly popular owing to the advantages of ease and cost of transportation and storage, as well as of adaptability to certain types of firing.
RDF-6	Combustible waste fraction processed into a liquid fuel.
RDF-7	Combustible waste fraction processed into a gaseous fuel.

Source: ASTM International, 1988, *Standard Definitions of Terms and Abbreviations Relating to Physical and Chemical Characteristics of Refuse Derived Fuel*, E856-83, Copyright ASTM International, West Conshohocken, PA.



FIGURE 9.15 Two types of densified RDF: pellets and cubettes.

TABLE 9.8
Analysis of Fuel Used in Boiler Tests

	RDF Pellets	Bituminous Coal
Calorific value, Btu/lb	8110	14,600
Moisture,%	9.6	9.2
Ash,%	8.1	6.2
Carbon,%	45.6	69.0
Hydrogen,%	6.3	4.8
Sulfur,%	0.3	1.8
Chlorine,%	1.8	0.02

The sulfur content of RDF is often significantly lower, in some cases less than 1/100 that of coal. Thus, there are obvious benefits in terms of air quality with co-combustion of RDF and coal. On the other hand, the chlorine content of RDF is higher than that of typical coals. The higher Cl content results from the presence of PVC in MSW; the presence of Cl in paper waste from the bleaching process; and other Cl-containing materials, for example, NaCl.

9.8.4 Utilization of RDF: Practical Issues

Densified RDF or *d-RDF* is available as a fuel immediately after processing, or is mixed with coal in the field (Figure 9.16), and is introduced to the loading hopper of a burner equipped to handle solid fuels (Figure 9.17). For RDF utilization to be successful, whether burned alone or as a co-fuel with coal, however, various potential difficulties must be addressed. For example, many coal-burning plants have experienced problems in handling, storing, and conveying materials; for starters, RDF is less dense than coal. It has been found that when coal and RDF are mixed and stored for long periods, the denser coal tends to sink to the bottom of the mixture. If the stratified mix enters the burner hopper, uneven combustion will take place, as the RDF is burned first and the coal second. Such uneven burning will cause fluctuations in steam production. This segregation problem can be partly alleviated by mixing the fuels in the field immediately prior to burning (Figure 9.16).

RDF may cause problems in storage. It is fibrous, carbonaceous, and of relatively low density. Contact with rainfall will rapidly alter its physical and chemical properties. Pelletized RDF will decompose, will lose its physical strength, and can no longer be easily handled. Additionally, wet material will rapidly undergo anaerobic reactions. RDF has many fine pores that will tenaciously retain moisture. Foul odors will be produced, and conditions will favor growth of mold and other undesirable organisms. The best precaution against this scenario is to store RDF indoors or in a covered facility in the field. Furthermore, storage should not be prolonged—ideally, RDF should be burned within 24 h of its production. Poslusny et al. (1987) found that addition of a $Ca(OH)_2$ binder to pellets during initial processing was successful in lengthening storage life of pellets.



FIGURE 9.16 Piles of coal and RDF to be mixed in the field prior to shipment to heating plant.



FIGURE 9.17 Truck loading a coal–RDF mixture for combustion at a heating plant.

Dust production is inevitable with storage and handling of dry RDF; therefore, dust control equipment must be provided within both the combustion and the storage areas. Forced ventilation combined with air filters is strongly recommended.

It should be clear by now that mechanical separation of MSW components is by no means 100% effective; contamination of RDF by food and yard waste and other undesirable components will occur. As a result, odor production is inevitable in stored RDF, particularly during warmer months. The RDF must, therefore, not be stored in the boiler building for extended periods; rather, it should be loaded into the building daily for combustion.

In a study by Fiscus et al. (1978), total airborne bacteria concentrations were measured in waste-handling facilities, including an RDF plant, incinerator, landfill, transfer station, waste collection vehicle, and wastewater treatment plant. The highest bacterial concentrations were detected in the RDF plant. Mahar (1999, 2002) studied the atmospheres in several locations within two RDF facilities. The data for particulate matter appear in Table 9.9, and those for total bioaerosols and endotoxins appear in Table 9.10. The particulates detected occurred primarily in the nonrespirable size range. Biologically derived particulates were measured in larger quantities in areas where the waste had been processed as opposed to stored.

TABLE 9.9
Particulate Comparisons[a] (mg/m³) in Different Areas of an RDF Plant

Location	Inhalable Particles	Total Particles	Respirable Particles
Floor	2.24 (7)	1.15 (6)	0.09 (7)
Loadout	0.52 (2)	0.15 (2)	0.04 (2)
Lunchroom	0.13 (3)	0.06 (3)	0.07 (3)
Magnetic separator	3.06 (4)	1.26 (4)	0.10 (4)
Processing	0.73 (4)	0.38 (3)	0.16 (4)

Source: Mahar, S., *Waste Manag Res* 17, 343–346, 1999. Reproduced with kind permission of the International Solid Waste Association.

[a] Geometric mean, n

TABLE 9.10
Comparisons of Bioaerosol[a] (10^{-6}/m³) and Endotoxin (EU/m³) Concentrations within an RDF Plant

Location	Total Bioaerosols[b]	Total Endotoxin[c]	Respirable Endotoxin[c]
Floor	0.08 (7)	38.1 (6)	0.70 (7)
Loadout	0.15 (2)	7.81 (2)	3.70 (2)
Lunchroom	0.13 (3)	1.02 (3)	0.89 (3)
Magnetic separator	3.22 (4)	72.0 (4)	12.9 (3)
Processing	0.58 (4)	2.80 (3)	3.09 (4)

Source: Mahar, S., *Waste Manag Res* 17, 343–346, 1999. Reproduced with kind permission of the International Solid Waste Association.

[a] Geometric mean, n.

[b] Bioaerosols, × 10^{-6} per m³;

[c] Endotoxins, EU per m³.

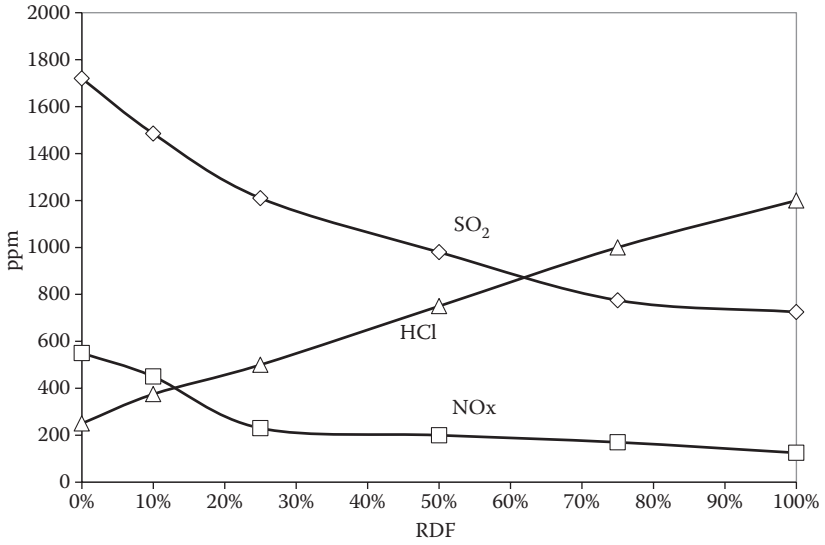


FIGURE 9.18 Concentration of gaseous SO_2, NO_x, and HCl with varied coal/RDF ratios.

9.8.5 Gaseous Emissions and Corrosion Issues

When combusting fuel containing 100% RDF, emissions of acid gases and hydrocarbons were consistently lower compared with emissions from combustion of bituminous coal alone (Pichtel 1991). Oxides of sulfur and NO_x measured approximately 700 and 200 mg/m^3, compared with 1600 and 550 mg/m^3, respectively, for coal emissions. When increasing proportions of RDF were added to a mixture with Illinois bituminous coal, concentrations of SO_2 and NO_x consistently declined (Figure 9.18) (Pichtel 1991). In contrast, total HCl concentrations increased in flue gas. These data correlated with fuel composition.

As is the case with mass-burn incineration of MSW, production of undesirable gaseous organic compounds from RDF combustion is a significant concern. A number of studies (U.S. EPA 1985a, 1985b; Poslusny et al. 1987; Pichtel 1991) have demonstrated that concentrations of PCDDs and PCDFs were below detectable limits. Concentrations of PAHs, however, have been variable. In one study (U.S. EPA 1985b), large quantities of PAHs were detected in combustion experiments where shredded and pelletized RDF were combusted. Poslusny et al. (1987) found that naphthalene was the major PAH emitted, and tetra- and penta-chlorinated biphenyls were the major PCB isomers released. In a study by Nammari et al. (2004), PCDD/F levels varied from 12.53 ng/Nm^3 to 14.09 ng/Nm^3. The maximum PAH concentration was 3.04 μg/Nm^3.

9.8.6 Properties of RDF Ash

As mentioned earlier in this chapter, ash quality from mass-burn incinerator ash is of concern to regulators and the general public due to the presence of heavy metals, chlorinated dibenzodioxins, furans, and other toxins. With processing via trommel screens, shredding, magnetic separation, and air classification, the chemical properties of the waste charge are drastically changed. Ash composition also improves in quality over that of mass-burn incinerator ash. The total elemental analysis of RDF ash is similar to that for coal ash.

When leached via the TCLP (U.S. EPA 1986), concentrations of TCLP metals and nonmetals, as well as reactive sulfide and cyanide, tend to be well below RCRA limits (Table 9.11) (Pichtel 1991). The pH of RDF ash varies somewhat; however, the majority of pH values fall within the alkaline range, a result of the presence of Ca, Mg, Al, Na, and other basic cations

TABLE 9.11
Analysis for Ignitability, Corrosivity, Reactivity, and TCLP Metals and Nonmetals in RDF Ash

Analyte	RCRA Limit[a]	Result
Flash point, °F	140°F	Negative
Corrosivity, pH	2–12	9.48
Reactive cyanide	250	<10
Reactive sulfide	500	25
Silver	5.0	<0.1
Arsenic	5.0	<0.2
Barium	100.0	0.1
Cadmium	1.0	<0.1
Chromium	5.0	<0.1
Mercury	0.20	<0.05
Lead	5.0	<0.1
Selenium	1.0	<0.2

[a] All units of mg/L unless otherwise noted.

in RDF. In addition, the concentration of TCLP-extractable and volatile organics, chlorinated dibenzodioxins and furans, and PCBs is well below regulatory limits. RDF ash, therefore, can be disposed with much less concern about potential environmental and health impacts as compared with mass-burn incinerator ash.

9.8.7 Process-Engineered Fuel

As discussed in Chapter 6, plastics are derived from petroleum and natural gas and are composed mostly of C, H, and O. Given the high energy content of polymers, there is interest in using segregated post-use plastics and paper in fuel applications. When materials derived from residential, commercial, and industrial waste sources are used as industrial fuel, they may be termed *process engineered fuel* (PEF). Conventional PEF contains 70%–90% paper, and the remaining percentage is plastic (APC 1999). Common reasons for encouraging a higher plastics content include the beneficial effect on densified PEF integrity and high heat value in comparison with conventional fuels. The American Plastics Council has explored formulations containing in excess of 30% plastics.

PEF can be produced in either shredded (fluff) or densified form. Preselected postuse plastic waste as well as wood, sawdust, or scrap paper is freed of glass and metal contaminants and ground to uniform size by a primary grinder. In some cases, a secondary grinder further processes the materials, which then are densified. The most common methods for densifying PEF are cubing and pelletizing. Densification makes the final fuel product easier to transport and handle and assures consistent heating value. A typical commercial product is a densified pellet measuring about 5–8 cm (2–3 in.) long and ¾-in. in diameter.

Compared with conventional RDF, PEF is a more refined, low ash, low moisture, high heat value fuel. The high heating value of PEF is directly related to its plastics content. Plastics contribute to heating values in the range of 15,650–35,750 kJ/kg (7000–16,000 Btu/lb). Conventional RDF has a heating value of about 14,000–15,650 kJ/kg (6500–7,000 Btu/lb), and most coals 20,000–27,000 kJ/kg (9000–12,000 Btu/lb). As is the case with RDF, using PEF as a supplement to coal reduces certain undesirable environmental emissions, particularly sulfur dioxide.

9.8.8 Tire-Derived Fuel

In recent years, tire burning for fuel recovery has increased (U.S. EPA 2012). Facilities such as cement kilns and pulp and paper mills use scrap tires (shredded or whole, depending on the industry) as a combustion fuel, burning approximately 42% of all scrap tires generated annually. Tires are shredded into small particles, the steel is removed magnetically, and the particles are often shredded a second time to produce crumb rubber. The fine rubber particles are mixed with coal, typically less than 10%–20% (by weight) and fed directly to the combustion chamber. The so-called *tire-derived fuel* (TDF) possesses the equivalent energy per unit weight as petroleum, and comparatively more energy than coal (average 32,500 kJ/kg or 14,000 Btu/lb). New technologies and pollution control equipment allow facilities to burn tires at high temperatures, thus reducing pollutant emissions.

When tires are burned as fuel, atmospheric emissions are similar to those emitted when coal or petroleum are burned. As with other fossil fuels, emissions include criteria pollutants such as particulates, CO, SO_x, NO_x, and noncriteria hazardous air pollutants such as PAHs, PCDDs, PCDFs, and trace metals. When operated properly, the burning of tires for fuel is a reasonably safe and economical practice that has been approved by EPA. Air emissions usually are improved with incorporation of TDF with coal due to its low sulfur and nitrogen content. The California Integrated Waste Management Board (CIWMB 1996) stated:

> In general, test results have shown that tire derived fuels have no additional adverse effect on emissions when compared to coal. In fact, test results indicate a net reduction of SO_x (sulfur oxides), NO_x (nitrous oxides) and particulate matter.

The EPA's Office of Research and Development published a study in 1997 entitled "Air Emissions from Scrap Tire Combustion", which stated:

> TDF has been used successfully in properly designed combustors with good combustion control and appropriate add-on controls, particularly particulate controls, such as electrostatic precipitators (ESPs) or fabric filters. Air emissions characteristic of TDF combustion are typical of most solid fuels, such as coal and wood. The resultant air emissions can usually satisfy environmental compliance limits even with TDF representing up to 10 to 20% of the fuel requirements.

Each facility that uses TDF must, after being permitted, pass an initial compliance test to ensure that it complies with emission limits and operating conditions stated in the permit. Following the initial test, most coal-fired boilers must be equipped with continuous emission monitors. This rule ensures that the facility is in regulatory compliance at all times.

QUESTIONS

1. MSW combustion involves physical and chemical transformations in which solid materials are converted into gases and some solid residues. What factors affect the types of gases produced? What factors influence the quantity of solid residues, both carbonaceous and inorganic?
2. Compare the operation of a mass-burn incinerator with that of a RDF-burning facility, in terms of: fuel types; waste processing operations and equipment; convenience; resource recovery; energy utilization.
3. What are the functions of combustion chamber overfire and underfire air? How can they be adjusted to optimize incineration?
4. List the engineering and design factors that serve to enhance MSW combustion in an incinerator.
5. Define *stoichiometric air* and *heat value*.
6. Discuss the major gaseous emissions from a mass-burn incinerator and how each may be effectively removed from the flue.

7. SO_2 production may be controlled during mass-burn incineration by addition of limestone directly to the combustion chamber. What are the advantages and disadvantages of this procedure over flue gas desulfurization?
8. An incinerator operating at a sufficiently high temperature and air inflow rate may still generate PICs. Explain how such a phenomenon may occur.
9. How do PCDDs and PCDFs form during mass-burn incineration (given that the firebox temperature is sufficiently high, for example, >1000°C, to destroy virtually all organic compounds)? In what physical form(s) are these compounds emitted?
10. Describe *particulate matter* as relates to MSW combustion. What are its chemical and physical properties? What size range of particulates are the most potentially damaging when inhaled? How do certain toxins (e.g., metallic vapors, chlorinated hydrocarbons) react with particulate matter to increase their risk of exposure?
11. Generation of atmospheric pollutants is directly related to MSW charge rate and combustion chamber conditions, among other factors. Explain.
12. Explain how the following air pollutants can be removed from stack gases: SO_2, particulates, mercury, and PCDDs.
13. Explain why the majority of MSW incinerators in the United States are mass-burn rather than RDF-fired.
14. How do electrostatic precipitators and cyclone separators differ in terms of efficiency of removal of particulate matter, SO_2, and PCDDs.
15. Cd occurring in raw MSW can become significantly more soluble (and hence more leachable) following MSW combustion in a mass-burn incinerator. Explain.
16. Discuss the major concern(s) with RDF storage, both indoors and outdoors.
17. Which of the following is a significant concern when considering RDF production and utilization with coal: (a) dust production; (b) odor production; (c) separation of RDF and coal during handling; (d) some plants are unable to market the RDF; (e) all of the above.
18. For RDF to produce the same amount of heat as coal, more ash will probably be produced. Explain.
19. Compare and contrast RDF and raw MSW in terms of fuel properties. How do they differ in heat content, moisture content, density, and ash content?
20. How do RDF and coal differ regarding emissions of SO_2, NO_x, and HCl? How do they differ in ash composition?
21. A materials recovery facility is being installed in Pristine, IL (pop. 110,000). The MRF will be receiving mixed MSW. RDF will be produced. For maximum efficiency and ease of mixing with coal, what form (e.g., fluff, wet-pulped, densified, etc.) of RDF is recommended?
22. How will the RDF be stored: (a) in the customers' yard for easy utilization; (b) in a covered pole barn; (c) no need to store the RDF as it will be immediately sent to market; (d) in 50:50 mixtures with coal in customers' yard.
23. An incinerator burns 120 MT/h of MSW with the formula $C_{285}H_{455}O_{235}N_4S$. How much air is needed to completely combust this waste? A rate of 35% excess air is used during combustion.
24. Calculate the heating value for the waste discussed in Question 23.

REFERENCES

APC (American Plastics Council). 1999. Information on Processed Engineered Fuels (PEF)/Plastics Derived Fuels. Available from: http://www.plasticsresource.com/recycling/recycling_backgrounder/bk_fuels.html

ASTM International. 1988. *Standard Definitions of Terms and Abbreviations Relating to Physical and Chemical Characteristics of Refuse Derived Fuel*. E856-83. West Conshohocken, PA: ASTM International

Berlincioni, M. and A. di Domenico, 1987. Polychlorodibenzo-*p*-dioxins and polychlorodibenzofurans in the soil near the municipal incinerator of Florence, Italy. *Environmental Science and Technology* 21: 1063–69.

Carpi, A. 1997. Mercury from combustion sources: A review of the chemical species emitted and their transport in the atmosphere. *Water Air Soil Pollut* 98, 241–254.

CIWMB (California Integrated Waste Management Board). 1996. *Effects of Waste Tires, Waste Tire Facilities, and Waste Tire Projects on the Environment*. Sacramento, CA: CIWMB.

Cheng, C., Tu, W., Zand, B., Butalia, T.S., Wolfe, W.E., and Walker, H. 2007. Beneficial reuse of FGD material in the construction of low permeability liners: Impacts on inorganic water quality constituents. *J Environ Eng* 133, 523–531.

Choudry, G.G., Olie, K., and Hutzinger, O. 1982. Mechanisms in the thermal formations of chlorinated compounds including polychlorinated dibenzo-*p*-dioxins. In O. Hutzinger, R.W. Frei, E. Merian, and F. Pocciari (Eds.). *Chlorinated Dioxins and Related Compounds, Impact on the Environment*. New York: Pergamon Press, 275–301.

Colmsjö, A.L., Zebühr, Y.U., and Östman, C.E. 1986. Polynuclear aromatic compounds in flue gases and ambient air in the vicinity of a municipal incineration plant. *Atmos Environ* 20, 2279–2282.

Davies, I.W., Harrison, R.M., Perry, R., Ratnayaka, D., and Wellings, R.A. 1976. Municipal incinerator as source of polynuclear aromatic hydrocarbons in environment. *Environ Sci Technol* 10, 451–453.

Denison, R.A. and Ruston, J. 1990. *Recycling and Incineration, Evaluating the Choices*. Washington, DC: Environmental Defense Fund.

Dvirka, M., 1986. Resource Recovery: Mass Burn Energy and Materials, In *The Solid Waste Handbook*. New York: John Wiley and Sons, 557–93.

Dyke, P.H. 2003. *PCB and PAH Releases from Incineration and Power Generation Processes*. R&D Technical Report P4-052. Bristol: Environment Agency.

Eiceman, G.A., Clement, R.E., and Karasek, F.W. 1981. Variations in concentrations of organic compounds including polychlorinated dibenzo-*p*-dioxins and polynuclear aromatic hydrocarbons in fly ash from a municipal incinerator. *Analyt Chem* 53, 955–959.

Fiscus, D.E., Gorman, P.G., Schrag, M.P., and Shannon, L.J. 1978. *Assessment of Bacteria and Virus Emissions at a Refuse Derived Fuel Plant and Other Waste Handling Facilities*. Washington, DC: U.S. EPA Publication 600/2-78–152.

Friend, M., Bloom, P., Halbach, T., Grosenheider, K., and Johnson, M. 2004. *Screening Tool for Using Waste Materials in Paving Projects (STUWMPP)*. Report nr MN/RC–2005-03. Saint Paul, MN: Office of Research Services, Minnesota Department of Transportation.

Gittinger, J.S., and W.J. Arvan. 1998. Waste-to-Energy Installations. Chapter 27 in Stultz S.C. and Kitto J.B. (Eds.). *Steam: Its Generation and Use*, 40th ed. Barberton, OH: Babcock & Wilcox.

Hasselriis, F. 1987. Optimization of combustion conditions to minimize dioxin emissions. *Waste Manag Res* 5, 311–325.

Hickman, H.L., Jr. 1984. *Thermal Conversion Systems for Municipal Solid Waste.* Park Ridge, NJ: Noyes Publications.

Hutzinger, O., Blumich, M.J., Gerg, M.V.D., and Olie, K. 1985. Sources and fate of PCDDs and PCDFs: An overview. *Chemosphere* 14, 581–600.

Kost, D., Bigham, J.M., Stehouwer, R.C., Beeghly, J.H., Fowler, R., Traina, S.J., Wolfe, W.E., and Dick, W.A. 2005. Chemical and physical properties of dry flue gas desulfurization products. *J Environ Qual* 34, 676–686.

Kukkonen, J. and Raunemaa, T. 1984. Dispersion studies on a solid waste refuse incinerator. *Int J Environ Stud* 23, 235–247.

Lee, W.-J., Liow, M.-C., Tsai, P.-J., and Hsieh, L.-T. 2002. Emission of polycyclic aromatic hydrocarbons from medical waste incinerators. *Atmos Environ* 36, 781–790.

Lisk, D.J. 1988. Environmental implications of incineration of municipal solid waste and ash disposal. *Sci Total Environ* 74, 39–66.

Liu, D.H.F. and Liptak, B.G. 2000. *Hazardous Waste and Solid Waste.* Boca Raton, FL: Lewis Publishing.

Mahar, S. 1999. Airborne particulates in refuse-derived fuel plants. *Waste Manag Res* 17, 343–346.

Mahar, S. 2002. Worker health in refuse–derived fuel plants, a five–year followup. *Arh Hig Rada Toksikol* 53, 191–196.

Manahan, S.E. 2009. *Environmental Chemistry*, 9th ed. Boca Raton, FL: CRC Press.

McKay, G. 2002. Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration: Review. *Chem Eng J* 86, 343–368.

Morselli, L., Passarini, F., and Bartoli, M. 2002. The environmental fate of heavy metals arising from a MSW incineration plant. *Waste Manag* 22, 875–881.

Nammari, D.R., Hogland, W., Marques, M. Nimmermark, S., and Moutavtchi, V. 2004. Emissions from a controlled fire in municipal solid waste bales. *Waste Manag* 24, 9–18.

Niessen, W.R. 2002. *Combustion and Incineration Processes*, 3rd ed. New York: Marcel Dekker.

Nishitani, T., Nomura, T., Fukunaga, I., and Itoh, H. 1999. The relationship between HCl and mercury speciation in flue gas from municipal solid waste incinerators. *Chemosphere* 39, 1–9.

NTP (National Toxicology Program). 2005. *11th Report on Carcinogens. 2,3,7,8-Tetrachlorodibenzo-p-dioxin (TCDD); "Dioxin."* Available from: http://ntp.niehs.nih.gov/index.cfm?objectid=2BA9724-F1F6-975E-7FCE50709CB4C932

Olie, K., Berg, M.V.D., and Hutzinger, O. 1983. Formation and fate of PCDD and PCDF from combustion processes. *Chemosphere* 12, 627–636.

Pichtel, J. 1991. *Assessment of Air Quality and Ash Residues from Combustion of Refuse-Derived Fuel*. Chicago, IL: Council of Great Lakes Governors.

Pierce, R.C. and Katz, M. 1975. Dependency of polynuclear aromatic hydrocarbon content on size distribution of atmospheric aerosols. *Environ Sci Technol* 9, 347–353.

Poslusny, M., Moore, P., and Daugherty, K. 1987. Organic emission studies of full-scale cofiring of pelletized RDF/coal. *AIChE Symposium Series* 84, 265 94–106.

Psomopoulos, C.S., Bourka, A., and Themelis, N.J. 2008. Waste-to-energy: A review of the status and benefits in USA. *Waste Manag* 29, 1718–1724.

Reimann, D.O. 1995. Future gas cleaning systems in accordance with EC regulations, solid waste management: Thermal treatment and waste to energy technologies. VIP-53. *Proceeding of International Speciality Conference sponsored by the Air & Waste Management* Association. Washington, DC, April 18–21, pp. 37–49.

Reynolds, J.P., Jeris, J.S., and Theodore, L. 2002. *Handbook of Chemical and Environmental Engineering Calculations.* New York: Wiley.

Sakai, Y., Matsumoto, S., and Sadakata, M. 2004. Alkali soil reclamation with flue gas desulfurization gypsum in China and assessment of metal content in corn grains. *Soil Sedim Contam* 13, 65–80.

U.S. EPA (U.S. Environmental Protection Agency). n.d. Lesson 14, Municipal Incinerators, Available from: http://yosemite.epa.gov/oaqps/EOGtrain.nsf/12f4a7ba1594b00d85256b450052f92a/be2e374ff50cf6f485256b88004e4c06/$FILE/si431-lesson14.pdf.

U.S. EPA (U.S. Environmental Protection Agency). 1973. *Air Pollution Engineering Manual*, 2nd ed., AP-40, NTIS PB-225132. Research Triangle Park, NC: Office of Air Quality Planning and Standards, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1985a. *Assessment of Organic Contaminants in Emissions from Refuse-Derived Fuel Combustion,* Project Summary, EPA/600/S2-85/115. Cincinnati, OH: Hazardous Waste Engineering Research Laboratory, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1985b. *Emissions Assessment Refuse-Derived Fuel Combustion*. Project Summary, EPA/600/S2-85/116. Cincinnati, OH: Hazardous Waste Engineering Research Laboratory, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1986. *Methodology for the Assessment of Health Risks Associated with Multiple Pathway Exposure to Municipal Waste Combustor Emissions*. Research Triangle Park, NC: Office of Air Quality Planning and Standards, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1990. *Operation and Maintenance of Hospital Medical Waste Incinerators*. EPA/625/6-89/024. Cincinnati, OH: Center for Environmental Research Information.

U.S. EPA (U.S. Environmental Protection Agency). 1993. *Operational Parameters for Hazardous Waste Combustion Devices*. EPA/625/R-93/008. Cincinnati, OH: Office of Research and development.

U.S. EPA (U.S. Environmental Protection Agency). 2002. *Industrial-Commercial-Institutional Boilers MACT Standards Development*. Available from: http://www.epa.gov/ttn/atw/combust/boiler/boilback.html

U.S. EPA (U.S. Environmental Protection Agency). 2002. Municipal Incinerators. APTI Virtual Classroom. Available from: http://yosemite.epa.gov/oaqps/EOGtrain.nsf/12f4a7ba1594b00d85256b4500052f92a/be2e374ff50cf6f485256b88004e4c06/$FILE/si431-lesson14.pdf

U.S. EPA (U.S. Environmental Protection Agency). 2012. *Tire-Derived Fuel*. Available from: http://www.epa.gov/wastes/conserve/materials/tires/tdf.htm

Vesilind, P.A., Worrell, W.A., and Reinhart, D. 2002. *Solid Waste Engineering*. Pacific Grove, CA: Brooks/Cole Thomson Learning.

WHO (World Health Organization). 2013. *Dioxins and Their Effects on Human Health.* Available from: http://www.who.int/mediacentre/factsheets/fs225/en/

Williams, P.T. 1998. *Waste Treatment and Disposal*. New York: McGraw-Hill.

Worrell, W.A. and Vesilind, A. 2011. *Solid Waste Engineering*, 2nd ed. Stamford, CT: Cengage Learning.

WSL (Warren Spring Laboratory). 1992. *Investigation of Polynuclear Aromatic Hydrocarbons (PAH) Releases from Two MSW Incinerators*. CR 3740. UK: WSL.

Zhang, F.-S., Kimura, K., Yamasaki, S., and Nanzyo, M. 2001. Evaluation of cadmium and other metal losses from various municipal wastes during incineration disposal. *Environ Pollut* 115, 253–260.

SUGGESTED READINGS

Brunner, C.L. 1984. *Incinerator Systems Selection and Design*. New York: Van Nostrand Reinhold.

Finnis, P. 1998. Heat Recovery Dry Injection Scrubbers for Acid Gas Control. *Proceedings of the ASME Asian–North American Solid Waste Management Conference (ANACON).* Los Angeles, CA, 136–163.

Gleiser, R., Nielsen, K., and Felsvang, K. 1993. Control of mercury from MSW combustors by spray dryer absorption systems and activated carbon injection. 3rd *International Conference, Municipal Waste Combustion*. Air and Waste Management Association.106–122.

Hasselriis, F. 1995. *Variability of Metals and Dioxins in Stack Emissions of Three Types of Municipal Waste Combustors over Four Year Period*, Paper No. 95-RP147B.03. San Antonio, TX: Air and Waste Management Association.

Licata, A., Schuttenhelm, W., and Klien, M. 2000. Mercury Control for MWCs Using the Sodium Tetrasulfide Process. 8th *Annual North American Waste-to-Energy Conference.* Nashville, TN, 1–12.

Robson, M. 2003. Methodologies for assessing exposures to metals: Human host factors. *Ecotoxicol Environ Saf* 56, 104–109.

Sarkar, B. 2002. *Heavy Metals in the Environment*. New York: Marcel Dekker.

U.S. EPA (U.S. Environmental Protection Agency). 1989. Emissions Test Results from the Stanislaus County, California, Resource Recovery Facility. *International Conference on Municipal Waste Combustion*. Hollywood, FL, U.S. EPA, Washington, DC.

U.S. EPA (U.S. Environmental Protection Agency). 1997. *Risk Assessment for the Waste Technologies Industries (WTI) Hazardous Waste Incineration Facility (East Liverpool, Ohio)*, EPA-905-R97-002a. Chicago, IL: U.S. Environmental Protection Agency Region 5.

Wang, L.K., Chen, J.P., Hung, Y.-T., and Shammas, N.K. 2009. *Heavy Metals in the Environment, Advances in Industrial and Hazardous Wastes Treatment*. Boca Raton, FL: CRC Press.

Wang, X., Sato, T., Xing, B., and Tao, S. 2005. Health risks of heavy metals to the general public in Tianjin, China via consumption of vegetables and fish. *Sci Total Environ* 350, 28–37.

10 The Sanitary Landfill

This is Anacreon's grave.
Here lie the shreds of his exuberant lust,
but hints of perfume linger by his gravestone still.

Antipater of Sidon (ca. 130 BCE)
This is Anacreon's Grave

10.1 INTRODUCTION

Prior to the enactment of Resource Conservation and Recovery Act (RCRA) in 1976, what Americans had referred to as "landfills" were typically not much more than open dumps (Figure 10.1). There was no requirement for a daily cover of soil, for example, which is important in deterring vectors and preventing other hazards and nuisance conditions. As a result, insect and rodent infestations were common at pre-RCRA facilities, and fires were frequently reported. These facilities were typically constructed without protective subsurface liners; therefore, contents readily leached into subsurface formations, including groundwater aquifers. Many were sited in locations thought to be convenient, without regard to subsurface hydrology or groundwater features. There was no requirement for impermeable substrata below the landfill unit that might prevent migration of liquids.

As a result of the RCRA regulations, modern sanitary landfills must meet stringent requirements for siting, construction, operation and maintenance, and final closure. The RCRA regulations apply to all municipal solid waste (MSW) landfills that are active (i.e., receiving waste) and do not apply to landfills that stopped accepting MSW before October 1991. Because of the complex technology required, the federal requirement for installing groundwater monitoring systems was phased in over a period of 5 years. To protect drinking water sources, landfills located nearest to groundwater resources were required to comply before those sited farther away. By 1994, landfill owners and operators had to demonstrate the ability to pay the costs of closure, postclosure care, and cleanup of any known releases (U.S. EPA 1993a).

10.2 RELEVANT DEFINITIONS UNDER THE RCRA REGULATIONS

Municipal solid waste landfill (MSWLF): A discrete area of land or an excavation that receives household waste, and which is not a land application unit, surface impoundment, injection well, or waste pile. An MSWLF unit may also receive other types of wastes as defined under subtitle D of RCRA, such as commercial solid waste, nonhazardous sludge, small quantity generator waste, and industrial solid waste. Such a landfill maybe publicly or privately owned.

Existing unit: An MSWLF unit that is receiving solid waste as of October 9, 1993. Waste placement in existing units must be consistent with previous operating practices or modified practices to ensure good management.

Lateral expansion: A horizontal expansion of the waste boundaries of an existing unit.

New unit: Any MSWLF unit that has not received waste prior to October 9, 1993.



FIGURE 10.1 Landfill operated and closed prior to the enactment of RCRA regulations. Subsidence has occurred, creating a toxic wetland. Leachate is exiting freely from the sides of the landfill.

10.3 SITING THE LANDFILL

Volume 40 of the Code of Federal Regulations (40 CFR) has instituted six restrictions as related to landfill siting in order to limit hazards to the local public and certain sensitive environments. Landfill owners and operators are required to demonstrate that their units meet all these criteria.

10.3.1 Airport Safety

Many landfills are cited along coastal areas; as a result, seagulls and other scavenging bird populations often occur in high numbers. Concentrations of birds increase the likelihood of bird and aircraft collisions that damage aircraft. As a result, RCRA requires that all new and existing MSWLF units, and lateral expansions located within 10,000 ft of an airport runway used by turbojet aircraft (or within 5000 ft of an airport runway end used by only piston-type aircraft), must not pose a bird hazard to aircraft (40 CFR 258.10). In other words, the facility must be sited far enough from an airport to prevent excessive bird populations from entering the airspace. Similarly, a thick daily soil cover over the landfill cell will limit attraction to birds.

10.3.2 Floodplains

Floodplains under the RCRA connotation are low-elevation, relatively flat areas adjoining inland and coastal waters that are inundated by a 100-year flood, defined as one with a magnitude that is equaled or exceeded once in 100 years. Operators of landfills and lateral expansions located in 100-year floodplains must demonstrate that the unit will not restrict the flow of the 100-year flood or result in washout of any deposited MSW, and therefore pose a hazard to health and the environment (40 CFR 258.11). *Washout* refers to the carrying away of solid waste by flood waters.

10.3.3 Wetlands

The U.S. government regulatory definition of wetlands, as per section 404 of the 1977 Clean Water Act Amendments, is (33 CFR 328.3[b]) (also 40 CFR 232.2[r]):

> those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes bogs and similar areas.

New or expanding municipal landfills may not be built or expanded within wetlands. However, exceptions can be made for units when the owner can show that:

- No siting alternative is available.
- Operation will not violate applicable regulations on water quality or toxic effluent, threaten endangered or threatened species or sensitive habitats, or violate protection of a marine sanctuary.
- The unit will not cause or contribute to significant degradation of wetlands.
- Steps have been taken to achieve no net loss of wetlands (e.g., restoring damaged wetlands or creating man-made wetlands).

The landfill operator must demonstrate the integrity of the landfill unit and its ability to protect local natural resources by addressing:

- Erosion, stability, and migration potential of native wetland soils used to support the unit
- The volume and chemical nature of the waste managed in the unit
- Possible impacts on aquatic and terrestrial wildlife and their habitat from release of the solid waste
- The potential effects of a catastrophic release of waste to the wetland and the resulting impacts on the environment

10.3.4 Fault Areas

New units or lateral expansions are prohibited within 200 ft of fault areas that have shifted since Holocene time (the most recent epoch of the Quaternary period, extending from the end of the Pleistocene epoch to the present) (40 CFR 258.13).

10.3.5 Seismic Impact Zones

RCRA requires that landfills not be sited in a seismic impact zone. In the event of siting in a potentially unstable area, the landfill must be designed to withstand the effects of surface motion due to an earthquake. All containment structures including liners, leachate collection systems, and surface water control systems must be designed to resist the maximum horizontal acceleration in earth material.

10.3.6 Unstable Areas

The landfill must be designed to ensure that the integrity of the unit will not be disrupted during destabilizing events such as (U.S. EPA 1993a):

- Flows of debris from heavy rains
- Fast-forming sinkholes caused by excessive withdrawal of groundwater
- Rock falls set off by explosives
- Sudden liquefaction of soil after a long period of repeated wet–dry cycles

Unstable areas are susceptible to forces that may impair the integrity of landfill structural components (e.g., liners, leachate collection systems, final covers, and run-on and runoff systems). Unstable areas include those susceptible to landslides, avalanches, debris slides, rock fall, and karst topography. Karst topography has developed from the dissolution of limestone or other soluble rock. Common physiographic features present in karst terrain include sinkholes, sinking streams, and caves. Such conditions may impair foundation conditions and result in inadequate support for the components of a landfill unit.

10.4 REQUIREMENTS OF OPERATION

The operating requirements for MSWLFs, provided in RCRA subpart C, came into effect in 1993. These detailed requirements were formulated to ensure the safe daily operation and management at MSWLF units and include:

- Detection and exclusion of hazardous waste from the facility
- Use of appropriate cover material for daily cells and the closed landfill
- Disease vector control
- Explosive gas control
- Air monitoring
- Facility access
- Run-on and runoff control systems
- Surface-water requirements
- Restrictions on liquids entering cells
- Record-keeping requirements

The subpart C requirements are by no means the sole determinants of landfill operation; operators must comply with a host of other federal laws. For example, discharges from an MSWLF to surface waters must be in conformance with sections of the Clean Water Act. In addition, burning of MSW (on those infrequent occasions when it is permitted) is regulated under the Clean Air Act.

10.4.1 Receipt of Hazardous Waste

A key concern of regulators, site owners, and lenders is the possible transformation of a sanitary landfill, designed to accept only municipal and commercial wastes, to a contaminated site. Unfortunately, prior to the enactment of subtitle D, several Superfund sites had their origins in this manner. Long before the enactment of RCRA, many sanitary landfills accepted industrial wastes, some of which were hazardous and many in liquid form. The hazardous composition of the waste, combined with their proximity to populations and other sensitive receptors, contributed to a high ranking on the National Priorities List. In order to prevent such situations from occurring in the future, operators of MSWLFs were required to implement a program for detecting and preventing

disposal of hazardous wastes and polychlorinated biphenyl (PCB) wastes at their facility (40 CFR 258.20). This program includes random inspections of incoming loads, training of facility personnel to recognize hazardous wastes and PCB wastes, and notification of regulatory authorities if a hazardous waste is discovered at the facility.

According to subpart D of 40 CFR part 261, a *solid waste* is deemed a *hazardous waste* if it (1) is listed in the regulations; (2) exhibits a specific characteristic of a hazardous waste (ignitability, corrosivity, reactivity, or toxicity) (see Chapter 11); or (3) is a mixture of a listed hazardous waste and a nonhazardous solid waste. PCBs are regulated under the Toxic Substances Control Act (TSCA). Commercial or industrial sources of PCBs include:

- Oil and dielectric fluids
- Transformers and other electrical equipment containing dielectric fluids
- Contaminated soil, dredged material, sewage sludge, and other debris from a release of PCBs
- Hydraulic machines

10.4.2 Inspections

An inspection is a visual observation of incoming waste loads by trained personnel. Ideally, all loads should be screened; however, this is impractical. Random inspections, therefore, are often the only feasible technique to control the receipt of inappropriate wastes. Loads should be inspected prior to disposal in the landfill cell to provide the opportunity to refuse wastes if necessary. Inspections can be conducted on a tipping floor of a transfer station before shipping to the disposal facility. Inspections may also occur inside the site entrance, at the disposal facility tipping floor, or as a last resort, near the working face of the landfill cell.

Inspections may be accomplished by tipping the vehicle load in an area designed to contain hazardous wastes. The waste is spread on to the surface using a front-end loader. Facility personnel should be trained to identify questionable wastes. Suspicious wastes may be identified by a number of clues, including:

- Placards or markings indicating hazardous contents
- Presence of sludges or liquids
- Presence of powders or dusts
- Bright or unusual colors of the contents
- Drums or commercial size containers
- Significant chemical odors

The receiving facility must always be aware that containers may arrive with suspicious contents. Only trained personnel should open an unmarked 55-gal drum. Occupational Safety and Health Administration (OSHA) regulations, as promulgated in 29 CFR 1910, provide clear guidelines as to how to handle and open drums having questionable contents. If the waste is deemed acceptable, it is transferred to the working face for disposal.

Analysis of suspicious wastes should include the Toxicity Characteristic Leaching Procedure (TCLP) and other tests for hazardous characteristics, including corrosivity, ignitability, and reactivity (see Chapter 11). Wastes suspected of being hazardous should be handled and stored as a hazardous waste until a full determination is complete. If the operator discovers hazardous waste while still in the possession of the transporter, the operator can refuse to accept the waste at the facility. Thus, the waste remains the responsibility of the transporter.

If wastes accepted at the site are determined to be hazardous, the landfill owner or operator becomes responsible for management of a hazardous waste. Management includes requirements

for packaging, storage, runoff control, documentation, and other practices. If the wastes are to be transported from the facility, the waste must be:

- Stored at the landfill in compliance with all requirements of a hazardous waste generator (see Chapter 12 of this book)
- Manifested (creation of a paper trail)
- Transported by a licensed transporter (i.e., having a U.S. EPA identification number)
- Shipped to a permitted treatment, storage, or disposal (TSD) facility for final disposal

Landfill operators must be prepared to handle hazardous wastes that are inadvertently received at the facility. This may include having 55 gal drums available and keeping a list of the nearest companies licensed to transport hazardous waste. Hazardous waste may be stored at the landfill for 90 days, provided that the following procedures are followed (40 CFR 262.34):

- The waste is stored in tanks or containers. Both terms are defined in the federal regulations.
- Date of receipt of the waste is noted on each container.
- Container is marked with the words "Hazardous Waste."
- An employee is designated for coordinating any emergency response measures.

If the landfill facility transports the wastes off-site, it must comply with 40 CFR part 262 or analogous state requirements, which include:

- Obtaining an EPA identification number (the landfill is now a *generator* of hazardous waste)
- Packaging the waste as per Department of Transportation (DOT) regulations (49 CFR parts 173, 178, and 179)
- Manifesting the waste designating a permitted facility to treat, store, or dispose of the waste

If the landfill decides to treat, store (for more than 90 days), or dispose the hazardous waste on-site, they are legally defined as a hazardous waste TSD facility and must comply with state or federal requirements for such facilities. This typically requires a permit. The major requirements for generators, transporters, and TSD facilities are discussed in detail in Chapters 12 through 17 of this chapter.

PCB wastes detected at a landfill must be stored and disposed according to 40 CFR part 761. The operator is required to

- Obtain an EPA PCB identification number
- Properly store the waste
- Mark containers with the words "Caution: Contains PCBs"
- Manifest the waste for shipment to a permitted incinerator, chemical waste landfill, or high-efficiency boiler for disposal

Clearly, it is to the facility's advantage to detect and remove any potential hazardous waste before it enters the tipping area. Preventing the entry of these wastes may be accomplished through other methods. For example, facilities may receive only household wastes and processed (shredded or baled) wastes that are adequately screened for the excluded items.

10.4.3 Training

Landfill operators must ensure that personnel are trained to identify hazardous and PCB wastes. The training program should emphasize methods to identify containers and labels typical of hazardous and PCB wastes. Training also should address hazardous waste handling procedures, safety

precautions, and record keeping. OSHA regulations provided in 29 CFR 1920.120 are extremely useful in providing proper protocols for investigations and worker safety.

10.4.4 Landfill Design

According to RCRA, the criteria for landfill design apply only to new units and new lateral expansions; existing landfills are not required to retrofit systems such as liners. The criteria provide for two basic design options. The first consists of a composite liner and a leachate collection system. Landfills in states without EPA-approved programs must use this design. The composite liner system consists of an upper synthetic geomembrane liner (also known as a flexible membrane liner [FML]) and a lower layer of compacted soil at least 0.61 m (2 ft) thick, with a hydraulic conductivity of not greater than 1×10^{-7} cm/s (Figure 10.2). The geomembrane liner must measure at least 30 mil thick (1 mil = 0.001 in.), except for high-density polyethylene (HDPE) geomembranes (60 mil thick). The geomembrane liner minimizes the exposure of the compacted clay liner to leachate. A leachate collection and removal (LCR) system is situated above the composite liner to collect, divert, and remove liquids during landfill operation and long after closure. The LCR must be designed to limit the depth (hydraulic head) of the leachate above the liner to less than 30 cm (U.S. EPA 1993b).

In states with EPA-approved programs, landfills may be constructed to comply with a design approved by the state regulatory agency. In approving the design, the agency must ensure that maximum contaminant levels (MCLs) not be exceeded in the uppermost aquifer at a "relevant point of compliance." This point is determined by the agency but must be located not further than 150 m from the landfill boundary. The EPA MCLs for a number of solid waste constituents are shown in Table 10.1. In planning such performance-based landfill designs, other factors must also be considered, such as the hydrogeologic characteristics of the facility and surrounding land, the local climate, and the quantity and composition of the leachate (U.S. EPA 1993b).

It must be emphasized that, in the design of subtitle D landfills, EPA provides minimum design standards only. Several states require double-composite liner systems in the design of subtitle D landfills.

10.4.5 Clay Liners

Clay is an extremely important component of soil liners because it is relatively available and amenable to mechanical and other stresses. Clay materials, being natural, incorporate readily with native soil materials and are obviously very durable. Additionally, clay ensures low hydraulic conductivity. EPA requires that soil liners be constructed so that hydraulic conductivity is less than 1×10^{-7} cm/s (Figure 10.3). To meet this requirement, certain characteristics of soil materials must be met. First, the soil should contain at least 20% fines (i.e., fine silt and clay-sized particles).

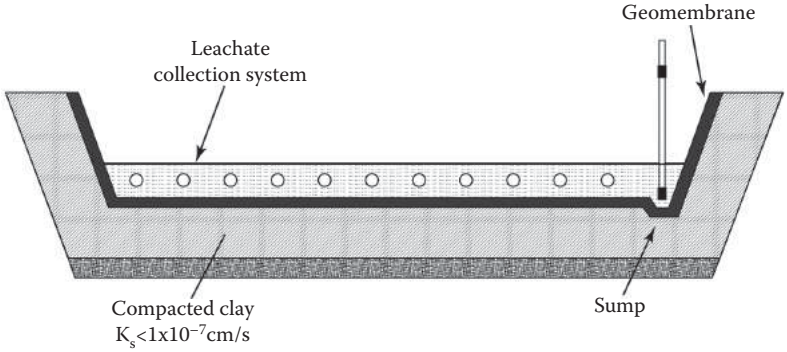


FIGURE 10.2 The layers beneath a sanitary landfill as required under RCRA. (Not to scale.)

TABLE 10.1
Maximum Contaminant Levels for MSW Constituents; Not to Be Exceeded in the Uppermost Aquifer under an MSW Landfill

Chemical	Maximum Contaminant Level (mg/L)
Arsenic	0.01
Barium	2.0
Benzene	0.005
Cadmium	0.005
Carbon tetrachloride	0.005
Chromium (hexavalent)	0.05
2,4-Dichlorophenoxy acetic acid	0.07
1,4-Dichlorobenzene	0.075
1,2-Dichloroethane	0.005
1,1-Dichloroethylene	0.007
Endrin	0.002
Fluoride	4.0
Lindane	0.0002
Lead	0.015
Mercury	0.002
Methoxychlor	0.04
Nitrate	10
Selenium	0.05
Silver	0.05
Toxaphene	0.003
1,1,1-Trichloroethane	0.2
Trichloroethylene	0.005
2,4,5-Trichlorophenoxy acetic acid	0.05
Vinyl chloride	0.002

Source: Code of Federal Regulations, *Vol. 40*, Part 258, Criteria for municipal solid waste landfills, U.S. Government Printing Office, Washington, DC, 2004.



FIGURE 10.3 Installation of a layer of low-permeability clay. The clay is spread in two lifts and then rolled. (Reproduced with kind permission of ISWM Operations, *Landfill*, No date, Available from: http://www.townofbourne.com/Departments/PUBLICWORKS/IntegratedSolidWasteManagment/ISWMOperations/tabid/333/Default.aspx.)

TABLE 10.2
Common Categories of Clays and Some Important Chemical and Physical Properties

Clay	Substitution	Interlayer Component	Swelling	Cation Exchange Capacity (cmol/kg)	Total Surface Area (m^2/g)
Kaolinite	None	None	None	3–15	10–20
Illite	T	K^+	None	15–40	65–100
Vermiculite	T/Oc	H_2O	Moderate	100–200	600–700
Smectite	Oc/T	Cations, H_2O	High	80–150	700–800
Chlorite	–	$Mg(OH)_2$	None	10–50	75–100

Note: T = tetrahedral layer; Oc = octahedral layer.

Second, the plasticity index (PI) must be greater than 10%. Third, coarse fragments should be screened to no more than about 10% gravel-size particles. Soils with a greater percentage of coarse fragments might contain pockets of excessive hydraulic conductivity. Finally, the material should not contain rocks larger than 2.5–5 cm (1–2 in.) in diameter (U.S. EPA 1989).

Many different clay types exist, with variations in surface area, external and internal charge, and interlayer cations. Such differences in chemical and physical properties influence swelling behavior, potential for cracking and liquid transmission, and ultimately determine their utility in landfill liners.

The clays of importance are the so-called silicate clays, that is, those possessing a crystalline structure composed of two relatively simple constituents, a silica tetrahedron (SiO_4) and an alumina octahedron ($Al_2[OH]_6$). Different clay minerals are formed as these basic units become stacked upon one other. In many cases, the central metal (Si or Al) is replaced by other metals of similar diameter, thus imparting a significant electrical charge to the clay units. Also, different ions may bind the clay units together. Some important clay properties are listed in Table 10.2. The smectite group is known for substantial swelling upon wetting; water molecules are easily inserted between the layers, which results in expansion. As a result, smectites (in particular bentonite clays) are popular for landfill liners and caps and also for the installation of slurry walls, that is, vertical barriers that restrict horizontal liquid migration.

10.4.6 Hydraulic Conductivity

Vertical seepage of leachate, and consequent contamination of groundwater, is an important consideration in the design of a subtitle D landfill. During routine landfill operations, leachate will collect at the base of a landfill, typically from inputs of natural precipitation and the presence of moisture within waste. It is of great practical importance, therefore, to appreciate the behavior of liquids such as water or leachate in a saturated soil (or clay) column.

Henri Darcy, a 19th-century French engineer, developed one of the earliest descriptions of groundwater flow. He observed a relationship between the volume of water flowing through sand and certain properties of the sand, and formulated the equation

$$Q/t = KA\ dH/dL \tag{10.1}$$

where Q is the volume of flow per unit time t through a column of a given cross-sectional area of flow A. The flow is under a pressure gradient dH/dL, and the change in water level over a given length is L. K is the saturated hydraulic conductivity, a proportionality constant. The difference in elevation of the water table, dH or $(h_2–h_1)$, over the length (L) is the slope of the water table or the hydraulic gradient. Darcy's law calculates the volumetric flow rate through a unit cross-section of the aquifer.

The hydraulic conductivity of saturated clays is dependent upon grain size and particle sorting and is relatively stable over time. Hydraulic conductivity in unsaturated clay is also influenced by grain size and sorting, and additionally by pore water content.

Example 10.1

Calculate the volumetric flow rate through a compacted clay liner at a landfill measuring 2.5 ha. Liner thickness is 1 m and the saturated hydraulic conductivity is 10^{-8} cm/s. Assume 0.3 m water ponded on the liner.

Solution

$$Q = K\ A\ dh/dL$$

$$Q = (K \times A \times H)/L$$

Convert all distances to meters, so 10^{-8} cm/s = 10^{-10} m/s.
Also, 2.5 ha = 2.5×10^4 m^3

$$Q = (10^{-10}\ \text{m/s} \times 2.5 \times 10^4\ \text{m}^3 \times 1.3\text{m})/1\text{m}$$

$$= 3.25 \times 10^{-5}\ \text{m}^3/\text{s}$$

$$= 2.81\ \text{m}^3/\text{day}\ (86{,}400\ \text{s} = 1\ \text{day})$$

10.4.7 Geomembrane Liners

Given its possible contact with a landfill leachate that is chemically complex, a geomembrane liner must provide for substantial chemical resistance and reliable seams. The polymers most commonly used in geomembranes are HDPE, linear low-density polyethylene (LLDPE), polyvinyl chloride (PVC), flexible polypropylene (fPP), and chlorosulfonated polyethylene (CSPE) (Table 10.3 and Figure 10.4) (Qian et al. 2002). A number of factors must be considered for successful geomembrane liner design and installation, including:

- Selection of proper membrane polymer materials (compatible with waste and leachate)
- Proper subgrade preparation
- Membrane transportation, storage, and placement
- Proper installation conditions (appropriate weather, temperature)
- Seaming and testing
- Use of construction quality assurance

TABLE 10.3
Types of Geomembranes and Their Approximate Formulations

Type	Resin	Plasticizer	Filler	Carbon Black or Pigment	Additives
HDPE	95–98	0	0	2–3	0.25–1.0
VLDPE	94–96	0	0	2–3	1–4
PVC	50–70	25–35	0–10	2–5	2–5
CSPE	40–60	0	40–50	5–40	5–15

Source: U.S. EPA, *Technical Manual, Solid Waste Disposal Facility Criteria,* EPA 530-R-93-182, Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 1993.

Note: HDPE = high-density polyethylene; VLDPE = very low-density polyethylene; PVC = polyvinyl chloride; CSPE = chlorosulfonated polyethylene.



FIGURE 10.4 Geomembrane material being installed at a land disposal facility. (From EPA.gov.)

The thickness of geomembrane liners range from 30 to 120 mil. The recommended thickness for all geomembrane liners is 30 mil (0.75 mm) with the exception of HDPE, which should be set at 60 mil (1.5 mm) (Qian et al. 2002).

10.4.8 Compatibility of Liners with Wastes

The chemical compatibility of a geomembrane with waste leachate is a critical consideration regarding choice of material. Polymers used in geomembranes must be expected to withstand a wide range of chemical stresses for very long periods. Many materials will deteriorate when exposed to leachate constituents over time. The waste may react with the liner, causing degradation of the polymer or its additives, or the waste may dissolve into the liner, resulting in swelling of the membrane without degrading it (Buss et al. 1995). Landfill owners and operators must anticipate the composition of leachate that a cell will generate and select the appropriate liner materials. The chemical resistance of geomembrane materials as well as LCR pipes should be thoroughly assessed prior to installation.

EPA Method 9090A (U.S. EPA 1986b) is used to evaluate the chemical compatibility of synthetic materials used in liner and LCR systems. A primary objective of compatibility testing is to ensure that liner materials will remain intact during the operating lifetime of a landfill, and also through the postclosure period and beyond. EPA Method 9090A is used to predict the effects of leachate under field conditions. The test is performed by immersing a synthetic membrane in a chemical mixture for 120 days at two different temperatures, i.e., ambient and elevated. Samples are removed every 30 days and evaluated for changes in physical properties. Tests performed on geomembranes are listed in Table 10.4.

Results from a 120-day test under controlled conditions offer limited predictive capability for a real-world landfill situation. Method 9090A has been verified, however, with field data. EPA conducted a 5-year study of the impact of MSW on common liner materials and measured little, if any, deterioration within that period. In other studies, however, chemical exposure of geomembranes resulted in minor effects such as discoloration, to more serious problems such as swelling. In extreme cases the liner may dissolve, tear, crack, or puncture.

TABLE 10.4
Selected ASTM Tests for Geomembrane Integrity

Number	Title
D4437-99	Standard Practice for Determining the Integrity of Field Seams Used in Joining Flexible Polymeric Sheet Geomembranes
D4545-86	Standard Practice for Determining the Integrity of Factory Seams Used in Joining Manufactured Flexible Sheet Geomembranes
D4716-01	Test Method for Determining the (In-Plane) Flow Rate per Unit Width and Hydraulic Transmissivity of a Geosynthetic Using a Constant Head
D4759-88	Standard Practice for Determining the Specification Conformance of Geosynthetics
D4833-00e1	Standard Test Method for Index Puncture Resistance of Geotextiles, Geomembranes, and Related Products
D4885-01	Standard Test Method for Determining Performance Strength of Geomembranes by the Wide Strip Tensile Method
D5262-97	Standard Test Method for Evaluating the Unconfined Tension Creep Behavior of Geosynthetics
D5321-92	Standard Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method
D5322-98	Standard Practice for Immersion Procedures for Evaluating the Chemical Resistance of Geosynthetics to Liquids
D5323-92	Standard Practice for Determination of 2% Secant Modulus for Polyethylene Geomembranes
D5397-99	Standard Test Method for Evaluation of Stress Crack Resistance of Polyolefin Geomembranes Using Notched Constant Tensile Load Test
D5494-93	Standard Test Method for the Determination of Pyramid Puncture Resistance of Unprotected and Protected Geomembranes
D5496-98	Standard Practice for In Field Immersion Testing of Geosynthetics
D5514-94	Standard Test Method for Large Scale Hydrostatic Puncture Testing of Geosynthetics
D5514-94	Standard Test Method for Microscopic Evaluation of the Dispersion of Carbon Black in Polyolefin Geosynthetics
D5617-99e1	Standard Test Method for Multi-Axial Tension Test for Geosynthetics
D5641-94	Standard Practice for Geomembrane Seam Evaluation by Vacuum Chamber
D5721-95	Standard Practice for Air-Oven Aging of Polyolefin Geomembranes
D5747-95a	Standard Practice for Tests to Evaluate the Chemical Resistance of Geomembranes to Liquids
D5820-95	Standard Practice for Pressurized Air Channel Evaluation of Dual Seamed Geomembranes
D5884-01	Standard Test Method for Determining Tearing Strength of Internally Reinforced Geomembranes
D5886-95	Standard Guide for Selection of Test Methods to Determine Rate of Fluid Permeation through Geomembranes for Specific Applications
D6214-98	Standard Test Method for Determining the Integrity of Field Seams Used in Joining Geomembranes by Chemical Fusion Methods
D6364-99	Standard Test Method for Determining the Short-Term Compression Behavior of Geosynthetics
D6365-99	Standard Practice for the Nondestructive Testing of Geomembrane Seams using the Spark Test
D6392-99	Standard Test Method for Determining the Integrity of Nonreinforced Geomembrane Seams Produced Using Thermo-Fusion Methods
D6434-99	Standard Guide for the Selection of Test Methods for Flexible Polypropylene (fPP) Geomembranes
D6455-99	Standard Guide for the Selection of Test Methods for Prefabricated Bituminous Geomembranes (PBGM)
D6495-02	Standard Guide for Acceptance Testing Requirements for Geosynthetic Clay Liners
D6496-99	Standard Test Method for Determining Average Bonding Peel Strength Between the Top and Bottom Layers of Needle-Punched Geosynthetic Clay Liners
D6497-02	Standard Guide for Mechanical Attachment of Geomembrane to Penetrations or Structures
D6574-00	Test Method for Determining the (In-Plane) Hydraulic Transmissivity of a Geosynthetic by Radial Flow
D6636-01	Standard Test Method for Determination of Ply Adhesion Strength of Reinforced Geomembranes
D6693-01	Standard Test Method for Determining Tensile Properties of Nonreinforced Polyethylene and Nonreinforced Flexible Polypropylene Geomembranes
D6706-01	Standard Test Method for Measuring Geosynthetic Pullout Resistance in Soil

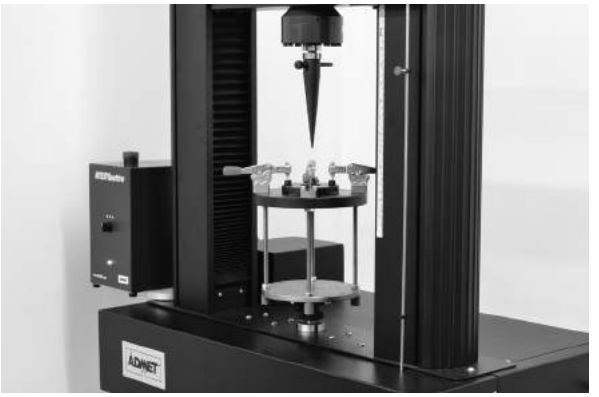


FIGURE 10.5 Puncture apparatus for geomembrane testing. (Reproduced with kind permission from ADMET, *Plastics and Elastomers*, 2013, Available from: http://admet.com/materials/plastics-elastomers-testing/.)

10.4.9 Survivability Tests

Several tests are available to determine the survivability of unexposed polymeric liners. For example, puncture tests estimate the survivability of geomembranes in the field. A 5/16 in. steel rod with rounded edges is pushed down through an anchored membrane (Figure 10.5). A geomembrane shown to have high strain capacity under mechanical tension is expected to experience great survivability in the field. High-density polyethylenes provide high penetration force but experience high brittle failure. Thus, puncture data may not always adequately predict field survivability (U.S. EPA 1989).

10.4.10 Permeability

Even if a liner is installed correctly, that is, without punctures and defects, liquid will inevitably diffuse through. Such rates are, fortunately, extremely low. EPA data (1988b) for water vapor transmission across various geomembranes are given in Table 10.5. Permeability of a geomembrane is evaluated using ASTM E96, the Water Vapor Transmission test (ASTM 2000). A sample of the membrane is attached to the top of a small aluminum cup containing a known volume of water. The cup is then placed in a chamber of controlled humidity and temperature. The chamber is typically set to 20% relative humidity, whereas the humidity in the cup is 100%; thus, a concentration gradient is established across the membrane. Moisture diffuses through the membrane, and

TABLE 10.5
Water Vapor Transmission for Different Geomembranes

	Thickness		Vapor Transmission Rate	
Geomembrane	**mm**	**mil**	**g/m²/day**	**gallon/acre/day**
PVC	0.75	30	1.9	2.03
CPE	1.0	40	0.4	0.43
CSPE	1.0	40	0.4	0.43
HDPE	0.75	30	0.02	0.021
HDPE	2.45	98	0.006	0.0064

Source: U.S. EPA, *Summary of Data on Municipal Solid Waste Landfill Characteristics – Criteria for Municipal Solid Waste Landfills*, EPA/530-SW-88-038, Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 1988.

Note: PVC = polyvinyl chloride; CPE = chlorinated polyethylene; CSPE = chlorosulfonated polyethylene; HDPE = high-density polyethylene.

with time the liquid level in the cup will fall. From these measurements, the rate at which moisture is moving though the membrane is measured and the permeability of the membrane is calculated with a simple diffusion equation (Fick's first law)

$$J = -D(dC/dx) \tag{10.2}$$

where J is the flux (mol/cm^2 s), D the diffusion coefficient (cm^2/s), C the concentration (mol/cm^3), and x the length in the direction of movement (cm).

It follows that Fick's first law controls leakage through a synthetic liner. The diffusion process is similar to the rate of flow governed by Darcy's law, except that the former is driven by concentration gradients as opposed to hydraulic head.

Data revealing problems with synthetic membranes have been documented for water utilities, where contamination of drinking water due to permeation of trace organic contaminants from soil through plastic pipes has occurred. Laboratory studies have also demonstrated the transport of solvents through membranes. Haxo and Lahey (1988) demonstrated the migration of trichloroethylene and toluene through a membrane. Park and Nibras (1993) measured diffusion parameters for a range of volatile organic compounds (VOCs) in HDPE liner materials and demonstrated that this might be a significant source of release from lined landfills. Diffusive mass transport could, in theory, have a significant environmental impact by allowing the escape of organic solvents though intact membranes at rates comparable with those involving leakage through a defect (i.e., hole) (Buss et al. 1995). Varank et al. (2011) developed an advection–dispersion transport model for estimating transport parameters of 14 different phenolic compounds and three inorganic contaminants.

Solvent gas transmission through geomembranes is also a serious practical concern. Very light gases, such as methane (CH_4), will rise from the waste cell and contact the membrane. Methane transmission rates for several geomembranes are shown in Table 10.6.

Factors in a landfill cell that might affect leachate diffusion rate through an intact liner include temperature, pressure, and elongation due to tensile stress. As temperature increases, diffusion will increase due to greater thermal motion in polymer chains, thus producing more voids through which leachate can escape (Buss et al. 1995).

Of more practical importance, however, is the occurrence of holes in the liner caused by improper placement and positioning over sharp stones. Giroud and Bonaparte (1989) state that with good quality control, 2.5 holes/ha of geomembrane (1 hole/acre) is a fairly typical occurrence. With poor

TABLE 10.6
Methane Transmission for Different Geomembranes

Geomembrane	Thickness		Methane Gas Transmission Rate (ml/m^2-day-atm)
	mm	mil	
PVC	0.25	10	4.4
PVC	0.5	20	3.3
LLDPE	0.45	18	2.3
CSPE	0.8	32	0.27
CSPE	0.85	34	1.6
HDPE	0.6	24	1.3
HDPE	0.85	34	1.4

Source: U.S. EPA, *Summary of Data on Municipal Solid Waste Landfill Characteristics – Criteria for Municipal Solid Waste Landfills*, EPA/530-SW-88-038, Office of Solid Waste and Emergency Response, Washington, DC, 1988.

Note: PVC = polyvinyl chloride; LLDPE = linear low-density polyethylene; CSPE = chlorosulfonated polyethylene; HDPE = high-density polyethylene.

TABLE 10.7
Calculated Flow Rates through a Geomembrane with a Liquid Head of 0.3 m (1 ft)

	Number of Holes		Flow Rate	
Size of Hole (cm^2)	Hole/hectare	Hole/acre	$L/m^2/day$	Gallon/acre/day
No holes	0	0	9.4×10^{-6}	0.01
0.1	2.5	1	0.31	330
0.1	75	30	9.4	10,000
1	2.5	1	3.1	3300
1	75	30	94	100,000
10	2.5	1	31	33,000

Source: U.S. EPA, *Action Leakage Rates for Leak Detection Systems*, EPA 530-R-92-004, Office of Solid Waste, Washington, DC, 1992.

quality control we can expect 75 holes/ha (30 holes/acre). Most defects tend to be small (<0.1 cm^2), but larger holes do occasionally occur (Qian et al. 2002). Table 10.7 provides data for estimated losses from geomembranes with holes.

The Bernoulii equation can be used to estimate the flow rates through holes in geomembranes, assuming that the size and shape of the holes are known.

$$Q = C_b \cdot a\,(2 \cdot g \cdot h)^{0.5} \tag{10.3}$$

where Q = flow rate through a geomembrane, cm^3/s
C_b = flow coefficient with a value of about 0.6 for a circular hole
a = area of circular hole, cm^2
g = acceleration due to gravity, 981 cm/s
h = liquid head acting on the liner, cm

The above equation applies to a geomembrane that has one or more holes that are widely spaced, such that leakage through each hole acts independently of the other holes, that the leachate head h is constant, and that the soil that underlies the geomembrane has a relatively large hydraulic conductivity (Qian et al. 2002).

10.4.11 Stress

Stress considerations are especially critical for the design of the side slopes and base of a landfill. For side slopes, both the weight of the membrane itself and waste settlement place severe tensile strains on the geomembrane.

The primary geomembrane must be able to support its own weight on the side slopes. In order to calculate self-weight, the specific gravity, friction angle, thickness, and yield stress of the geomembrane must be known. Waste settlement is an additional stress consideration. For the bottom of the cell, localized settlement must be considered in the design. As waste settles in the landfill, a downward force acts upon the primary geomembrane. A low friction component between the geomembrane and underlying material prevents the force from being transferred downward, thus limiting tension on the primary geomembrane (U.S. EPA 1989).

10.4.12 Geomembrane Liner Handling and Placement

The surface of the compacted soil liner must be smooth and sufficiently strong to provide continuous support for the geomembrane liner. The soil surface must be relatively free of rocks, roots,

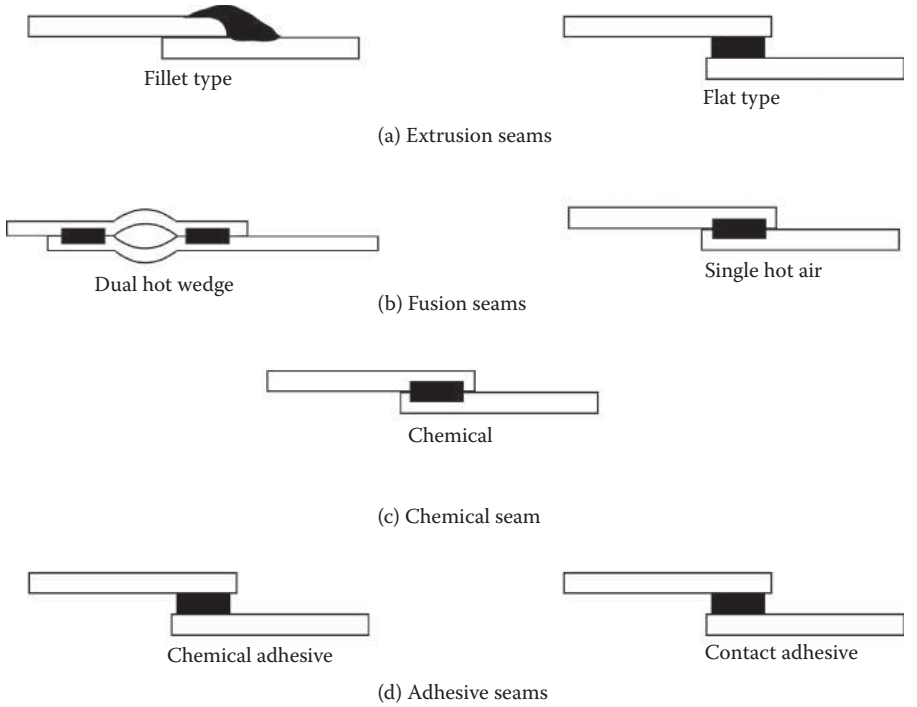


FIGURE 10.6 Seaming methods for landfill liners. (From U.S. EPA, *Design, Operation, and Closure of Municipal Solid Waste Landfills*, EPA 625/R-94/008, Seminar Publication, Office of Research and Development, Washington, DC, 1994.)

and excess water. EPA studies have demonstrated that nonangular stones present at the surface and smaller than ¾ in. in diameter will not damage most geomembrane liners. Geomembranes composed of PVC are commonly prefabricated into large panels, folded, and shipped on pallets. Liners manufactured from HDPE and PP must not be folded and are shipped to the site in rolls. Once delivered, liners should be stored to avoid direct contact with the soil surface. A protective surface such as a geotextile may be placed on the ground, or the geomembrane rolls could be wrapped in plastic at the factory. The stored liner should also be protected from exposure to excessive heat, dust, and water.

At the time of installation, the geomembrane liners are rolled out or spread out over the soil liner with each sheet overlapping adjacent sheets. The geomembranes are then seamed together to create a single, impermeable layer. A number of methods are available to create strong seams, including extrusion, fusion, chemical, and adhesive seaming (Figure 10.6). Thermal seaming is the most common method of attaching sheets. The process requires proper weather conditions—if a membrane surface is wet, water can vaporize and produce bubbles within the seam, which reduces seam strength and may ultimately result in leakage. Ambient temperature must also be considered during installation. Thermal seaming should be performed when the temperature is between 4.4°C and 40°C (40°F and 104°F). The presence of dust is an additional practical concern in geomembrane seaming; dust control is critical during seaming process.

Given that geomembrane liner seaming is a critical aspect in maintaining membrane integrity, a seam-testing program should be established for quality control.

10.4.13 Construction Quality Assurance

To minimize holes in a geomembrane liner (whether caused by product defects, transportation, installation, or seaming) and to meet required standards, a construction quality assurance (CQA)

program must be established for liner installation (U.S. EPA 1992a, 1994). The CQA program comprises a set of activities performed by landfill owners to ensure that the cells and associated facilities are constructed as specified in the design. The CQA program should be developed during the design stage, and the state regulatory agency should review it before a permit is issued for construction.

10.4.14 Daily Operations and Issues

10.4.14.1 Filling Sequences

After weighing the incoming truck at the weigh station, the waste is brought to the *working face* of the landfill. Waste is deposited into daily cells, i.e., small units of land that are filled with MSW and then covered at the end of the day by a layer of soil or similar material (e.g., compost, shredded tires). In a new landfill cell, waste must be placed at the base such that compactor wheels do not come into contact with leachate collection systems, liners, and other sensitive layers. Filling continues with the placement of successive *lifts*, typically starting in a corner and moving outward. The filling sequence is established at the time of landfill design and permitting. The working face must be large enough to accommodate several vehicles unloading simultaneously, approximately 4–6 m (12–20 ft) per vehicle (Worrell and Vesilind 2011).

The maximum working area for a landfill can be calculated by (Kiely 1997)

$$A_{max} = (0.1\ W)/R \tag{10.4}$$

where A_{max} is the maximum working area, R the average annual rainfall (m), and W the average annual waste input (metric tons). The above equation assumes an absorption capacity of the waste of 0.1 m^3/metric ton.

Example 10.2

Compute the maximum working area of a landfill cell if W is 12,000 MT/year and R is 1.1 m/year (approx. 43 in./year). Comment on the result.

Solution

$$A_{max} = (0.1 \times 12{,}000)/1.1 = 1090\ m^2$$

If the cell measures 75 m in length, then the average width of the working area would be 14.5 m.

As waste is placed in the landfill, heavy equipment passes over and compacts it (Figure 10.7). The degree of compaction is related to several factors, including thickness of the waste layer (see Figure 10.8), the number of passes made over the waste (see Figure 10.9), slope (flatter slopes and steeper slopes compact better by landfill compactors and track-type tractors, respectively, and moisture content (wetter waste compacts more effectively than dry waste) (Worrell and Vesilind 2011).

Example 10.3

Determine the area required for a new sanitary landfill with a projected lifetime of 25 years. The landfill will serve a population of 250,000 persons, generating 28 kg (62 lbs) per household per week. Waste density in the landfill averages 550 kg/m^3. Landfill height is not to exceed 25 m. Assume four persons per household.



FIGURE 10.7 Compactor vehicle at a sanitary landfill.

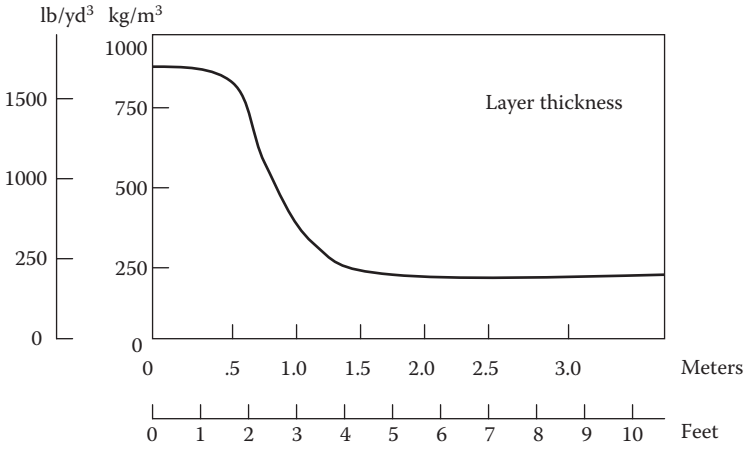


FIGURE 10.8 Density of MSW in a landfill cell as related to thickness of the waste layer.

Solution

$$\text{MSW generated} = 250{,}000/4 \times 28\text{kg}/10^3 = 1750 \text{ MT/week}$$

$$= 91{,}000 \text{ MT/year}$$

$$\text{Volume of landfill space needed} = (91{,}000 \text{ MT/year} \times 10^3 \text{ kg/MT})/550 \text{ kg/m}^3$$

$$= 165 \times 10^3 \text{ m}^3\text{/year}$$

$$\text{For a maximum height of 25 m, the required land area} = (165 \times 10^3 \text{ m}^3\text{/y})/25 \text{ m} = 6618 \text{ m}^2$$

$$= 0.7 \text{ ha or } 1.63 \text{ acres}$$

The above value, however, should be increased by about 50% to allow for use of daily cover, final cover, receiving areas, roads, fencing, and other structures.

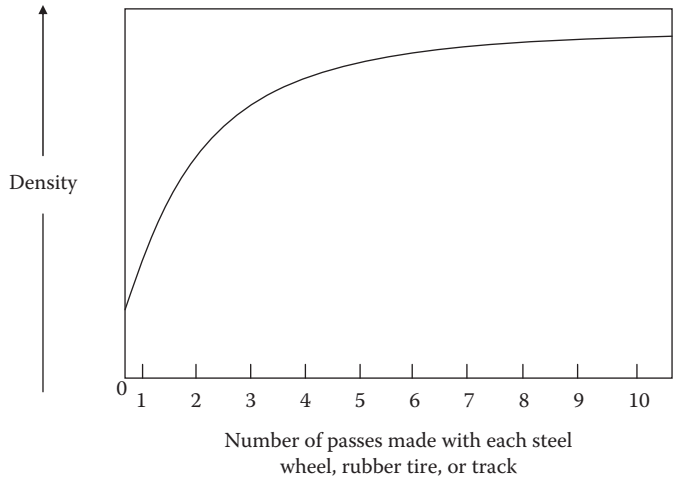


FIGURE 10.9 Density of MSW in a landfill cell as related to the number of passes by machinery over the waste.

Required land area for 25 years = 0.7 ha × 25 years × 1.5

= 26.25 ha or 64.8 acres

In the above example, what is the daily waste generation rate per capita? How does this figure compare with the estimated national average (Chapter 1)?

10.4.14.2 Cover Materials

At the end of each operating day, active landfill cells must be covered with at least 6 in. of soil or similar material to control disease vectors, fires, odors, blowing litter, and scavenging by animals (40 CFR 258.21) (Figure 10.10). More frequent application of soil may be required if a specific nuisance or hazard condition occurs at the facility, for example, strongly malodorous or gas-producing wastes.

In some situations, local soil may not be readily available as cover; therefore, alternative materials are required. The alternative cover must be shown to control all relevant hazards and nuisances (disease vectors, fires, and odors). Materials may be natural or commercially produced and must not pose a threat to human health and the environment. Some candidate materials are those that may be considered waste; therefore, applying them serves as an efficient utilization of landfill space. Examples of alternative covers include (U.S. EPA 1992b):

- Fly ash and bottom ash from utilities and municipal waste incinerators
- Composted MSW or sewage sludge
- Foundry sands
- Yard waste (lawn clippings, leaves, shredded branches)
- Construction and demolition debris
- Commercially available cover materials
  - Foam sprayed onto the working face
  - Slurry products (e.g., fibers from recycled newspaper and wood chip slurry) (U.S. EPA 1992b).

Some of the commercial alternatives may require specially designed application equipment.



FIGURE 10.10 Application of daily cover prevents pest infestations and controls odors.

10.4.14.3 Disease Vector Control

Vectors include rodents, flies, mosquitoes, or other organisms that transmit diseases to humans. Putrescible waste attracts vectors, as it serves as a readily available food source. Application of cover at the end of the operating day is typically sufficient to control disease vectors; however, other practices may be necessary (40 CFR 258.22) and include (U.S. EPA 1993c):

- Reducing the area of the working face
- Increasing the thickness of the daily cover
- Changing cover type, for example, to a material less permeable to air and water
- Application of repellents, insecticides, and rodenticides
- Composting of organic wastes prior to disposal
- Use of predators for the control of insect, bird, and animal populations

Standing water serves as a potential breeding ground for mosquitoes. Water collects in depressions, open containers, leachate storage ponds, and siltation basins. To control mosquitoes, standing water should be removed and an insecticide possibly applied. Table 10.8 lists insecticides commonly used at sanitary landfills. In order to control rodent populations, various birds of prey, for example, hawks, falcons, and owls, can be introduced.

10.4.14.4 Biological Control of Pests

Insecticides may serve as an effective means of combating insect pests at landfills; however, genetic resistance to applied chemicals should always be a consideration. Biological control methods may be a viable alternative to chemical control at landfills. Hanley et al. (2004) examined the efficacy of targets treated with (*Z*)-9-tricosene, a sex pheromone. Other researchers have surveyed the parasitoids and predators active in municipal wastes and animal manures. Rueda et al. (1997)

TABLE 10.8
Insecticides Approved for Use at U.K. MSWLFs, Their Chemical Grouping, and Target Pest

Pest	Active Ingredient	Approved Insecticide	Chemical Group
Ants, beetles, bugs, cockroaches, crickets, earwigs, fleas, mites, moths, silverfish	Fenitrothion	Antec Kurakil EC-Kill	Organophosphorus
Flies	Chloropyrifos-methyl	Smite	Organophosphorus
	Diflubenzuron	Dimilin Flo	Insect growth regulator
	Fenitrothion	Antec Durakil EC-Kill	Organophosphorus
	Pyrethrin	Multispray Pybuthrin 33	Pyrethroid
	Trichlorfon	Dipterex 80[a]	Organophosphorus
	Bioresmethrin	Blade	Pyrethroid
General insect control	Alphacypermethrin	Fendona ASC	Pyrethroid
	Bendiocarb	Various products	Carbamate
	Bioalletrin + bioresmethrin	Pybuthrin 33 BB	Pyrethroid
	Bioresmethrin	Biosol RTU Safe kill RTU	Pyrethroid
	Chlorpyrifos-methyl	Smite	Organophosphorus
	Chlorpyrifos-methyl+ Permethrin + pyrethrins	Multispray	Organophosphorus+ Pyrethroid
	Cypermethrin	Various products	Pyrethroid
	Deltamethrin+ S-bioallethrin	Crackdown Rapide	Pyrethroid
	Diazinon	Knox Out 2 FM	Organophosphorus
	Fenitrothion	Various products	Organophosphorus
	Fenitrothion + resmethrin + Permethrin	Turbair beetle killer	Organophosphorus+ Pyrethroid
	Fenitrothion + tetramethrin	Killgerm Fenitrothion Pyrethroid concentrate	Organophosphorus+ Pyrethroid
	Permethrin	Various products	Pyrethroid
	Permethrin + bioallethrin	Various products	Pyrethroid
	Permethrin + S-bioallethrin	Various products	Pyrethroid
	Pirimiphos–methyl	Actellic 25 EC Actellic Dust	Organophosphorus
	Propoxur	Killgerm Propoxur 20 EC	Organophosphorus
	Pyrethrins	Various products	Pyrethroid
	Tetramethrin	Killgerm Py-kill W	Pyrethroid
	Tetramethrin + d-phenothrin	Various products	Pyrethroid
	Tetramethrin + resmethrin	Swat A	Pyrethroid

Source: Reprinted with kind permission from British Crop Protection Council and Contract Report for Enventure, Ltd, *Fly Control on Landfill: A Literature Review*, 1999, Available from: http://www.enventure.co.uk/docs/Fly%20control%20on%20landfill%20sites %20-%20literature%20study.pdf.

[a] Off-label approval—although approved, off-label uses are not endorsed by the manufacturers and such treatments are made entirely at the risk of the user.

recorded five species of wasp parasitoids in the pupae of house flies and two in blow flies. Sulaiman et al. (1990) identified nine species of pupal parasitoids of flies breeding in municipal wastes and on poultry farms. Hoyer (1986) found 22 species of fly parasitoids. In Washington State, biological control was used in preference to chemical control of flies associated with manure pits (Guhlke 1985); flies had reportedly developed resistance to insecticides. Parasitic chalcid wasps had the advantage of providing continuous control of fly populations. Costs for biological control were a fraction of what they would have been for chemical control. In addition, reduced use of insecticides allows populations of other naturally occurring parasites and predators to proliferate (Ellis and Blood-Smyth, n.d.).

10.4.14.5 Generation of Landfill Gases

Gases occurring in active and closed landfills include methane (CH_4), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), hydrogen sulfide (H_2S), ammonia (NH_3), nitrogen (N_2), and oxygen (O_2). The most common gases produced within landfills are CH_4 and CO_2, with lesser quantities of the other gases, typically in concentrations below 1% (v/v) (U.S. EPA, 1986a) (Table 10.9). Data on molecular weight and density of specific gaseous components are presented in Table 10.10. Virtually all landfill gases are generated from microbial decomposition of solid waste. Figure 10.11 shows the major phases of MSW decomposition in a landfill cell and the resultant gaseous products. Table 10.11 lists several biodegradable organic constituents of MSW that are related to gas generation.

Phase I: Aerobic phase. During Phase I, the biodegradable components of MSW undergo microbial decomposition immediately following placement in the landfill cell. Initially, oxygen occurs in sufficient quantities in the interstices (voids) to allow for aerobic degradation of the organic waste fraction. The sources of the heterotrophic microbial populations responsible for waste decomposition, both aerobic and anaerobic, are the waste itself and soil material used as daily cover. Wastewater treatment plant sludge, disposed in many MSWLFs, and recycled leachate are other sources of organisms.

TABLE 10.9
Common Landfill Gases and Their Concentrations

Component	Percent (Dry Volume Basis)
Methane	45–60
Carbon dioxide	40–60
Nitrogen	2–5
Oxygen	0.1–1.0
Sulfides, disulfides, mercaptans, etc.	0–1.0
Ammonia	0.1–1.0
Hydrogen	0–0.2
Carbon monoxide	0–0.2
Trace constituents	0.001–0.6
Characteristic	**Value**
Temperature, °C (°F)	38–50 (100–120)
Specific gravity	1.02–1.06
Moisture content	Saturated
High heating value kJ/m^3 (BTU/ft^3)	900–1100 (400–500)

Source: Data reproduced with kind permission from Tchobanoglous, G. et al., *Integrated Solid Waste Management: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1993.

TABLE 10.10
Selected Chemical and Physical Properties of Gases Found in a Sanitary Landfill

Gas	Formula	Molecular Weight	Density, g/L
Air		28.97	1.2928
Ammonia	NH_3	17.03	0.7708
Carbon dioxide	CO_2	44.00	1.9768
Hydrogen	H_2	2.016	0.0898
Hydrogen sulfide	H_2S	34.08	1.5392
Methane	CH_4	16.03	0.7167
Nitrogen	N_2	28.02	1.2507
Oxygen	O_2	32.00	1.4289

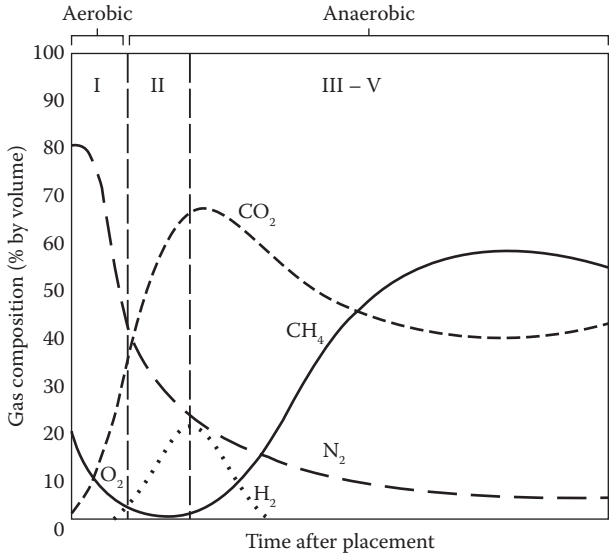


FIGURE 10.11 The stages of decomposition in a sanitary landfill. (From Agency for Toxic Substance Disease Registry, *Landfill Gas Primer – An Overview for Environmental Health Professionals*, 2006, Available from: http://www.atsdr.cdc.gov/HAC/landfill/PDFs/Landfill_2001_ch2mod.pdf.)

TABLE 10.11
Rapidly and Slowly Biodegradable Organic Constituents in MSW

Organic Waste Component	Rapidly Biodegradable	Slowly Biodegradable
Food wastes	x	
Newspaper	x	
Office paper	x	
Cardboard	x	
Yard wastes	x	x[a]
Textiles		x
Rubber		x
Leather		x
Wood		x

[a] Branches, twigs, and other woody portions of yard wastes.

The reaction for the aerobic oxidation of a glucose molecule was shown in Equation 8.1. Common products of Phase I include CO_2, H_2O, NO_3^-, and other oxygenated compounds. Oxygen is rapidly depleted in the covered landfill cell by the action of the heterotrophic aerobic microorganisms. Diffusion of oxygen into the void spaces is negligible; once the O_2 level drops below 10%–15% (v/v), anaerobic microorganisms are activated (Phase II).

Phase II: First anaerobic phase. By the onset of Phase II, anaerobic conditions have already been initiated. Nitrate and sulfate ions serve as electron acceptors for anaerobic heterotrophs and are reduced to N_2 and H_2S (see Equations 10.5 and 10.6). The extent of anaerobic conditions is monitored by measuring the oxidation–reduction (redox) potential of the waste. Redox conditions sufficient to support reduction of nitrate and sulfate occur at about −50 to −100 mV.

$$1/5NO_3^- + 1/4\{CH_2O\} + 1/5H^+ \rightarrow 1/10N_2 + 1/4CO_2 + 7/20H_2O \quad (10.5)$$

$$SO_4^{2-} + 2\{CH_2O\} + 2H^+ \rightarrow H_2S + 2CO_2 + 2H_2O \quad (10.6)$$

In Phase II, the pH of landfill liquids decreases due to formation of organic acids and the effect of elevated concentrations of CO_2 within the voids, which partly dissolves and forms carbonic acid, H_2CO_3.

$$CO_2 + H_2O \rightarrow H_2CO_3 \quad (10.7)$$

Phase III: Second anaerobic phase. In Phase III, also known as the *acid phase*, anaerobic microbial activity is accelerated with the concomitant production of organic acids and small quantities of H_2 gas. This phase is the result of enzyme-mediated hydrolysis of high-molecular weight compounds such as lipids, polysaccharides, and proteins into smaller molecules. Microbial populations subsequently convert these to organic acids such as acetic acid (CH_3COOH), butyric acid ($CH_3CH_2CH_2COOH$), and lactic acid ($CH_3CH(OH)COOH$), and small concentrations of fulvic acid and other complex organic acids. Carbon dioxide is the principal gas generated during Phase III.

The pH of landfill liquids decreases to ~5 due to the presence of organic acids and the relatively high concentrations of CO_2 within void spaces. There is no methane production during this period, as methane-producing bacteria cannot tolerate acidic conditions. The biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), and conductivity of the leachate increase significantly during Phase III due to the presence of the organic acids. Also, because of the low pH values, metals and other inorganic constituents are solubilized during this phase.

Phase IV: Methane fermentation. In Phase IV, a second consortium of anaerobic microorganisms becomes prominent, which converts organic acids and H_2 to CH_4 and CO_2. The microorganisms responsible for this conversion (*methanogens*) are strict anaerobes. In Phase IV, formation of both methane and acid proceed simultaneously. Many of the acids have already decomposed, however, so the pH rises and stabilizes at about 6.8–8 (Tchobanoglous et al. 1993). Consequently, metals that had previously been soluble will precipitate. The concentration of BOD_5 and COD and conductivity decline.

Phase V: Maturation. Phase V occurs after the readily available biodegradable organic material has been converted to CH_4 and CO_2 (Phase IV). The rate of gas generation declines significantly because most of the available nutrients have been removed during previous phases, and the substrates that remain are only slowly biodegradable. The principal landfill gases evolved are CH_4 and CO_2. During the maturation phase, landfill liquids often contain humic and fulvic acids, which are complex and highly stable compounds.

The duration of each phase described above will vary as a function of distribution of organic components in the landfill cell, availability of nutrients, moisture content of the waste, and degree of initial compaction. For example, the generation of landfill gas will be limited if sufficient moisture is not available. Increasing the density of the MSW in the landfill may prevent adequate water movement to all areas within the cell, thereby reducing the rate of biological reactions and subsequent

TABLE 10.12
Landfill Gas Composition over the First 48 Months after Closure of a Landfill Cell

	Average (% by Volume)		
Time Since Closure (Months)	**N_2**	**CO_2**	**CH_4**
0–3	5.2	88	5
3–6	3.8	76	21
6–12	0.4	65	29
12–18	1.1	52	40
18–24	0.4	53	47
24–30	0.2	52	48
30–36	1.3	46	51
36–42	0.9	50	47
42–48	0.4	51	48

Source: Data reproduced with kind permission from Tchobanoglous, G. et al., *Integrated Solid Waste Management: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1993.

gas production. Data on the distribution of gases occurring in a newly closed landfill cell as a function of time are shown in Table 10.12.

The volume of the gases released during anaerobic decomposition can be estimated in a number of ways. For example, if the individual organic constituents found in MSW (excepting plastics) are represented with a generalized formula $C_aH_bO_cN_d$, then the total volume of gas can be estimated using Equation 10.8, assuming complete conversion to CO_2 and CH_4:

$$C_aH_bO_cN_d + (4a - b - 2c + 3d)/4\ H_2O \rightarrow (4a + b - 2c - 3d)/8\,CH_4 + (4a - b + 2c + 3d)/8\,CO_2 + dNH_3 \quad (10.8)$$

The organic component of MSW can be divided into two categories: (1) those materials that decompose rapidly (3 months to 5 years), and (2) those that decompose slowly (up to 50 years or more) (Worrell and Vesilind 2011). The rapidly and slowly decomposable components of the organic fraction of MSW are listed in Table 10.11.

10.4.14.6 Predicting Gas Production

It is essential for landfill operators to estimate the volume of gas generated from an active or closed landfill. Similarly, the composition of the gas (e.g., CH_4, S content, moisture) is important to energy users. Engineers use mathematical models to predict landfill gas generation. Models are designed based on population data, per capita waste generation, waste composition and moisture content, and expected gas yield per unit dry weight of waste. Mathematical models are also used to predict and formulate gas recovery systems, including layout, equipment type, operational parameters, and failure simulation (Worrell and Vesilind 2011). The following parameters must be known if gas production is to be accurately estimated: gas yield per unit weight of waste, lag time prior to gas production, shape of the gas production curve, and duration of gas production.

In theory, the biological decomposition of 1 ton of MSW produces 442 m^3 (15,600 ft^3) of landfill gas containing 55% CH_4 and a heat value of 19,730 kJ/m^3 (530 Btu/ft^3). Only a portion

of the waste converts into CH_4 due to the presence of inaccessible waste and nonbiodegradable components; therefore, the actual average methane yield is closer to 100 m^3/MT (3900 ft^3/ton) of MSW. Significant variation in gas production data has been noted at landfills across the United States due to differences in climate, waste types, and landfill management. Methane generation usually is between 0.06 and 0.12 m^3/kg (1–2 ft^3/lb) of waste, on a dry basis over 10–40 years. Gas yields based on waste generation have been predicted using assumptions such as

- 50% of the organic material placed in the landfill will actually decompose
- 50% of the landfill gas generated is recoverable
- 50% of landfills are operating within a favorable pH range

Once the expected yield is determined, a model is applied to predict the pattern of gas generation over time. EPA has published the Landfill Gas Emissions Model (LandGEM) based on the following equation (Pelt et al. 1998):

$$Q_T = \sum_{i=1}^{n} 2kL_0M_ie_i^{-kt} \tag{10.9}$$

where Q_T is the total gas emission rate from a landfill (volume and time), n the total time period of waste placement, k the landfill gas emission constant ($time^{-1}$), L_0 the methane generation potential (volume/mass of waste), t_i the age of the i-th section of waste (time), and M_i the mass of wet waste, placed at time i.

In this model, gas generation rate is based on a first-order decomposition model, which uses two parameters: L_o, the potential methane generation capacity of the waste, and k, the methane generation decay rate. The methane generation rate is assumed to be maximal upon MSW placement in the landfill. This model allows the user to enter L_o and k values from test data, or use default L_o and k values (Pelt et al. 1998).

The quantity of MSW occurring in the landfill is calculated for this model using site-specific data entered by the user, such as the years the facility has been in operation, quantity of MSW delivered per unit time, and landfill capacity. Emission rates are estimated for CH_4, CO_2, nonmethane organic compounds (NMOCs), and air pollutants expected to be emitted based on test data compiled in the EPA compilation of air pollutant emission factors, AP-42 (U.S. EPA 1997a).

Example 10.4

A landfill cell receives about 225,000 metric tons of MSW per year. Calculate the gas production for the first year, given a landfill gas emission constant of 0.0335 $year^{-1}$ and a methane generation potential of 175 m^3/metric ton.

Solution

For the first year,

$$Q_T = 2\ (0.0335)\ (175)\ (225{,}000)\ (e^{-0.0335(1)}) = 2{,}551{,}067\ m^3$$

Note: In the second year, this same cell will generate less total gas; however, the new layer added during the second year will produce gas, so the yields of the two cells will be combined to calculate the total gas generation for the second year, and so on.

The lag period prior to CH_4 generation may range from a few weeks to a few years, depending on landfill conditions. The duration of gas production is also influenced by environmental conditions within the landfill.

Example 10.5

Using data from the table below, estimate the chemical composition and the amount of gas that can be generated from the rapidly and slowly decomposable organic constituents in MSW. Note that some of the yard wastes will decompose rapidly (e.g., grass clippings), whereas others will be more stable (branches).

Solution

1. Determine the distribution of the major elements within the waste.

Component	Wet Weight, kg	Dry Weight, kg	Composition, kg					
			C	H	O	N	S	Ash
Rapidly Decomposable Constituents								
Food wastes	4.2	1.9	0.59	0.08	0.47	0.04	0.00	0.73
Paper	19.0	17.0	6.26	0.86	6.30	0.05	0.04	3.49
Cardboard	2.5	2.2	0.89	0.08	1.02	0.01	0.00	0.20
Yard wastes	6.1	2.5	0.85	0.12	0.75	0.05	0.00	0.72
Total	31.8	23.6	8.58	1.14	8.54	0.15	0.05	5.14
Slowly Decomposable Constituents								
Textiles	1.0	0.8	0.45	0.05	0.25	0.04	0.0	0.01
Rubber	0.2	0.2	0.17	0.02	0.00	0.00	0.0	0.00
Leather	0.22	0.21	0.11	0.01	0.02	0.02	0.0	0.05
Yard wastes	3.5	1.9	0.63	0.08	0.51	0.04	0.0	0.63
Wood	0.9	0.7	0.36	0.05	0.29	0.00	0.0	0.01
Total	5.82	3.81	1.71	0.22	1.08	0.10	0.0	0.7

2. Compute the molar composition of the elements neglecting the ash.

	C	H	O	N	S
lb/mole	12.01	1.01	16.0	14.01	32.06
Total moles					
Rapidly decomposable	0.7144	1.1262	0.5337	0.0109	0.0015
Slowly decomposable	0.1423	0.2139	0.0673	0.0071	0.0001

3. Calculate an approximate chemical formula, excluding sulfur. Determine mole ratios of all components.

Component	Mole Ratio (Nitrogen = 1)	
	Rapidly Decomposable	Slowly Decomposable
Carbon	65.4	20.0
Hydrogen	103.1	30.1
Oxygen	48.9	9.5
Nitrogen	1.0	1.0

The chemical formulas for the waste mixtures (excluding sulfur) are

Rapidly decomposable

$$C_{65}H_{103}O_{49}N + 16H_2O \rightarrow 57\ CH_4 + 24\ CO_2 + NH_3$$

g/mol	1684.1	288	912	1056	17

Slowly decomposable

$$C_{20}H_{30}O_{10}N + 9H_2O \rightarrow 11CH_4 + 9CO_2 + NH_3$$

g/mol	436	162	176	396	17

Note: The equations do not balance exactly due to rounding.

4. Calculate the volume of CH_4 and CO_2 that can be generated from the different waste fractions.

Rapidly decomposable

$$CH_4 = [(912)(23.6\ kg)]/[(1684.1)(0.718\ kg/m^3)] = 17.8\ m^3 \text{ at STP}$$

$$CO_2 = [(1056)(23.6\ kg)]/[(1684.1)(1.98\ kg/m^3)] = 7.5\ m^3 \text{ at STP}$$

(Density of CH_4 = 0.718 kg/m^3; density of CO_2 = 1.98 kg/m^3)

Slowly decomposable

$$CH_4 = [(176)(3.81\ kg)]/[(436.4)(0.718\ kg/m^3)] = 2.14\ m^3$$

$$CO_2 = [(396)(3.81\ kg)]/[(436.4)(1.98\ kg/m^3)] = 1.75\ m^3$$

5. Determine the total theoretical quantity of gas generated per unit weight of organic matter.

Rapidly decomposable

$$\text{Volume/kg} = (17.83\ m^3 + 7.5\ m^3)/23.6\ kg = 1.07\ kg/m^3$$

Slowly decomposable

$$\text{Volume/kg} = (2.14\ m^3 + 1.75\ m^3)/3.81\ kg = 1.02\ kg/m^3$$

(Adapted from Tchobanoglous, G. et al., *Integrated Solid Waste Management: Engineering Principles and Management Issues,* McGraw-Hill, New York, 1993.)

10.4.14.7 Control of Explosive Gases

Landfill gas emissions contribute to local smog and cause unpleasant odors, triggering complaints from neighbors. Methane is the primary concern in evaluating landfill gas generation because it is highly combustible. Methane accumulation in structures near a landfill may result in fire and explosions. Methane hazards can be prevented through monitoring of landfill gas and corrective action.

Although methane is lighter than air and carbon dioxide is heavier, these gases tend to remain mixed. They migrate as a function of the density of the mixture and other gradients such as temperature and partial pressure (Tchobanoglous et al. 1993; U.S. EPA 1994). In an ideal situation, landfill gas

would simply diffuse to the surface of the unit and disperse into the atmosphere. Unfortunately, however, several variables promote lateral, rather than vertical, landfill gas migration. Landfill gas will travel along the path of least resistance. The direction of migration is controlled in part by the permeabilities of the soil and fill material. This is especially relevant in pre-RCRA landfills, which may lack a complete subsurface liner. Coarse, porous media such as sand and gravel adjacent to the landfill will promote greater lateral transport of gases than would fine-grained soils. In a closed unit, landfill gas will migrate laterally if the final cover is dense or impermeable and if the side slopes do not contain a gas barrier. A saturated or frozen surface will promote lateral migration. The effects of geology and surface conditions on gas migration are shown in Figure 10.12. Lateral gas migration is more common in older facilities that lack liners and gas control systems.

In order to ensure safety to humans and structures, landfill gas must be regularly monitored. Methane concentrations must not exceed 25% of the lower explosive limit (LEL) in facility structures, and must not exceed the LEL at the perimeter of the facility property. The LEL is defined as the lowest percent by volume of a mixture of explosive gases in air that will propagate a flame at 25°C and atmospheric pressure (see Figure 10.13). Methane is explosive when present in the range of 5%–15% (by vol.) in air. At methane concentrations greater than 15%, the gas mixture will not explode, as the gaseous mixture is considered "rich." This 15% threshold is the upper explosive limit (UEL), defined as the maximum concentration of a gas, above which the substance will not explode when exposed to a source of ignition. The explosive hazard range occurs between the LEL and

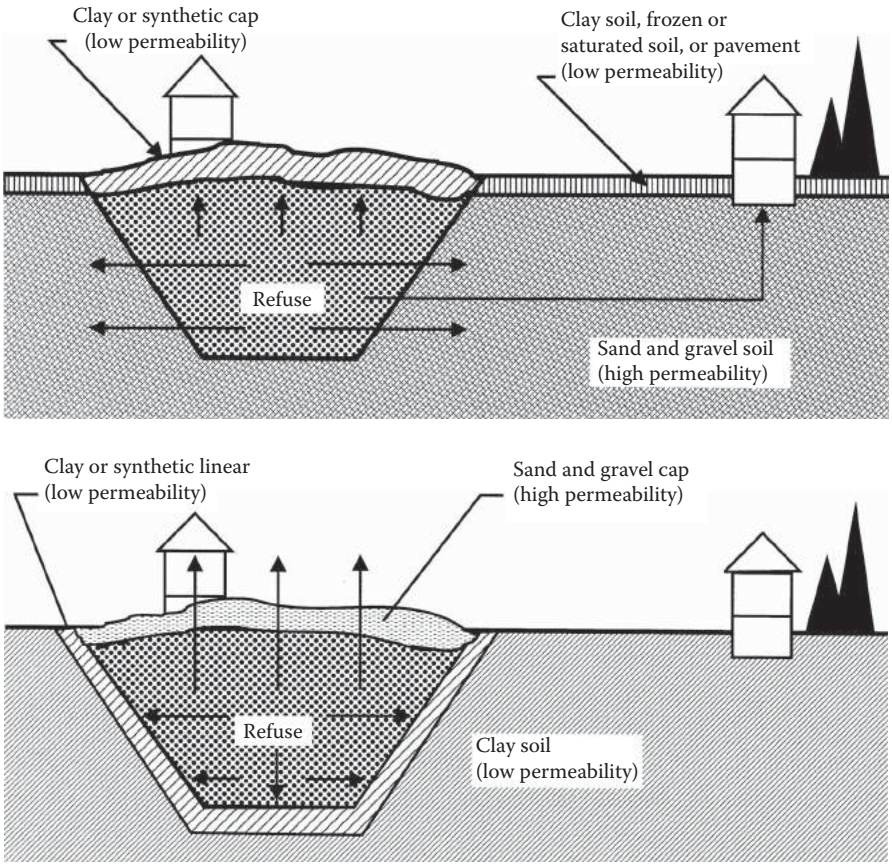


FIGURE 10.12 Effects of surrounding geology and surface features on landfill gas migration. (From U.S. EPA, *Design, Operation, and Closure of Municipal Solid Waste Landfills*, EPA 625/R-94/008, Seminar Publication, Office of Research and Development, Washington, DC, 1994.)

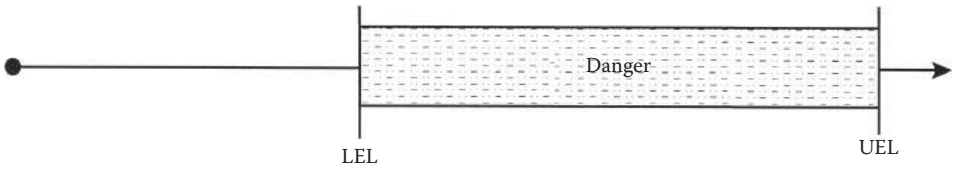


FIGURE 10.13 The lower explosive limit, upper explosive limit, and explosive range for a hypothetical gas.

the UEL. It must be noted that at methane concentrations above the UEL, asphyxiation is a hazard. In addition, a sudden dilution of the methane in the local atmosphere can bring the mixture back within the explosive range.

Methane is generated from MSW only when the moisture content of the waste exceeds 40% under anaerobic conditions. Therefore, if a landfill stores wastes having 15% moisture, the waste will be "fossilized"; i.e., it will not decay and therefore will produce very little methane (Worrell and Vesilind 2011).

The frequency of landfill gas monitoring is determined based on soil conditions, surface hydrology, hydrogeology, and location of facility structures. If methane gas levels exceed established limits, a remediation plan must be prepared within 60 days of detection. Air must be sampled within facility structures where gas may accumulate, and in soil at the property boundary. Other monitoring methods may include sampling gases from probes within the landfill unit. A typical gas-monitoring probe installation is shown in Figure 10.14. The frequency of monitoring should be sufficient to detect landfill gas migration based on subsurface conditions and changing landfill conditions. Monitoring must be conducted at least quarterly (40 CFR 258.23). The number and location of gas probes are site-specific and dependent on subsurface conditions, land use, and location and design of facility structures. At the facility and in neighboring properties, structures with basements or crawl spaces are more susceptible to landfill gas infiltration and must also be monitored.

Methane measurements are made in the field with a portable methane meter or an organic vapor analyzer (Figure 10.15). Gas samples may also be collected and brought to the laboratory for analysis. Measurements, for example, using gas chromatography–mass spectrometry, can confirm the identity and concentrations of landfill gas. In addition to measuring gas composition, other indications of gas migration may be observed. These include odor (described as either a strongly "sweet" or a rotten egg [H_2S] odor), septic soil, and audible or visual venting of gases, especially in standing water. Stressed vegetation is a useful indicator of gas migration. Landfill gas in soil pores creates anaerobic conditions by displacing oxygen. Plant roots require sufficient oxygen to carry out respiration processes, and methane gas acts as a simple asphyxiant to roots (Flower et al. 1982).

10.4.15 Trace Gases

Table 10.13 lists many trace gaseous compounds detected at most MSWLFs. The quantities of these gases are a function of their initial concentrations and their solubility in aqueous liquids. The occurrence of significant concentrations of VOCs in landfill gas is associated with older landfills that had accepted industrial and commercial wastes containing VOCs. In newer landfills in which the disposal of hazardous waste is banned, concentrations of VOCs in landfill gas are very low.

10.4.16 Landfill Gas Control

Landfill gas may vent naturally or be directed to the atmosphere by engineered controls. Systems used to control or prevent gas migration are categorized as either passive or active. Passive systems provide

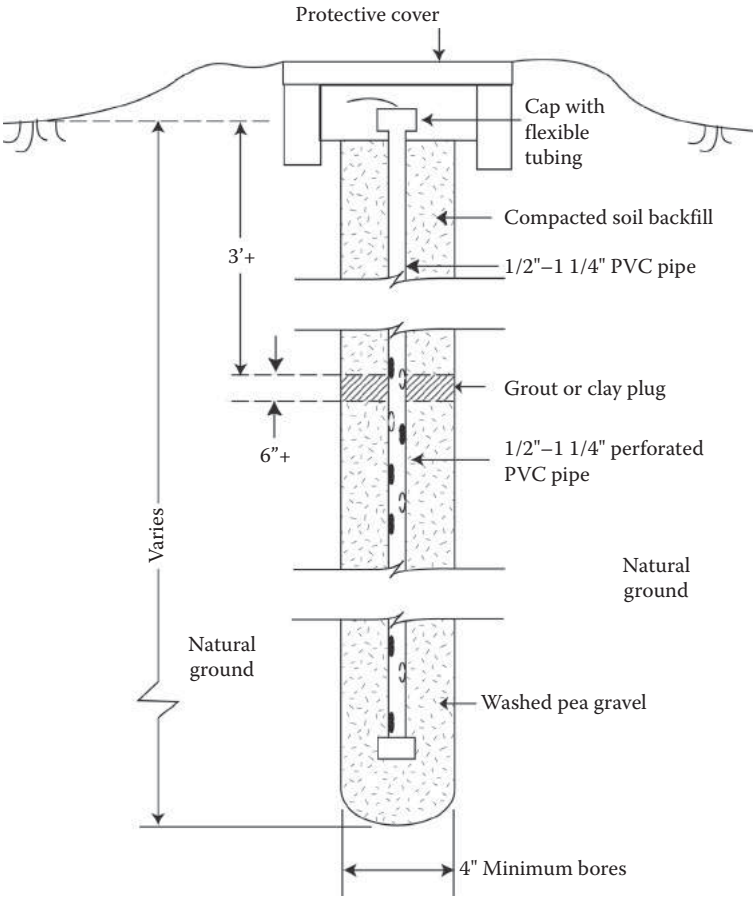


FIGURE 10.14 Typical gas-monitoring probe. (From U.S. EPA, *Design, Operation, and Closure of Municipal Solid Waste Landfills*, EPA 625/R-94/008, Seminar Publication, Office of Research and Development, Washington, DC, 1994.)

preferential flow paths by means of natural pressure, concentration, and density gradients. In contrast, active gas control uses mechanized systems to direct landfill gas by providing pressure gradients, in essence, forcing landfill gas out by applied convective forces. The choice of system is based on design and age of the landfill unit and on soil and hydrogeologic conditions of the local environment. In other words, the degree of potential gas hazard plays a role in choice of the particular system.

10.4.16.1 Passive Systems

Passive gas control systems rely on natural pressure and convection to vent landfill gas to the atmosphere. Passive systems involve "high-permeability" or "low-permeability" techniques. High-permeability systems incorporate pathways such as trenches, vent wells, or perforated vent pipes surrounded by coarse material to guide landfill gas to the surface. Low-permeability systems block lateral migration via the use of barriers such as synthetic membranes and clayey soils. Passive systems may be incorporated into a landfill design or may be installed later for corrective purposes. They may be installed within a landfill unit along the perimeter, or between the landfill and facility property boundary.

At the time of landfill closure, a passive system may be incorporated into the final cover. This may consist of perforated collection pipes and high-permeability soils located directly below



FIGURE 10.15 Portable organic vapor analyzer. (From Federal Emergency Management Agency, *Landfill Fires. Their Magnitude, Characteristics, and Mitigation*, May 2002/FA -225, 2002, Available from: http://www.usfa.fema.gov/downloads/pdf/publications/fa-225.pdf.)

TABLE 10.13
Typical Concentrations of Trace Compounds Found in Landfill Gas at 66 California MSW Landfills

Compound	Mean Concentration (ppb, v)	Maximum (ppb, v)
Acetone	6,838	240,000
Benzene	2057	39,000
Chlorobenzene	82	1640
Chloroform	245	12,000
1,1-Dichloroethane	2801	36,000
Dichloromethane	25,694	620,000
1,1-Dichloroethene	130	4000
Diethylene chloride	2835	20,000
Trans-1,2-Dichloroethane	36	850
Ethylene dichloride	59	2100
Ethyl benezene	7334	87,500
Methyl ethyl ketone	3092	130,000
1,1,1-Trichloroethane	615	14,500
Trichloroethane	2079	32,000
Toluene	34,907	280,000
1,1,2,2-Tetrachloroethane	246	16,000
Tetrachloroethylene	5244	180,000
Vinyl chloride	3508	32,000
Styrenes	1517	87,000
Vinyl acetate	5663	240,000
Xylenes	2651	38,000

Source: Data reproduced with kind permission from Tchobanoglous, G. et al., *Integrated Solid Waste Management: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1993.

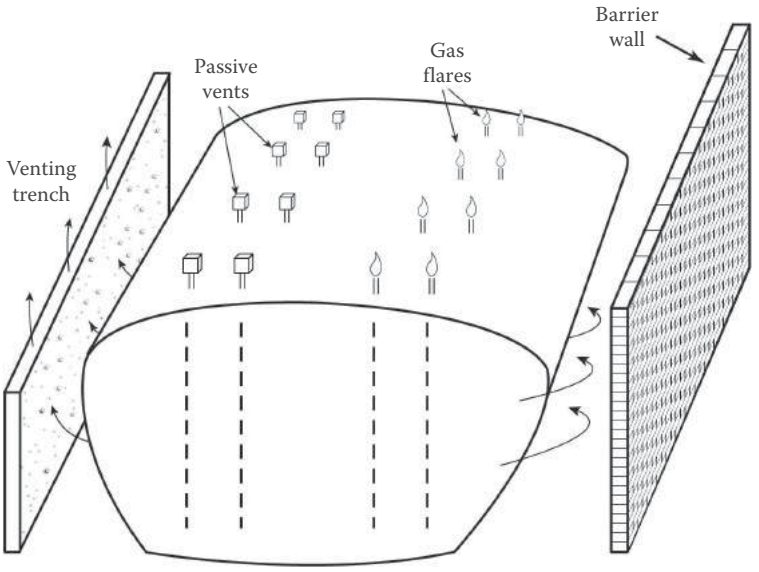


FIGURE 10.16 Passive gas control systems showing venting to the atmosphere by convective forces, and a barrier wall.

the impermeable cover. Vent systems may be connected to header pipes located along the perimeter of the landfill unit. Figure 10.16 illustrates two passive systems.

Some practical problems have been associated with passive systems. For example, snow and soil may accumulate in vent pipes, thus preventing gas migration and venting. Biological clogging of pipes and soil pores is also common.

10.4.16.2 Active Systems

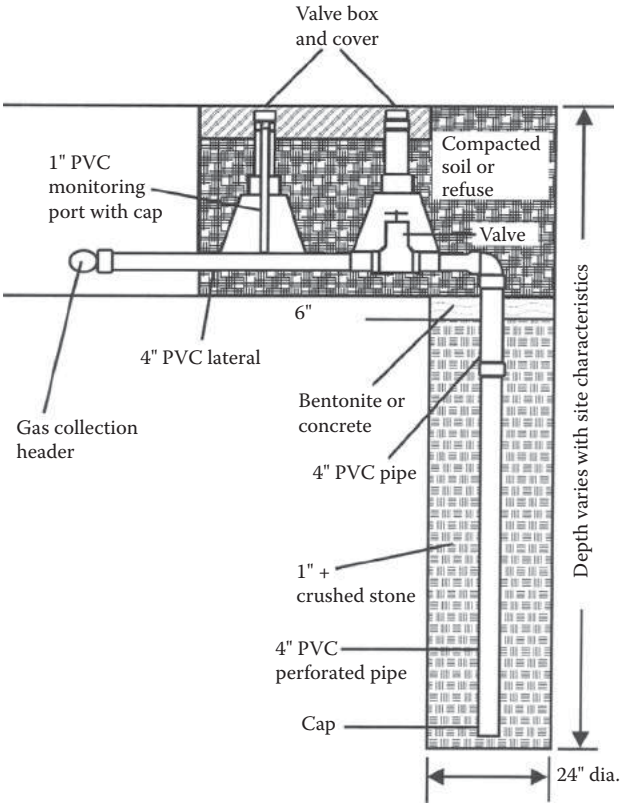
Active gas control systems use some mechanical means to remove landfill gas, consisting of either positive pressure (air injection) or negative pressure (extraction) systems. Negative pressure systems are more commonly used and extract gas using a blower. The gas may be recovered for energy conversion, treated, or combusted in a flare system (Figures 10.17a through 10.17c) (U.S. EPA 1985). Gas extraction wells may be installed within landfill cells or beyond the landfill, in nearby extraction trenches (Figure 10.18). Active systems are not as sensitive to freezing or saturation of cover soils as are passive systems.

The capital, operational, and maintenance costs of active gas systems are higher than are those for passive systems. These costs continue throughout the postclosure period. It is possible to convert active gas control to a passive system when gas production diminishes.

When designing the gas control system, several other practical issues must be taken into account. For example, construction materials may be indirectly affected by the elevated temperatures within a landfill unit as compared with the relatively cooler ambient air. Leachate water containing corrosive and toxic constituents may condense within plumbing and adversely affect pipes and pumps. Provisions for managing condensate should be incorporated to prevent accumulation. The condensate can be returned to the landfill.

10.4.17 Gas Utilization

Current regulations under the Clean Air Act require many large landfills to collect and combust landfill gas. Several compliance options are available, including flaring the gas or installing a gas recovery and utilization system. A number of environmental and economic benefits accrue



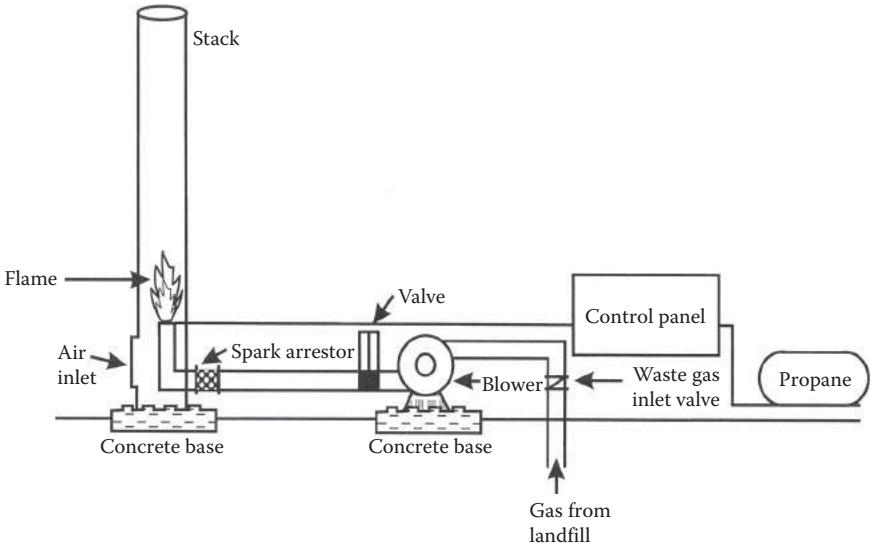
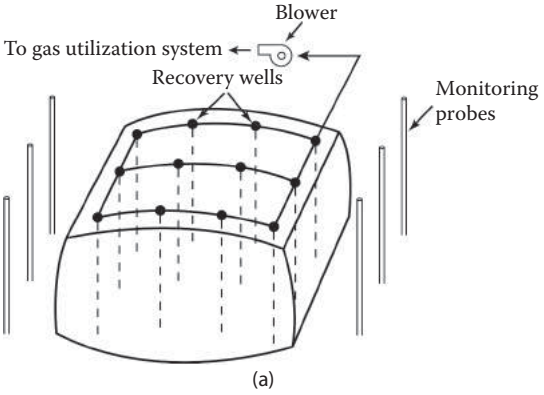


FIGURE 10.17 A flaring system for landfill gas: (a) schematic of extraction system; (b) surface features; (c) photo. ([a] From U.S. EPA, Design, Operation, and Closure of Municipal Solid Waste Landfills, EPA 625/R-94/008, Seminar Publication, Office of Research and Development, Washington, DC, 1994; [b] reproduced with kind permission of MACTEC Engineering and Consulting, Inc.; [c] reproduced with kind permission of the Brevard County, FL Solid Waste Management Department.)

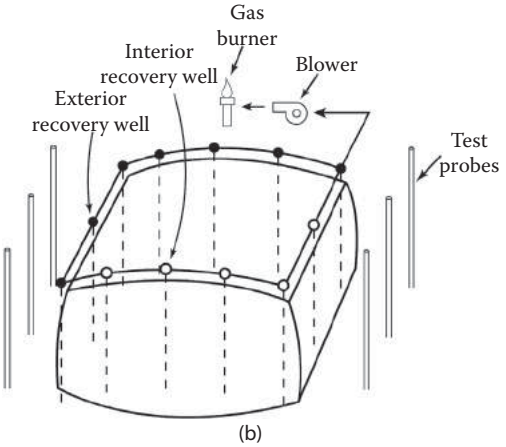


(c)

FIGURE 10.17 (*Continued*) A flaring system for landfill gas: (a) schematic of extraction system; (b) surface features; (c) photo. ([a] From U.S. EPA, Design, Operation, and Closure of Municipal Solid Waste Landfills, EPA 625/R-94/008, Seminar Publication, Office of Research and Development, Washington, DC, 1994; [b] reproduced with kind permission of MACTEC Engineering and Consulting, Inc.; [c] reproduced with kind permission of the Brevard County, FL Solid Waste Management Department.)



(a)



(b)

FIGURE 10.18 Gas recovery systems for active landfill gas removal: (a) interior wells; (b) perimeter wells. (From U.S. EPA, *Design, Operation, and Closure of Municipal Solid Waste Landfills*, EPA 625/R-94/008, Seminar Publication, Office of Research and Development, Washington, DC, 1994.)

when recovering landfill gas. Gas recovery systems reduce odors and gas migration, reduce the dangers of explosion and fire, and may be used as a source of revenue to reduce the costs of closure. Raw landfill gas, requiring removal of only water and particulates, may be used for heating small facilities. A fairly concentrated and cleaned gas can be used for both water and space heating, as well as lighting, electrical generation, co-generation, and as a fuel for industrial boilers. Landfill gas is also upgraded to pipeline standards and can be sold to local utilities (SWANA 1992).

According to EPA (2002), 0.9 million MT (1 million tons) of MSW in a landfill generates about 8.5 m^3 min (300 ft^3/min, cfm) of landfill gas, which can generate 7,000,000 kWh (kilowatt hours) per year, energy sufficient to power 700 homes. In a broader environmental sense, using 300 cfm/year of landfill gas yields the same reduction in greenhouse gases as removing 6100 automobiles from the road for 1 year.

Generally, landfills closed for less than 5 years are ideal for energy recovery because of their content of relatively fresh and moist MSW. With time, the ability of a landfill to generate gas decreases. Under optimum conditions, a landfill might produce gas for 15 years or more, depending on rate of gas generation, moisture content of the waste, and the manner in which the landfill was closed. Current closure requirements are intended to restrict the entry of moisture into the landfill. These requirements will lead to greatly reduced gas generation after closure.

The heat value of unprocessed landfill gas is 18,600 kJ/standard m^3 (500 Btu/standard cubic foot), about one-half that of natural gas, essentially because only one-half of landfill gas is methane (Table 10.9). At a small landfill, gas with this heat value can be used to run a modified internal combustion engine or a generator to convert gas to electrical energy. At a larger facility, moisture and CO_2 removal (via scrubbing and gas polishing with carbon or polymer adsorption) enables the gas to be used to run boilers and turbine generators for energy recovery. Purification of landfill gas to pipeline quality involves greater investment in terms of removal of impurities. Landfill gas and pipeline-quality natural gas differ substantially in composition and energy content. Landfill gas has a lower Btu content, combusts at a lower temperature, is more corrosive, and contains much greater concentrations of undesirable gases (CO_2, H_2S, O_2, and N_2) than pipeline-quality natural gas. Extensive purification is therefore necessary to separate undesirable components from methane. The required cleanup protocol includes nearly complete CO_2 removal. Processing increases the heat value of the gas to approximately 1000 Btu/scf. The conversion of landfill gas to natural gas quality is sufficiently costly, such that only large landfills can attain the economies of scale necessary to support operations. Fewer than 50 U.S. landfills convert gas for pipeline use (Worrell and Vesilind 2011).

Municipalities are using landfill gas to generate electricity, heat, or steam for industrial use. Local governments are discovering that the use of landfill gas reduces electrical demand for local utilities, delaying the need for building new power plants. The Rhode Island Solid Waste Management Corporation (RISWMC), responsible for managing the 62 ha (154 acre) Central Landfill, captures landfill gas to supply up to 12.3 MW of electrical power, a capacity sufficient to serve roughly 17,000 households. The company sells this electricity to a local subsidiary of New England Power, who pays the RISWMC $50,000 per month in royalties for the rights to the gas. A public–private partnership to develop an electricity-generating landfill gas (LFG) energy project at Catawba County's Blackburn Landfill in Newton, NC, will generate revenues of $7.1 million for the County over the project's lifetime. Among other things, this will allow the County to keep tipping fees at their current level for at least 10 years.

Private companies have also discovered the economic benefits of using landfill gas. General Motors converted one of three powerhouse boilers at an Indiana plant to use landfill gas in addition to natural gas. The facility saves about $500,000 annually in energy costs. Springfield Gas and International Truck and Engine Corporation developed a direct-use project in Springfield, OH. Five years after their efforts began, International Truck and Engine Corporation began using landfill gas in place of natural gas in paint ovens, boilers, and other equipment, for an expected savings of $100,000 per year in fuel costs (U.S. EPA 2009).

10.4.18 Other Air Criteria

Open burning of solid waste, except for the infrequent burning of agricultural residues, land-clearing debris, diseased trees, or debris from emergency cleanup operations, is prohibited at all MSWLFs (40 CFR 258.24).

10.4.19 Public Access

The general public and other unauthorized persons may be unaware of the hazards associated with landfills, which include:

- The inability of equipment operators to see people during equipment operation
- Direct exposure to waste materials (e.g., sharp objects, pathogens)
- Falls
- Exposure to fires
- Earth-moving activities

Operators of MSW landfills must control public access and prevent unauthorized traffic and the illegal dumping of wastes (40 CFR 258.25). This is accomplished by constructing natural or artificial barriers. Specific measures include installation of gates and fences, trees, hedges, berms, ditches, and embankments. Chain link, barbed wire added to chain link, and open farm-type fencing are examples of appropriate fencing. Access to facilities should be controlled through gates that can be locked when the site is unsupervised.

10.4.20 Control of Run-on and Runoff

The landfill operator is required to prevent run-on to the active portion of the landfill, and also to collect runoff (40 CFR 258.26). Run-on and runoff control systems must be designed based on the volume of water anticipated from a 24-h, 25-year storm. The run-on control system collects and redirects surface water to minimize that which might enter landfill cells. As discussed below, minimizing the volume of water entering a landfill will limit the volume of leachate generated. Run-on control is accomplished by constructing berms and swales up-gradient of the fill area to redirect water to stormwater control structures.

If stormwater enters the landfill unit and contacts waste, the stormwater, according to regulations, is considered leachate and must be managed accordingly. Such leachate generation increases costs and can overload leachate treatment systems.

Runoff control systems must collect and handle runoff from the active portion of the landfill, including areas that contact MSW. Runoff control can be accomplished through stormwater conveyance structures that divert liquids to a storage system for eventual treatment. Other structures for run-on and runoff control include seepage ditches, seepage basins, and sedimentation basins (Figures 10.19 and 10.20).

After a landfill unit has been sealed with a final cover, stormwater runoff is managed as stormwater, and not leachate. Therefore, water running off the final cover system of closed areas may not require treatment and can be combined with run-on water. Run-on and runoff must be managed in accordance with the discharge requirements of the Clean Water Act, including the National Pollutant Discharge Elimination System (NPDES) (U.S. EPA 1994).

10.4.21 Management of Surface Water

MSWLFs are required to prevent any discharge of pollutants into surface water, including wetlands (40 CFR 258.27). The facility should determine if it is in conformance with requirements of the

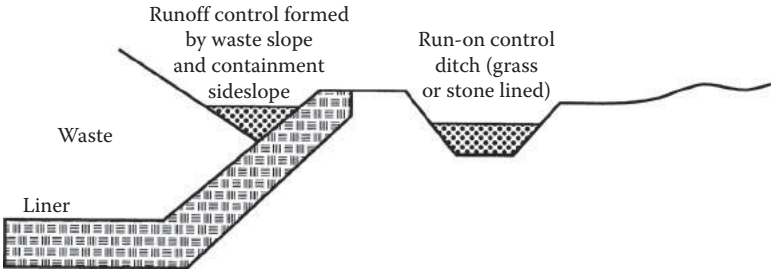


FIGURE 10.19 Schematic of run-on and runoff controls at a landfill. (Reproduced with kind permission of MACTEC Engineering and Consulting, Inc.)



FIGURE 10.20 Landfill runoff ready for treatment.

Clean Water Act and the NPDES requirements under the Clean Water Act. The EPA and approved states have jurisdiction over discharge of pollutants into U.S. waters, including wetlands. Landfills discharging pollutants into U.S. waters require a section 402 (NPDES) permit.

Landfill units that have a point source discharge must have a NPDES permit. Point source discharges from landfills include:

- The release of leachate from a leachate collection or on-site treatment system into water
- Disposal of solid waste into water

10.4.22 Restrictions on Liquids in Landfills

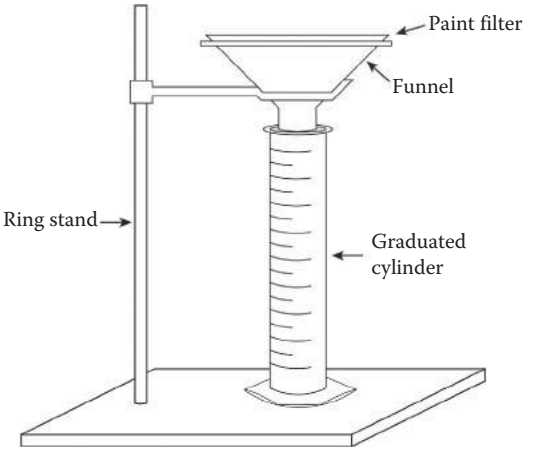
As mentioned previously, many older land disposal facilities in the United States have become environmental nightmares because of the disposal of toxic wastes, often in liquid form. As a result, RCRA regulations require that bulk or noncontainerized liquid wastes not be placed in MSWLFs unless (40 CFR 258.28):

- The waste is household waste.
- The waste is leachate derived from the landfill and the unit is designed with proper liners and a leachate collection system.

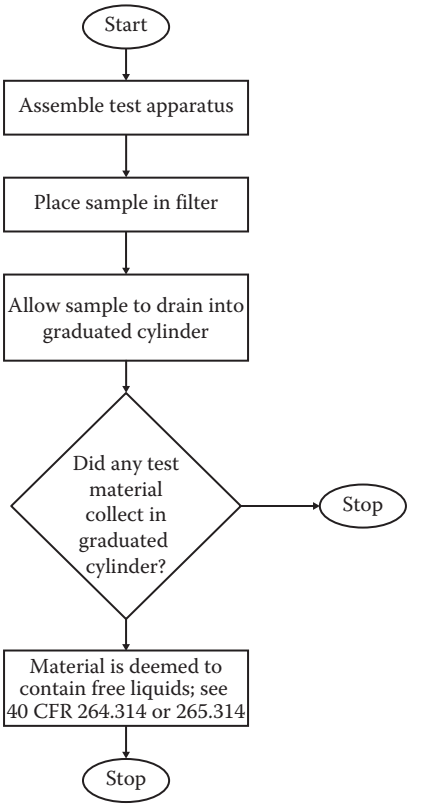
The restriction of free liquids is intended to limit the generation of leachate. Liquid waste refers to any waste material that is determined to contain free liquids as defined by SW-846

(U.S. EPA 1986b) Method 9095—Paint Filter Liquids Test. The test is performed by placing a 100-mL sample of waste in a conical, 400-μm paint filter. The waste is considered a liquid waste if any liquid from the waste passes through the filter within 5 min. The apparatus used for performing the paint filter test is illustrated in Figure 10.21.

Due to concerns over cost and practicality, it is impossible to regulate household waste for its content of liquids. Containers holding liquid waste may not be placed in a landfill unless the waste



(a)



(b)

FIGURE 10.21 Testing for free liquids: (a) paint filter test apparatus; (b) U.S. EPA test for free liquids.

is a household waste. If the waste is considered a liquid waste, absorbent materials may be added to render it a "solid" material (i.e., it becomes a mixture that no longer fails the paint filter liquids test). Sludges are a common waste stream that may contain significant quantities of liquid. Sludge is a mixture of water and solids that has been produced during water and wastewater treatment in commercial or industrial operations. Sludge disposal is acceptable, provided that the sludge is nonhazardous and passes the paint filter test.

10.4.23 Leachate Formation

Landfill leachate production and migration are among the most acute concerns for operators of municipal sanitary landfills. Leachate is the liquid generated by the action of water (rainwater or infiltrating groundwater) and liquids within the waste percolating through the stored waste within a landfill cell. As the absorbent components of the waste become saturated, free leachate forms.

Many factors contribute to the chemical, biochemical, and physical variations of landfill leachate. The chemical complexity of leachate reflects the extreme heterogeneity of the input wastes. Furthermore, as the waste within a landfill cell ages, leachate chemical properties will change. Climate, season, and moisture content also affect composition. Chemical properties of concern include pH, BOD_5, suspended solids, N content, salt content, and the presence of trace toxic compounds. Some significant chemical components of landfill leachates are listed in Table 10.14. Major classes of microbes present within leachate include bacteria, actinomycetes, fungi, and protozoa. Microbes include aerobes, and facultative and obligate anaerobes. The physical characteristics of leachate are determined by the quantity of dissolved and suspended solids, temperature, color, and quantities of inorganic solids, such as Fe and Pb compounds. Leachate sampling parameters are listed in Table 10.15.

10.4.23.1 Estimation of Leachate Volume Produced

The volume of leachate generated in a sanitary landfill cell is primarily influenced by the volume of precipitation entering the site. Assuming the facility is permitted under RCRA subtitle D (and therefore must possess a liner), it is necessary for engineers to estimate leachate production and to determine relevant factors for its collection, for example, spacing of leachate collection pipes (discussed below) at the base of the landfill.

An estimate of leachate quantity generated, after steady state is attained, can be developed using a simple water-balance method. The contributing factors to water infiltration include that received via precipitation, run-on of surface water, and water seeping through the sides and base of the cell. Water leaving the site from surface runoff, evaporation, and transpiration by plants is subtracted from this balance. Water loss via evaporation from the soil and from plant uptake and transpiration are typically combined into a single term, *evapotranspiration*. Design requirements under RCRA should result in negligible quantities of surface water run-on and water entering through the sides and bottom of the fill.

The hypothetical water balance is represented by the equation:

$$L = P + R_{on} + U - E - R_{off} \tag{10.10}$$

where

L = Leachate
P = Precipitation
R_{on} = Run-on surface water
U = Underflow of groundwater into the cell
E = Evapotranspiration
R_{off} = Runoff surface water

TABLE 10.14
Municipal Landfill Leachate Data: Indicator Parameters, Inorganic, and Organic Compounds

	Leachate Concentration Reported	
	Minimum (mg/L)	Maximum (mg/L)
Indicator Parameters		
Alkalinity	470	57,850
Ammonia	0.39	1200
Biological oxygen demand	7	29,200
Calcium	95.5	2100
Chemical oxygen demand	42	50,450
Chloride	31	5475
Fluoride	0.11	302
Iron	0.22	2280
Phosphorus	0.29	117.18
Potassium	17.8	1175
Sulfate	8	1400
Sodium	12	2574
Total dissolved solids	390	31,800
Total suspended solids	23	17,800
Total organic carbon	20	14,500
Inorganic Compounds		
Aluminum	0.01	5.8
Antimony	0.0015	47
Arsenic	0.0002	0.982
Barium	0.08	5
Beryllium	0.001	0.01
Cadmium	0.0007	0.15
Chromium (total)	0.0005	1.9
Cobalt	0.04	0.13
Copper	0.003	2.8
Cyanide	0.004	0.3
Lead	0.005	1.6
Manganese	0.03	79
Magnesium	74	927
Mercury	0.0001	0.0098
Nickel	0.02	2.227
Vanadium	0.009	0.029
Zinc	0.03	350
Organic Compounds		
Acetone	8	11,000
Acrolein	270	270
Aldrin	NA	NA
α-Chlordane	NA	NA
Aroclor-1242	NA	NA
Aroclor-1254	NA	NA
Benzene	4	1080
Bromomethane	170	170

Continued

TABLE 10.14 (*Continued*)
Municipal Landfill Leachate Data: Indicator Parameters, Inorganic, and Organic Compounds

	Leachate Concentration Reported	
	Minimum (mg/L)	**Maximum (mg/L)**
Butanol	10,000	10,000
1-Butanol	320	360
2-Butanone (methyl ethyl ketone)	110	27,000
Butyl benzyl phenol	21	150
Carbazole	NA	NA
Carbon tetrachloride	6	397.5
4-Chloro-3-methylphenol	NA	NA
Chlorobenzene	1	685
Chloroethane	11.1	860
Bis(2-chloroethyoxy)methane	18	25
2-Chloroethyl vinyl ether	2	1100
Chloroform	7.27	1300
Chloromethane	170	400
Bis(chloromethyl)ether	250	250
2-Chloronaphthalene	46	46
p-Cresol	45.2	5100
2,4-D	7.4	220
4,4'-DDE	NA	NA
4,4'-DDT	0.042	0.22
Dibromethane	5	5
Di-*N*-butyl phthalate	12	150
1,2-Dichlorobenzene	3	21.9
1,4-Dichlorobenzene	1	52.1
3,3-Dichlorobenzidine	NA	NA
Dichlorodifluoromethane	10.3	450
1,1-Dichloroethane	4	44,000
1,2-Dichloroethane	1	11,000
1,2-Dichloroethane (Total)	NA	NA
cis-1,2-Dichloroethane	190	470
trans-1,2-Dichloroethylene	2	4800
1,2-Dichloropropane	0.03	500
1,3-Dichloropropane	18	30
Diethyl phthalate	3	330
2,4-Dimethyl phenol	10	28
Dimethyl phthalate	30	55
Endrin	0.04	50
Endrin ketone	NA	NA
Ethanol	23,000	23,000
Ethyl acetate	42	130
Ethyl benzene	6	4900
Ethylmethacrylate	NA	NA
Bis(2-ethylhexyl) phthalate	16	750
2-Hexanone (methyl butyl ketone)	6	690
Isophorone	4	16,000
Lindane	0.017	0.023

TABLE 10.14 (*Continued*)
Municipal Landfill Leachate Data: Indicator Parameters, Inorganic, and Organic Compounds

	Leachate Concentration Reported	
	Minimum (mg/L)	**Maximum (mg/L)**
4-Methyl-2-pentanone (methyl isobutyl ketone)	10	710
Methelene chloride (dichloromethane)	2	220,000
2-Methylnaphthalene	NA	NA
2-Methylphenol	NA	NA
4-Methylphenol	NA	NA
Methoxychlor	NA	NA
Naphthalene	2	202
Nitrobenzene	4	120
4-Nitrophenol	17	17
Pentachlorophenol	3	470
Phenanthrene	NA	NA
Phenol	7.3	28,000
1-Propanol	11,000	11,000
2-Propanol	94	26,000
Styrene	NA	NA
1,1,2,2-Tetrachlorothane	210	210
Tetrachloroethylene	2	620
Tetrahydrofuran	18	1300
Toluene	5.55	18,000
Toxaphene	1	1
2,4,6-Tribromophenol	NA	NA
1,1,1-Trichloroethane	1	13,000
1,1,2-Trichloroethane	30	630
Trichloroethylene	1	1300
Trichlorofluormethane	4	150
1,2,3-Trichloropropane	230	230
Vinyl chloride	8	61
Xylenes	32	310

Source: U.S. EPA, *Summary of Data on Municipal Solid Waste Landfill Characteristics – Criteria for Municipal Solid Waste Landfills*, EPA/530-SW-88-038, Office of Solid Waste and Emergency Response, U.S. EPA, Washington, DC, 1988.

If the landfill is designed and operated properly, surface water will be diverted from the waste and therefore $R_{on} = 0$. Additionally, a landfill constructed above the water table and possessing an impermeable liner will give U = 0 (i.e., there is no underflow). The equation can thus be simplified to

$$L = P - E - R_{off}$$

The integration of these concepts is shown in Figure 10.22.

The quantity of runoff depends upon soil permeability, the slope of the surface, the type of vegetation, the duration and frequency of precipitation, and whether the precipitation is in the form of rain or snow. The fraction of precipitation that becomes runoff is expressed by a runoff coefficient. The fraction converted to runoff ranges between 0.05 and 0.35 (Table 10.16). In applying the water-balance approach for predicting leachate production, a number of references are available (Thornwaite and Mather 1957; Fenn et al. 1975; Bagchi 1994) for estimating evapotranspiration rates.

TABLE 10.15
Leachate Sampling Parameters

Physical Properties	Organic Constituents	Inorganic Constituents	Biological Constituents
Appearance	Organic chemicals	Suspended solids, total dissolved solids	Biochemical oxygen demand
pH	Phenols	Volatile suspended solids, volatile dissolved solids	Coliform bacteria (total; fecal; fecal streptococci)
Oxidation-reduction potential	Chemical oxygen demand	Chloride	Standard plate count
Conductivity	Total organic carbon	Sulfate	
Color	Volatile acids	Phosphate	
Turbidity	Tannins, lignins	Alkalinity and acidity	
Temperature	Organic-N	Nitrite-N	
Odor	Ether soluble (oil and grease)	Nitrate-N	
	Methylene blue active substances	Ammonia-N	
	Organic functional groups as required	Sodium	
	Chlorinated hydrocarbons	Potassium	
		Calcium	
		Magnesium	
		Hardness	
		Heavy metal (Pb, Cu, Ni, Cr, Zn, Fe, Mn, Hg, Ba, Ag)	
		Arsenic	
		Cyanide	
		Fluoride	
		Selenium	

Source: Data reproduced with kind permission from Tchobanoglous, G. et al., *Integrated Solid Waste Management: Engineering Principles and Management Issues*, McGraw-Hill, New York, 1993.

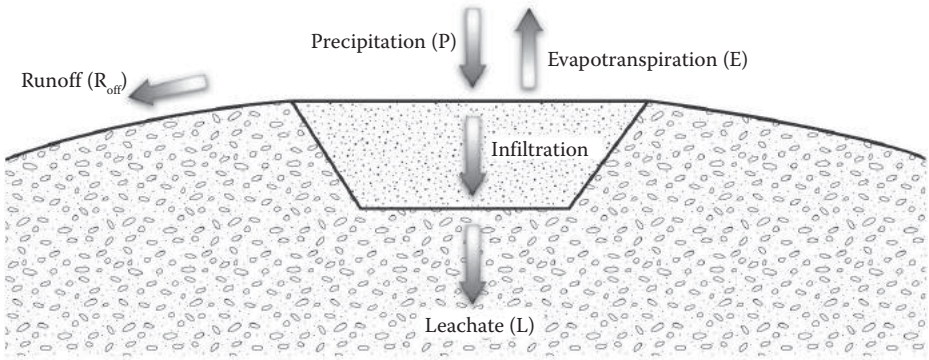


FIGURE 10.22 Mass balance of moisture in a sanitary landfill.

TABLE 10.16
Runoff Coefficients for Various Slopes and Soil Permeabilities

Surface	Slope	Runoff Coefficient
Grass; sandy soil	0–2%	0.05–0.10
	2–7%	0.10–0.15
	>7%	0.15–0.20
Grass, heavy soil	0–2%	0.13–0.17
	2–7%	0.17–0.25
	>7%	0.25–0.35

Source: Fenn, D.G. et al., *Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites,* EPA-530/SW-168, U.S. Government Printing Office, Washington, DC, 1975.

Example 10.6

Calculate the annual volume of leachate generated per hectare for a sanitary landfill located in the northcentral United States. The climate is temperate, average annual rainfall is 1.07 m/year (42 in./year), and evapotranspiration is estimated at 55%. The wastes are covered with soil, and runoff from the site is 10%. There is no run-on of surface water; similarly, there is no underflow of groundwater into the cell (i.e., $R_{on} = 0$ and $U = 0$).

Solution

For these calculations, it is necessary to convert depth of precipitation to volume. This is easily accomplished because the depth of water is received over a known area (units of 1 ha). The precipitation depth is thus converted to 1.07 h m. The quantity of leachate is then calculated using the equation:

$$L = P - E - R_{off}$$

$$L = 1.07 \text{ ha m} - (0.55)(1.07 \text{ ha m}) - (0.10)(1.07 \text{ ha·m})$$

$$L = 0.37 \text{ ha m}$$

$$= 3750 \text{ m}^3 \quad (1 \text{ ha} = 10{,}000 \text{ m}^2)$$

$$= 3.75 \times 10^6 \text{ L or } 990{,}645 \text{ gal}$$

10.4.23.2 Leachate Collection and Removal System

A LCR system is designed to collect leachate and convey it out of the landfill for eventual treatment. The LCR system is constructed so that less than 30 cm of leachate (the amount of leachate the liner is designed to maintain according to subtitle D) accumulates above the composite liner. When designing and constructing a LCR system, the following components must be considered (U.S. EPA 1994):

- Area collector—the drain that covers the liner and collects leachate
- Collection laterals—the pipe network that drains the area collector
- Sump—the low point where the leachate exits the landfill
- Stormwater and leachate separation system

10.4.23.3 Area Collector

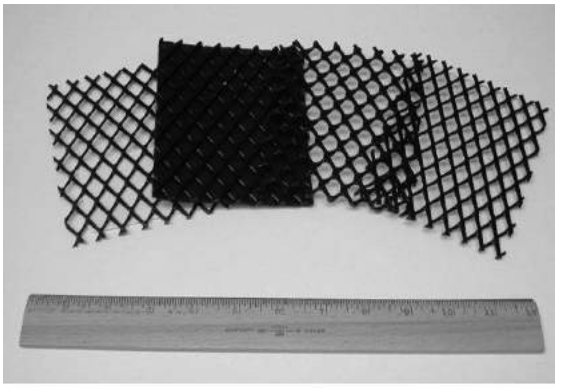
The area collector, also known as the blanket drain, covers the entire surface of the geomembrane liner and collects leachate. The area collector system is typically constructed with at least a 30 cm (12 in.) layer of sand having a hydraulic conductivity greater than 10^{-2} cm/s. An alternative blanket drain can be constructed using geosynthetic drainage nets (geonets), which are porous, synthetic materials applied over the geomembrane liner. A brief discussion of geosynthetic materials for landfill construction follows.

10.4.24 Geosynthetic Materials

Geosynthetic materials comprise a wide group of polymer-based mats, sheets, grids, nets, and composite materials that have found extensive use not only in modern landfills, but in water management and other engineering applications. Depending on design, geosynthetics perform five major functions: separation, reinforcement, filtration, drainage, and containment (Koerner and Daniel, 1997). Several common geosynthetics will be discussed below.

Geonets (also known as geospacers) are used to convey liquids (Figure 10.23a). Geonets are manufactured with layers of intersecting ribs designed so that liquid can flow within the open spaces. A geonet can be defined as (ASTM 2002)

> a geosynthetic material consisting of integrally connected parallel sets of ribs overlying similar sets at various angles for biaxial or triaxial drainage of liquids or gases. Geonets are often laminated with geotextiles on one or both surfaces and are then referred to as drainage geocomposites.

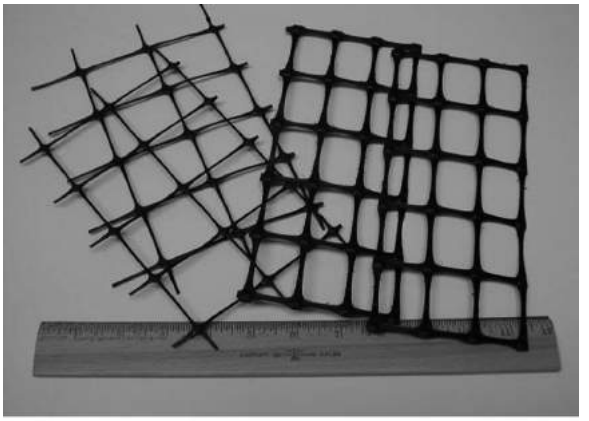


(a)



(b)

FIGURE 10.23 Common geosynthetic materials: (a) geonet; (b) geotextile.



(c)

FIGURE 10.23 (*Continued*) Common geosynthetic materials: (c) geogrid.

Geonets vary in thickness from 4.0 to 6.9 mm (U.S. EPA 1993c). Geonets require the installation of a geotextile directly above them.

Geotextiles (also known as filter fabrics) are defined as (ASTM 2002)

> A permeable geosynthetic comprised solely of textiles. Geotextiles are used with foundation, soil, rock, earth, or any other geotechnical engineering-related material as in integral part of a human-made project, structure, or system.

Geotextiles (Figure 10.23b) are manufactured from synthetic polymers such as polypropylene, polyester polyethylene, and nylon. More than 90% of all geotextiles are made of polypropylene resin, and the remainder is composed of polyester or nylon (Geosynthetics 2013). The polymers are formed into fibers and then into a woven or nonwoven fabric. They promote liquid flow across their planes, and also within their thickness, to varying degrees. There are over one hundred specific applications for geotextiles; however, they always perform at least one of five discrete functions (Koerner 1998):

- Separation
- Reinforcement
- Filtration
- Drainage
- Containment (barrier, when impregnated)

Since geotextiles are composed of synthetic fibers rather than natural ones such as cotton, wool, or silk, biodegradation is not a concern.

Geogrids (Figure 10.23c) are designed to function as reinforcement materials. Koerner (1998) defines a geogrid as

> a geosynthetic material consisting of connected parallel sets of tensile ribs with apertures of sufficient size to allow strike-through of surrounding soil, stone, or other geotechnical material.

Geogrids are plastics formed into a very open, grid-like configuration. Geogrids contain large open spaces (*apertures*) that typically measure 10–100 mm between the ribs. The ribs are manufactured from a number of different polymers. The primary function of geogrids is reinforcement, and there are many application areas.

Geosynthetic clay liners are used as a composite component beneath a geomembrane or by themselves in environmental and containment applications, as well as in transportation, geotechnical, and hydraulic applications (Koerner 1998).

Geocomposites consist of various combinations of geotextiles, geogrids, geonets, geomembranes, and other materials. The capabilities of geocomposites embrace the entire range of functions listed above for geosynthetics: separation, reinforcement, filtration, drainage, and containment. The general reason for the existence of geocomposites is the higher performance attained by combining the characteristics of two or more materials.

Geomembranes were discussed earlier in this chapter and shown in Figure 10.4. They are manufactured from essentially impervious polymeric materials, and are used primarily for linings and covers of liquid or solid storage facilities. The range of applications, however, is broad. According to ASTM D4439 a geomembrane is defined as

> a very low permeability synthetic membrane liner or barrier used with any geotechnical engineering related material so as to control fluid migration in a human-made project, structure, or system.

Geomembranes are manufactured from continuous polymeric sheets, but they can also be made from the impregnation of geotextiles with asphalt or elastomer sprays, or as multilayered bitumen geocomposites (Koerner 1998).

10.4.25 Collection Laterals

According to EPA (1994), the regulatory limit of a 30-cm-maximum liquid head above a liner cannot be achieved using an area collector alone; therefore, collection laterals are needed. Collection laterals are perforated pipes that direct leachate to sumps. During landfill operation, leachate passes through the area collector, into collection laterals, and drains to the sump where it is removed from the landfill.

A number of materials are appropriate for the manufacture of leachate collection systems. Polymeric pipes are by far the most common. HDPE and PVC are used almost exclusively, and are available as either profiled or smooth wall construction (Qian et al. 2002).

The design of collection pipes must address the following issues (Qian et al. 2002):

- The required flow
- Maximum drainage slope
- Maximum pipe spacing
- Pipe size
- Structural strength of the pipe

Spacing of the collection laterals depends on the permeability of the collection pipes, the slope of the liner, and the assumed entry rate of rainfall (Figure 10.24). The lower the permeability, the closer the pipes. The slope of collection laterals should be greater than 2% in order to achieve adequate flow velocity and clean the pipes. A 2% slope will also ensure that MSW settlement will not reverse the slope of the pipes.

Predicting the maximum leachate head on top of the landfill liner is important in landfill design. Factors affecting leachate head include permeability of drainage materials, drainage slope, drainage length, and infiltration rate. Darcy's law and the law of continuity can be used to calculate the depth of leachate ponded on a liner (McBean et al. 1982; McEnroe 1993). One equation that has been proposed is (Richardson and Zhao 2000):

$$Y_{max} = \frac{p}{2} \times \frac{q}{K}\left[\frac{K \tan^2\alpha}{q} + 1 - \frac{K \tan\alpha}{q}\left(\tan^2\alpha + \frac{q}{K}\right)^{\frac{1}{2}}\right] \tag{10.11}$$

where Y_{max} = maximum head on liner (cm), L the horizontal drainage distance (cm), tan α the inclination of liner from horizontal (deg), q the vertical inflow (infiltration), defined in this equation as

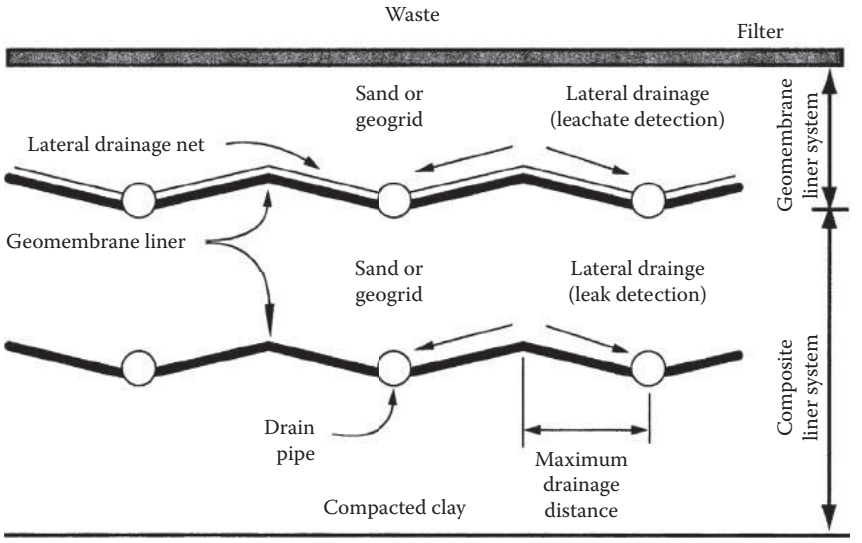


FIGURE 10.24 Schematic of the base of a landfill liner (not to scale).

from a 25-year, 24-h storm (cm/day), K the hydraulic conductivity of the drainage layer (cm/day), and p the distance between collection pipes (cm).

This equation can be used to calculate the maximum allowable pipe spacing based on the maximum allowable design head, anticipated leachate impingement rate, slope of the liner, and permeability of drainage materials. The equation suggests that, holding all other parameters constant, the closer the pipes are placed the lower the head will be. A reduced head on the liner results in a lower hydraulic driving force through the liner, and the consequence of a puncture in the liner is similarly reduced.

Example 10.7

Determine the spacing between pipes in a leachate collection system by using granular drainage material and the following properties. Assume that in the most conservative design all stormwater from a 25-year, 24-h storm enters the leachate collection system.

Design storm (25 years, 24 h) = 8.2 in = 0.00028 cm/s

Hydraulic conductivity = 10^{-2} cm/s

Drainage slope = 1.5%

Maximum design depth on liner = 14.2 cm

$$P = \frac{2Y_{max}}{\left(\frac{q}{K}\right)\left[\frac{K\tan^2\alpha}{q} + 1 - \frac{K\tan\alpha}{q}\left(\tan^2\alpha + \frac{q}{K}\right)^{1/2}\right]}$$

$$P = \frac{2(14.2)}{\left(\frac{0.00028}{0.01}\right)\left[\frac{0.01(0.015)^2}{0.00028} + 1 - \frac{0.01(0.015)}{0.00028}\left((0.015)^2 + \frac{0.00028}{0.01}\right)^{1/2}\right]} = 1105 \text{ cm}$$

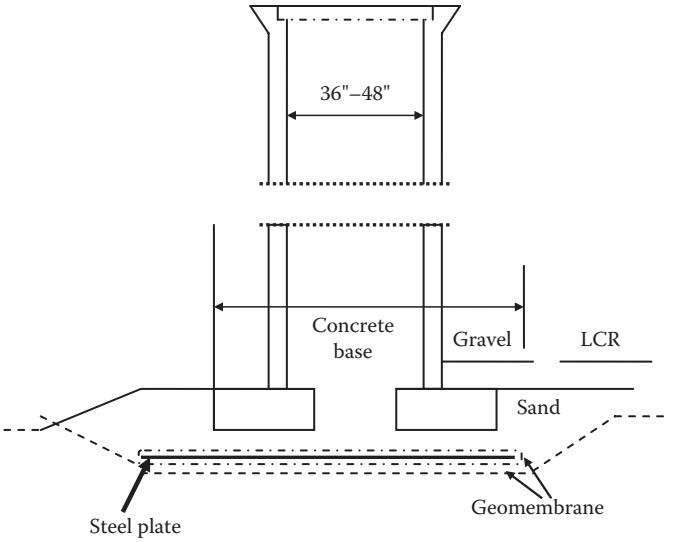


FIGURE 10.25 A low-volume sump. (From U.S. EPA, *Requirements for Hazardous Waste Landfill Design, Construction and Closure*, EPA/625/4-89/022, Seminar Publication, Office of Research and Development, Cincinnati, OH, 1989.)

10.4.26 Sumps

Sumps are constructed to collect leachate and are thus situated in engineered low points in the composite liner system. Figure 10.25 shows a low-volume sump. The leachate removal standpipe must be extended through the entire landfill from lowest liner to the cover, and then through the cover itself. The sump and standpipe must be maintained for the entire postclosure care period of 30 years or longer. Because of the difficulty in seam-testing sumps, sump areas often are designed with an additional layer of geomembrane. Figure 10.26 shows a sump being installed in a landfill.

10.4.27 Leachate Treatment

The recovered leachate is either stored in a tank until it can be safely removed, diverted directly to a sanitary sewer, or reapplied to the surface of the landfill. Leachate collection tanks should be both corrosion-resistant and able to withstand climatic extremes.

Treatment of leachate must meet water quality standards set by regulatory authorities. Six primary types of leachate treatment are in use:

- Aerobic biological
- Anaerobic biological
- Land application
- Physicochemical
- Recycling leachate through the landfill
- Treatment with municipal wastewater

10.4.28 Groundwater Monitoring and Corrective Action

The EPA landfill criteria establish requirements for groundwater monitoring and corrective action for landfills. The criteria include a systematic process that requires routine groundwater monitoring



FIGURE 10.26 Landfill sump installation. (Reproduced with kind permission of Environmental Research and Education Foundation, *Bioreactor Landfill Project Northern Oaks Landfill*, 2002, Available from: http://www.erefdn.org/rpts_summary_ordrs/northernoaks.htm.)

(*detection monitoring*). In detection monitoring, a minimum number of indicator parameters must be tested at least annually. Figure 10.27 depicts a typical groundwater monitoring well. If statistically significant increases above background concentrations of any indicator parameters are detected, a more comprehensive monitoring program must be instituted. If concentrations of pollutant parameters persist or increase, the facility is required to develop and implement a corrective action program (U.S. EPA 1994).

10.4.29 Record Keeping

As part of routine operations, the facility must retain the following information (40 CFR 258.29):

- Inspection records, training procedures, and notification procedures
- Gas-monitoring results from routine monitoring
- Design documentation for placement of leachate or gas condensate in a landfill
- Closure and postclosure care plans
- Any monitoring, testing, or analytical data
- Cost estimates and financial assurance documentation

10.5 CLOSURE

Subtitle D requires, at the time of landfill closure, the installation of a final cover (cap) system (40 CFR 258.60). The primary purposes of the cover are to minimize infiltration of rainwater (thus

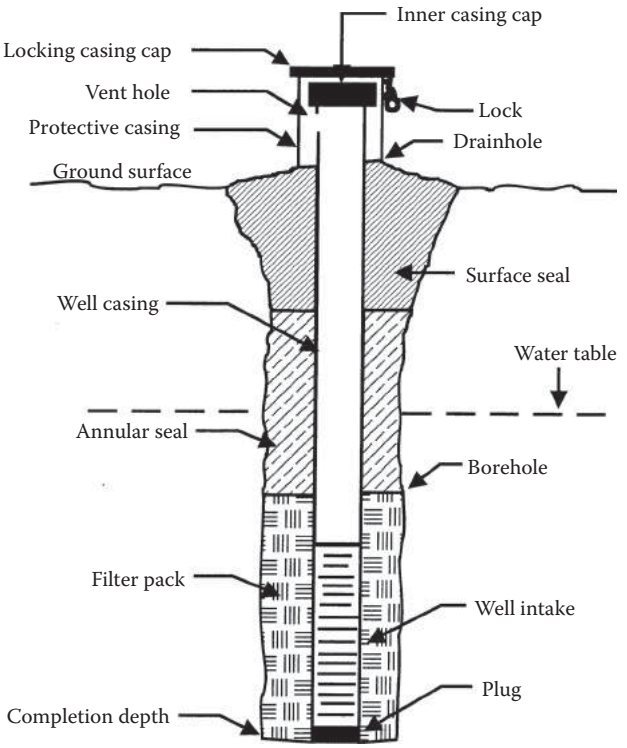


FIGURE 10.27 Typical groundwater monitoring well. (From U.S. EPA, *Design, Operation, and Closure of Municipal Solid Waste Landfills*, EPA 625/R-94/008, Seminar Publication, Office of Research and Development, Washington, DC, 1994.)

limiting production of leachate) and to prevent erosion (thus protecting buried wastes from exposure and possible dispersal). The final cover system must be constructed to

- Have a permeability less than 1×10^{-5} cm/s
- Minimize infiltration through the landfill by using a layer that contains at least 46 cm (18 in.) of soil material (the *barrier layer*)
- Minimize erosion of the final cover by using an *erosion layer* that contains a minimum of 15 cm (6 in.) of soil material capable of sustaining plant growth

Written closure plans must describe all the steps that are necessary to close landfill units. After closure of a unit, postclosure care is required for at least 30 years. The following issues must be addressed at a minimum:

- Maintain the integrity and effectiveness of the final cover
- Maintain and operate the leachate collection system in accordance with 40 CFR 258.40
- Monitor groundwater in accordance with 40 CFR 258 and maintain the groundwater monitoring system
- Maintain and operate the gas-monitoring system in accordance with 40 CFR 258.23

Figure 10.28 provides a schematic of a recommended landfill cover. By restricting the entry of water into the landfill by a cover system, generation of leachate is substantially minimized. However, the dry conditions that are maintained will hinder MSW biodegradation, making most landfills merely storage facilities (Worrell and Vesilind 2011), sometimes termed *dry tombs*.

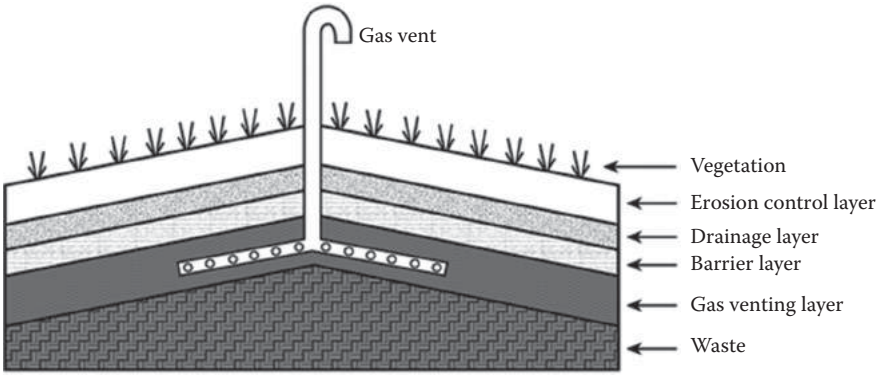


FIGURE 10.28 Cover design for a closed landfill. (From U.S. EPA, *Design, Operation, and Closure of Municipal Solid Waste Landfills*, EPA 625/R-94/008, Seminar Publication, Office of Research and Development, Washington, DC, 1994.)

Components for landfill closure include (40 CFR 258.60) an infiltration (barrier) layer, a drainage layer, an erosion control layer, and a gas venting system.

10.5.1 Low-Permeability (Barrier) Layer

The barrier layer consists of a compacted soil layer, or a soil and geomembrane liner. Both are designed to reduce the rate at which surface water infiltrates into the landfill unit. An alternative barrier system may be used if approved by the state regulatory agency. The membrane material used for the final cover must be composed of a long-lasting material and must tolerate subsidence-induced strains (U.S. EPA 1994).

10.5.2 Drainage Layer

A drainage layer is installed above the low-permeability layer and maintains the stability of cover slopes by eliminating pore water. A drainage layer in the cover system is not required under RCRA subtitle D; however, large landfills benefit from its presence. This layer prevents any water that infiltrates the erosion control layer from accumulating above the barrier layer. Accumulated water can generate pressure above the membrane and cause the erosion control layer to slide off the cover slopes. The side slope drainage layer is drained to a large-capacity toe drain (see Figure 10.19).

10.5.3 Erosion Control Layer

The erosion control layer consists of soil planted with vegetation to protect the cover from the effects of erosion. The minimum thickness of the erosion layer required under subtitle D is 15 cm (6 in.). A mixture of dense-rooted grasses and legumes is recommended. Erosion-related soil loss should not exceed 1.8 metric tons (2 tons) per acre per year to minimize long-term maintenance. To attain such a level of erosion control typically requires construction of slopes less than 1:4 and drainage swales placed at 6-m (20-ft) vertical increments. Erosion from the effects of water is kept under control by the presence of vegetation and drainage swales, and by hardening the cover surface by using stones or riprap (U.S. EPA 1994).

Erosion control maintenance includes routine vegetation management (mowing, fertilization, liming, replanting), repair of any areas undergoing subsidence, and run-on or runoff control. Sedimentation basins and drainage swales must be inspected after every major rainstorm and be repaired as needed.

10.5.4 Gas Collection System

A minimum of one passive gas vent per acre of cover should be installed to allow for the release of gas pressure beneath the cover. The venting system can use vertical gravel walls, blanket collectors beneath the barrier layer, or gravel trench drains (also beneath the barrier layer) to capture landfill gases. The recovered gases are routed through the cover by using vent pipes as shown in Figure 10.18.

10.5.5 Landfill Cap

Slope stability and soil erosion are important concerns in the design and installation of landfill caps. The landfill cover slope must be sufficiently stable to sustain infiltration and runoff from a 24-h, 25-year storm. Side slopes typically measure 1:3–1:4, and the friction between adjacent layers must resist seepage forces. On slide slopes, composite liner caps (membranes placed directly above a low-permeability soil layer) are not advisable (Worrell and Vesilind 2011). For slopes steeper than 1:5, a drainage layer should be provided. If slippage occurs, liner systems will be damaged, soil may enter surface water, and the cover will need to be repaired or rebuilt. Two different cover systems are depicted in Figure 10.29. Also see the photo in Figure 10.30.

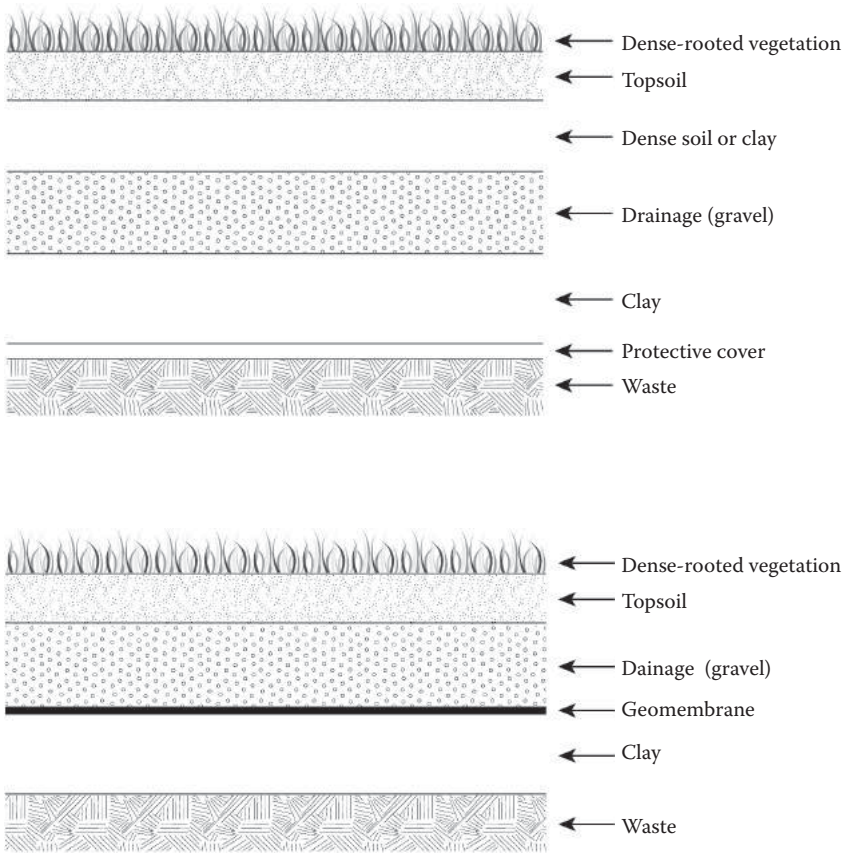


FIGURE 10.29 Two different cover types for a sanitary landfill.



FIGURE 10.30 Landfill cap under construction showing overlapping sheets of geomembrane cap.

10.5.6 Subsidence Effects

Landfill subsidence can be large scale ("global," due to uniform settlement of MSW) or localized (e.g., collapse of a large void directly below a portion of the cover). In general, global subsidence does not result in excessive tensile strains on the cover and may enhance cover stability by reducing sliding. Localized subsidence, however, can produce depressions on the cover that may create excessive strain in cover layers and cause ponding of water. The impact of tensile strains is minimized using a flexible geomembrane composed of PVC, low-density polyethylene, or polypropylene. Ponding of water must be avoided because it can kill or distress cover vegetation, and the weight of the water can promote further expansion of a pond.

10.5.7 Weather Effects

The cover must withstand extreme weather conditions and function with minimal maintenance. Extreme weather conditions include heavy rains, extreme drought, and ground freezing. Cover management for heavy rains includes growing dense-rooted vegetation, maintaining a modest slope, and constructing adequate conveyances for excess runoff. Extreme drought is another relevant concern in design of the erosion control layer. Certain plants are more drought-tolerant and should be included in the original seed mixture. Periodic irrigation with water and leachate may be required. Freezing of the cover is a concern because of the impact of freezing on clay permeability. Repeated cycles of freezing and thawing increase the permeability of compacted clays by causing large cracks to form. Damage to the clay layer is difficult to correct in such a scenario; however, the impermeability of the clay layer can be greatly augmented by the installation of a geomembrane cap directly below or above.

10.6 POSTCLOSURE

After a landfill cell is closed and the final cover is installed, monitoring and maintenance are necessary to ensure that the landfill remains stable. subtitle D requires that postclosure care and monitoring be performed for at least 30 years. A postclosure care and monitoring plan is required by the state regulatory agency and must include (40 CFR 258.61):

- The start and completion dates of the postclosure period
- The monitoring plan description
- The maintenance program description

- The facility's personnel list of contacts for emergencies
- A description of the end-use plan for the site

Postclosure care activities must include (U.S. EPA 1994):

- Maintaining the integrity and effectiveness of erosion controls
- Maintaining and operating the leachate collection system
- Maintaining and operating the gas venting system
- Monitoring groundwater for contamination

After a final cover is installed, the leachate collection system will receive only a very small leachate load and should be relatively easy to maintain. Leachate generation should decrease to less than 9350 L/ha (1000 gal/acre)/day. During the postclosure period, leachate production rates should be monitored to detect any marked decline in production. If leachate generation falls markedly, leachate pipes should be inspected for biological clogging. The LCR should be flushed if clogging is detected.

The vent pipes in a passive gas venting system must be inspected regularly for damage caused by mowing or other traffic. A damaged vent pipe can allow surface water to enter the venting system and bypass the cover. Damaged vent pipes must be repaired promptly. During the postclosure period, groundwater monitoring must continue to be conducted on a routine basis. The facility must be aware of any indications of contamination and must take necessary remedial action if contamination occurs.

10.7 BIOREACTOR LANDFILL

When MSW is deposited in a conventional subtitle D landfill, certain events such as partial waste decomposition, gas production, leachate generation, and stabilization inevitably occur. Investigations involving core sampling of sanitary landfills have revealed that wastes do not degrade significantly even after many decades, resulting in terms such as "dry tombs" for these systems (Rathje and Murphy 1992).

An innovative approach to MSW disposal, which actually encourages rapid MSW decomposition and speeds stabilization, is the *bioreactor landfill*. The accelerated waste degradation and stabilization carried out by indigenous microbial populations within waste is accomplished through the addition of liquid (typically leachate) and air. The enhanced microbiological processes within a bioreactor can transform and stabilize the decomposable organic waste within 5–10 years of implementation, compared with many decades for conventional subtitle D landfills where wastes are essentially sealed off from air and moisture.

To date, there is still disagreement among scientists and engineers as to the precise definition of a bioreactor landfill. The Solid Waste Association of North America has defined a bioreactor landfill as

> any permitted subtitle D landfill or landfill cell, subject to New Source Performance Standards/Emissions Guidelines, where liquid or air, in addition to leachate and landfill gas condensate, is injected in a controlled fashion into the waste mass in order to accelerate or enhance biostabilization of the waste.

Bioreactor landfill technology has been in use for over a century. The concept originated from the systematic treatment of urban wastewater that began in the late 19th century. Bioreactor landfills can be conceptualized as an extension of anaerobic and aerobic digestion at wastewater treatment plants.

Three general types of bioreactor landfill configurations are currently in use (U.S. EPA 2003) and are outlined below.

10.7.1 Anaerobic Bioreactors

Landfill degradation of MSW frequently is rate-limited by insufficient moisture. The average landfilled MSW has a moisture content from 15% to 40%, depending on the composition of the wastes, season of the year, and weather conditions (Emcon Associates 1980; Kiely 1997). However, maximum methane production in landfills occurs at a moisture content of 60%–80% wet weight (Farquhar and Rovers 1973), suggesting that most landfills are well below the optimum moisture content for methane generation.

In an anaerobic bioreactor landfill, moisture is added to the waste mass uniformly in the form of recirculated leachate, local water, or other sources to obtain optimal moisture levels. Liquid is injected into the waste via horizontal trenches, vertical wells, surface infiltration ponds, spraying, and prewetting of waste (Figure 10.31). Biodegradation occurs under anaerobic conditions and generates landfill gas, primarily methane and carbon dioxide, in approximately equal proportions.

Anaerobic bioreactor landfills require careful monitoring at startup. If the waste is wetted too rapidly, a buildup of volatile organic acids might lower leachate pH, inhibiting the methane-producing bacterial population and reducing biodegradation rate. Optimal conditions for methanogenic bacteria include a pH near the neutral point. Leachate parameters such as pH, volatile organic acid concentration and alkalinity, and gas parameters such as methane content are direct indicators of the activity of the methanogenic bacterial population. A high-volatile organic acids to alkalinity ratio (>0.25) indicates that the leachate might possess a low buffering capacity and conditions may inhibit methane generation (Campman and Yates 2002).

When the methane content of the landfill gas exceeds approximately 40%, the methanogenic bacterial populations are considered established. A decline in methane below 40% may indicate that the waste is too wet or dry. Once the methanogenic bacteria have become established, the rate of leachate recirculation may be increased.

Costs for piping, pumps, electricity, and equipment for increased landfill gas generation for the anaerobic bioreactor should be offset by the avoided cost of leachate treatment and landfill gas-to-energy royalties from gas usage by manufacturers or utilities (Campman and Yates 2002; Townsend et al. 2008).

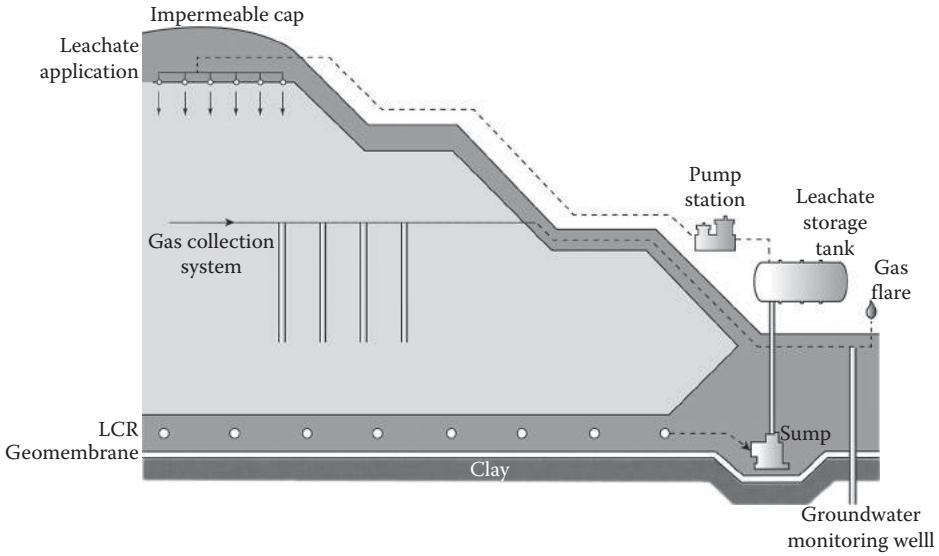


FIGURE 10.31 Schematic of a bioreactor landfill.

Benefits of anaerobic bioreactor landfills include:

- Leachate storage within the waste mass
- Accelerated rate of landfill settlement
- More rapid waste stabilization compared with conventional landfills
- Increased methane generation rates (200%–250% increase typical)
- Lower postclosure costs

10.7.2 Aerobic Bioreactors

The aerobic bioreactor process is analogous to a composting operation in which input materials are rapidly biodegraded using air and moisture, and by the increased temperatures triggered by biological activity. Aerobic bioreactors operate by the controlled injection of moisture and air into the waste mass through a network of pipes.

Prior to air injection, liquid is pumped under pressure into the waste mass through injection wells in order to wet the mass to a moisture content between 50% and 70% (by wt). Once optimal moisture conditions have been reached, air is injected using vertical or horizontal wells. Blowers are used to force air into the waste mass through a network of perforated wells. Leachate is removed from the base, directed to storage tanks, and recirculated into the landfill in a controlled manner. Air and liquid injection rates are similar to application rates used in composting systems.

Optimum temperatures for waste degradation within an aerobic bioreactor landfill are between 60°C and 72°C (about 140°F and 160°F) (Campman and Yates 2002). The aerobic process continues until most of the readily degradable compounds have decomposed and the waste temperature gradually decreases during the final phase of maturation of the remaining organic matter.

Due to the substantial amounts of heat generated in an aerobic bioreactor, large volumes of leachate can evaporate. In a study of two bioreactor landfills, leachate volume was reduced by 86% and 50% (Hudgins and Green 1999). Changing the rate of air and liquid injection will alter the temperature of the waste pile. To ensure against possible waste combustion, the waste mass is wetted adequately and air injection is uniform throughout the waste mass.

Aerobic bioreactor landfills require significantly greater inputs compared with their anaerobic counterparts. According to Weathers et al. (2001, as cited in Yates and Campman), the additional power required to inject air into an aerobic bioreactor was 12 times higher than the power required to extract landfill gas from an anaerobic bioreactor. However, postclosure costs should be reduced due to reductions in gas generation and cover settlement (Townsend et al. 2008).

Because of the higher reaction rates, aerobic biodegradation is a more rapid process compared with anaerobic biodegradation. Aerobic landfills have the potential to achieve waste stabilization in 2 or 4 years, as opposed to decades or longer for conventional landfills. The rapid rate of waste stabilization in aerobic landfills also offers the potential for eventual "mining" of the landfill waste.

Aerobic bioreactors offer many of the same benefits as anaerobic bioreactors; however, they are achieved more rapidly. The following benefits have been observed at aerobic bioreactor landfills (Hudgins and Green 1999; Campman and Yates 2002):

- More rapid waste and leachate stabilization
- Increased rate of landfill settlement
- Reduction of methane generation by 50%–90%
- Capability of reducing leachate volumes by up to 100% due to evaporation
- Potential for landfill mining
- Reduction of environmental liabilities

Since aerobic bioreactors do not produce significant quantities of methane, there is little potential to sell landfill gas for energy (U.S. EPA 2013).

10.7.3 Anaerobic vs. Aerobic

Recall from the discussion of conventional sanitary landfills that MSW deposited in a landfill undergoes five phases of decomposition, starting with a brief aerobic phase, through two anaerobic phases followed by a methane generation phase, and finally maturation. Aerobic bioreactor landfills attempt to sustain the Phase I activity over a longer period than that occurring in a conventional MSWLF. In contrast, anaerobic bioreactor landfills attempt to reduce the time involved for Phase IV activities (methane generation) to possibly 5–10 years (a 75% reduction), with 5–7 years for Phase IV considered optimum (U.S. EPA 2000).

10.7.4 Hybrid Bioreactors (Sequential Aerobic–Anaerobic)

The hybrid bioreactor landfill accelerates waste degradation by using sequential aerobic–anaerobic treatment to rapidly degrade organics in the upper lifts and collect gas from lower sections. Operation as a hybrid results in the early onset of methanogenesis (U.S. EPA 2003).

10.7.5 Practical Operational Issues

10.7.5.1 Waste Preprocessing

Wastes may be placed directly into a bioreactor landfill, after which they are compacted by heavy machinery, or wastes can be shredded prior to placement. The goal for such preprocessing is to achieve optimum exposure of waste material to the bioreaction process. Concerns have arisen regarding the absence of decomposition in bioreactor landfills when MSW is placed inside plastic bags, which may or may not be broken open during compaction with heavy equipment. It may be feasible to either break open bags to expose the contents (by equipment or during emplacement) or require the use of degradable bags for optimum bioreactor performance.

10.7.5.2 Daily Cover

Daily cover materials should be selected to avoid creation of low-permeability layers within the landfill cell. For example, clay can become a barrier to leachate drainage and recirculation, whereas soil, compost, foams, slurries, and sludges will provide the benefits of daily cover without preventing infiltration and drainage.

10.7.5.3 Liquid Addition and Recirculation

A major landfill stability concern involves leachate (i.e., hydraulic head) buildup on the landfill liner system. Ponding of liquid on the liner can be a significant source of failure as a result of associated hydrostatic forces. Addressing this in the initial design phase should be a straightforward issue for bioreactor landfills because liquid levels and other variables are generally known.

Considerations in addressing liquid addition to bioreactor landfills should include:

- How to determine appropriate amounts of liquid needed by different types and sizes of landfills
- Use of temperature as a guide for liquid injection, since wetting the waste mass results in the most uniform temperature
- Timing of liquid addition, for example, at the time of waste disposal, or deposit dry waste first and add liquid later
- Determination of the desired moisture content and the amount of liquid required is necessary for the design of an effective distribution system

10.7.5.4 Alternative Liquid Sources

Alternatives to landfill leachate for liquid addition include wastewater, biosludges, biosolids from publicly owned treatment works, stormwater runoff, and groundwater. Biosolids considered most

suitable for bioreactor use are those in liquid form that typically undergo land application, rather than dewatered sludge (U.S. EPA 2002). Use of the liquid form will circumvent dewatering costs by the POTW but will require more trucks to transport the larger volumes of dilute wastewater. Concerns exist regarding operational health and safety impacts related to biosolids. Of particular concern is potential worker exposure to pathogens and risks to workers and nearby residential areas from aerosols resulting from biosolids application to the landfill surface.

As should be clear by now, the moisture content of wastes is critical for optimum bioreactor operation. Addition of significant quantities of liquid may be required. Some estimates (U.S. EPA 2000) indicate that about 50 million L (13 million gal) of liquid might be needed for 365,000 MT (400,000 tons) of waste; others estimate this requirement as 270 L of water/m^3 (54 gal/yd^3) of waste. Landfills in states with dry conditions may require significantly larger liquid quantities. Also, more liquid may be needed to sustain bioreactions after a low-permeability cover or cap is installed, because landfill moisture will be removed via the gas collection system. Thus, leachate generated in the landfill should not be considered sufficient to support the moisture needs for bioreactors.

10.7.5.5 Fires

Active landfill gas collection systems are a source of fires. Other initiators of fire include drilling operations on the landfill and lightning strikes. Potential fire hazards during drilling are easily controlled through safe work practices such as no smoking and the use of spark-free tools and equipment. Note that surface fires are much easier to control and eliminate than are the underground fires.

Aerobic bioreactor landfills rely on high temperatures as well as the addition of oxygen to sustain the bioreaction. For such operations, careful regulation of moisture and oxygen levels enables control of the waste mass temperature, as well as fire potential.

10.7.6 Other Considerations

10.7.6.1 Leachate Strength Reduction

Bioreactor landfills decrease the strength of landfill leachate more rapidly than do conventional subtitle D landfills. COD serves as a common indicator of leachate strength. Reinhart and Townsend (1998) summarized measurements of COD half-lives (i.e., the time it takes for COD to be reduced by 50%) for conventional and bioreactor landfills. The half-life is about ten times shorter in a bioreactor landfill compared with a conventional landfill. Data thus far, however, are limited (Campman and Yates 2002).

10.7.6.2 Waste Mass Shear Strength

Dry waste may be rigid, as evidenced by some modern landfills being relatively tall, with slopes steeper than 3:1. However, addition of water to waste adds weight but decreases shear strength, which affects traditional landfill design factors, such as waste mass geometry. Some geometries used for dry landfills may not work with bioreactor landfills because of differences in shear strength of the waste and elastic displacement caused by water addition (Townsend et al. 2008).

10.7.6.3 Waste Settlement

Accelerating MSW degradation may reduce the need for new landfills by conserving volume. Settlement of conventional landfills is typically around 10% of landfill height and generally occurs over a number of decades as the waste decomposes (Koerner and Daniel 1997). Settlement of the waste mass in a bioreactor landfill can be significant over time, involving 10%–25% of the landfill height. Aerobic bioreactors might achieve this settlement within 2–4 years, whereas anaerobic bioreactors might require 5–10 years (Campman and Yates 2002). Pilot-scale landfill cells in Sonoma County and Mountain View, CA, experienced settlement by as much as 20% and 14%,

respectively, in leachate recirculation cells and approximately 8%–10%, respectively, in conventional dry cells (Reinhart and Townsend 1997). Waste settlement varies markedly and is dependent on type of waste, amount of cover, and compaction. Settlement also will not be consistent across the landfill surface. Gas collection and other internal landfill systems (such as leachate collection and recirculation) must be able to shift with this settlement (U.S. EPA 2000).

Increased rates of settlement before closure may permit additional MSW to be placed in the landfill before a cap is installed. Additional waste placement can therefore reduce the need for new landfills. Such benefits can be realized only when waste decomposes prior to closure. Landfill operators may choose to delay closure in order to take advantage of the increased space created by additional waste settlement.

10.7.6.4 Metals

The long-term fate of metals in bioreactor systems is generally unknown. Since heavy metals tend to concentrate during wastewater biosolids treatment, similar effects should be anticipated in bioreactor landfills during waste decomposition, and changes in heavy metal concentrations may be observed in leachate. Issues regarding behavior of metals in the landfill environment include:

- Microorganisms may concentrate metals.
- pH and sulfides may affect metal mobilization.
- Potential for remobilization of metals if landfill conditions become anaerobic.

Research conducted at Georgia Tech and elsewhere indicate the potential for metal mobilization in bioreactors; however, there are multiple mechanisms for their attenuation. Therefore, metals generally precipitate within the waste mass. In addition, a review of data from 12 landfills indicated that heavy metals were not an issue for a fully stabilized anaerobic landfill. Over a pH range of 7–9, as is typically encountered in these landfills, metals were mostly immobilized. Although metals were present in landfill leachate, all values were below drinking water standards (U.S. EPA 2000).

10.7.6.5 Advantages of Bioreactor Landfills

As was the case for the conventional sanitary landfill, gases emitted from a bioreactor landfill consist primarily of methane and carbon dioxide, along with lesser amounts of volatile organic compounds and hazardous air pollutants. A bioreactor is expected to generate landfill gas earlier and at a higher rate compared with a conventional landfill. Bioreactor landfill gas is also generated over a shorter period of time because emissions decline as the accelerated decomposition process depletes microbial substrates faster than in a traditional landfill. According to EPA (2003), the bioreactor produces more landfill gas overall than the conventional landfill.

Some studies indicate that the bioreactor increases the feasibility for cost-effective landfill gas recovery, which, in turn, reduces fugitive emissions. This presents an opportunity for beneficial reuse of bioreactor gas in energy recovery projects. Currently, the use of landfill gas in traditional and bioreactor landfills for energy applications is about 10% of its potential. The U.S. Department of Energy estimates that if the controlled bioreactor technology were applied to 50% of the waste currently being landfilled, it could provide over 270 billion ft^3 of methane per year, which is equivalent to 1% of electrical needs in the United States. Other potential advantages of bioreactor landfills include (U.S. EPA 2003):

- Decomposition and biological stabilization in years vs. decades in conventional landfills ("dry tombs")
- Lower waste toxicity and mobility
- Reduced leachate disposal costs
- A 15%–30% gain in landfill space due to increased density of waste mass
- Reduced postclosure care

10.7.6.6 Summary of Bioreactor Landfills

Bioreactor landfills are engineered systems that incur higher initial capital costs and require additional monitoring and control during their operating life but are expected to involve less monitoring over the duration of the postclosure period than conventional "dry tomb" landfills. Moisture content is the single most important factor that accelerates decomposition.

Bioreactor technology relies on maintaining moisture content near field capacity (approximately 35%–65% v/v) and requires addition of liquids to maintain that percentage. The moisture content, combined with the action of naturally occurring microbes, promotes waste decomposition. Issues to be addressed during both design and operation of a bioreactor landfill include:

- Increased gas emissions
- Increased odors
- Physical instability of waste mass due to increased moisture and density
- Instability of liner systems
- Surface seeps
- Landfill fires

10.8 LANDFILL RECLAMATION

Landfill reclamation is a relatively new approach for expanding landfill capacity and avoiding the high costs of acquiring additional land (U.S. EPA 1997b). Reclamation costs may be offset by the sale of recovered materials such as recyclables, including ferrous metals, aluminum, plastic, and glass, and the sale of carbonaceous wastes that can be burned as fuel. Reclaimed soil can be used as daily cover material or sold as construction fill. Other benefits of landfill reclamation include the avoided liability through site remediation, reduction in closure costs, and conversion of the landfill site to other uses. Reclamation projects have been successfully implemented at MSWLFs across the United States since the 1980s (U.S. EPA 1997b).

The process of landfill reclamation is summarized as follows: the contents of the landfill cell are excavated using a bulldozer or front-end loader. A loader then organizes the excavated materials into manageable piles and separates out bulky material, such as appliances and steel cable. A trommel screen (see Chapter 7) or vibrating screen separate soil (including old cover material) from solid waste in the excavated mixture. The size and type of screen used depend on the desired end-use of the recovered material. For example, if the reclaimed soil typically is used as landfill cover, a 2.5 in. screen is used for separation. If, however, the reclaimed soil is sold as construction fill, a smaller mesh screen is used to remove small pieces of metal, plastic, glass, and paper.

The excavated waste can be processed at a materials recovery facility to remove valuable components (e.g., steel and aluminum) or burned in a municipal waste incinerator to produce energy. In 1986, the Collier County (FL) Solid Waste Management Department at the Naples Landfill conducted one of the earliest landfill reclamation projects in the United States. The Naples facility, a 33-acre unlined landfill, contained MSW buried for up to 15 years. In a study conducted on several of the state's unlined landfills, it was discovered that the Naples Landfill, along with 27 others, posed a threat to groundwater. City officials formulated a reclamation plan with the following objectives:

- Decreasing site closure costs
- Reducing the risk of groundwater contamination
- Recovering and burning combustible waste in a proposed waste-to-energy facility
- Recovering soil for use as landfill cover material
- Recovering recyclable materials

An EPA assessment of the reclamation project found the processing techniques to be efficient for recovering soil, but not for recovering recyclables of marketable quality. During a demonstration project,

the county efficiently recovered a soil fraction deemed environmentally safe. A total of 45,000 MT (50,000 tons) of reclaimed soil were suitable for use as landfill cover and as a medium for plant growth.

In 1990, the Lancaster County (PA) Solid Waste Management Authority constructed a municipal solid waste incinerator as a means of reducing the volume of waste entering the Frey Farm Landfill, a lined site containing MSW deposited for up to 5 years. City officials initiated a landfill reclamation project to augment the incinerator's supply of fresh waste with reclaimed waste. The reclaimed waste had a modest heating value (approximately 6900 kJ/kg or 3100 Btu/lb). To achieve a higher heating value, fresh waste, containing wood chips and discarded tires, was mixed with reclaimed waste. Approximately 220,000 m^3 (287,000 yd^3) of MSW was excavated from the landfill, and 2400 MT (2645 tons) of screened waste was processed per week for the incinerator. As a result, the county converted 56% of the reclaimed waste into fuel. They also recovered 41% of the reclaimed material as soil during screening (trommeling) operations. The remaining 3% proved noncombustible and was reburied in the landfill. By the end of the project in 1996, landfill operators had reclaimed 230,000–305,000 m^3 (300,000–400,000 yd^3) of landfill waste. Benefits of the project at Frey Farm Landfill included:

- Reclaimed landfill space
- Supplemental energy production
- Recovered soil and ferrous metals

Drawbacks included:

- Increased generation of ash at the incinerator caused by the high soil content in the reclaimed waste
- Increased odor and air emissions
- Increased traffic between the incinerator and the landfill
- Increased wear on incinerator equipment due to the abrasive properties of the reclaimed waste

Additional difficulties confront landfill reclamation. During excavation, methane and other gases from decomposing wastes are released to the atmosphere. Excavation may also uncover hazardous materials, which are costly to manage. In addition, excavation activities may cause adjacent landfill areas to sink or collapse. To identify potential problems, engineers and landfill operators considering reclamation should conduct a site characterization study.

QUESTIONS

1. List and discuss the passive approaches to landfill gas removal.
2. What is the minimum landfill CH_4 concentration that poses an explosion hazard? At what concentration is methane of possible commercial (heating) value?
3. Under RCRA, new landfills cannot be located in seismic zones unless the operator can demonstrate that all containment structures (e.g., liners) are designed to resist the maximum horizontal shifting (true or false).
4. Landfill bird hazards to airports can be limited to a certain extent by shredding and baling MSW prior to disposal. Explain.
5. Landfill sizing is affected by the desired landfill lifetime, population served, and shape and height of the landfill, among other factors. Explain.
6. What chemical changes occur during earliest anaerobic stage of decomposition in a sanitary landfill? Discuss in terms of pH, BOD, and transformations of metals.
7. Methanogenic microorganisms prefer what specific environmental conditions? How do they respond to pH?

8. What factors influence methane gas migration below the land surface? Consider soil texture, soil temperature, soil moisture, and barometric pressure.
9. What waste types are restricted from sanitary landfills under current federal regulations? Be specific.
10. What is the significance of saturated hydraulic conductivity (K_s) in assessing soil for landfill liners and caps, and as landfill foundation? How is K_s influenced by soil texture and engineering practices (e.g., compaction)? What is the RCRA limit for liner K_s?
11. RCRA calls for stringent controls in MSWLF operation for air quality, explosive gases, stormwater runoff, wetlands protection, cover material, and vectors. Discuss the specific requirements for each.
12. Geomembrane installation practices may influence future losses of leachate. List and discuss the factors that must be considered for successful geomembrane installation.
13. Explain the various phases of MSW decomposition in a closed landfill cell. How do leachate quality and gas composition differ between each phase?
14. Under what conditions is passive landfill gas control acceptable? When is active gas control a requirement?
15. How does landfill gas differ from utility-grade natural gas in terms of chemical composition? How must landfill gas be processed to render it suitable for sale to an energy utility?
16. If stormwater enters a landfill unit and contacts waste, how does its regulatory designation change (i.e., according to RCRA)—is it considered nonhazardous, hazardous, special waste, or another designation? How is it to be managed?
17. RCRA regulations require that bulk or noncontainerized liquid wastes are not to be placed in MSWLFs, with two exceptions. What are they?
18. Landfill leachates vary in terms of physical characteristics, inorganic and organic composition, microbial populations, and toxicity. How are the above variables affected by waste type and by age in the landfill cell?
19. Subtitle D requires, at the time of landfill closure, the installation of a final cover (cap) system. What are the primary purposes of the cover? Consider erosion, subsidence, and limiting leachate production.
20. What are the subtitle D requirements for proper landfill cover design and construction?
21. How does landfill reclamation occur, i.e., what mechanical steps are required for successful reclamation? How is reclamation beneficial in terms of extending landfill lifetime and enhancing resource recovery?
22. The Second Law of Thermodynamics states, in essence, that all systems proceed toward maximum disorder (i.e., chaos, entropy). How can a landfill metamorphose over time in the context of the Second Law? In other words, discuss how landfill liners, LCR systems, and caps can be transformed 100 years after landfill closure. Will the landfill remain impervious *ad infinitum*?
23. Soil material is being assessed as a possible liner for a sanitary landfill. A soil core was collected and brought to the laboratory. A 10 cm tall section of soil has 2 cm of water continuously ponded on it. The area of the core surface is 78 cm^2. A total of 62 mL water is collected per hour. Calculate the K_s. Given RCRA requirements for liner K_s, is this soil suitable for a liner?
24. Determine the area required for a new sanitary landfill with a projected lifetime of 20 years. The landfill will serve a population of 175,000 people. It is estimated that per capita waste generation is 1.9 kg/day (4.1 lb/day). Waste density in the landfill averages 625 kg/m^3. Landfill height is not to exceed 20 m.
25. Calculate the annual volume of leachate generated per hectare for a sanitary landfill located along the east coast of the United States. The climate is temperate, average annual rainfall is 122 cm/year (48 in./year), and evapotranspiration is estimated at 48%. The wastes are

covered with soil and runoff from the site is 10%. There is no run-on of surface water and no underflow of groundwater into the cell.

EXERCISE: GROUNDWATER QUALITY AT A MIDWEST LANDFILL

File Name: Landfill.Xls

The Situation

In the 1970s, a gravel pit located in the midwestern United States was converted to a landfill operation. At that time, no state regulations existed that would prohibit such a conversion. Therefore, although the land was completely unsuitable for such use, landfilling began. Initial operation was relatively small (30 acres), and in 1977, the owners expanded operations to a total of 55 acres. In 1979, the state began to regulate landfill activities and, where the site did not meet the instituted state regulations, it was permitted to continue operations under a "grandfather clause."

In 1982, a new operator purchased the facility. During the first year of operations, the company experienced problems with leachate, runoff, and trash released from the site. The company, therefore, decided to institute sound landfill management practices. They also began to buy land surrounding the original site. Since that time, landfill operations improved, meeting the requirements of the state regulatory agency. Trees were planted to improve the aesthetics of the operation. The perimeter of the facility was patrolled, and the company conducted business in the community. The landfill currently employs over 30 members of the community.

This year, the owners began petitioning the Area Planning Commission to expand the land that was permitted for landfill operation. The land for which they are seeking zoning is an additional 100 acres.

Practical Issues of the Landfill

1. Contamination from the current landfill has the potential to contaminate drinking water, not only of the immediate community, but also of other nearby communities. This potential results from two conditions:
   (a) The landfill is situated on a drainage divide. The drainage to the south of the landfill enters one river basin, and the drainage to the north enters a second basin. Therefore, contamination from the landfill will pollute two water systems that pass through as many as 18 counties.
   (b) The subsurface of the land in question contains at least three aquifers. Test wells show that water occurs at depths of 20–25 ft. In addition, a moraine that lies beneath the landfill conducts groundwater away from the site in several directions. Data for a range of inorganic contaminants in test wells appears in the spreadsheet "GW_LF," Sheet 1.
2. Limited tests of water collected from wells at the perimeter of the landfill have shown contamination from total organic carbon. The presence of certain halogenated organic compounds also was identified. Other volatile organic compounds, such as trichloromethane and dichloroethane, were detected. These data appear in Sheet 2.
3. The effects of leachate contamination from special waste and other wastes disposed at the landfill are not presently known. The potential for adverse environmental, health, safety, and social impacts must be considered.
4. Now that the number of landfills in the state have decreased significantly, it is probable that this facility will handle even greater amounts of wastes in the coming decade.

The data for this exercise can be located at www.crcpress.com/e_products/downloads/download.asp?cat_no = 3525

Tasks

Using the monitoring well data from the tables, determine whether or not groundwater in the landfill environs is contaminated. Indicate where contaminants are occurring and if they are in excess of regulatory limits.

1. Determine the direction of groundwater flow and draw directional arrows.
2. From the contaminated wells identified, define the extent of any plume and sketch its outline on the map.
3. Discuss any observable trends in migration of contaminants over the study period.
4. Based on the behavior of the metals, what can you conclude about the pH of the leachate?
5. Do the data for chlorinated organics indicate a possible human health hazard? What could be the possible source of these chemicals? Can any arise from natural decomposition of disposed wastes?
6. Based on groundwater data and the need for additional landfill space, is an extension of this landfill facility justifiable? Give reasons.

REFERENCES

ADMET. 2013. *Plastics and Elastomers*. Available from: http://admet.com/materials/plastics-elastomers-testing/

ASTM (American Society for Testing and Materials). 2000. *Standard Test Methods for Water Vapor Transmission of Materials*, ASTM E96-00. West Conshohocken, PA: ASTM.

ASTM (American Society for Testing and Materials). 2002. *Standard Terminology for Geosynthetics*, ASTM D4439-02. West Conshohocken, PA: ASTM.

ATSDR (Agency for Toxic Substance Disease Registry). 2001. Chapter 2: Landfill Gas Basics. In *Landfill Gas Primer – An Overview for Environmental Health Professionals.* Available from: http://www.atsdr.cdc.gov/HAC/landfill/PDFs/Landfill_2001_ch2mod.pdf

Bagchi A. 1994. *Design, Construction, and Monitoring of landfills. 2nd Edition*, New York: Wiley-Interscience Publisher. 361p

Bourne, Massachusetts. 2000. *Landfill Liner System, Phase 3, Integrated Solid Waste Management Department*. Available from: http://www.townofbourne.com/Town%20Offices/ISWM/Layer2.htm

British Crop Protection Council and Contract Report for Enventure, Ltd. 1999. *Fly Control on Landfill: A Literature Review*. Available from: http://www.enventure.co.uk/docs/Fly%20control%20on%20landfill%20sites %20-%2 0literature%20study.pdf

Buss, S.E., Butler, A.P., Johnston, P.M., Sollars, C.J., and Perry, R. 1995. Mechanisms of leakage through synthetic landfill liner materials. *J. Chartered Insti Water Environ Manage* 9, 353–359.

CFR (Code of Federal Regulations). 2004a. *Vol. 40, Part 258*, *Criteria for Municipal Solid Waste Landfills*. Washington, DC: U.S. Government Printing Office.

CFR (Code of Federal Regulations). 2004b. *Vol. 40, Part 761*, *Polychlorinated Biphenyls (PCB) Manufacturing, Processing, Distribution in Commerce, and Use Prohibitions*. Washington, DC: U.S. Government Printing Office.

Ellis, H., and J. Blood-Smyth. n.d. *Fly Control on Landfill. A Literature Review.* West Yorkshire: Contract Report for Enventure Ltd.

Emcon Associates. 1980. *Methane Generation and Recovery from Landfills*. Ann Arbor, MI: Ann Arbor Science Publications.

Environmental Research and Education Foundation. 2002. *Bioreactor Landfill Project Northern Oaks Landfill*. Available from: http://www.erefdn.org/rpts_summary_ordrs/northernoaks.htm

Farquhar, G.J., and F.A. Rovers. 1973. Gas production during refuse decomposition. Air, Water and Soil Pollution. 2: 483–495.

FEMA (Federal Emergency Management Agency). 2002. *Landfill Fires. Their Magnitude, Characteristics, and Mitigation*. May 2002/FA -225. Available from: http://www.usfa.fema.gov/downloads/pdf/publications/fa-225.pdf

Fenn, D.G., Hanley, K.J., and Degeare, T.V. 1975. *Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites.* EPA-530/SW-168. Washington, DC: U.S. Government Printing Office.

Flower, F.B., Leone, I.A., Gilman, E.F., and Arthur, J.J. 1982. *Vegetation Kills in Landfill Environs*. New Brunswick, NJ: Cook College, Rutgers University.

Geosynthetics. 2013. *Geosynthetics Overview*. Available from: http://geosyntheticsmagazine.com/materials/geotextiles.

Giroud, J.P. and Bonaparte, R. 1989. Leakage through liners constructed with geomembranes Part I, Geomembrane liners. *Geotextiles Geomembranes* 8, 1, 27–67.

Guhlke, M.R. 1985. Management program to control flies and odor in poultry manure storage and disposal. *J Environ Health* 47, 314–317.

Hanley, M.E., Dunn, D.W., Abolins, S.R., and Goulson, D. 2004. Evaluation of (Z)-9-tricosene baited targets for control of the housefly (*Musca domestica*) in outdoor situations. *J Appl Entomol* 128, 478–482.

Haxo, H.E. and Lahey, T.P. 1988. Transport of dissolved organics from dilute aqueous solutions through flexible membrane liners. *Hazard Waste Hazard Mater* 5, 275–94.

Hoyer, H. 1986. *Survey of Europe and North Africa for Parasitoids that Attack Filth Flies*. Miscellaneous Publications of the Entomologist Society of America, No-61, 1986, 35–38.

Hudgins, M. and Green, L. 1999. Innovative Landfill Gas Control Using an Aerobic Landfill System. *Proceedings of the SWANA 22nd Annual Landfill Gas Symposium,* Lake Buena Vista, FL, 187–200.

ISWM Operations. No date. *Landfill*. Available from: http://www.townofbourne.com/Departments/PUBLICWORKS/IntegratedSolidWasteManagment/ISWMOperations/tabid/333/Default.aspx

Kiely, G. 1997. *Environmental Engineering.* New York: McGraw-Hill.

Koerner, R.M. and Daniel, D.E. 1997. *Final Covers for Solid Waste Landfills and Abandoned Dumps.* Reston, VA: ACSE Press.

McBean, E.A., Pohland, F.G., Rovers, F.A., and Crutcher, A.J. 1982. Leachate design for containment landfills. *J Environ Engin Div* 108, 204–209.

McEnroe, B.M. 1993. Maximum saturated depth over landfill liner. *J Environ Engin Div ASCE* 119, 262–270.

Park, J.K. and Nibras. M. 1993. Mass flux of organic chemicals through polyethylene geomembranes. *Water Environ Res* 65, 227–237.

Pelt, R., White, C., Blackard, A., Bass, R. L., Burklin, C., Heaton, R.E., and Reisdorph, A. 1998. *User's Manual, Landfill Gas Emissions Model, Version 2.0.* Washington, DC: Office of Research and Development, U.S. Environmental Protection Agency.

Qian, X., Koerner, R.M., and Gray, D.H. 2002. *Geotechnical Aspects of Landfill Design and Construction.* Upper Saddle River, NJ: Prentice-Hall.

Rathje, W. and Murphy, C. 1992. *Rubbish: The Archaeology of Garbage.* New York: Harper Collins.

Reinhart, D.R. and Townsend, T.G. 1997. *Landfill Bioreactor Design and Operation*. New York: Lewis Publishing.

Richardson, G. and Zhao, A. 2000. *Design of Lateral Drainage Systems for Landfills*. Baltimore, MD: Tenax Corporation.

Rueda, L.M, Roh, P.U., and Rya, J.L. 1997. Pupal parasites (Hymenoptera: Pteromalidae) of filth flies breeding in refuse and poultry and livestock manure in South Korea. *J Med Entomol* 34, 82–85.

Sulaiman, S., Omar, B., Jeffrey, J., Ghauth, I., and Busparani,V. 1990. Survey of the microhymenoptera, hymenoptera, chacidoidae, parasitising filth flies, *Diptera, Muscidae, Calliphoridae* breeding in refuse and poultry farms on peninsular Malaysia. *J Med Entomol* 27, 851–855.

SWANA (Solid Waste Association of North America). 1992. *A Compilation of Landfill Gas Field Practices and Procedures*. Landfill Gas Division of the Solid Waste Association of North America.

Tchobanoglous, G., Theisen, H., and Vigil, S. 1993. *Integrated Solid Waste Management: Engineering Principles and Management Issues.* New York: McGraw-Hill.

Thornthwaite, C.W., and J.R. Mather. 1957. The Water Balance. *Publications in Climatology* VIII(1): 1–104. Centerton, NJ: Drexel Institute of Climatology.

Townsend, T., Kumar, D., and Ko, J. 2008. *Bioreactor Landfill Operation: A Guide for Development, Implementation and Monitoring: Version 1.0 (July 1, 2008)*. Prepared for the Hinkley Center for Solid and Hazardous Waste Management, Gainesville, FL, 2008, 1–43.

U.S. EPA (U.S. Environmental Protection Agency). 1985. *Handbook – Remedial Action at Waste Disposal Sites*, EPA/625/6-85/006. Cincinnati, OH: Office of Research and Development, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1986a. *Air Emissions from Municipal Solid Waste Landfills – Background Information for Proposed Standards and Guidelines*, EPA-450/3-90-011a. PB91-197061. Cincinnati, OH: National Technical Information Service.

U.S. EPA (U.S. Environmental Protection Agency). 1986b. *SW-846, Method 9095 – Paint Filter Liquids Test, Test Methods for Evaluating Solid Waste, Volume 1A: Laboratory Manual Physical/Chemical Methods*. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1988a. *Loading Point Puncturability Analysis of Geosynthetic Liner Materials*, PB88-235544. Cincinnati, OH: National Technical Information Service.

U.S. EPA (U.S. Environmental Protection Agency). 1988b. *Summary of Data on Municipal Solid Waste Landfill Characteristics – Criteria for Municipal Solid Waste Landfills*, EPA/530-SW-88-038. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1989. *Requirements for Hazardous Waste Landfill Design, Construction and Closure*, EPA/625/4-89/022. Cincinnati, OH: Seminar Publication, Office of Research and Development, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1991. *Calculated flow rates through a geomembrane with a liquid head of 0.3m*. Washington DC.

U.S. EPA (U.S. Environmental Protection Agency). 1992. Action Leakage Rates for *Leak Detection Systems*. EPA 530-R-92-004. Washington, DC: Office of Solid Waste.

U.S. EPA (U.S. Environmental Protection Agency). 1992a. *Technical Guidance Document: Quality Assurance and Quality Control for Waste Containment Facilities*, EPA/600/R-92/182. Cincinnati, OH: U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1992b. *Alternative Daily Cover Materials for Municipal Solid Waste Landfills*. San Francisco, CA: U.S. EPA Region IX.

U.S. EPA (U.S. Environmental Protection Agency). 1993a. *Safer Disposal for Solid Waste, The Federal Regulations for Landfills*, EPA/530 SW-91 092. Washington, DC: Office of Solid Waste and Emergency Response (OS-305), U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1993b. *Criteria for Solid Waste Disposal Facilities, A Guide for Owners/Operators*, EPA/530-SW-91-089. Washington, DC: Solid Waste and Emergency Response (OS-305), U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1993c. *Technical Manual, Solid Waste Disposal Facility Criteria,* EPA 530-R-93-182. Washington, DC: Solid Waste and Emergency Response, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1994. *Design, Operation, and Closure of Municipal Solid Waste Landfills*, EPA 625/R-94/008. Washington, DC: Seminar Publication, Office of Research and Development, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1997a. *Compilation of Air Pollutant Emission Factors, AP-42*, 5th ed, Supplement C. Office of Air Quality Planning and Standards. Research Triangle Park, NC: U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1997b. *Landfill Reclamation,* EPA530-F-97-001. Washington, DC: Office of Solid Waste and Emergency Response (5306W), U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2002. *The Benefits of Utilizing Landfill Gas*. Available from: http://www.epa.gov/lmop/about.htm#lfgte

U.S. EPA (U.S. Environmental Protection Agency). 2003. *Bioreactors*. Available from: http://www.epa.gov/epaoswer/nonhw/muncpl/landfill/bioreactors.htm#3

U.S. EPA (U.S. Environmental Protection Agency). 2009. *Landfill Gas Energy Basics*. Available from: http://www.epa.gov/lmop/documents/pdfs/pdh_chapter1.pdf

U.S. EPA (U.S. Environmental Protection Agency). 2013. *Bioreactors*. Available at http://www.epa.gov/osw/nonhaz/municipal/landfill/bioreactors.htm#1

Varank, G., Demir, A., Yetilmezsoy, K., Bilgili, M.S., and Top, S. 2011. Estimation of transport parameters of phenolic compounds and inorganic contaminants through composite landfill liners using one-dimensional mass transport model. *Waste Manag* 31, 2263–2274.

Vesilind, P.A., Worrell, W.A., and Reinhart, D. 2002. *Solid Waste Engineering*. Pacific Grove, CA: Brooks/Cole Thomson Learning.

Whitehead, R. 1998. *The UK Pesticide Guide.* Wallingford, UK: CAB International, British Crop Protection Council.

Worrell, W.A. and Vesilind, P.A. 2011. *Solid Waste Engineering,* 2nd ed. Pacific Grove, CA: Brooks/Cole.

Yates, A., and Campman, C. 2002. *Bioreactor Landfills: An Idea Whose Time Has Come A summary of the current bioreactor landfill situation. MSW Management*. Sept.-Oct. 2002. http://www.mswmanagement.com/MSW/Articles/Bioreactor_Landfills_An_Idea_Whose_Time_Has_Come_3987.aspx?pageid=5d5e95b7-6171-4a42-aaf0

SUGGESTED READINGS

Augello, A.1995. Evaluation of solid waste landfill performance during the Northridge Earthquake, in Earthquake design and performance of solid waste landfills. *Proceedings, ASCE Annual Convention*, San Diego, CA, ASCE Geotechnical Special Publication ASCE, New York, 1995, pp. 17–50.

Baldwin, T., Stinson, J., and Ham, R. 1998. Decomposition of specific materials buried within sanitary landfills. *J Environ Eng* 124, 1193–1202.

Barlaz, M.A., Shaefer, D.M., and Ham, R.K. 1989. Bacterial population development and chemical characteristics of refuse decomposition in a simulated sanitary landfill. *Appl Environ Microbiol* 55, 55–65.

Chanton, J., Rutkowski, C.M., and Mosher, B. 1999. Quantifying methane oxidation from landfills using stable isotope analysis of downwind plumes. *Environmental Science and Technol.* 33(21): 3755–3760.

Coons, L.M., Ankeny, M., and Bulik, G.M. 2000. Alternative Earthen Final Covers for Industrial and Hazardous Waste Trenches in Southwest Idaho. *Proceedings of the 3rd Annual Arid Climate Symposium,* SWANA, Albuquerque, NM, 14.1–14.6.

Deipser, A. and Stegmann, R. 1994. The origin and fate of volatile trace components in municipal solid waste landfills. *Waste Manage Res*12, 129–139.

El-Fadel, M., Shazbak, S., Saliby, E., and Leckie, J. 1999. Comparative assessment of settlement models for municipal solid waste landfill application. *Waste Manage Res* 17, 347–368.

Fisher, S.R. and Potter, K.W. 1998. *Evaluation of the Use of DUMPSTAT to Detect the Impact of Landfills on Groundwater Quality*. Madison, WI: Wisconsin Department of Natural Resources.

Herrera, T.A., Lang, R., and Tchobanoglous, G. 1989. A study of the emissions of volatile organic compounds found in landfills. *Proceeding of the 43rd Annual Purdue Industrial Waste Conference*. Lewis Publishing, Chelsea, MI, 229–238.

Manna, L., Zanetti, M.C., and Genon, G. 1999. Modeling biogas production at landfill sites. *Resour Conservat Recycl* 26(1): 1–14.

Pohland, F.G. and Kim, J.C. 2000. Microbially mediated attenuation potential of landfill bioreactor systems. *Water Sci Technol* 41, 247–254.

Senior, E. 1995. *Microbiology of Landfill Sites.* Boca Raton, FL: Lewis Publishing.

Stark, T.D. 1999. Stability of waste containment facilities. *Proceedings of Waste Tech '99*. National Solid Wastes Management Association, New Orleans, LA, 1–24.

Stark, T.D., Arellano, D., Evans, D., Wilson, V., and Gonda, J. 1998. Unreinforced geosynthetic clay liner case history. *Geosynthetics Int J* 5, 521–544.

Stessel, R.I., Barrett, W.M., and Li, X. 1998. Comparison of the effects of testing conditions and chemical exposure of geomembranes using the comprehensive testing system. *J Appl Polymer Sci* 70(11), 2097–2110.

UN Framework Convention on Climate Change. 2012a. *Landfill Gas Recovery and Combustion with Renewable Energy Generation from Sanitary Landfill Sites under Land Bank of the Philippines Carbon Finance Support Facility*. Available from: https://cdm.unfccc.int/ProgrammeOfActivities/poa_db/NJ25MHG0PAZ4RWTDF3LO6KI9VEU7SC/view

UN Framework Convention on Climate Change. 2012b. *Tianjin Shuangkou Landfill Gas Recovery and Electricity Generation*. Available from: http://cdm.unfccc.int/Projects/DB/JQA1193375340.58/view

UN Framework Convention on Climate Change. 2012c. *Guangzhou Xingfeng Landfill Gas Recovery and Electricity Generation CDM Project*. Available from: http://cdm.unfccc.int/Projects/DB/JCI1175576815.21

Watts, K.S. and Charles, J.A. 1999. Settlement characteristics of landfill wastes. *Proceedings of the Institution of Civil Engineers*, Geotechnical Engineering, UK, 225–233.

Williams, G.M., Ward, R.S., and Noy, D.J. 1999. Dynamics of landfill gas migration in unconsolidated sands. *Waste Manage Res* 17, 327–343.

Part III

Hazardous Waste Management

This section addresses the management of those wastes that pose a significant threat, both now and in the future, to human health and the environment when improperly managed. Wastes considered hazardous are those that are ignitable, corrosive, reactive, toxic, or all of these. It follows that such wastes cannot be adequately managed or disposed without observing special precautions. Wastes designated as "hazardous" are generated by a wide range of industries of varying sizes. As we shall see in this section, specific requirements for waste management by a generator will vary as a function of the amounts generated over a specified time frame.

Regulations addressing hazardous waste management were few prior to 1976, when the Resource Conservation and Recovery Act (RCRA) was enacted. Under RCRA, the U.S. Environmental Protection Agency (U.S. EPA) was granted specific authority to regulate the generation, transportation, and disposal of hazardous waste. Topics in this section will reflect the requirements of RCRA (and, to a lesser extent, other key regulatory and legal frameworks such as those of the Department of Transportation and the Clean Air Act) and include identification of hazardous waste; hazardous waste generator requirements; hazardous waste transportation; treatment, storage, and disposal facility requirements; incineration; hazardous waste treatment; and land disposal of hazardous waste. This chapter makes frequent reference to 40 CFR, that is, volume 40 of the Code of Federal Regulations, in order to cite specific waste management requirements. The Code can be accessed on the Internet.

Management of nuclear (radioactive) waste is not presented in this book; radioactive wastes are not addressed by RCRA but by other laws, for example, the Nuclear Waste Policy Act of 1982.

11 Identification of Hazardous Waste

There are evils that have the ability to survive identification and go on forever... money, for instance, or war.

Saul Bellow, 1915–2005

11.1 INTRODUCTION

As discussed in Chapter 3, the Resource Conservation and Recovery Act (RCRA) was the first truly significant step in the comprehensive management of hazardous, as well as municipal wastes, in the United States. The ultimate goal of RCRA is to promote the protection of public health and the environment, and to conserve material and energy resources. RCRA requires the Environmental Protection Agency (EPA) to promulgate and enforce regulations regarding management of hazardous waste. These regulations have established mandatory procedures and requirements for compliance. RCRA has remained current with waste management issues and problems by being amended several times. The most sweeping set of amendments was included in 1984 as the Hazardous and Solid Waste Amendments (HSWA).

RCRA has nine subtitles, each of which addresses specific aspects of resource conservation and waste management. Subtitle C has its sole focus on management of hazardous waste. Its goal is to identify a hazardous waste and to set standards for its accumulation, storage, transportation, treatment, and disposal. The provisions of subtitle C apply to a waste from the moment it becomes hazardous until it is no longer a hazardous waste. This embraces the so-called cradle-to-grave approach to regulation of hazardous waste.

Hazardous waste management regulations are published in the *Federal Register*, which is published daily. The *Federal Register* provides a system for making regulations and legal notices issued by federal agencies available to the public.

11.2 RCRA SUBTITLES

U.S. EPA regulations are compiled in title 40 of the Code of Federal Regulations (40 CFR), *Protection of the Environment*. The topics are as follows:

Subtitle	Topic
A	General Provisions
B	Office of Solid Waste, Authorities of the EPA administrator
C	Hazardous Waste Management
D	State or Regional Solid Waste Plans
E	Duties of the Secretary of Commerce in Resource Recovery
F	Federal Responsibilities
G	Miscellaneous Provisions
H	Research, Development, Demonstration, and Information
I	Underground Storage Tanks

Subtitle A declares that the generation of hazardous waste is to be reduced; furthermore, land disposal is the least favored method of hazardous waste disposal. Wastes are to be disposed in order to minimize all threats to human health and the environment. Subtitle A includes a set of objectives to achieve these goals, including:

- Prohibition of open dumping of waste
- State control of RCRA programs
- Promotion of research and development activities for sound waste management
- Encouragement of waste recovery, recycling, and treatment as alternatives to waste disposal

A summary of federal regulations implementing the hazardous waste management requirements of RCRA is shown in Table 11.1. Parts 124, 260 through 268, 270, 273, and 279 specifically address management of hazardous wastes.

Part 124 contains EPA procedures for issuing, modifying, revoking, and reissuing or terminating RCRA permits.

Part 261 identifies the wastes that are subject to regulation as hazardous waste. This part defines the terms *solid waste* and *hazardous waste*, identifies those wastes that are excluded from regulations, and establishes management requirements for hazardous waste generated by *conditionally exempt small quantity generators*, and for hazardous waste that is recycled. Part 261 identifies characteristics and contains the various lists of hazardous wastes.

Part 262 contains the rules with which generators of hazardous waste must comply. This part requires a facility to evaluate all wastes generated on-site to determine if they meet the definition of hazardous waste. It also explains the conditions under which a hazardous waste manifest must be used, describes a generator's transportation requirements, and details the record keeping and reporting requirements.

Part 263 establishes standards that apply to persons transporting hazardous waste within the United States. In promulgating the regulations, the EPA adopted those of the Department of Transportation (DOT) governing the transportation of *hazardous materials*. These regulations pertain to container labeling, marking, placarding, using proper containers, and reporting discharges of hazardous waste.

TABLE 11.1
Summary of Federal Regulations Implementing the Hazardous Waste Management Requirements of RCRA

40 CFR Part	Coverage of the Regulations
124	Public Participation
260	General Requirements, Definitions, Petitions
261	Identification and Listing of Hazardous Waste
262	Generators of Hazardous Waste
263	Transporters of Hazardous Waste
264	Permitted Hazardous Waste Facilities
265	Interim Status Hazardous Waste Facilities
266	Certain Specific Hazardous Wastes and Facilities
268	Land Disposal Restrictions
270	EPA-Administered Permits
271	State Hazardous Waste Program Requirements
273	Universal Hazardous Waste
279	Standards for the Management of Used Oil

Part 264 presents the requirements that apply to facilities that treat, store, or dispose of hazardous waste. It contains general standards by which all hazardous waste treatment, storage, and disposal facilities must be operated, as well as specific requirements for surface impoundments, waste piles, landfills, incinerators, land treatment facilities, and facilities with containers and tank systems used for storing or processing hazardous waste.

Part 265 establishes minimum standards that apply to facilities that treat, store, or dispose of hazardous waste and have interim status. Part 265 regulations apply to facilities that were operating before the RCRA regulations were finalized and have not yet received a final permit to operate their facility, or have closed but are under EPA orders to correct some problems on-site. This part also contains requirements for training, preparedness and prevention, and contingency planning.

Part 266 contains standards for the management of specific hazardous wastes and specific types of hazardous waste management facilities. This part includes regulations that apply to recyclable materials, hazardous waste burned for energy recovery, precious metal recovery, and reclamation of spent lead–acid batteries.

Part 268 identifies hazardous wastes that are restricted from land disposal and defines those circumstances under which a restricted waste may continue to be land disposed.

Part 270 covers basic EPA permitting requirements for hazardous waste management facilities, such as information to be included in the permit application, monitoring and reporting requirements, and conditions under which permits can be transferred or modified.

Part 271 specifies the minimum requirements with which a state must comply to receive authorization to administer and enforce its own hazardous waste management program in lieu of the federal programs.

Part 273 includes the management system for hazardous waste batteries, pesticides, and thermostats. This program is referred to as the Universal Waste Program. These regulations cover the standards for universal waste handlers, transporters, and destination facilities.

Part 279 establishes minimum management standards that apply to used oil generators, collection centers, aggregation points, transporters, transfer facilities, processors, re-refiners, burners, and marketers of used oil fuel. This part also places limitations on the use of used oil as a dust suppressant and on the disposal of used oil.

11.3 SUBTITLE C: THE HAZARDOUS WASTE MANAGEMENT PROGRAM

11.3.1 Definition of a Solid Waste

Before a regulatory agency and a potential generator (i.e., a facility) address the issue of whether or not a specified waste is hazardous, they must first determine whether or not the waste is a solid waste. According to 40 CFR 261.2, a solid waste is any *discarded material* that is not excluded from the regulations. Going further into the definition, a discarded material is any material that is abandoned, recycled, "inherently waste-like," or military munitions identified as a solid waste in 40 CFR 266.202.

An *abandoned* material is one that is (1) disposed, (2) burned or incinerated, or (3) accumulated or stored.

Materials are also solid wastes if they are *recycled*, accumulated, stored, or treated before recycling. This includes being: (1) placed on the land in a manner that constitutes disposal, (2) burned for energy recovery, (3) reclaimed, or (4) accumulated speculatively.

Some major types of materials that are recycled include (40 CFR 261.2):

- *Spent material*. These have been used and, as a result of contamination, can no longer serve the purpose for which they were produced without processing.
- *Sludges*. Solid, semisolid, or liquid waste generated from a municipal, commercial, or industrial wastewater treatment plant, water supply treatment plant, or air pollution control facility.

- *By-product*. A material that is generated as part of a production process but is not a primary product of the process. An example is process residue such as slag.
- *Scrap metal*. Metal parts (e.g., bars, rods, sheets, and wire) that, when worn out or no longer needed, can be recycled.
- Discarded commercial chemical products, off-specification items, container residues, and spill residues.

Inherently waste-like materials are those that have no other possible fate except disposal. For example, hazardous waste designated by the numbers F020, F021, F022, F023, F026, and F028 (all chlorinated hazardous wastes) fall into the inherently waste-like category. The F-listing and other hazardous waste listings are described below.

11.3.2 What Is a Hazardous Waste?

If a solid waste does not qualify for an exemption, it is declared a hazardous waste if it is listed by EPA in 40 CFR part 261, subpart D, or if it exhibits any of the four hazardous waste characteristics identified in 40 CFR part 261, subpart C.

11.3.3 Exemptions and Exclusions

The EPA regulations automatically exempt certain solid wastes from the "hazardous waste" designation under subtitle C. Three categories of exclusion exist: wastes excluded from the definition of solid waste, wastes excluded from the definitions of hazardous waste, and hazardous wastes that are partially excluded, provided that they are managed in accordance with specific requirements. Table 11.2 lists the wastes contained under these exclusions.

TABLE 11.2
Exclusions from Subtitle C of RCRA

Excluded from the Solid Waste Definition	Excluded from the Hazardous Waste Definition	Excluded Materials Requiring Special Management
Domestic sewage	Household wastes	Product storage wastes
Mixture of domestic sewage and wastes going to POTW	Agricultural wastes used as fertilizers	Waste identification samples
Industrial point source-discharges under 402 CWA[a]	Mining overburden returned to site	Treatability samples
Irrigation returns flows	Discarded wood treated with arsenic	Empty containers
Sources, special nuclear, or by-product material under AEA	Chromium wastes	Small quantity generator wastes
	Underground storage tank cleanup wastes	
In-situ mining waste	Specific ore processing wastes	Farm wastes (pesticides)
Reclaimed pulping liquors	Specific utility wastes	
Regenerated sulfuric acid	Oil and gas exploration, development, and production wastes	
Secondary materials returned to the original process under certain conditions	Cement kiln dust	

Source: Code of Federal Regulations, Vol. 40, Part 261, *Identification and Listing of Hazardous Waste*, U.S. Government Printing Office, Washington, DC, 2004.

[a] Section 402 of Clean Water Act: National Pollutant Discharge Elimination System.

11.3.4 Hazardous Waste Lists

11.3.4.1 Hazardous Wastes from Nonspecific Sources

Wastes in this category are placed on the so-called F-list. These wastes are determined to be hazardous; however, they are not generated by a specific industry or manufacturing process. Wastes on the F-list include certain solvent wastes, plating wastes, metal-treating wastes, wood-preserving wastes, petroleum refinery oil–water–solids separation sludge, leachate from treatment, storage or disposal facilities, wastes from the manufacture of certain chlorinated compounds, and treatment residue from incineration of soil contaminated with certain chlorinated compounds. The general categories of F-listed wastes are as follows:

- Solvent wastes (F001–F005)
- Electroplating wastes (F006–F009)
- Metal-treating wastes (F010–F019)
- Wood-preserving wastes (F032–F035)
- Petroleum-refining wastes (F037–F038)

11.3.4.2 Hazardous Wastes from Specific Sources

Wastes on the K-list originate from specific sources or industries that EPA has determined to be hazardous. For example, sludge from the treatment of wastewaters by the wood-preserving industry fall into this category (K001). K048 and K052 include certain petroleum-refining wastes. Wastes on the K-list include those generated by the following industries:

- Wood preservation
- Inorganic pigment production
- Organic chemical production
- Inorganic chemical production
- Pesticide production
- Explosives manufacturing and production
- Petroleum refining
- Iron and steel production
- Primary copper, lead, zinc, and aluminum production
- Ferroalloy production
- Secondary lead smelting
- Veterinary pharmaceutical production
- Ink formulation
- Coking industries

11.3.4.3 Discarded Commercial Products, Off-Specification Materials, Container Residues, and Spill Residues

Materials on the P- and U-lists are classified as acute hazardous waste and as toxic waste, respectively. These wastes include certain commercial chemical products whose generic names are included on the P- and U-lists (40 CFR 261.33) when they are discarded.

Examples of commercial chemical hazardous wastes include products from hospitals (e.g., pharmaceuticals past their expiration date and unused reagents), research laboratories (expired or unused reagents intended for disposal), photography laboratories, and analytical laboratories. These items become hazardous waste when it is determined that they must be disposed. Some products, however, can be tested in order to determine if their expiration date can be extended. If there is another use for the material, it can be stored or used for that purpose without being classified as hazardous waste.

11.3.5 Characteristic Tests

New chemical products are put onto the marketplace on a regular basis. As a result, new types of wastes are being produced. Since many wastes are chemical newcomers, they will obviously not be listed in the CFR. Other methods are therefore needed to determine potential hazards of a waste. EPA has established the four so-called characteristic tests to determine whether or not a waste is hazardous.

11.3.6 Ignitability

The ignitability characteristic indicates those wastes that pose a fire hazard during routine handling, for example, storage, transport, processing, or disposal. Specifically, a solid waste exhibits the characteristic of ignitability if a sample possesses any of the following properties (40 CFR 261.21):

- It is a liquid containing less than 24% alcohol (by vol.) and has flashpoint less than 60°C (140°F) as determined by a Pensky–Martens Closed Cup Tester (U.S. EPA 1986b; ASTM Standard D-93-79 or D-93-80) or a Setaflash Closed Cup Tester (ASTM Standard D-3278-78).
- It is not a liquid and is capable of causing fire through friction, absorption of moisture, or spontaneous chemical changes, and, when ignited, burns so vigorously and persistently that it creates a hazard.
- It is an ignitable compressed gas as defined in 49 CFR 173.300.
- It is an oxidizer as defined in 49 CFR 173.151.

Examples of characteristic (D-list) hazardous wastes include:

- Solvents used for parts cleaning or degreasing
- Paint thinners and paint removing compounds
- Carbon remover and nail polish remover solutions
- Organic solvent-based paint strippers

A solid waste that exhibits the characteristic of ignitability is assigned the EPA hazardous waste number D001.

11.3.7 Corrosivity

Corrosive wastes occur at extremes in pH. Wastes with very low or high pH values can corrode standard drums, oxidize skin and other living tissue, and dissolve components (e.g., metals) from certain wastes. Examples of corrosive wastes include acid and alkali wastes. A solid waste exhibits the characteristic of corrosivity if a sample has either of the following properties (40 CFR 261.22):

- It is aqueous and has a pH < 2 or > 12.5 as determined by a pH meter (Method 9040, U.S. EPA 1986a).
- It is a liquid and corrodes steel at a rate greater than 6.35 mm (0.25 in.) per year and at a temperature of 55°C (130°F) as determined by the National Association of Corrosion Engineers Standard TM-01-69 (U.S. EPA 1986b).

Wastes generated from the following processes are examples of corrosive hazardous wastes:

- Parts cleaning operations using highly alkaline cleaning solutions
- Alkaline strippers used to strip paint
- Acidic wastes generated from electroless metal plating lines

- Battery acid and other waste acids
- Phenol wastes

A solid waste that exhibits the characteristic of corrosivity is assigned the EPA hazardous waste number D002.

11.3.8 Reactivity

Wastes possessing the characteristic of reactivity are often unstable, and pose hazards of explosion and release of toxic gases during routine management. Examples of reactive wastes include picrate salts (derived from picric acid, 2,4,6-trinitrophenol), and certain epoxides and peroxides.

Other wastes generated from the following processes are examples of reactive hazardous wastes:

- Cyanide-bearing electroplating solutions
- Ordinance and explosives listed by DOT as Division 1.1, 1.2, or 1.3 Explosive, or Forbidden Explosives

The characteristic of reactivity in a waste sample is often difficult to determine quantitatively in the laboratory. A waste exhibits the characteristic of reactivity if a representative sample possesses any of the following properties (40 CFR 261.23):

- It is normally unstable and readily undergoes violent changes without detonating.
- It reacts violently with water.
- It forms potentially explosive mixtures with water.
- When mixed with water, it generates toxic gases, vapors, or fumes in a quantity sufficient to present a danger to human health or the environment.
- It is a cyanide- or sulfide-bearing waste that, when exposed to pH values between 2 and 12.5, generates toxic vapors in a quantity sufficient to harm human health or the environment.
- It is capable of detonation or explosive reaction if it is subjected to a strong initiating source or if heated under confinement.
- It is capable of detonation or an explosive reaction at ambient conditions.
- It is a Forbidden Explosive as defined in 49 CFR 173.51, a Class A Explosive as defined in 49 CFR 173.53, or a Class B Explosive as defined in 49 CFR 173.88, DOT regulations.

A solid waste that exhibits the characteristic of reactivity is assigned the EPA hazardous waste number D003.

11.3.9 Toxicity

The Toxicity Characteristic Leaching Procedure (TCLP) was formulated to simulate environmental conditions in an exposed landfill. The intent of the test is to determine whether potentially toxic components of waste could leach to groundwater and soil if exposed to acidic precipitation.

The TCLP replaced the EP toxicity test in 1990. The new test includes 25 organic compounds, as well as the eight metals and six pesticides originally in the EP test. In the TCLP, a representative sample is shaken in dilute acetic acid for 18 ± 2 h and filtered, and the filtrate is analyzed for the required metals and organic compounds. Details of the method are provided in TCLP, Method 1311 (U.S. EPA 1986c).

If the filtrate contains any of the contaminants listed in Table 11.3 at a concentration greater than or equal to the regulatory level, the waste is regarded as exhibiting the toxicity characteristic. The following wastes are examples of common toxicity characteristic wastes (40 CFR 261.24):

- Paint waste containing metals such as lead, chromium, silver, or cadmium
- Metal strip baths used to remove paint and chrome plating

TABLE 11.3
Details on the Toxicity Characteristic Compounds

EPA Hazardous Waste Number	Contaminant	CAS No.	Regulatory Level (mg/L)
D004	Arsenic	7440-38-2	5.0
D005	Barium	74401-39-3	100.0
D018	Benzene	71-43-2	0.5
D006	Cadmium	7440-43-9	1.00
D019	Carbon tetrachloride	56-23-5	0.5
D020	Chlordane	57-74-9	0.03
D021	Chlorobenzene	108-90-7	100.0
D022	Chloroform	67-66-3	6.0
D007	Chromium	7440-47-3	5.0
D023	*o*-Cresol	95-48-7	200.0
D024	*m*-Cresol	108-39-4	200.0
D025	*p*-Cresol	106-44-5	200.0
D026	Cresol		200.0
D016	2,4-D	94-75-7	10.0
D027	1,4-Dichlorobenzene	106-46-7	7.5
D028	1,2-Dichloroethane	107-06-2	0.5
D029	1,1-Dichloroethylene	75-35-4	0.7
D030	2,4-Dinitrotoluene	121-14-2	0.13
D012	Endrin	72-20-8	0.02
D031	Heptachlor (and its epoxide)	76-44-8	0.008
D032	Hexachlorobenzene	118-74-1	0.13
D033	Hexachlorobutadiene	87-68-3	0.5
D034	Hexachloroethane	67-72-1	3.0
D008	Lead	7439-92-1	5.0
D013	Lindane	58-89-9	0.4
D009	Mercury	7439-97-6	0.2
D014	Methoxychlor	72-43-5	10.0
D035	Methyl ethyl ketone	78-93-3	200.0
D036	Nitrobenzene	98-95-3	2.0
D037	Pentachlorophenol	87-86-5	100.0
D038	Pyridine	110-86-1	5.0
D010	Selenium	7782-49-2	1.0
D011	Silver	7440-22-4	5.0
D039	Tetrachloroethylene	127-18-4	0.7
D015	Toxaphene	8001-35-2	0.5
D040	Trichloroethylene	79-01-6	0.5
D041	2,4,5-Trichlorophenol	95-95-4	400.0
D042	2,4,6-Trichlorophenol	88-06-02	2.0
D017	2,4,5-TP (silvex)	93-72-1	1.0
D043	Vinyl chloride	75-01-4	0.2

Source: Code of Federal Regulations, Vol. 40, Part 261, *Identification and Listing of Hazardous Waste*, U.S. Government Printing Office, Washington, DC, 2004.

TABLE 11.4
Codes for Hazardous Wastes under RCRA

Waste Type	EPA Number	EPA Code
Ignitable	D001	(I)
Corrosive	D002	(C)
Reactive	D003	(R)
Toxicity characteristic	D004-D043	(E)
Toxic	F, K, and U lists	(T)
Acutely hazardous	F and P lists	(H)

Source: U.S. EPA, *National Analysis, The National Biennial RCRA Hazardous Waste Report (Based on 2011 Data),* http://www.epa.gov/epawaste/inforesources/data/br11/national11.pdf.

- Mercury waste from analytical instruments, dental amalgam, and batteries
- Wastewater and sludge from fabric finishing containing tetrachloroethylene
- Oily wastes and sludge from the petroleum industry containing benzene

A solid waste that exhibits the characteristic of toxicity has the EPA Hazardous Waste Number specified in Table 11.3.

EPA has assigned specific hazardous waste numbers and codes to both characteristic and listed wastes. Each listed hazardous waste will have one or more designated codes (Table 11.4). Many hazardous wastes meet the requirements of more than one waste type. During a waste determination, all applicable waste codes must be identified and documented.

To summarize, if a solid waste is not a listed hazardous waste and does not exhibit one of these five characteristics, it is not in the RCRA system. Even if this is the case, however, the waste may still be subject to regulation, for example under state codes.

11.3.10 Mixtures of Hazardous Wastes with Other Materials

In addition to the hazardous waste designations provided above, a waste is also classified as hazardous if it is (1) a mixture of a listed hazardous waste and a solid waste (i.e., the Mixture Rule); (2) a listed hazardous waste contained within another material (the Contained-in Rule); or (3) a solid waste generated from the treatment, storage, or disposal of a listed hazardous waste (the Derived-from Rule).

11.3.11 Mixture Rule

A mixture of any quantity of hazardous waste and a solid (nonhazardous) waste is considered a hazardous waste (40 CFR 261.3). There is no *de minimis* concentration that qualifies for an exclusion from the Mixture Rule, except for certain mixtures in wastewater treatment systems. If a plant employee mixes spent ethyl ether (F003) with an absorbent clay to reduce liquid content, the entire mixture is classified as F003.

An exception to the Mixture Rule is as follows: if the waste is hazardous solely because it exhibits a characteristic and the resultant mixture no longer exhibits the same characteristic, it is not considered a hazardous waste. An example is an ignitable paint waste. A mixture of such paint waste with a nonignitable, nonhazardous waste (e.g., machine oil) would become nonhazardous, provided that the mixture no longer exhibits the ignitability characteristic. It must be emphasized, however, that such wastes become nonhazardous only by the inadvertent, unavoidable mixing that occurs

during standard processes at the facility. In other words, a facility cannot deliberately mix a nonhazardous waste with a hazardous waste to render it nonhazardous. Treating a hazardous waste to render it nonhazardous may require a permit (40 CFR 262.34).

11.3.12 Contained-in Rule

The Contained-in Rule (40 CFR 261.3) relates to the incorporation of hazardous waste with natural materials (e.g., soil, groundwater). For example, if a surface impoundment leaks a listed hazardous waste into local groundwater, the resulting contaminated groundwater is to be managed as hazardous waste.

11.3.13 Derived-from Rule

The Derived-from Rule presented in 40 CFR 261.3 states that any solid waste generated from the treatment, storage, or disposal of a hazardous waste, including any sludge (pollution control residue), spill residue, ash, emission control dust, or leachate, is a hazardous waste. Thus, in the case of residues generated from the treatment of a listed waste, all residues remain hazardous unless specifically delisted. A facility that treats F-listed hazardous wastes, for example via incineration, must manage the ash as hazardous waste, although the toxicity of the waste may be greatly reduced. This rule also applies to treatment of hazardous wastes during a corrective action.

11.4 GENERATION OF HAZARDOUS WASTES

Table 11.5 presents national hazardous waste generation totals divided into characteristic waste, listed waste, or a mixture of the two. Wastes categorized as only characteristic wastes represented 58% (19.8 million tons) of the national generation total, whereas only listed wastes comprised 12% (4.3 million tons), and wastes with both characteristic and listed waste codes constituted 30% (10.2 million tons) of the national total.

11.4.1 Quantities of Toxics Release Inventory Chemicals in Waste by Industry

The Toxics Release Inventory (TRI) is a publicly available database that contains information on waste management activities reported annually by certain industries and federal facilities.

TABLE 11.5
Tons of Generated Waste that Were Only Characteristic Waste, Only Listed Waste, or Both

Only Characteristic Wastes		Only Listed Wastes		Both Characteristic and Listed Wastes	
Ignitable only	425,203	F code only	806,656		
Corrosive only	573,955	K code only	2,218,404		
Reactive only	30,703	P code only	13,354		
D004-17	1,339,884	U code only	30,298		
D018-43	5,650,009				
Has more than one characteristic code	11,815,082	More than one listed code	1,203,820		
Total	19,834,836	Total	4,272,531	Both characteristic and listed	10,225,595

Source: U.S. EPA, *National Analysis. The National Biennial RCRA Hazardous Waste Report (Based on 2011 Data)*, Available from: http://www.epa.gov/epawaste/inforesources/data/br11/national11.pdf.

TABLE 11.6
Quantities of TRI Chemicals in Waste by Industry, 2010

Industry Type	Quantity, Tons
Basic chemical manufacturing	18,921,471
Petroleum and coal products manufacturing	6,645,129
Waste treatment and disposal	2,036,930
Pesticide, fertilizer, and other agricultural chemical manufacturing	1,643,979
Iron and steel mills and ferroalloy manufacturing	1,367,335
Nonferrous metal (except aluminum) production and processing	995,286
Coating, engraving, heat treating, and allied activities	255,537
Resin, synthetic rubber, and artificial synthetic fibers and filaments	228,376
Pharmaceutical and medicine manufacturing	214,270
Other chemical product and preparation manufacturing	188,745
Waste collection	131,313
Other electrical equipment and component manufacturing	117,353
Paint, coating, and adhesive manufacturing	115,736
National security and international affairs	90,244
Remediation and other waste management services	84,560
Aerospace product and parts manufacturing	82,022
Semiconductor and other electronic component manufacturing	81,048
Alumina and aluminum production and processing	78,739
Scheduled air transportation	78,323
Steel product manufacturing from purchased steel	56,565
Warehousing and storage	49,183
Plastic product manufacturing	47,541
Cement and concrete product manufacturing	43,358
Animal food manufacturing	43,071
Motor vehicle parts manufacturing	38,188

Source: U.S. EPA, *National Analysis, The National Biennial RCRA Hazardous Waste Report (Based on 2011 Data)*, Available from: http://www.epa.gov/epawaste/inforesources/data/br11/national11.pdf.

Nearly 650 toxic chemicals and chemical categories figure on the list that must be reported to EPA and the states. These chemicals do not always correspond exactly to RCRA wastes; however, they provide a useful overview of the types and amounts of toxic chemicals generated nationwide.

According to the TRI, the chemical manufacturing industry reported the largest quantity of toxic chemicals in production-related waste managed in 2010, with 18.9 million tons, or 56% of the total reported by all industries (Table 11.6). The petroleum and coal products manufacturing industry reported the second largest quantity, with 6.6 million tons, or 19.5% of the total. The waste treatment and disposal industry reported the third largest quantities of toxic chemicals in 2010. With 2 million tons, this industry accounted for 6% of the toxic chemicals in production-related waste.

11.4.2 Quantities of TRI Chemicals in Waste by Chemical

Table 11.7 lists the 25 TRI chemicals managed in production-related waste in 2010 in the largest quantities. The top five TRI chemicals in waste for all industries were methanol, zinc compounds, toluene, HCl, and lead compounds. Waste from the top 25 TRI chemicals totaled 17.6 billion pounds, i.e., 78% of all toxic chemicals in production-related waste.

TABLE 11.7
Top 25 Chemicals with the Largest Total Production-Related Waste, 2010

Chemical	Total Production-Related Waste, lb
Methanol	2,154,776,488
Zinc compounds	1,442,676,439
Toluene	1,395,335,654
Hydrochloric acid	1,237,298,940
Lead compounds	1,236,201,725
Ammonia	1,164,933,961
Ethylene	1,006,712,743
n-Hexane	820,796,734
Nitrate compounds	724,147,576
Sulfuric acid	702,851,493
Copper	660,440,443
Propylene	602,329,131
Chlorine	545,267,202
Nitric acid	449,977,042
1,2-Dichloroethane	386,486,114
Copper compounds	384,967,279
Xylene (mixed isomers)	372,586,152
Arsenic compounds	342,415,800
Ethylene glycol	322,374,744
Freon 113	314,783,840
Manganese compounds	309,608,082
Barium compounds	256,460,162
Hydrogen fluoride	244,927,429
Acrylonitrile	242,258,398
Dichloromethane	233,719,008
Total (all chemicals)	22,584,276,900

Source: U.S. EPA, *National Analysis, The National Biennial RCRA Hazardous Waste Report (Based on 2011 Data),* Available from: http://www.epa.gov/epawaste/inforesources/data/br11/national11.pdf.

QUESTIONS

1. What is the top priority for hazardous waste management (*general method*) under RCRA, and what is the lowest priority?
2. Which of the following under RCRA is (are) not excluded from the rules and regulations applicable to hazardous waste generators, treatment, storage, disposal, and transportation? (a) domestic sewage, (b) spent nuclear or by-product material, (c) household waste, (d) spent halogenated solvents.
3. What are acute hazardous wastes? Provide an accurate technical definition.
4. Which of the following property(ies) is (are) *not* characteristics that define a RCRA hazardous waste? (a) radioactive, (b) corrosive, (c) ignitable, (d) reactive, (e) biohazard.
5. What pH range does noncorrosive waste display?
6. What is the name of the test method used to determine if a waste is *toxic*? Outline the procedures of the method.

7. Can a generator legally mix a listed hazardous waste with sufficient nonhazardous solid waste to the point where the mixture is diluted and therefore no longer classified as a hazardous waste? Discuss.
8. The Hi-Jinx Metalworks Corp. has produced several gallons of spent paint stripper. Based solely on the Material Safety Data Sheet (see following pages), could this waste be a RCRA hazardous waste?
9. Outside one of the Hi-Jinx warehouses (which had stored paint stripper in the past), several leaking drums are discovered by a state inspector. A sweet solvent odor permeates the air. Is the contaminated soil considered a hazardous waste? Explain.
10. The environmental safety officer at the Hi-Jinx plant identifies dozens of drums containing a reddish filter cake near the site's electroplating wastewater treatment plant. After analyzing the filter cake, the level of chromium in the sludge is determined to be 75 mg/kg and the TCLP test measures 2 mg/L in the resulting leachate. What can the facility conclude regarding the waste and its appropriate management?
11. Can a waste be both a listed hazardous waste and a characteristic hazardous waste? Explain.
12. At an automobile body shop and painting facility, metal parts are reworked and repainted, engine components are cleaned and reworked, and fiberglass and metal body parts are repaired and painted. List at least ten different types of waste generated at the facility. Separate into solid (nonhazardous) and hazardous (listed and characteristic) wastes.
13. List potential sources of hazardous waste generated in your university or company. Name all listed hazardous wastes. To what list(s) do they belong? If they are not listed, what specific characteristics render them hazardous?
14. Write in the name of each hazardous waste list in the table below:

Name of List	Waste Types Covered
-List Provide examples of wastes your university generates on this list:	Non-specific source wastes • Solvents • Electroplating wastes • Wood preserving wastes • Chlorinated aliphatic hydrocarbons • Certain pesticide wastes
-List Provide examples of wastes your university generates:	Specific source wastes • Wood preserving • Chemical Manufacturing • Petroleum refining • Explosives manufacturing • Metal processing
-List Provide examples of wastes your university generates:	Acutely hazardous commercial chemical products
-List Provide examples of wastes your university generates:	Toxic commercial chemical products

15. For the four hazardous waste characteristics, list their hazardous waste numbers:

Characteristic	EPA Waste Number
Ignitable	
Corrosive	
Reactive	
Toxicity characteristic	

MATERIAL SAFETY DATA SHEET

Product Identification: METHYLENE CHLORIDE INDUST GRADE

ITEM DESCRIPTION
Item Name: DICHLOROMETHANE, TECHNICAL
Type of Container: DRUM

HAZARDS IDENTIFICATION, EMERGENCY OVERVIEW
Health Hazards, Acute and Chronic:
ACUTE: IRRITATION OF EYES, SKIN, AND RESPIRATORY TRACT; CNS EFFECTS; DIZZINESS; WEAKNESS; FATIGUE; NAUSEA; HEADACHE; G.I. TRACT
DISTURBANCES; VOMITING; DIARRHEA.
CHRONIC: INCREASE OF CO LEVEL IN BLOOD CAUSING CARDIOVASCULAR STRESS, CNS EFFECTS.
Signs and Symptoms of Overexposure:
EYE, SKN: IRRT, INHL: IRRT, DIZZ, WEAK, FATIGUE, NAUS, HEAD, UNCONSC. INGEST: ALSO GI IRRT, NAUS, VOMIT, DIARR.
Medical Conditions Aggravated by Exposure:
PRE-EXISTING CONDITIONS MAY BE WORSENED.
Route of Entry Indicators:
Inhalation: YES
Skin: YES
Ingestion: YES
Carcinogenicity Indicators
NTP: NO
IARC: YES
OSHA: N/P
Carcinogenicity Explanation: METHYLENE CHLORIDE IS SUSPECTED CARCINOGEN BY IARC OR ACGIH; LIVER ABNORMALITIES, LUNG DAMAGE (AMONG LAB ANIMALS).

FIRST AID MEASURES
First Aid:
INHAL: RMV TO FRESH AIR. IF NOT BRTHNG GIVE CPR; IF BRTHNG DIFF GIVE OXYGEN. EYE: IMMED
FLUSH W/PLENTY OF WATER. SKIN: WASH W/SOAP & WATER. RMV CONTAM CLTHG & SHOES.
INGEST: DO NOT INDUCE VOMIT. NOTHG BY MOUTH IF UNCONSC. GET MEDICAL ATTN.

FIRE FIGHTING MEASURES
Fire Fighting Procedures:
SELF-CONTAINED BREATHING GEAR, W/FULL FACE SHIELD
Unusual Fire or Explosion Hazard:
EMITS CARBON MONOXIDE, CARBON DIOXIDE, HYDROGEN CHLORIDE, AND PHOSGENE WHEN BURNED.
Extinguishing Media:
WATER FOG, CARBON DIOXIDE, DRY CHEMICAL
Flash Point: Flash Point Text: NONE
Autoignition Temperature:
Autoignition Temperature Text: N/R

Lower Limit(s): 13
Upper Limit(s): 23.0

ACCIDENTAL RELEASE MEASURES
Spill Release Procedures:
ABSORB SPILL. STOP SPILL AT SOURCE.DIKE AREA. USE PROTECTIVE EQUIP. WHEN IN AREA. FOR LARGE SPILLS PUMP LIQUID TO HOLDING TANK

EXPOSURE CONTROLS & PERSONAL PROTECTION
Respiratory Protection:
SELF-CONTAINED WITH FULL FACE SHIELD-OSHA/MESA APPROVED
Ventilation: MECHANICAL OR LOCAL AS NEEDED TO KEEP BELOW TLV
Protective Gloves: IMPERVIOUS
Eye Protection: CHEM SPLASH GOGGLES
Other Protective Equipment: IMPERVIOUS CLOTHING, EYE-WASH FACILITIES, BOOTS.
Work Hygienic Practices: AVOID CONTACT WITH EYES AND SKIN; DO NOT BREATHE VAPORS/MIST; WASH
THOROUGHLY AFTER USE; DO NOT USE CONTAMINATED CLOTHES.

PHYSICAL & CHEMICAL PROPERTIES
Boiling Point: Boiling Point Text: 104°F, 40°C
Melting/Freezing Point: Melting/Freezing Text: N/A
Decomposition Point: Decomposition Text: N/A
Vapor Pressure: 355 MMHG; Vapor Density: 2.9
Specific Gravity: 1.322
pH: N/P
Evaporation Weight and Reference: 1.8 (ETHYL ETHER = 1)
Solubility in Water: SLIGHT
Appearance and Odor: CLEAR, COLORLESS LIQUID. ETHER-LIKE ODOR.
Percent Volatiles by Volume: 100

STABILITY & REACTIVITY DATA
Stability Indicator: YES
Materials to Avoid: ALUMINUM, STRONG ALKALIS
Hazardous Decomposition Products: CARBON MONOXIDE, CARBON DIOXIDE, HYDROGEN CHLORIDE, PHOSGENE
Hazardous Polymerization Indicator: NO

DISPOSAL CONSIDERATIONS
Waste Disposal Methods:
PLACE ABSORBED MATERIAL IN CONTAINERS SUITABLE FOR SHIPMENT TO DISPOSAL AREAS. ENVIRONMENTAL LAWS TAKE PRECEDENCE. LIQUID WASTES MAY BE DESTROYED BY LIQUID INCINERATION WITH OFF GAS SCRUBBER

DEPARTMENT OF TRANSPORTATION INFORMATION
DOT Proper Shipping Name: DICHLOROMETHANE
Hazard Class: 6.1
UN ID Number: UN1593
DOT Packaging Group: III
Label: KEEP AWAY FROM FOOD

Nonbulk Packaging: 203
Bulk Packaging: 241
Maximum Quantity in Passenger Area: 60 L
Maximum Quantity in Cargo Area: 220 L
Stow in Vessel Requirements: A

REFERENCES

CFR (Code of Federal Regulations). 2004. *Vol. 40, Part 261, Identification and Listing of Hazardous Waste*. Washington, DC: U.S. Government Printing Office.

U.S. EPA (U.S. Environmental Protection Agency). 1986a. *Methods for Evaluating Solid Waste, Physical/Chemical Methods*, EPA SW-846, Washington, DC: U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1986b. *Pensky–Martens Closed-Cup Method for Determining Ignitability, Method 1010*. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, EPA SW-846. Washington, DC: U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1986c. *TCLP, Method 1311, Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, EPA SW-846. Washington, DC: U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2011. *National Analysis, The National Biennial RCRA Hazardous Waste Report (Based on 2011 Data)*. Method 9040. U.S. Environmental Protection Agency. Available from: http://www.epa.gov/epawaste/inforesources/data/br11/national11.pdf

SUGGESTED READINGS AND WEBSITES

EHSO (Environment Health and Safety Online). 2003. *State Government Downloads and Links*. Available from: http://www.ehso.com/stategov.php

EHSO (Environment Health and Safety Online). 2011. *Identifying Hazardous Waste*. Available from: http://www.ehso.com/hazwaste_ID.htm

U.S. EPA (U.S. Environmental Protection Agency). 2012a. *Chemical Manufacturing Center*. Available from: http://www.epa.gov/compliance/assistance/sectors/chemical.html

U.S. EPA (U.S. Environmental Protection Agency). 2012b. *Metal Ore Mining/Nonmetallic Mineral Mining and Quarrying Sector/Stone, Clay, Glass and Concrete Sector*. Available from: http://www.epa.gov/compliance/assistance/sectors/mineralsmining.html

U.S. EPA (U.S. Environmental Protection Agency). 2012c. *Power Generators*. Available from: http://www.epa.gov/compliance/assistance/sectors/power.html

U.S. EPA (U.S. Environmental Protection Agency). 2012d. *Pulp/Paper/Lumber Sector*. Available from: http://www.epa.gov/compliance/assistance/sectors/pulp.html

USGS (U.S. Geological Survey). 2012. *Mineral Commodity Summaries*. Available from: http://minerals.usgs.gov/minerals/pubs/mcs/

12 Hazardous Waste Generator Requirements

Always do right; this will gratify some people and astonish the rest.

Mark Twain (1835–1910)

12.1 INTRODUCTION

Resource Conservation and Recovery Act (RCRA) regulations call for cradle-to-grave management of hazardous wastes, i.e., they are to be tracked from the point of initial generation through storage and transportation, to final treatment and disposal. As a first step in this management framework (and as discussed in Chapter 11), the waste generator is required to determine if any solid wastes generated at their facility are hazardous so that they will be managed and tracked properly. Second, a waste generator's responsibilities regarding storage, transport, and disposal options depend upon the volume of waste generated per calendar month. Hazardous waste generators are classified as large quantity generators (LQGs), small quantity generators (SQGs), and conditionally exempt small quantity generators (CESQGs), based on these monthly volumes.

12.2 DETERMINING THE GENERATOR CATEGORY

According to RCRA (40 CFR part 262), the generator must measure (*count*) the quantity of hazardous waste generated per calendar month. Wastes that must be counted include those:

- Accumulated on-site before disposal or recycling
- Placed into a treatment or disposal unit at the facility site
- Collected as sludges and removed from product storage tanks

In the early days of RCRA, counting requirements had resulted in confusion on the part of both generators and regulators. In some situations, for example, the regulations were interpreted such that the same waste was counted several times. The requirements have since been fine tuned. Basic principles of waste counting are as follows:

- Materials generated on-site that are either listed or characteristic hazardous wastes must be counted.
- Materials are not counted until they are removed from the production process. For example, plating baths that are being used and reused, or a spent solvent still in the production process, are not counted until they are removed from the process.
- Waste is counted only once in a calendar month. In some cases, for example, a waste may be used more than once a month by recycling within the facility. Under current requirements, only the initial quantity is counted.
- Wastes discharged to a publicly owned treatment works, in compliance with Clean Water Act standards, are not covered under the RCRA system.

12.3 GENERATOR TYPES

12.3.1 LQG

Facilities that generate more than 1000 kg (2204 lb) of hazardous waste per calendar month or more than 1 kg of acutely hazardous waste per month are designated LQGs. In 2011, a total of 14,262 LQGs reported that they generated 34.3 million tons of RCRA hazardous waste (U.S. EPA 2012). A comparison of 1999 data with 2011 data shows that the number of LQGs decreased by 5821, and the quantity of hazardous waste generated decreased by 5.7 million tons, or 14.2%.

The five states that contributed most to the national hazardous waste generation total in 2010 were: Texas (15.7 million tons), Louisiana (4.4 million tons), Mississippi (1.8 million tons), Ohio (1.6 million tons), and Kansas (1.2 million tons). The LQGs in these states accounted for 72% of the national total quantity generated. Sixteen of the top 50 generators are located in Texas, the top-ranked state in hazardous waste generation (U.S. EPA 2011).

Table 12.1 illustrates the relationship between hazardous waste generation quantities and number of generators. Of the fifty largest RCRA generators, between 52.6 thousand and 4.3 million tons of hazardous waste of hazardous waste were generated in 2011. Ten LQGs generated over 1 million tons of hazardous waste per year (U.S. EPA 2012).

Wastes types generated by larger industries include tanks bottoms, dusts, discarded or off-specification chemicals or by-products, lab packs, slags, sludges, slurries, spent liquors, waste packages, and wastewaters. Selected examples of manufacturing operations that generate these wastes are shown in Table 12.2.

12.3.2 SQG

Facilities that generate more than 100 kg (220.4 lb) but less than 1000 kg per calendar month, or less than 1 kg of acutely hazardous waste per month are designated SQGs. SQGs comprise a wide range of commercial and industrial activities ranging from equipment repair (degreasing and rust removal), to construction (paint preparation), to consumer service shops (auto repair). Examples of SQGs along with the types of wastes produced are listed in Table 12.3.

12.3.3 EPA Waste Codes for Common SQG Wastes

Some of the more common wastes generated by SQGs are discussed below. The EPA waste codes also are provided for these wastes.

Solvents, spent solvents, solvent mixtures, or solvent still bottoms are often hazardous. The following are some commonly used hazardous solvents (also see ignitable wastes for other hazardous solvents, and 40 CFR 261.31 for listed hazardous waste solvents):

Benzene	F005
Carbon disulfide	F005
Carbon tetrachloride	F001
Chlorobenzene	F002
Cresols	F004
Cresylic acid	F004
o-Dichlorobenzene	F002
Ethanol	D001
2-Ethoxyethanol	F005
Ethylene dichloride	D001
Isobutanol	F005
Isopropanol	D001
Kerosene	D001

TABLE 12.1
Quantity of RCRA Hazardous Waste Generated and Number of Hazardous Waste Generators by State, 2011

	Hazardous Waste Quantity		Generator Type	
State	**Tons Generated**	**%**	**LQG**	**Non-LQG**
Alabama	578,348	1.7	223	16
Alaska	2524	0.0	27	19
Arizona	202,942	0.6	210	14
Arkansas	922,732	2.7	123	19
California	534,704	1.6	1223	26
Colorado	31,801	0.1	107	51
Connecticut	24,967	0.1	278	16
Delaware	43,307	0.1	49	10
District of Columbia	1137	0.0	23	1
Florida	198,406	0.6	279	171
Georgia	211,127	0.6	334	52
Guam	86	0.0	8	0
Hawaii	425,644	1.2	31	20
Idaho	3742	0.0	19	21
Illinois	675,534	2.0	641	230
Indiana	888,054	2.6	503	14
Iowa	51,013	0.1	128	33
Kansas	1,238,342	3.6	170	46
Kentucky	142,246	0.4	269	0
Louisiana	4,399,520	12.8	331	38
Maine	2406	0.0	52	14
Maryland	44,250	0.1	132	2
Massachusetts	35,554	0.1	402	42
Michigan	282,895	0.8	342	125
Minnesota	357,412	1.0	320	3
Mississippi	1,828,886	5.3	128	0
Missouri	251,015	0.7	282	58
Montana	5883	0.0	41	0
Navajo Nation	23	0.0	1	0
Nebraska	35,425	0.1	64	20
Nevada	9839	0.0	68	33
New Hampshire	3949	0.0	100	52
New Jersey	290,456	0.8	575	100
New Mexico	1,042,387	3.0	39	6
New York	186,483	0.5	1471	0
North Carolina	83,114	0.2	437	94
North Dakota	455,868	1.3	19	0
Ohio	1,617,758	4.7	716	199
Oklahoma	44,294	0.1	179	21
Oregon	93,180	0.3	181	0
Pennsylvania	308,720	0.9	671	176
Puerto Rico	37,335	0.1	80	3
Rhode Island	8619	0.0	65	27
South Carolina	140,496	0.4	257	27

Continued

TABLE 12.1 (*Continued*)
Quantity of RCRA Hazardous Waste Generated and Number of Hazardous Waste Generators by State, 2011

	Hazardous Waste Quantity		Generator Type	
State	**Tons generated**	**%**	**LQG**	**Non-LQG**
South Dakota	1347	0.0	33	9
Tennessee	89,352	0.3	334	0
Texas	15,683,405	45.7	1006	0
Trust Territories	14	0.0	1	2
Utah	49,726	0.1	111	1
Vermont	1978	0.0	39	9
Virgin Islands	1251	0.0	2	0
Virginia	74,803	0.2	219	171
Washington	333,960	1.0	412	1
West Virginia	62,334	0.2	98	44
Wisconsin	289,401	0.8	394	145
Wyoming	4079	0.0	15	4
Total	34,334,072	100.0	14,262	2185

Source: U.S. EPA, *National Analysis, The National Biennial RCRA Hazardous Waste Report (Based on 2011 Data)*, Available from: http://www.epa.gov/epawaste/inforesources/data/br11/national11.pdf.

TABLE 12.2
Examples of Hazardous Wastes Generated by Large Quantity Generators

Category	Examples of Materials Potentially Used
Chemical reprocessing options	Nonhalogenated solvents, cupric chloride, pyrophosphate, acids, caustics, others
Coking operations	Ammonia, benzene, phenols, cyanide
Degreasing operations	Perchloroethylene, trichloroethylene, methylene chloride, 1,1,1-trichloroethane, carbon tetrachloride, chlorinated fluorocarbons
Distillation operations	Chlorobenzene, trichloroethylene, perchloroethylene, aniline, cumene, ortho-xylene, naphthalene, others
Electroplating processes	Cyanides, nickel, copper, acids, chrome, cadmium, gold
Ink formulation	Solvents, caustics, chromium- or lead-containing pigments and stabilizers
Leather tanning	Tannic acid, chromium
Painting operations	Methylene chloride, trichloroethylene, toluene, methanol, turpentine
Petroleum processes	Arsenic, cadmium, chromium, lead, halogenated solvents, flammable oils, distillate products
Primary metal processes	Cyanides, salt baths, heavy metals such as chromium and lead
Pulp and paper operations	Chlorine, sodium sulfite, sodium hydroxide, dioxins, furans, phenols
Textile finishing	Solvents, solutions of dyes
Weapons manufacture	Trinitrotoluene (TNT), nitroglycerin, uranium alloys, plutonium
Wood-preserving processes	Creosote, pentachlorophenol, other creosote and chlorophenolic formulations, copper, arsenic, chromium

Source: Reproduced with kind permission from Woodside, G., *Hazardous Materials and Hazardous Waste Management: A Practical Guide,* John Wiley & Sons, New York, 1993.

TABLE 12.3
Typical Hazardous Waste Generated by Small Quantity Generators

Type of Business	How Generated	Types of Wastes	Waste Codes
Dry cleaning and laundry plants	Commercial dry cleaning processes	Still residues from solvent distillation, spent filter cartridges, cooked powder residue	D001, D039, F002
Furniture- and wood manufacturing and refinishing	Wood cleaning and wax removal, refinishing and stripping, staining, painting, finishing, brush cleaning and spray brush cleaning	Ignitable wastes, toxic wastes, solvent wastes, paint wastes	D001, F001-F005
Construction	Paint preparation and painting, carpentry and floor work, other specialty contracting activities, heavy construction, wrecking and demolition, vehicle and equipment maintenance for construction activities	Ignitable wastes, toxic wastes, solvent wastes, paint wastes, used oil, acids and bases	D001, D0002, F001-F005
Laboratories	Diagnostic and other laboratory testing	Spent solvents, unused reagents, reaction products, testing samples, contaminated materials	D001, D002, D003, F001-F005, U211
Vehicle maintenance	Degreasing, rust removal, paint preparation, spray booth, spray guns, brush cleaning, paint removal, tank cleanout, installing lead–acid batteries	Acids and bases, solvents, ignitable wastes, toxic wastes, paint wastes, batteries	D001, D002, D006, D008, F001-F005
Printing and allied industries	Plate preparation, stencil preparation for screen printing, photo processing, printing, cleanup	Acids and bases, heavy metal wastes, solvents, toxic wastes, ink	D002, D006, D008, F001-F005
Equipment repair	Degreasing, equipment cleaning, rust removal, paint preparation, painting, paint removal, spray booth, spray guns, and brush cleaning	Acids and bases, toxic wastes, ignitable wastes, paint wastes, solvents	D001, D002, D006, D008, F001-F005
Pesticide end-users and application services	Pesticide application and cleanup	Used and unused pesticides, solvent wastes, ignitable wastes, contaminated soil (from spills), contaminated rinse water, empty containers	D001, F001-F005, U129, U136, P094, P123
Educational and vocational Shops	Automobile engine and body repair, metal-working, graphic arts-plate preparation, woodworking	Ignitable wastes, solvent wastes, acids and bases, paint wastes	D001, D002, F001-F005

Source: U.S. EPA, *Managing Your Hazardous Wastes. A Guide for Small Businesses*, EPA-530-K-01-005, Solid Waste and Emergency Response (5305W), U.S. EPA, Washington, DC, 2001.

Methyl ethyl ketone	F005
Methylene chloride	F001, F002
Naphtha	D001
Nitrobenzene	F004
2-Nitrobenzene	F004
Petroleum solvents (flashpoint < 140°F)	D001
Pyridine	F005
1,1,1-Trichloroethane	F001, F002
1,1,2-Trichloroethane	F002
Tetrachloroethylene (perchloroethylene)	F001, F002
Toluene	F005
Trichloroethylene	F001, F002
Trichlorofluoromethane	F002
Trichlorotrifluoroethane (Valclene)	F002
White spirits	D001

In the cleaning industries, filtration residues such as cooked powder residue (perchloroethylene), still residues, and spent cartridge filters containing perchloroethylene or valclene are hazardous and have the waste code F002. Still bottom residues containing petroleum solvents with a flashpoint less than 60°C (140°F) are considered hazardous and have the waste code D001.

Acids, bases, or corrosive mixtures (40 CFR 261.22) have the waste code D002. The following are some of the more commonly used corrosives:

Acetic acid
Ammonium hydroxide
Oleum
Chromic acid
Hydrobromic acid
Hydrochloric acid
Hydrofluoric acid
Nitric acid
Perchloric acid
Phosphoric acid
Potassium hydroxide
Sodium hydroxide
Sulfuric acid

Heavy metals and other inorganic wastes are considered hazardous if the extract from a representative sample (see discussion of TCLP, Chapter 11) has any of the specific constituent concentrations as shown in 40 CFR 262.24 (see Table 11.3). Waste sources include dusts, solutions, wastewater treatment sludges, paint wastes, and waste inks. The following are common heavy metals and inorganics:

Arsenic	D004
Barium	D005
Cadmium	D006
Chromium	D007
Lead	D008
Mercury	D009

Selenium	D010
Silver	D011

Ink sludges containing chromium and lead include solvent sludges, caustic sludges, and water sludges from cleaning tubs; equipment used in the formulation of ink from pigments, driers, soaps, and stabilizers containing these metals. All ink sludges have the waste code K086.

Examples of ignitable wastes are spent solvents, solvent still bottoms, epoxy resins and adhesives, and waste inks containing flammable solvents. Unless specified, all ignitable wastes have the waste code D001.

Acetone	F003
Benzene	F005
n-Butyl alcohol	F003
Chlorobenzene	F002
Cyclohexanone	F003
Ethyl acetate	F003
Ethyl benzene	F003
Ethyl ether	F003
Ethylene dichloride	D001
Methanol	F003
Methyl isobutyl ketone	F003
Petroleum distillates	D001
Xylene	F003

Used lead–acid batteries should be reported only if they are not recycled. Specific wastes from used batteries include:

Lead dross	D008
Spent acids	D002
Lead–acid batteries	D008

Pesticides, wastewaters, sludges, and by-products from pesticide formulations are another category of wastes produced by SQGs. The pesticides listed below are hazardous and those marked with an asterisk (*) have been designated acutely hazardous (40 CFR 261.32).

Aldicarb*	P070
Amitrole	U011
1,2-Dichloropropene	U084
Heptachlor*	P059
Lindane	U129
Methyl parathion*	P071
Parathion*	P089
Phorate*	P094

Reactive wastes (40 CFR 2612.23) all have the waste code D003. The following are examples of wastes commonly considered to be reactive:

Acetyl chloride
Chromic acid
Cyanides
Hypochlorites

Organic peroxides
Perchlorates
Permanganates
Sulfides

Spent plating and cyanide wastes contain cleaning solutions and plating solutions with caustics, solvents, heavy metals, and cyanides. Cyanide wastes may also be generated from heat treatment operations and pigment production. Plating wastes typically have the waste codes F006 to F009, F007 and F009, designating wastes containing cyanide. Cyanide heat-treating wastes generally have the waste codes F010 to F012 (40 CFR 261.31).

Sludges from wastewater treatment operations at wood-preserving facilities are considered hazardous. Bottom sediment sludges from treatment of wastewater that use creosote and pentachlorophenol have the waste code K001. In addition, wood-preserving compounds may include:

Chromated copper arsenate	D004
Creosote	U051
Pentachlorophenol	F027

12.3.4 Conditionally Exempt SQG

Facilities that generate 100 kg or less of hazardous waste or 1 kg or less of acutely hazardous waste per month are designated CESQGs. The total number of CESQGs in both manufacturing and nonmanufacturing sectors nationwide is approximately 450,000. Total waste volume generated by all CESQGs nationwide is about 183,000 metric tons (201,600 tons) per year. In a survey published by EPA for 22 industry groups, approximately 80% of CESQGs were in the nonmanufacturing sector and generated 88% of the CESQG waste volume. The remaining establishments are in the manufacturing sector.

The major CESQG waste types for industry groups surveyed are spent lead–acid batteries, spent solvents and still bottoms, and perchloroethylene. Approximately 80% of CESQG waste is managed off-site. The predominant off-site management methods include:

- Recycling
- Disposal at a nonhazardous solid waste landfill
- Disposal at a permitted subtitle C landfill

The primary on-site management methods include:

- Disposal in the sewer or septic system
- Disposal in a nonhazardous solid waste landfill

The vehicle maintenance industry is the largest CESQG industry both in terms of number of CESQGs and waste volume. Other major CESQG waste–generating industries include:

- Metals manufacturing
- Laundries
- Printing and ceramics
- Pesticide end users and application services
- Construction

The CESQG is exempt from most hazardous waste management requirements. A facility meeting the test for a conditionally exempt generator (generating <100 kg per month and <1 kg of acute

TABLE 12.4
Major CESQG Industries and Waste Types

Major CESQ Generating Industries	Major CESQG Waste Types
Vehicle maintenance	Lead–acid batteries (61%)
Metals manufacturing	Spent solvents and still bottoms (18%)
Laundries	Dry cleaning filter residues (5%)
Printing and ceramics	Photographic wastes (4%)
	Formaldehyde (3%)
Pesticide users and appliers	Acids and alkalis (2%)
Construction	
Stone, clay, glass, and concrete	
Food and kindred products	
Primary steel and iron	
Textile manufacturing	
Pulp and paper	

hazardous waste monthly) is out of the RCRA cradle-to-grave system, provided that the waste is sent to a facility that is at least state -approved. Details of the major CESQG industries and waste types are listed in Table 12.4.

12.3.5 Episodic Generators

Depending on the type of business and the amount of hazardous waste generated monthly, a facility might be regulated under different rules at different times. If, for example, a metal plating firm generates between 100 and 1000 kg (220 and 2200 lb) of hazardous waste during January, it would be considered an SQG for that month and its waste would be subject to the hazardous waste management requirements for SQGs. If, however, in June it generates more than 1000 kg (2200 lb) of hazardous waste, it would be considered an LQG for the month. Its waste for that month would be subject to the management requirements for LQGs. For such generators, it is to the company's advantage to maintain all records, management protocols for storage, transportation, and so on, as an LQG.

12.4 REQUIREMENTS FOR LQGs AND SQGs

Once the waste is determined to be hazardous and is counted, the LQG must comply with the full spectrum of federal hazardous waste regulations under 40 CFR as well as 49 CFR (Department of Transportation; see Chapter 13). The SQG is subject to less stringent requirements. The LQG and SQG must notify the EPA and the state regulatory agency of hazardous waste activity and obtain an EPA ID number.

12.4.1 EPA Identification Number

Identification numbers are required for facilities that generate or manage hazardous waste, including LQGs and SQGs; transporters; and treatment, storage, and disposal facilities (TSDFs) (Chapter 14). Once the state regulatory authority is notified, the generator will be sent EPA Form 8700-12, Notification of Regulated Waste Activity (Figure 12.1). An EPA identification number will be subsequently provided for each facility location.

OMB#: 2050-0175 Expires 12/31/2003

MAIL THE COMPLETED FORM TO: The Appropriate State or EPA Regional Office.	United States Environmental Protection Agency **RCRA SUBTITLE C SITE IDENTIFICATION FORM**	
1. Reason for Submittal (See instructions on page 23) MARK CORRECT BOX(ES)	**Reason for Submittal:** ❑ To provide Initial Notification of Regulated Waste Activity (to obtain an EPA ID Number for hazardous waste, universal waste, or used oil activities). ❑ To provide Subsequent Notification of Regulated Waste Activity (to update site identification information). ❑ As a component of a First RCRA Hazardous Waste Part A Permit Application. ❑ As a component of a Revised RCRA Hazardous Waste Part A Permit Application (Amendment #_____). ❑ As a component of the Hazardous Waste Report.	
2. Site EPA ID Number (See instructions on page 24)	**EPA ID Number:** |_|_|_|_|_|_|_|_|_|_|_|_|	
3. Site Name (See instructions on page 24)	**Name:**	
4. Site Location Information (See instructions on page 24)	**Street Address:**	
	City, Town, or Village:	**State:**
	County Name:	**Zip Code:**
5. Site Land Type (See instructions on page 24)	**Site Land Type:** ❑ Private ❑ County ❑ District ❑ Federal ❑ Indian ❑ Municipal ❑ State ❑ Other	
6. North American Industry Classification System (NAICS) Code(s) for the Site (See instructions on page 24)	**A.**	**B.**
	C.	**D.**
7. Site Mailing Address (See instructions on page 25)	**Street or P. O. Box:**	
	City, Town, or Village:	
	State:	
	Country:	**Zip Code:**
8. Site Contact Person (See instructions on page 25)	**First Name:** **MI:**	**Last Name:**
	Phone Number:	**Phone Number Extension:**
9. Legal Owner and Operator of the Site (See instructions on pages 25 to 26)	**A. Name of Site's Legal Owner:**	**Date Became Owner (mm/dd/yyyy):**
	Owner Type: ❑ Private ❑ County ❑ District ❑ Federal ❑ Indian ❑ Municipal ❑ State ❑ Other	
	B. Name of Site's Operator:	**Date Became Operator (mm/dd/yyyy):**
	Operator Type: ❑ Private ❑ County ❑ District ❑ Federal ❑ Indian ❑ Municipal ❑ State ❑ Other	

EPA Form 8700-12 (Revised 5/2002) Page 1 of 2

FIGURE 12.1 Notification of Regulated Waste Activity form (pages 1–2 only).

OMB#: 2050-0175 Expires 12/31/2003

EPA ID No.

10. Type of Regulated Waste Activity (Mark the appropriate boxes for activities that apply to your site. See instructions on pages 26 to 30)

A. Hazardous Waste Activities

1. Generator of Hazardous Waste (Choose only one of the following three categories.)

- ❑ a. LQG: Greater than 1,000 kg/mo (2,200 lbs./mo.) of non-acute hazardous waste; or
- ❑ b. SQG: 100 to 1,000 kg/mo (220 - 2,200 lbs./mo.) of non-acute hazardous waste; or
- ❑ c. CESQG: Less than 100 kg/mo (220 lbs./mo.) of non-acute hazardous waste

In addition, indicate other generator activities. (Mark all that apply)

- ❑ d. United States Importer of Hazardous Waste
- ❑ e. Mixed Waste (hazardous and radioactive) Generator

For items 2 through 6, mark all that apply.

- ❑ **2. Transporter of Hazardous Waste**
- ❑ **3. Treater, Storer, or Disposer of Hazardous Waste (at your site)** Note: A hazardous waste permit is required for this activity.
- ❑ **4. Recycler of Hazardous Waste (at your site)** Note: A hazardous waste permit may be required for this activity.
- **5. Exempt Boiler and/or Industrial Furnace**
  - ❑ a. Small Quantity On-site Burner Exemption
  - ❑ b. Smelting, Melting, and Refining Furnace Exemption
- ❑ **6. Underground Injection Control**

B. Universal Waste Activities

1. Large Quantity Handler of Universal Waste (accumulate 5,000 kg or more) [refer to your State regulations to determine what is regulated]. Indicate types of universal waste generated and/or accumulated at your site. (Mark all boxes that apply):

	Generate	Accumulate
a. Batteries	❑	❑
b. Pesticides	❑	❑
c. Thermostats	❑	❑
d. Lamps	❑	❑
e. Other (specify) _____	❑	❑
f. Other (specify) _____	❑	❑
g. Other (specify) _____	❑	❑

❑ **2. Destination Facility for Universal Waste**
Note: A hazardous waste permit may be required for this activity.

C. Used Oil Activities (Mark all boxes that apply.)

1. Used Oil Transporter - Indicate Type(s) of Activity(ies)
- ❑ a. Transporter
- ❑ b. Transfer Facility

2. Used Oil Processor and/or Re-refiner - Indicate Type(s) of Activity(ies)
- ❑ a. Processor
- ❑ b. Re-refiner

❑ **3. Off-Specification Used Oil Burner**

4. Used Oil Fuel Marketer - Indicate Type(s) of Activity(ies)
- ❑ a. Marketer Who Directs Shipment of Off-Specification Used Oil to Off-Specification Used Oil Burner
- ❑ b. Marketer Who First Claims the Used Oil Meets the Specifications

11. Description of Hazardous Wastes (See instructions on page 31)

A. Waste Codes for Federally Regulated Hazardous Wastes. Please list the waste codes of the Federal hazardous wastes handled at your site. List them in the order they are presented in the regulations (e.g., D001, D003, F007, U112). Use an additional page if more spaces are needed.

EPA Form 8700-12 (Revised 5/2002) Page 2 of 2

FIGURE 12.1 (*Continued*) Notification of Regulated Waste Activity form (pages 1–2 only).

12.4.2 Managing Hazardous Waste On-Site

LQGs are permitted to accumulate any quantity of waste in containers, tanks, and containment buildings for up to 90 days without a permit. Other forms of on-site storage (e.g., in a lined pond) require a permit. Generators must mark the date when the accumulation begins on each waste storage container so that it is visible for inspection. If the LQG facility accumulates wastes for more than 90 days, it is considered a TSDF and must follow the regulations described in 40 CFR parts 264 and 270. Designation of a hazardous waste generator as a TSDF is undesirable for a generator, resulting in a long list of new requirements along with increased costs for compliance.

In order to provide for more cost-effective shipments, SQGs may accumulate up to 6000 kg (13,228 lb) of hazardous waste on-site for up to 180 days without a permit. The wastes may be accumulated for up to 270 days if they must be transported more than 200 miles away for recovery, treatment, or disposal. There are limited circumstances in which the state administrator may grant extensions beyond 270 days. If regulatory limits are exceeded, the generator is designated a TSDF and must obtain an appropriate operating permit. Special storage requirements apply to liquid hazardous wastes containing polychlorinated biphenyls (PCBs). The requirements for management of PCBs appear in 40 CFR part 761.

Both LQGs and SQGs must accumulate waste in tanks or containers. The EPA defines "container" as

> Any portable device in which a material is stored, transported, treated, disposed of, or otherwise handled.

The most common example of a container is a 55 gal drum. A "tank" is defined as

> A stationary device, designed to contain an accumulation of hazardous waste constructed primarily of non-earthen materials (e.g., wood, concrete, steel, plastic), which provide structural support.

Storage tanks and containers must be managed according to EPA requirements summarized below. Each container holding hazardous waste must:

- Be labeled with the words "Hazardous Waste"
- Be marked with the date the waste was first generated
- Be constructed of, or lined with, a material that is compatible with the waste. This precaution will prevent waste from reacting with the container, causing leakage, or creating a hazardous condition such as the evolution of toxic or explosive vapors
- Not be stored together with incompatible wastes
- Be kept closed during storage, except when adding or removing waste
- Not be opened, handled, or stacked in a way that would cause containers to fail
- Be located more than 50 ft from the facility property line if the waste is ignitable or reactive

This requirement does not apply to SQGs, whose ignitable or reactive wastes are to be located as far as practicable from the property line.

The generator, whether LQG or SQG, must:

- Inspect container storage areas at least weekly.
- Maintain containers in good condition. If a container is found to be leaking, the waste must be transferred to another container immediately.

For tank systems, the generator must:

- Label each tank with the words "Hazardous Waste."
- Mark each tank with the beginning of the accumulation period.
- For those tanks equipped with an automatic waste feed, a feed cutoff or bypass system must be installed in the event of an overflow.

- Inspect monitoring equipment and the level of waste in uncovered tanks at least once per day. Inspect the tanks and surrounding areas for leaks and corrosion at least weekly.
- Use the National Fire Protection Association (NFPA) buffer zone requirements for covered tanks containing ignitable or reactive wastes.
- Not mix incompatible wastes.
- Provide at least 2 ft of freeboard (i.e., space at the top of each tank) in uncovered tanks, unless the tank is equipped with a containment structure.
- Report spills from a tank system to the state regulatory agency.

12.4.3 Requirements for New Tank Systems

All new tank systems are required to be equipped with secondary containment with interstitial monitoring (Figure 12.2). This precaution should immediately alert operators of a leak from the primary tank, thus ensuring prompt corrective action. An independent, qualified, and registered Professional Engineer must certify the design and installation of new tanks.

12.4.4 Containment Buildings

In limited circumstances, hazardous wastes may be stored in piles within containment buildings. Such storage is a permitted process that typically falls under the direction of EPA as opposed to the state regulatory agency. Requirements for the proper operation of containment buildings are as follows. The building is to be

- Certified by a registered Professional Engineer.
- Completely enclosed to prevent exposure to the elements.
- Of sufficient strength to support the waste and any personnel and heavy equipment that operate within the unit.
- Equipped with secondary containment and a collection system if liquid wastes are present.
- Designed and operated to prevent fugitive dust emissions. Special precautions (e.g., negative air pressure to prevent releases to the outside) may be required.
- Routinely inspected.

12.4.5 Emergency Preparation

Waste-generating facilities must be operated to minimize the possibility of a fire, explosion, or release of hazardous waste to the environment.

All LQG facilities must be equipped with the following:

- Internal communications or alarm system
- Telephone or two-way radio for contacting local police, fire department, or emergency response team

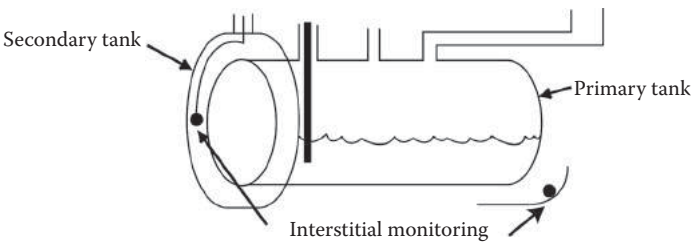


FIGURE 12.2 Schematic of a tank showing interstitial monitoring capability.

- Fire extinguishers, fire control equipment (e.g., foam, inert gas, dry chemicals), spill control equipment, and decontamination equipment
- Water supply for hoses, foam-producing equipment, or automatic sprinklers

At LQG facilities, aisle space must be maintained to permit the movement of personnel, and equipments for fire protection, spill control, and decontamination to any area within the facility in an emergency (Figure 12.3). The facility must familiarize police, fire department, and other emergency response teams with the layout of the facility, types of hazardous waste handled and associated hazards, locations where personnel are working, entrance roads to the facility, and evacuation routes. It is the generator's responsibility to familiarize local hospitals with the properties of the hazardous wastes handled and the types of injuries that could result from fire, explosion, or release. Some hospitals do not have the capability of treating persons exposed to certain chemical hazards; therefore, the appropriate hospital and emergency medical service team must be identified and documented.

12.4.6 Emergency Response

LQGs are responsible for preparing a thorough written contingency plan and must provide training to employees on hazardous waste management and emergency response. The LQG must have a written contingency plan available for their facility in the event of an emergency. The plan must be designed to minimize hazards from fires, explosion, or any release of hazardous waste. The contingency plan must include:

- Actions in response to fire, explosion, or release of hazardous waste at the facility
- Arrangements with local police departments, hospitals, and emergency response teams
- Names, addresses, and telephone numbers of all persons qualified to act as emergency coordinators
- All emergency equipment at the facility (e.g., fire extinguishing systems, spill control equipment, communication and alarm systems, decontamination equipment)
- Evacuation plan, which must include alternative evacuation routes

An up-to-date copy of the contingency plan must be maintained at the facility and be on file with the police and fire department, hospitals, and emergency response teams. The contingency plan



FIGURE 12.3 Aisle space must be sufficient to allow the movement of persons and equipment. (This facility is *not* in compliance.)

must be reviewed and amended whenever the regulations are revised, the plan fails in an emergency, the facility changes its design and operation, or the facility changes the response required for an emergency.

The facility must, at all times, designate an employee (either on facility premises or on call) with the responsibility for coordinating emergency response measures. This coordinator must be familiar with the facility contingency plan, all operations at the facility, the location and characteristics of waste regularly handled, and the facility layout.

12.4.7 Personnel Training

As an additional safety precaution at LQGs, facility personnel must be trained in hazardous waste management protocols within 6 months of starting a new position and must be trained annually thereafter. The training program must ensure that personnel are able to respond to emergencies by becoming familiar with emergency procedures and equipment, including:

- Procedures for using, inspecting, repairing, and replacing emergency and monitoring equipment
- Automatic waste feed cutoff systems
- Communications or alarm systems
- Responses to groundwater contamination incidents
- Shutdown of operations

12.4.8 Emergency Response Requirements for SQGS

Emergency response requirements are less stringent for the SQG. There must be one employee either on the premises or on-call with the responsibility for coordinating emergency response measures. In contrast to LQGs, however, the SQG does not require a full contingency plan, but must post relevant emergency response information next to office telephones, including:

- Name and telephone number of the emergency coordinator
- Location of fire extinguishers, spill control material, and fire alarm
- Telephone number of fire department

The emergency coordinator is responsible for responding to emergencies on-site. Certain specific responses include:

- In the event of fire, contact the fire department or attempt to extinguish it.
- In the event of a spill, contain the flow of hazardous waste and clean it plus any contaminated materials.
- In the event of fire, explosion, or a release that could threaten human health outside the facility, immediately notify the National Response Center (1-800-424-8802).

The SQG must ensure that all employees are familiar with proper waste handling and emergency procedures relevant to their responsibilities during facility operations and emergencies. No paper plan is required for the SQG (U.S. EPA 2001).

12.4.9 Reporting

The LQG is responsible for submitting a biennial report to the state regulatory agency. Reports must include the facility's EPA identification number, a description and quantity of the wastes generated, and actions taken to reduce the volume and toxicity of the waste generated. These reports can be

used to encourage waste reduction at the facility. For wastes being shipped off-site, the LQG must include information regarding the transporter and permitted TSDF. Some states require the LQG to report annually to the regulatory agency.

12.4.10 Shipment of Wastes Off-Site

The generator must package, label, and mark all waste containers and placard vehicles that carry wastes, according to Department of Transportation requirements (49 CFR parts 172, 173, 178, and 179) (see Chapter 13 of this book). In addition, a Uniform Hazardous Waste Manifest must accompany all hazardous waste shipped off-site.

12.4.11 Uniform Hazardous Waste Manifest

The Uniform Hazardous Waste Manifest is a paper form initiated by a generator that removes hazardous waste off-site for treatment, recycling, storage, or disposal. Both DOT and EPA require the manifest. Every party that handles the waste, including the generator, all transporters, and TSDFs, signs the manifest and retains a copy. Once the waste reaches its final destination, the TSDF returns a signed copy of the manifest to the generator. This cycle of signatures and paperwork confirms that the waste has been received and that the loop is closed. Several states require the TSDF to forward a copy of the completed manifest to the state regulatory agency as well. When completed, the manifest contains information on the type and quantity of waste transported, instructions for handling the waste, and signatures of all parties involved in the management process (Figure 12.4). CESQGs are not required to use a manifest when shipping wastes off-site.

If the LQG facility does not receive a signed manifest from the TSDF after 35 days (60 days for SQGs), it must attempt to locate the hazardous waste by contacting the TSDF. If there is no response after 45 days, the LQG must submit an Exception Report to the state regulatory agency. The exception report (40 CFR 262.42) notifies the agency of a potential problem in the cradle-to-grave tracking process. The exception report contains a copy of the original manifest and a cover letter describing efforts made to locate the shipment. A flow chart for the manifest paper trail is shown in Figure 12.5. A completed (albeit questionable) uniform hazardous waste manifest is shown in Figure 12.6.

The manifest requirements outlined above apply only to domestic shipments of hazardous waste by road. Domestic shipments by rail or water are subject to other manifest requirements. Hazardous wastes exported from the United States are subject to additional regulatory requirements (40 CFR part 261, 262).

12.4.12 Record Keeping

The LQG must retain the following records at the facility for at least 3 years: signed manifests, biennial and exception reports, test results, and waste analyses. The 3-year period is automatically extended in the event of an on-going enforcement action (40 CFR 262.40).

12.4.13 Management of Empty Containers

Empty containers must be managed to comply with EPA regulations and to prevent contamination from residues. A container or inner liner that stored hazardous waste is considered “empty” and is not regulated as a hazardous waste if (40 CFR 261.7):

- All waste has been removed that can be feasibly removed
- No more than 1 in. of residue remains at the bottom of the container
- No more than 3% (by weight) of the total capacity of the container remains

Please print or type (Form designed for use on elite (12 - pitch) typewriter)

Form Approved. OMB No. 2050 - 0039 Expires 9 - 30 - 91

UNIFORM HAZARDOUS WASTE MANIFEST

1 Generator's US EPA ID No. | Manifest Document No. | 2. Page 1 of | Information in the shaded areas is not required by Federal law

3. Generator's Name and Mailing Address

4. Generator's Phone ( )

A. State Manifest Document Number

B. State Generator's ID

5. Transporter 1 Company Name | 6. US EPA ID Number

C. State Transporter's ID

D. Transporter's Phone

7. Transporter 2 Company Name | 8. US EPA ID Number

E. State Transporter's ID

F. Transporter's Phone

9. Designated Facility Name and Site Address | 10. US EPA ID Number

G. State Facility's ID

H. Facility's Phone

GENERATOR

11. US DOT Description (including Proper Shipping Name, Hazard Class, and ID Number)	12. Containers No.	12. Containers Type	13. Total Quantity	14. Unit Wt/Vol	I. Waste No.
a.					
b.					
c.					
d.					

J. Additional Descriptions for Materials Listed Above

K. Handling Codes for Wastes Listed Above

15. Special Handling Instructions and Additional Information

16. **GENERATOR'S CERTIFICATION:** I hereby declare that the contents of this consignment are fully and accurately described above by proper shipping name and are classified, packed, marked, and labeled, and are in all respects in proper condition for transport by highway according to applicable international and national government regulations.

If I am a large quantity generator, I certify that I have a program in place to reduce the volume and toxicity of waste generated to the degree I have determined to be economically practicable and that I have selected the practicable method of treatment, storage, or disposal currently available to me which minimizes the present and future threat to human health and the environment; **OR,** if I am a small quantity generator, I have made a good faith effort to minimize my waste generation and select the best waste management method that is available to me and that I can afford.

Printed/Typed Name | Signature | Month Day Year

TRANSPORTER

17. Transporter 1 Acknowledgement of Receipt of Materials

Printed/Typed Name | Signature | Month Day Year

18. Transporter 2 Acknowledgement of Receipt of Materials

Printed/Typed Name | Signature | Month Day Year

FACILITY

19. Discrepancy Indication Space

20. Facility Owner or Operator: Certification of receipt of hazardous materials covered by this manifest except as noted in item 19.

Printed/Typed Name | Signature | Month Day Year

EPA Form 8700 - 22 (Rev. 9 - 88) Previous editions are obsolete.

FIGURE 12.4 The Uniform Hazardous Waste Manifest. (Reproduced with kind permission from EHSO, *Diagram of the Current Hazardous Waste Manifest System*, 2003, Available from: http://www.ehso.com/Hazwaste/hazwaste_Manifest_process.htm.)

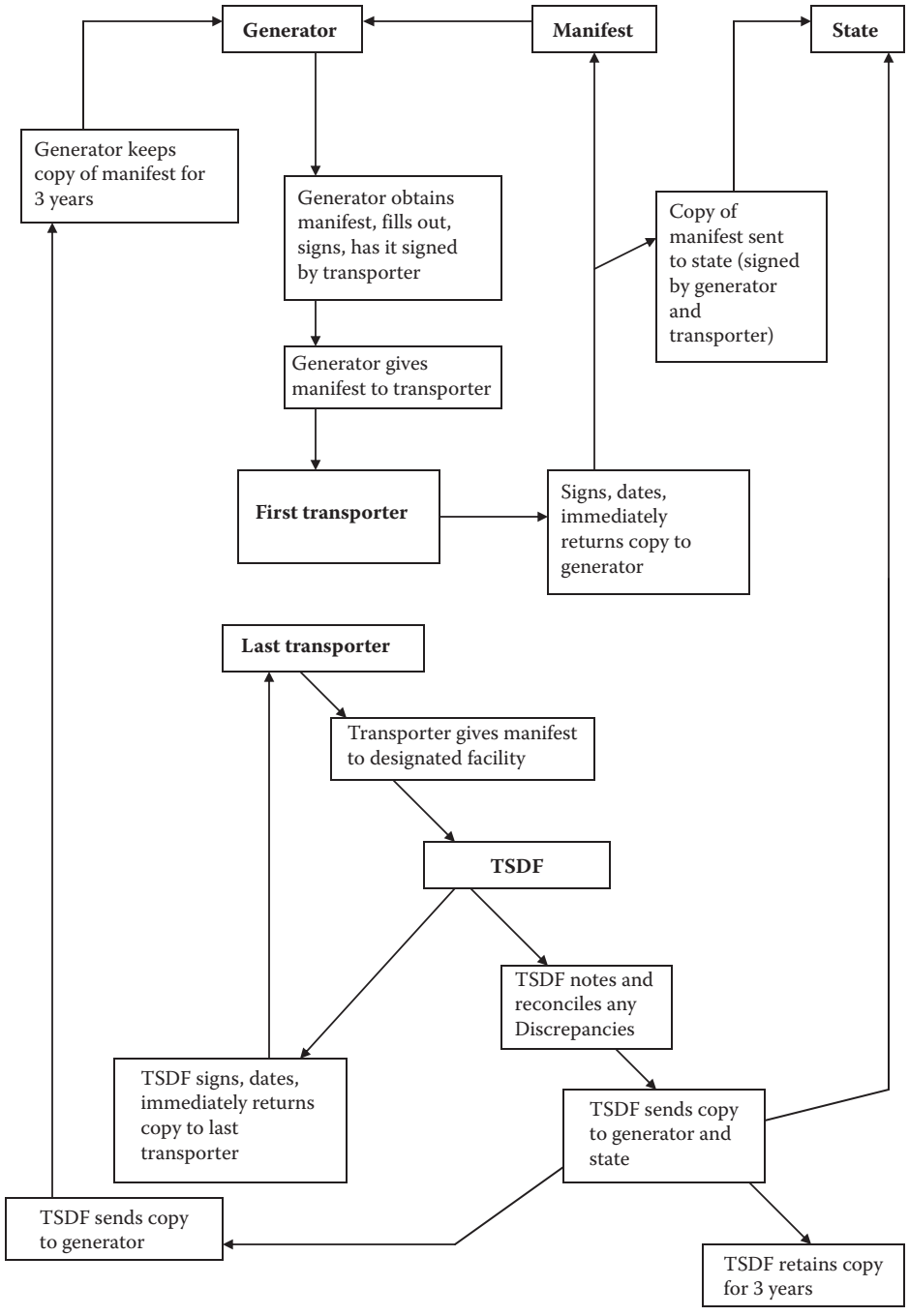


FIGURE 12.5 Flow chart for the manifest paper trail. (Reproduced with kind permission from EHSO, *Diagram of the Current Hazardous Waste Manifest System*, 2003, Available from: http://www.ehso.com/Hazwaste/hazwaste_Manifest_process.htm.)

Please print or type (Form designed for use on elite (12 - pitch) typewriter) Form Approved OMB No 2050 - 0039 Expires 9 - 30 - 91

UNIFORM HAZARDOUS WASTE MANIFEST

1 Generator's US EPA ID No. I N A 1 1 2 2 3 3 4 4 5 0 Manifest Document No. 0 1 0 1 0 1 0

2. Page 1 of — Information in the shaded areas is not required by Federal law

3. Generator's Name and Mailing Address
ACME DISCOUNT PETROCHEMICALS
118 A STREET WESTVILLE, IN 49301

4. Generator's Phone (765) 555 - 2188

A. State Manifest Document Number

B. State Generator's ID

5. Transporter 1 Company Name: Haz - R - Dus, Inc.
6. US EPA ID Number: I N T 1 2 3 4 5 6 7 8 9
C. State Transporter's ID
D. Transporter's Phone 765-555-0100

7. Transporter 2 Company Name: Clean Itall
8. US EPA ID Number
E. State Transporter's ID
F. Transporter's Phone 765-555-4301

9. Designated Facility Name and Site Address
ABC WASTE TECHNOLOGIES
2732 NORTHERN BLVD.
HASTINGS, OH 43202
10. US EPA ID Number: O H A 9 9 8 8 6 5 3 3 2
G. State Facility's ID
H. Facility's Phone 614 - 555 - 3297

11. US DOT Description (Including Proper Shipping Name, Hazard Class, and ID Number)	12. Containers No.	Type	13. Total Quantity	14. Unit Wt/Vol	I. Waste No.
GENERATOR a. RQ, Waste tetrachloroethylene, 6.1 UN1897, PG III (liquid) (F002)	0 0 1	D M	0 0 0 2 0	0 G	F002
b. Waste paint material UN 1263, PG II (D001)	0 2 4		0 1 4 3 0	0 G	D035
c.					
d.					

J. Additional Descriptions for Materials Listed Above
11a. Dry cleaning waste.
11b. Clean up solvent (D035, F003, F005)

K. Handling Codes for Wastes Listed Above

15. Special Handling Instructions and Additional Information
Emergency Contact: (765)555-0123 (8am - 5pm)

16. **GENERATOR'S CERTIFICATION:** I hereby declare that the contents of this consignment are fully and accurately described above by proper shipping name and are classified, packed, marked, and labeled, and are in all respects in proper condition for transport by highway according to applicable international and national government regulations.

If I am a large quantity generator, I certify that I have a program in place to reduce the volume and toxicity of waste generated to the degree I have determined to be economically practicable and that I have selected the practicable method of treatment, storage, or disposal currently available to me which minimizes the present and future threat to human health and the environment; OR, if I am a small quantity generator, I have made a good faith effort to minimize my waste generation and select the best waste management method that is available to me and that I can afford.

Printed/Typed Name: Norma Lee Snoozin — Signature — Month 1 2 Day 0 3 Year 0 3

TRANSPORTER
17. Transporter 1 Acknowledgement of Receipt of Materials
Printed/Typed Name: Warren Peace — Signature — Month 1 2 Day 0 3 Year 0 3

18. Transporter 2 Acknowledgement of Receipt of Materials
Printed/Typed Name: Pete Moss — Signature — Month 1 2 Day 0 4 Year 0 3

FACILITY
19. Discrepancy Indication Space

20. Facility Owner or Operator: Certification of receipt of hazardous materials covered by this manifest except as noted in item 19.
Printed/Typed Name: Norman Conquest — Signature — Month Day Year

EPA Form 8700 - 22 (Rev. 9 - 88) Previous editions are obsolete.

FIGURE 12.6 Questionable Uniform Hazardous Waste Manifest.

If the container stored an acute hazardous waste, one of the following conditions must be met for it to be considered empty:

- The container or inner liner is triple rinsed with a solvent capable of removing the waste.
- The inner liner is removed from the container.

There are several management options for used drums. They may be reconditioned and reused as shipping containers, processed for steel scrap recycling, crushed and buried at a permitted TSDF,

or sent to a solid waste disposal facility. Reconditioning or recycling is preferred because of the cost involved in disposal of empty drums at a TSDF.

12.4.14 Hazardous Waste at Satellite Accumulation Points

A *satellite accumulation point* is a location within the generator's facility in which wastes are generated; however, it is not the primary accumulation point. Accumulation is permitted at satellite points in order to increase the efficiency of waste collection and reduce overall disposal costs.

Wastes may be collected at the satellite point indefinitely until 55 gal of hazardous waste, or 1 qt of acutely hazardous waste, is accumulated. There is no need to ship partially full drums of waste off-site because of accumulation time restrictions. All wastes at satellite accumulation points are under the control of the operator of the process generating the waste. EPA has established the following management standards for wastes collected at satellite accumulation points:

- Containers must be marked with the words "Hazardous Waste" or with other words that identify their contents
- Containers must be maintained in good condition
- Wastes must be compatible with the container
- The container must always be kept closed during accumulation, except when adding or removing waste

12.5 REQUIREMENTS OF CESQGs

The CESQG is only required to: (1) determine which wastes are hazardous, and (2) treat or dispose wastes on-site or deliver to an off-site TSDF that is permitted under 40 CFR 270. Such a disposal site is not necessarily a hazardous waste facility—it might be a materials recovery facility or a solid waste landfill. The state, however, may require disposal of hazardous wastes at a facility dedicated for hazardous waste management.

12.A.1 APPENDIX: HAZARDOUS WASTE MANAGEMENT SCENARIOS

12.A.1.1 Introduction

This section includes several situations that are intended to apply the regulatory foundation provided in this chapter. All situations are based on actual events and inspections conducted by hazardous waste regulatory personnel. Names of companies and individuals have been changed.

After reading each scenario, discuss what, if any, violations may have occurred. How would these violations be best addressed (i.e., via changes in engineering design, a modified storage or disposal program, some use of common sense, etc.)? These are open-ended situations. Note that there is often not one "right" solution to these situations—it must be emphasized that the regulations are often open to interpretation (just ask any state regulatory inspector or company attorney).

12.A.1.2 The Scenarios

1. The Hi-Jinx Stripping Company conducts a number of commercial activities, one of its most profitable being the stripping of paint from metal parts.

   The working piece is immersed in a 500-gal vat filled with methylene chloride, where most of the paint is removed. After a designated time, the piece is removed and allowed to air-dry. The workpiece is then blasted with crushed walnut shells at high pressure to remove any residual paint.

After blasting, the walnut shells become impregnated with paint chips and residual methylene chloride. The contaminated shells are transported directly from the air handling system (a dust collector) to a dumpster, following which they are shipped to a local subtitle D landfill for disposal.

The paint chips are collected from the bottom of the vat, washed with water, and air-dried. The paint chips are stored in a trailer to allow any remaining solvent to volatilize, after which they are shipped to the local subtitle D landfill. The state inspector notes that the paint chips in the trailer are releasing a strong aromatic smell. Her photoionization detector (PID) reads several hundred ppm of hydrocarbon vapor.

The wash water is used to cover the open vats of the heavier methylene chloride. Mr. Roosterson, the company's president, informs the inspector that the water layer prevents volatilization losses of the methylene chloride solvent. Any leftover washwater or methylene chloride mix is stored in 55-gal drums. The methylene chloride is pumped and returned to the process vats. The water is reused again as washwater. The methylene chloride wastes have been stored on-site for at least 4–5 months.

Relevant portions of an MSDS for methylene chloride are shown in Figure 12.A.1.

2. The Hi-Jinx Company has had other run-ins with the state. A neighbor contacts the state environmental regulatory agency to announce that Hi-Jinx has been deliberately dumping methylene chloride directly onto the soil (witnessed on several occasions). Neighbors rely on well water for their homes and businesses. An unconfined aquifer occurs at approximately 20 ft below ground surface (bgs) and a second, confined aquifer at approximately 75 ft bgs. Local soils are predominantly silty clay and other similarly dense material. Mr. Roosterson is certain that if anyone had "inadvertently" spilled a "small quantity" of methylene chloride, this would evaporate quickly and could not possibly migrate into the soil due to its dense structure.

   Soil sampling and analysis results indicate the presence of methylene chloride, acetone, tetrachloroethane, and toluene.
3. An LQG of hazardous waste uses toluene as a solvent in its manufacturing operations. An inspector walks the perimeter of the company property and eventually discovers several open and rusting drums of an aromatic-smelling substance behind an old wooden shed. Weeds had grown tall around the drums, which, incidentally, had no labels. The inspector states that this situation is a violation of waste storage regulations. Pop, the company's health and safety person, however, claims that this is not waste but is actually *product* on hand to be used in future operations.
4. At a degreasing operation, trichloroethylene (TCE) and perchloroethylene (PCE) are routinely used as solvents. Workers have been encouraged by their supervisors to "extend the lifetime" of company clothing and rags. At lunch breaks and at the end of the workday, employees place solvent-soaked gloves, lab coats, and rags on drying racks. Once dried, they are reused (Figure 12.A.2).
5. An auto manufacturing facility uses spray booths to paint individual auto parts. Solvents, characteristic for ignitability and toxicity (due to the presence of methyl ethyl ketone), are periodically forced, under pressure, into the guns to clean out accumulated paint. The paint–solvent mixtures are collected in a 35-gal "purge pot" situated under the floor. The purge pots are emptied by way of plumbing, which directs them to a large tank outside the building (Figure 12.A.3). The company claims that the purge pots should not be regulated as hazardous waste tanks; rather, both solvents and purge pots are part of the cleaning process, that is, without removing the solvent–paint mixture daily, the painting process would cease. Incidentally, the company claims that the plumbing should not be regulated either.
6. What is wrong with the picture in Figure 12.A.4?
7. Shy-Nee Automotive Coatings, Inc., is an LQG of F019 sludge (wastewater treatment sludge from chemical conversion coating of aluminum); F001 and F002 waste solvents; and still bottoms, spent filters, and contaminated rags.

METHYLENE CHLORIDE

Section 2 - Composition/Information on Ingredients

Ingredient Name: METHYLENE CHLORIDE (SARA III)
Ingredient CAS Number: 75-09-2 Ingredient CAS Code: M
RTECS Number: PA8050000 RTECS Code: M
OSHA PEL: 500 PPM/C,1000; Z2 OSHA PEL Code: M
OSHA STEL: OSHA STEL Code:
ACGIH TLV: 50 PPM, A2; 9192 ACGIH TLV Code: M
ACGIH STEL: N/P ACGIH STEL Code:
EPA Reporting Quantity: 1000 LBS
DOT Reporting Quantity: 1000 LBS
Ozone Depleting Chemical: N

Section 3 - Hazards Identification, Including Emergency Overview

Health Hazards Acute & Chronic: N/P

Signs & Symptoms of Overexposure:
LIGHT HEADEDNESS,MENTAL CONFUSTION,NAUSEA,HEADACHE.TINGLING OR CREEPING SKIN FEELING ON INHALATION.

Medical Conditions Aggravated by Exposure: N/P

LD50 LC50 Mixture: N/P

Route of Entry Indicators:
Inhalation: N/P
Skin: N/P
Ingestion: N/P

Carcenogenicity Indicators
NTP: N/P
IARC: N/P
OSHA: N/P

Carcinogenicity Explanation: N/P

Section 4 - First Aid Measures

First Aid:
REMOVE TO FRESH AIR,IF UNCONSCIOUS,USE ARTIFICIAL RESPIRATION & CALL A PHYSICIAN,KEEP WARM & COMFORTABLE. FOR EYE CONTACT.WASH WITH WATER FOR 15 MIN. IN CASE OF SKIN CONTACT, WASH WITH SOAP & WATER

Section 5 - Fire Fighting Measures

Fire Fighting Procedures:
WEAR SELF-CNTD BRTHG,APP H_20 SPRAY TO COOL CONTR.
Unusual Fire or Explosion Hazard:
MAY DECOMPOSE & GIVE PHOSGENE GAS.
Extinguishing Media:
CO_2, FOAM, DRY CHEM & H_2O FOG.
Flash Point: Flash Point Text: NON-FLAMMABLE

FIGURE 12.A.1 Portions of MSDS for methylene chloride.



FIGURE 12.A.2 Used rags left out for volatilization of TCE and PCE.

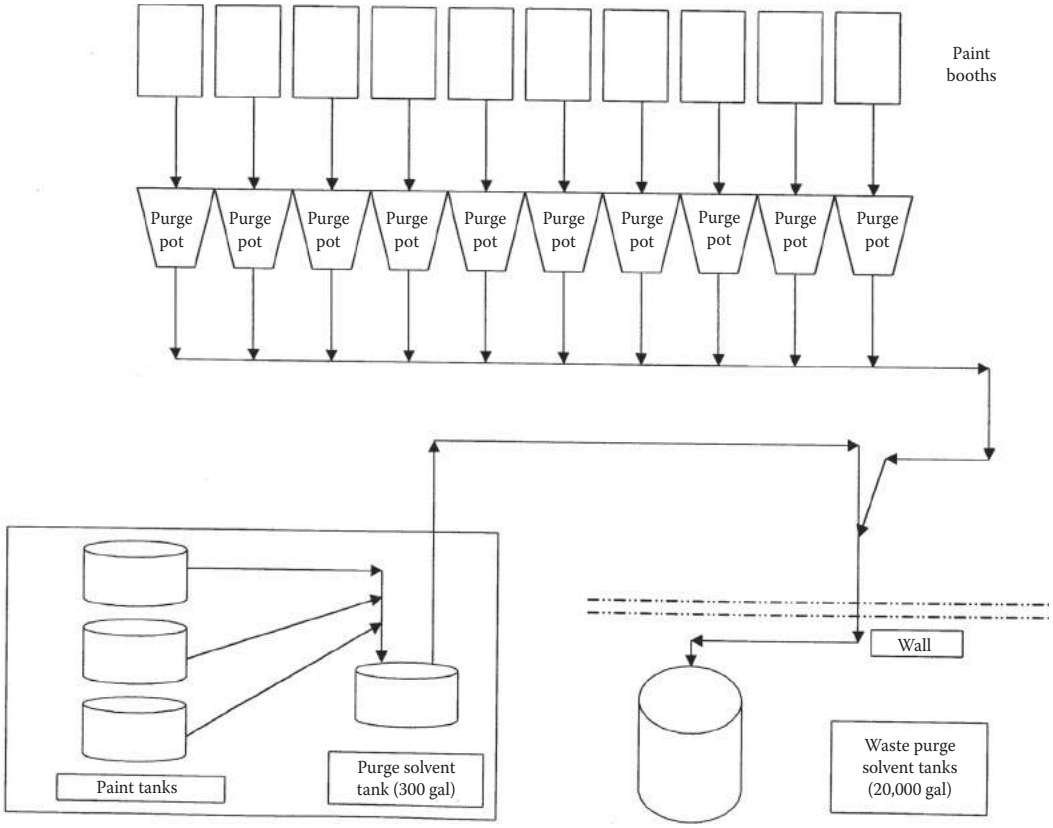


FIGURE 12.A.3 Spray booths indicating waste paint and solvent storage.



FIGURE 12.A.4 Drum with questionable dates on label.



FIGURE 12.A.5 Roll-off container storing wastewater treatment sludge.

F019 sludge from the facility's wastewater treatment system is fed by gravity into a large (900 m^3) roll-off container that is housed in a 5 m x 5 m (15 ft x 15 ft) shed. The roll-off is removed through a garage-style door (Figure 12.A.5). An inspector notes that sludge has leaked from the roll-off onto the ground, thus constituting a violation. The plant manager, however, refutes her statement, claiming that "the building acts as secondary containment." The inspector adds that sludge is migrating outside the shed, creating a dispersal hazard (Figure 12.A.6). The plant manager replies that drains occur throughout the facility, including outside the buildings, all of which empty to a wastewater treatment plant. Therefore, there is no hazard of a release to the surrounding environment.

8. The I.O. Silver Company manufactures and processes numerous metallic durable products. The company is a LQG of metallic sludges, chlorinated solvents, and other organic wastes. There are two 90-day hazardous waste accumulation areas on the facility property. One stores F006 sludges (from electroplating operations), and the second stores assorted chlorinated solvents (F002), spent filters, laboratory gloves, and so on. The inspector discovers that neither area has its own spill prevention equipment; rather, the equipment is kept on a large mobile cart near one processing area.

   The distance from the process area to the F006 sludge accumulation area is approximately 75 m, and the distance to the solvent accumulation area is almost 100 m. The inspector



FIGURE 12.A.6 Sludge migration.

considers that this distance may be a violation, but the company environmental official claims that they can move the spill equipment cart "quickly enough to contain any size spill."

9. Baghouse dust is generated at a steel production facility. The dust is a K061 listed waste (emission control dust from steel manufacture in electric arc furnaces) and is stored in a steel silo (tank). The inspector informs the plant manager that an integrity assessment of the silo is needed. An integrity assessment is defined and regulated as follows (40 CFR 264.191(a)):

   For each tank system that does not have secondary containment, the owner or operator must determine that the tank system is not leaking or is unfit for use. The owner or operator must obtain and keep on file at the facility a written assessment reviewed and certified by an independent, qualified registered professional engineer, in accordance with section 270.11(d), that attests to the tank system's integrity. This assessment must determine that the tank system is adequately designed and has sufficient structural strength and compatibility with the wastes to be stored or treated, to ensure that it will not collapse, rupture, or fail. At a minimum, this assessment must consider the following:

   a. Design standards according to which the tank and ancillary equipment were constructed
   b. Hazardous characteristics of the wastes that will be handled
   c. Existing corrosion protection measures
   d. Documented age of the tank system, if available (otherwise, an estimate of the age)
   e. Results of a leak test, internal inspection, or other tank integrity examination.

   The manager complains that since the baghouse dust is a *solid* material, an integrity assessment is not warranted; only *liquid* waste tanks should undergo such assessments.
10. What is wrong with this picture (Figure 12.A.7)?
11. Figure 12.A.8 depicts a satellite accumulation area for a facility that manufactures truck caps. What is wrong with this photo?
12. A utility power plant combusts coal for electricity production. The facility generates large quantities of fly ash. The TCLP test fails the characteristic for arsenic. The question arises as to how to appropriately dispose this waste; if such large quantities were to be disposed in an EPA-approved secure landfill, costs for waste disposal would be prohibitive.
13. A Midwestern metal plating facility generates large quantities of strongly acidic waste. The spent acid waste is mixed with sodium hydroxide in a large (20,000 L) tank in order to neutralize it. The neutralized mixture, approximately pH 6.5, has been disposed on the company's property using a permitted deep-well injection system.

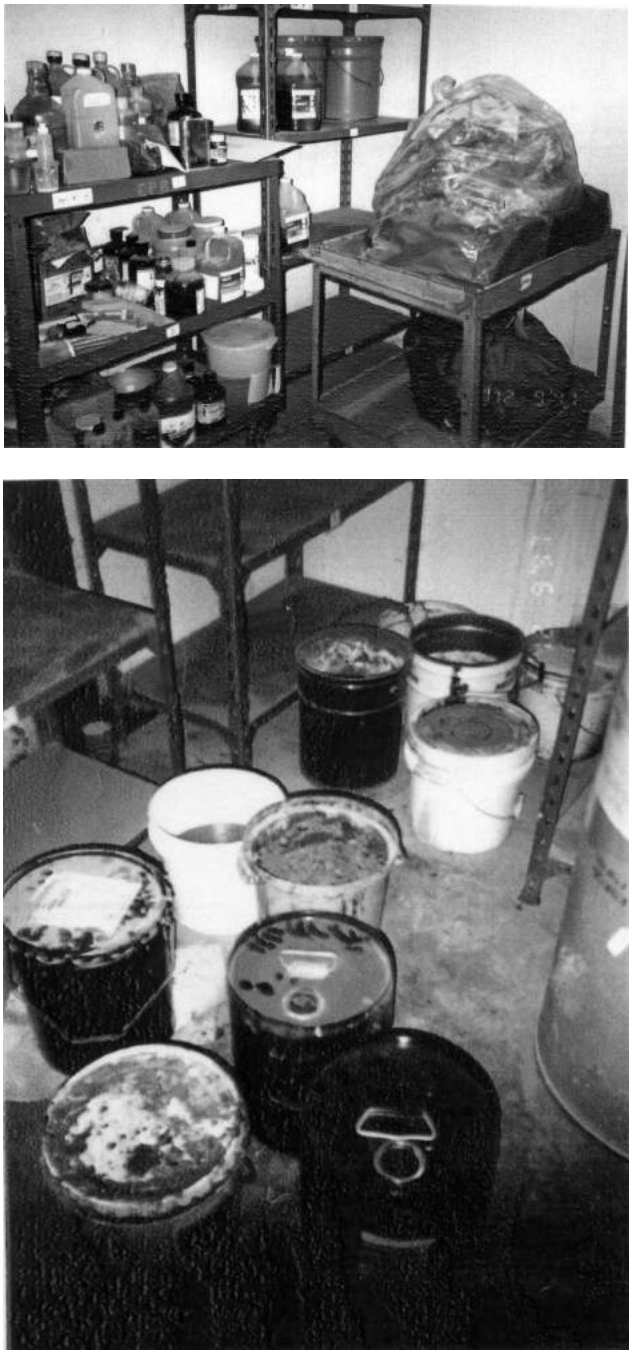


FIGURE 12.A.7 Hazardous waste storage areas.

For financial reasons, the facility owner abandoned the company premises. State inspectors visited the facility and immediately detected substantial quantities of liquids in most of the facility tanks. As a result, the state required the owner to return and conduct a waste determination for all tanks. In the neutralization tank, liquids failed the TCLP test for chromium. Since the contents of these tanks have consistently been deep-well injected, there was concern that high levels of chromium were also being injected.



FIGURE 12.A.8 Satellite accumulation area.



FIGURE 12.A.9 Roll-off containers.

During an interview with an inspector, the owner stated that "We don't know how that chromium got there."

14. A technician at a university laboratory has discovered an aging bottle of picric acid. The bottle has never been opened, and the technician is hoping to find some inexpensive, simple means of disposal.
15. A metalworking operation uses trichloroethylene (TCE) for degreasing parts. The facility has a vapor degreaser that it uses to distill spent TCE on-site. The recovered TCE is used several times for degreasing. Although TCE can have an F001 or F002 listing, the facility does not consider this particular TCE to be a waste at all, as it is recycled and reused immediately; therefore, they are not a hazardous waste generator.
16. The roll-offs (containers) shown in Figure 12.A.9 are storing a K-listed waste. What is the problem regarding its management?

12.A.1.3 Responses to Questions about Scenarios

1. (a) Although allowed to air-dry, the paint chips are by no means free of this hazardous solvent (as indicated by the aromatic smell and PID readings). The facility should have conducted a waste determination on both the paint chips and the walnut shells, that is, determine whether the solid waste they produce is a hazardous waste.

   The paint chips are both a listed (F002) and a characteristic (toxic) hazardous waste; therefore, disposal in an ordinary MSWLF is not permitted. Similarly, the walnut shells are a listed waste according to the Mixture Rule.

   (b) Given that hazardous waste is indeed generated on the premises, the generator must prepare a Uniform Hazardous Waste Manifest according to 40 CFR 262.20. In addition,

the generator must send a one-time written notification to each land disposal facility receiving the waste.

(c) A generator may accumulate hazardous waste on-site for up to 90 days without a permit. The Hi-Jinx facility has been storing the methylene chloride for at least 4–5 months.

(d) The facility was conducting *treatment* of a hazardous waste by drying the methylene chloride–contaminated paint chips in the trailer. They do not have a permit to treat hazardous waste.

(e) A title V air permit is needed, as a hazardous solvent is being allowed to volatilize. The affected state has stipulated, in its own regulations, that:

> A person may not discharge, emit, cause … or allow any contaminant or waste, including any noxious odor … into the environment.

2. (a) Regardless of soil type, groundwater contamination is possible from direct disposal onto soil. According to the MSDS, the specific gravity for methylene chloride is 1.33; it will therefore sink once it contacts the groundwater, making any recovery and remediation operations slow and expensive.

   (b) The deliberate disposal of methylene chloride, an F002-listed RCRA hazardous waste, to soil constitutes illegal disposal. The company owner should contact his attorney.

   Many states encourage voluntary notification and cleanup of spills and disposal sites rather than waiting for whistleblowers to report the problem or inspectors to discover them.

3. (a) According to 40 CFR 261.2, a solid waste is any discarded material. "Discarded" means abandoned, recycled, or inherently waste-like. Based on the fact that the drums are rusted and overgrown with weeds, it is concluded that this material is abandoned and is therefore a solid waste. Based on company use of toluene, it is further concluded that these mystery liquids are probably also toluene.

   (b) Since the drums were obviously on-site for a long time, it is concluded that the facility has engaged in >90 days day storage without a permit.

   (c) It is possible that wastes have been released to the surrounding soil and air. The company is responsible for assessing the degree of soil contamination; it should arrange with an outside firm to collect soil samples and analyze them for possible hydrocarbon contamination.

   (d) A waste determination should be carried out to identity the specific composition of the waste drums.

4. (a) The lab gloves and lab coats are technically hazardous waste according to The Mixture Rule.

   (b) By deliberately allowing solvent vapors to volatilize, this facility is treating a hazardous waste. A TSDF permit is required for such an activity.

   (c) Workers are potentially being exposed to high levels of hazardous vapors, so this activity is probably a violation of Occupational Safety and Health Administration regulations.

5. True, the process would likely halt if the solvent–paint wastes accumulated and overflowed into the paint booth. However, the mixture is a hazardous waste, and the purge pots and the ancillary equipment (i.e., all associated plumbing) are indeed considered a tank system. Tank systems are defined in 40 CFR 260.10 as

   > a hazardous waste storage or treatment tank and its associated ancillary equipment and containment system.

   Regulations as to management of tank systems appear in subpart J, Tank Systems (40 CFR 264.190-264.200).

6. For a 55-gal drum, a date is to be noted on the hazardous waste label once it has been filled; counting the days (90 for an LQG, 180 for an SQG) begins immediately thereafter.

   One cannot change the start date of accumulation. In the current situation (LQG), it is probable that the drum was on-site for over the 90-day storage period. According to 40 CFR 262.34(a)(2):

   > A generator may accumulate hazardous waste on-site for 90 days or less without a permit provided that the date upon which the period of accumulation begins is clearly marked and visible for inspection on each container;

   As a side note, for a container greater than 55 gal, the date is marked on the Hazardous Waste label *at the first addition of waste*, not when the container is full.
7. (a) According to 40 CFR 265.31:

   Facilities must be maintained and operated to minimize the possibility of fire, explosion, or any unplanned release of hazardous waste to air, soil, or surface water that could threaten human health or the environment. The building was open to the outside by way of the garage door and spaces in the walls, so secondary containment is not intact.

   (b) The inspector encouraged simple improvements in housekeeping, that is, if the shed floor is kept free of sludge, dispersal is no longer an issue.

   (c) Wastes that are tracked outside could easily be dispersed off the plant site by wind. The argument of the presence of waste drains is therefore inadequate.
8. There is no requirement that spill prevention equipment be situated directly within the 90-day accumulation area.
9. Although the waste is a solid hazardous waste, an integrity assessment of the tank is nonetheless required. However, the assessment does not have to be as involved as for a tank storing liquid hazardous wastes. Incidentally, the issue over secondary containment came up between inspector and plant manager. When brought to the EPA, it was decided that secondary containment was not required.
10. This hazardous waste storage area has its share of problems.
    (a) Most wastes are unidentified and unlabeled; a waste characterization is required.
    (b) Incompatible wastes are stored side-by-side.
    (c) Many containers are open. Containers must remain closed with few exceptions, for example, from 40 CFR 264.173: when it is necessary to add or remove waste.
    (d) Also from 40 CFR 264.173: A container holding hazardous waste must not be handled or stored in a manner which may rupture the container or cause it to leak.
11. Although not of the highest quality printing, the labeling of this drum is actually acceptable. Federal regulations (40 CFR 262.34) state that, in a satellite accumulation area, a waste drum must simply be labeled, describing the contents; there is no requirement for a specific label in a satellite area. If, however, the drum were in a 90-day accumulation area, this "label" is unacceptable. A standard yellow "Hazardous Waste" label must be affixed to the drum and dated. This drum is situated in the middle of the aisle and must be moved.
12. The fly ash is indeed a solid waste, as it is "discarded" material. However, according to 40 CFR 261.4(b)(4), fly ash generated from the combustion of coal or other fossil fuels is excluded from being defined as a hazardous waste.
13. Unfortunately, there is no simple method to determine if Cr wastes were deep-well injected; the claim by the inspector would be difficult to prove. Corroboration by a plant employee or witnesses would have been extremely useful. This case is still under investigation.
14. Since the container has never been opened, it is designated an *unused commercial chemical product*. Picric acid is not, however, a U- or P-listed hazardous waste. During prolonged periods of storage, picric acid can form picrate salts, which are highly sensitive to shock and are violently explosive. As a result, such a waste is considered a characteristic reactive

waste and must be handled with utmost care. It would be wise to contact the local emergency response team for handling and disposing this container.

15. If the TCE solvent was never removed from the system before it was reused, it is not a waste. In the current situation, however, the solvent is reclaimed (treated) before reuse and is therefore considered a solid waste. Based on the listing procedure, this is an F001 hazardous waste. The facility must manage their waste stream, including requirements for generators (counting, manifesting, and so on), according to the requirements of 40 CFR 262.
16. (a) Containers must be covered at all times. Large openings in the covers allowed rainfall to enter. In addition, covers were not pulled tight across the top; as a result, rain accumulated on the surface, causing the covers to collapse, thus letting in more water.
    (b) The puddles under the roll-off are stained and may contain some of the released waste. If the inspector is suspicious of a leak, he should require this facility to conduct a waste determination. A facility must be managed to minimize the possibility of a release to the environment.

QUESTIONS

1. Define "cradle-to-grave responsibility" for a hazardous waste generator. Discuss the regulatory requirements for packaging, storage, transportation, and manifesting. For how long is the generator responsible for this waste?
2. After a satellite container becomes full, within how many days must it be removed and transferred to the central accumulation area or shipped to an off-site facility?
3. List the criteria required for a RCRA-approved secondary containment unit.
4. An SQG, as defined under RCRA, generates at least _____ pounds of hazardous waste in a calendar month, whereas an LQG generates at least _____ pounds of hazardous waste per month.
5. The hazardous waste accumulation period normally begins at what point? (a) when wastes are first added to the container, (b) when the container is full, (c) when the hazardous label is affixed to the drum, (d) when the waste is determined to be listed hazardous waste.
6. How often is a facility hazardous waste report to be submitted to EPA?
7. List the instances when containers of hazardous waste can be opened at the generator's facility.
8. Under RCRA, up to what height should drums containing ignitable wastes be stacked (i.e., two drums, three drums, etc.)?
9. An LQG may ship its hazardous wastes to a landfill that is approved only by the state, to handle municipal or industrial waste (true or false).
10. LQGs must have double liners on all new containers for hazardous wastes stored on-site (true or false).
11. Which of the following are acceptable management practices for a satellite accumulation point? (a) stores a maximum of 55 gal of hazardous waste, (b) stores a maximum of 1 qt of acute hazardous waste, (c) it is under the continuous control of the personnel who generate the waste.
12. What are the requirements for an acceptable container used at a satellite accumulation area?
13. As a result of a new manufacturing process, the Hi-Jinx Chemical Company is generating a new waste stream. The waste has the following properties: pH = 10, flashpoint = 75°F, high concentrations of Cd and Cr (which exceed TCLP limits), approximately 2500 lb/month. Based on the *waste alone*, is the generator an LQG, SQG, or CESQG? Must the generator comply with DOT regulations for packaging the wastes and placarding the vehicles? For how long can the generator stockpile waste on-site without a permit? Is there a requirement for the submission of a written emergency response plan to the state environmental agency?

14. Based on question 13, is the waste to be classified as corrosive, ignitable, or toxic?
15. Based on the waste properties given in question 13, can the waste be stored in a single-lined tank on the premises? How far must it be stored from the property line? To what type of facility (e.g., state-approved, EPA-approved) must the waste be shipped for final disposal?
16. If the waste in question 13 could be used (recycled) at another facility, must it be considered a RCRA hazardous waste?
17. The waste in question 13 may possibly serve as a boiler fuel and therefore need not be managed as a waste at all (true or false).
18. At Bogus Metalworks, 2500 lb of tetrachloroethylene (a listed hazardous waste) was transferred to a machine degreasing booth and reused a total of four times in September. How much waste must be counted at the end of the month?
19. At the Hi-Jinx facility, pentachlorophenol, a listed hazardous waste, was mixed with clean soil during a small spill. Is the new mixture still a hazardous waste? Justify your answer.
20. Also at the Hi-Jinx plant, the tops and bungs of several drums of pentachlorophenol are damaged and severely rusting. Since wastes are not leaking, can they remain in these containers until they are to be transported?
21. By what specific requirements are individual households subject to RCRA?
22. For how long do RCRA regulations require that manifests be retained?
23. List and discuss what is incorrect about the Uniform Hazardous Waste Manifest shown in Figure 12.6.
24. If the signed return copy of a manifest is not received by an LQG within 35 days, an investigation must be conducted to locate the return copy. When must exception reports be submitted to the state?
25. If an SQG does not receive a return copy of the manifest within 60 days, what action is required?

For some of the following questions, it may be useful to refer to 40 CFR 262, Generator Requirements.

26. A generator of hazardous waste determines that more than 100 kg of waste will be generated in a calendar month. What documentation, identification, and so on, must they acquire?
27. What is the maximum quantity of hazardous waste that can be accumulated in a satellite accumulation point?
28. Accumulation points for containers must be inspected weekly. What specific items should be inspected?
29. How frequently should hazardous waste storage tanks be inspected?
30. While in satellite accumulation points, what must all hazardous waste containers be marked with?
31. While in primary accumulation points, what must all hazardous waste containers be marked with?
32. Tanks used for accumulation of hazardous waste must be equipped with secondary containment, leak detection, and overflow protection. How often should this equipment be inspected?

REFERENCES

CFR (Code of Federal Regulations). 2004. *Vol. 40, Part 261, Identification and Listing of Hazardous Waste*. Washington, DC: U.S. Government Printing Office.

CFR (Code of Federal Regulations). 2004. *Vol. 40, Part 262, Standards Applicable to Generators of Hazardous Waste*. Appendix to Part 262 – Uniform Hazardous Waste Manifest and Instructions (EPA forms 8700-22 and 8700-22 and Their Instructions). Washington, DC: U.S. Government Printing Office.

CFR (Code of Federal Regulations). 2004. *Vol. 40, Part 761, Polychlorinated Biphenyls (PCB) Manufacturing, Processing, Distribution in Commerce, and Use Prohibitions*. Washington, DC: U.S. Government Printing Office.

EHSO (Environment Health and Safety Online). 2003. *Diagram of the Current Hazardous Waste Manifest System*. Available from: http://www.ehso.com/Hazwaste/hazwaste_Manifest_process.htm

U.S. EPA (Environmental Protection Agency). 2011. *National Analysis, The National Biennial RCRA Hazardous Waste Report (Based on 2011 Data)*. Available from: http://www.epa.gov/epawaste/inforesources/data/br11/national11.pdf

U.S. EPA (U.S. Environmental Protection Agency). 2012. *Hazardous Waste Generator Regulations: A User-Friendly Reference Document*. Version 6. Available from: http://www.epa.gov/osw/hazard/downloads/tool.pdf

Woodside, G. 1993. *Hazardous Materials and Hazardous Waste Management: A Practical Guide*. New York: John Wiley & Sons.

SUGGESTED READINGS AND WEBSITES

Business and Legal Reports. 2003. *Federal Hazardous Waste Generators*. Available from: http://enviro2.blr.com/topic.cfm/topic/179/state/155

California Environmental Protection Agency, Department of Toxic Substances Control. 2002. *Hazardous Waste Generator Requirements*. Available from: http://www.coastal.ca.gov/ccbn/Apndx11.pdf

Massachusetts Department of Environmental Protection. 2000. *A Summary of Requirements for Small Quantity Waste Generators of Hazardous Waste*. Boston, MA: Bureau of Waste Prevention.

U.S. EPA (U.S. Environmental Protection Agency). 1996. *RCRA Environmental Indicators Progress Report: 1995 Update*. Washington, DC: Office of Solid Waste. Available from: http://www.epa.gov/epaoswer/hazwaste/data/ei/envind.pdf

U.S. EPA (U.S. Environmental Protection Agency). 2001. *RCRAINFO File Specification Guide, 2001 Hazardous Waste Report Submissions*. Available from: http://www.epa.gov/epaoswer/hazwaste/data/brs01/8-01spec.pdf

U.S. EPA (U.S. Environmental Protection Agency). 2003. *Generate and Transport*. Available from: http://www.epa.gov/epaoswer/osw/generate.htm

U.S. EPA (U.S. Environmental Protection Agency). 2012. *Hazardous Waste Generator Regulations: A User-Friendly Reference Document*. Version 6. Available from: http://www.epa.gov/osw/hazard/downloads/tool.pdf

Washington State Department of Ecology. n.d. *Hazardous Waste Generator Checklist*. Washington's Hazardous Waste and Toxics Reduction Program. Available from: http://www.ecy.wa.gov/pubs/9112b.pdf

13 Hazardous Waste Transportation

From here to nowhere. And back again.
Blow foul, blow fair
All come to anchor finally in the tomb.
Passengers armed, we travel from room to room.
Whose Baggage from Land to Land is Despair

Palladas (360–430 CE)

13.1 INTRODUCTION

Hazardous waste transportation comprises a key component of the comprehensive cradle-to-grave Resource Conservation and Recovery Act (RCRA) program for the management of hazardous wastes. Transportation most commonly involves transferring from the point of generation to an Environmental Protection Agency (EPA)-registered treatment, storage, and disposal facility (TSDF). Transportation is a significant potential source of releases to the environment and exposure to workers and the public; hence, regulations addressing proper waste shipping procedures are numerous and comprehensive.

In the late 1980s, the National Solid Wastes Management Association reported that trucks traveling over public highways moved 98% of the hazardous waste that was treated off-site, and rail transport moved the remainder. In 1993, a total of 20,800 transporters of hazardous waste were reported by EPA. In 1999, 17,914 shippers carried 8.1 million tons of RCRA hazardous waste. By 2010, a total of 16,345 shippers transported 5.9 million tons (U.S. EPA 2001, 2011). When comparing 2010 data with that of 1999, the number of shippers decreased by 2886, and the quantity of waste shipped decreased by 2.1 million tons, or 27%.

Of the 5.9 million tons of RCRA hazardous waste shipped in 2010, 3.5 million tons were exported from the state of origin to other states. Between 1999 and 2010, the quantity of waste exported across state lines increased by 2.2 million tons, or 39%.

When the Hazardous and Solid Waste Amendments of 1984 (HSWA) were enacted, more than 100,000 new small quantity generators (SQGs) were brought under the RCRA regulations. A majority of the SQGs had no options other than to ship hazardous wastes off-site for final treatment and disposal. In addition, the inclusion, in 1990, of 25 new chemical constituents to 40 CFR 261.24, brought about 17,000 new generators under RCRA regulation (Blackman 2001).

Hazardous waste transportation is regulated under both RCRA and U.S. Department of Transportation (DOT) hazardous materials regulations. The DOT rules are compiled in 49 CFR and were formulated to regulate the transport of *any* hazardous material, that is, whether new product or waste. The DOT program had been in existence long before the promulgation of RCRA subtitle C; furthermore, DOT regulations were originally designed to address the transport of individual chemicals. When dealing with hazardous wastes, however, a complex waste stream, composed of many chemicals in various physical forms, may be transported. As a result, the DOT program has been modified to allow for managing hazardous wastes and their mixtures.

The DOT program requires appropriate *hazard communication* (e.g., classification, labeling, marking, packaging, placarding) of a material that is to be transported. If hazardous waste is being transported for treatment, storage, disposal, or reclamation, the waste generator is then classified as a *shipper* by the DOT and must comply with hazardous materials regulations (49 CFR parts 171 to 179) in addition to hazardous waste (RCRA) regulations (40 CFR part 262).

13.2 MODES OF HAZARDOUS WASTE TRANSPORTATION

Cargo tanks are the main carriers of bulk hazardous materials over roadways; however, large quantities of hazardous wastes are shipped in 55-gal drums. Cargo tanks are usually manufactured of steel or aluminum alloy, stainless steel, nickel, or titanium. Tanks range in capacity from 15,000 to 45,000 L (4000–12,000 gal). Federal road weight laws usually limit motor vehicle weights to 36,000 kg (80,000 lb) gross. Table 13.1 lists DOT cargo tank specifications for bulk shipment of common hazardous materials and example cargos.

Nearly 155 million tons of chemicals are transported by rail in North America annually, which constitutes 1.75 million rail cars of hazardous materials. The volume of hazardous materials moving by rail has more than doubled since 1980 (Spraggins 2007). The major classifications of rail tank cars, for transporting both gases and liquids, are *pressure* and *nonpressure*. Both categories have several subclasses that differ in terms of test pressure, presence or absence of bottom discharge valves, type of pressure relief system, and type of thermal shielding. Ninety percent of tank cars are steel; aluminum is also common. DOT tank car design specifications are covered in 49 CFR part 179. Rail car specifications for transporting pressurized hazardous materials appear in DOT 105, 112, and 114; for unpressurized shipments, the numbers are DOT 103, 104, and 111. Capacities for tank cars carrying hazardous materials are limited to 131,000 L (34,500 gal) or 119,000 kg (263,000 lb) gross weight.

Since the implementation of the RCRA regulations, most hazardous waste transporters fall into one of the following categories:

- Generators transporting their wastes to a TSDF
- Contract haulers collecting wastes from generators and transporting to TSDFs
- TSD facilities collecting wastes from generators for transport back to their facilities

Highway transportation of hazardous wastes is considered the most versatile method—tank trucks can gain access to most industrial generators and TSD facilities; rail shipping, in contrast, requires installation of sidings and is suitable only for very large-quantity shipments (Blackman 2001).

TABLE 13.1
Cargo Tank Table as Specified by Dot Regulations

Cargo Tank Specification Number	Types of Commodities Carried	Examples
MC-306 (DOT-406)	Combustible and flammable liquids of low vapor pressure	Fuel oil, gasoline
MC-307 (DOT-407)	Flammable liquids, Poison B materials with moderate vapor pressure	Toluene, diisocyanate
MC-312 (DOT-412)	Corrosives	Hydrochloric acid, caustic solution
MC-331	Liquefied compressed gases	Chlorine, anhydrous ammonia
MC-338	Refrigerated liquefied gases	Oxygen, methane

Source: Code of Federal Regulations, Volume 49, parts 172.101 and 1.78.315–178.343.

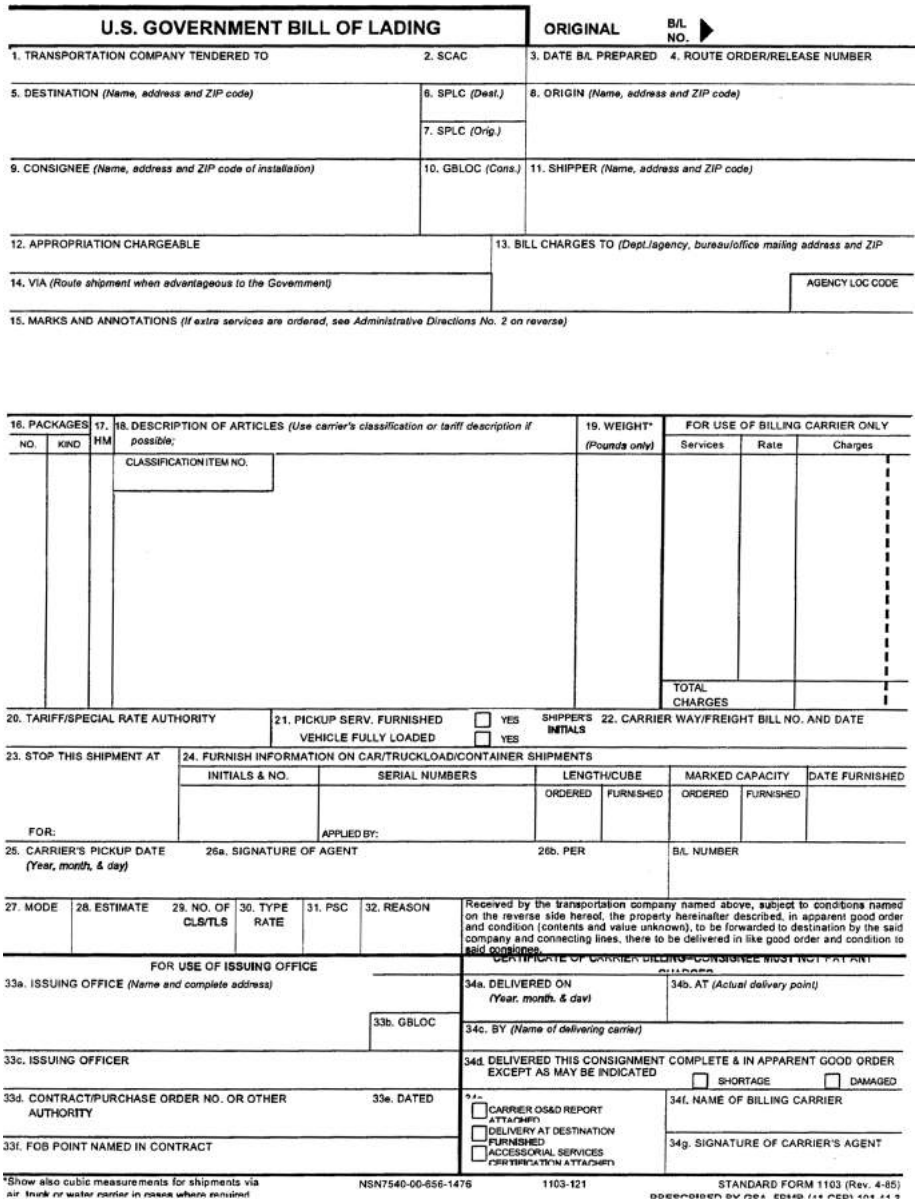
13.3 TRANSPORTATION REQUIREMENTS

13.3.1 Shipping Papers

Shipping papers are required for the transport of hazardous materials (Figure 13.1). Such documentation provides detailed information about the materials being transported and the potential hazards involved. It is the transporter's responsibility to complete the shipping papers.

Although the format of the papers may vary, all are required to include the following details for each hazardous material transported:

- Proper shipping name
- Hazard class or division number



U.S. GOVERNMENT BILL OF LADING

ORIGINAL B/L NO.

1. TRANSPORTATION COMPANY TENDERED TO
2. SCAC
3. DATE B/L PREPARED
4. ROUTE ORDER/RELEASE NUMBER
5. DESTINATION (Name, address and ZIP code)
6. SPLC (Dest.)
7. SPLC (Orig.)
8. ORIGIN (Name, address and ZIP code)
9. CONSIGNEE (Name, address and ZIP code of installation)
10. GBLOC (Cons.)
11. SHIPPER (Name, address and ZIP code)
12. APPROPRIATION CHARGEABLE
13. BILL CHARGES TO (Dept./agency, bureau/office mailing address and ZIP
14. VIA (Route shipment when advantageous to the Government)
AGENCY LOC CODE
15. MARKS AND ANNOTATIONS (If extra services are ordered, see Administrative Directions No. 2 on reverse)

16. PACKAGES NO. KIND
17. HM
18. DESCRIPTION OF ARTICLES (Use carrier's classification or tariff description if possible;)
CLASSIFICATION ITEM NO.
19. WEIGHT* (Pounds only)
FOR USE OF BILLING CARRIER ONLY
Services Rate Charges
TOTAL CHARGES
20. TARIFF/SPECIAL RATE AUTHORITY
21. PICKUP SERV. FURNISHED ☐ YES
VEHICLE FULLY LOADED ☐ YES
SHIPPER'S INITIALS
22. CARRIER WAY/FREIGHT BILL NO. AND DATE
23. STOP THIS SHIPMENT AT
FOR:
24. FURNISH INFORMATION ON CAR/TRUCKLOAD/CONTAINER SHIPMENTS
INITIALS & NO. SERIAL NUMBERS LENGTH/CUBE MARKED CAPACITY DATE FURNISHED
ORDERED FURNISHED ORDERED FURNISHED
APPLIED BY:
25. CARRIER'S PICKUP DATE (Year, month, & day)
26a. SIGNATURE OF AGENT
26b. PER
B/L NUMBER
27. MODE 28. ESTIMATE 29. NO. OF CLS/TLS 30. TYPE RATE 31. PSC 32. REASON
Received by the transportation company named above, subject to conditions named on the reverse side hereof, the property hereinafter described, in apparent good order and condition (contents and value unknown), to be forwarded to destination by the said company and connecting lines, there to be delivered in like good order and condition to said consignee.
CERTIFICATE OF CARRIER BILLING—CONSIGNEE MUST NOT PAY ANY CHARGES
FOR USE OF ISSUING OFFICE
33a. ISSUING OFFICE (Name and complete address)
33b. GBLOC
33c. ISSUING OFFICER
33d. CONTRACT/PURCHASE ORDER NO. OR OTHER AUTHORITY
33e. DATED
33f. FOB POINT NAMED IN CONTRACT
34a. DELIVERED ON (Year, month, & day)
34b. AT (Actual delivery point)
34c. BY (Name of delivering carrier)
34d. DELIVERED THIS CONSIGNMENT COMPLETE & IN APPARENT GOOD ORDER EXCEPT AS MAY BE INDICATED ☐ SHORTAGE ☐ DAMAGED
☐ CARRIER OS&D REPORT ATTACHED
☐ DELIVERY AT DESTINATION FURNISHED
☐ ACCESSORIAL SERVICES CERTIFICATION ATTACHED
34f. NAME OF BILLING CARRIER
34g. SIGNATURE OF CARRIER'S AGENT
*Show also cubic measurements for shipments via air, truck or water carrier in cases where required
NSN7540-00-656-1476 1103-121 STANDARD FORM 1103 (Rev. 4-85)
PRESCRIBED BY GSA, FPMR (41 CFR) 101-41.3

FIGURE 13.1 Copy of a bill of lading.

- ID number
- Packing group
- Total quantity

13.3.2 Uniform Hazardous Waste Manifest

The cradle-to-grave program requires generators to manifest all hazardous waste shipments. The Hazardous Waste Manifest System, discussed in Chapter 12, is a set of procedures and paperwork designed to track hazardous waste from the time it leaves the generator's facility until it reaches the TSDF. The manifest, a multipart paper form, allows the waste generator to verify whether the wastes have been properly delivered and that all waste is accounted for.

13.3.3 Hazard Communication

13.3.3.1 Identification of the Waste Being Transported

When hazardous waste is to be transported off-site from the point of generation, the shipper must comply with regulations for its identification, classification, labeling, packaging, markings, placards, and shipping documentation, which is collectively known as hazard communication. These actions are designed to protect the health of both employees and the local public who may be exposed to such wastes during transportation. Most of the requirements are contained within DOT's hazardous materials table (HMT) (49 CFR §172.101) (see below).

For purposes of safety and regulatory compliance, all materials scheduled for shipment must be fully identified. This information must also be available to the public, as well as to emergency response teams and regulators. Requirements for proper shipping of a hazardous waste include:

- *Shipping name:* The generator (shipper) must determine the proper shipping name of the hazardous waste.
- *Hazard class:* A total of 23 DOT hazard classes of transportable materials exist. The generator must select the appropriate hazard class.
- *Identification number:* The generator must select the identification number that corresponds to the shipping name and hazard class.
- *Label:* The generator must determine if labels are required.
- *Packages:* Determine the appropriate package type for the waste.
- *Markings:* Apply the required DOT and EPA markings to the package.
- *Placards:* The shipper must provide the proper placards to the transporter vehicle.
- *Shipping documentation:* The shipper must prepare a Uniform Hazardous Waste Manifest to verify the identification and classification of the materials being shipped.

13.3.3.2 Hazardous Materials Table

The HMT, found in 49 CFR §172.101, lists those materials designated by DOT as hazardous for transportation. This table provides most of the information required for preparing hazardous materials for transport. The table identifies shipping names; hazard classifications; United Nations or North American identification numbers; and references for labeling, packaging, marking, placarding, and shipping procedures. It also compiles regulations into an index that generators use to determine the appropriate procedures for waste transport.

For each hazardous material listed, the HMT identifies the hazard class or specifies that the material is forbidden for transportation, and provides the proper shipping name. In addition, the table specifies requirements pertaining to labeling, packaging, quantity limits aboard aircraft, and stowage of hazardous materials aboard vessels. A portion of the HMT appears in Figure 13.2. The specific columns are:

1. Notes (symbols) regarding requirements for shipping modes (e.g., water, air)
2. Materials descriptions and proper shipping names

§ 172.101 HAZARDOUS MATERIALS TABLE (*Continued*)

Symbols	Hazardous materials descriptions and proper shipping names	Hazard class or Division	Identification Numbers	PG	Label Codes	Special provisions (§ 172.102)	(8) Packaging (§ 173.***)			(9) Quantity limitations (see § 173. 27 and 175.75)		(10) Vessel stowage	
							Exceptions	Non-bulk	Bulk	Passenger aircraft/rail	Cargo aircraft only	Location	Other
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8A)	(8B)	(8C)	(9A)	(9B)	(10A)	(10B)
	Chloropicrin mixture, flammable (pressure not exceeding 14.7 psia at 115 degrees F flash point below 100 degrees F) see toxic liquids flammable, etc.	.....			.....		.....	.....	.....	.....	.....		.....
	Chloropicrin mixtures, n.o.s ...	6.1	UN1583	I	6.1	5	None ...	201	243	Forbidden	Forbidden	C	40
	.....	.....		II	6.1	IB2	153	202	243	Forbidden	Forbidden	C	40
	.....	.....		III	6.1	IB3	153	203	241	Forbidden	Forbidden	C	40
D	Chloropivaloyl chloride	6.1	NA9263	I	6.1, 8	2, B9, B14, B32, B74, T20, TP4 TP12, TP13 TP38, TP45	None ...	227	244	Forbidden	Forbidden	B	40
	Chloroplantic acid, solid	8	UN2507	III	8	IB8, IP3, T1 TP33	154	213	240	25 kg	100 kg	A	.....
	Chloroprene, stabilized	3	UN1991	I	3, 6.1	B57, T14, TP2, TP13	None ...	201	243	Forbidden	30 L	D	40
	Chloroprene, uninhibited	Forbidden			.....		.....	.....	.....	.....	.....		.....
	1-Chloropropane	3	UN1278	II	3	IB2, IP8, N34, T7, TP2	None ...	202	242	Forbidden	60L	E	.....
	2-Chloropropane	3	UN2356	I	3	N36, T11, TP2, TP13	150	201	243	1L	30L	E	.....
	3-Chloropropanol-1	6.1	UN2849	III	6.1	IB3, T4, TP1,	153	203	241	60L	220L	A	.....
	2-Chloropropene	3	UN2456	I	3	A3, N36, T11, TP2	150	201	243	1L	30L	E	.....
	2-Chloropropionic acid.....	8	UN2511	III	8	IB3, T4, TP2,	154	203	241	5L	60L	A	8
	2-Choropyridine.....	6.1	UN2822	II	6.1	IB2, T7, TP2,	153	202	243	5L	60 L	A	40
	Chlorosilanes, corrosive, n.o.s ...	8	UN2987	II	8	B2, IB2, T14, TP2, TP27	None	202	242	1 L	30 L	C	40.
	Chlorosilanes, flammable, corosive, n.o.s.	3	UN2985	II	3, 8	IB1, T11, TP2, TP13, TP27	None	201	243	1 L	5 L	B	40.
	Chlorosilanes, toxic, corrosive, n.o.s.	6.1	UN3361	II	6. 1, 8	IB1, T11, TP2, TP13	None	202	243	1 L	30 L	C	40.
	Chlorosilanes, toxic, corrosive, flammable, n.o.s.	6.1	UN3362	II	6. 1, 3, 8.	IB1, T11, TP2, TP13	None	202	243	1 L	30 L	C	40, 125.
	Chlorosilanes, water-reactive, flammable, corrosive, n.o.s..	4.3	UN2988	I	4.3, 3, 8.	A2, T10, TP2, TP7, TP13	None	201	244	Forbidden	1 L	D	21, 28, 40, 49, 100

FIGURE 13.2 Portion of the HMT as created by DOT. (From Code of Federal Regulations, Volume 49, *Department of Transportation*, U.S. Government Printing Office, Washington, DC, 2004.)

3. Hazard classes and divisions
4. Identification numbers
5. Packing groups
6. Labels required
7. Special provisions
8. Packaging requirements
9. Quantity limitations
10. Requirements specifically for water shipments (e.g., vessel stowage requirements)

13.3.3.3 Hazardous Material Classes

DOT considers hazardous wastes to be a subset of the larger universe of hazardous materials. Thus, to apply the HMT for hazardous waste management, the waste is considered by DOT to be a hazardous material subject to additional requirements. Hazardous materials are defined by DOT under 49 CFR §171.8 as products that "are capable of posing an unreasonable risk to health, safety and property when transported." A material is deemed hazardous under one of the following conditions:

- It meets one or more hazard class definitions (see below)
- It is a hazardous substance, hazardous waste, marine pollutant, or elevated temperature material

Regardless of the above hazards, these items are still permitted for transport. Safe transportation is facilitated when the materials are properly classified. Classification dictates the correct handling, packaging, and emergency response actions. DOT has established various classes of hazardous materials, established placarding and marking requirements for containers and packages, and created an international numbering system for cargo. Hazardous materials are classified for transportation into the categories shown below.

Class 1—Explosives. An explosive is defined by DOT as "any substance or article which is designed to function by explosion (i.e., an extremely rapid release of gas and heat)." Explosives in Class 1 are divided into six divisions:

Division 1.1—explosives that have a mass explosion hazard. A mass explosion is one that affects almost the entire load instantaneously. These explosives are among the most powerful and include bombs, mines, torpedoes, and ammunition used by the military; high explosives such as nitroglycerin and dynamite, blasting caps, detonating fuses, and rocket propellants.

Division 1.2—explosives that have a projection hazard but not a mass explosion hazard. These are generally less powerful and typically function by rapid combustion rather than detonation. This class includes fireworks, flash powders, liquid or solid propellants, some smokeless powders, and certain types of ammunition.

Division 1.3—explosives that pose a fire hazard and a minor blast, projection hazard, or both.

Division 1.4—explosives that present a minor explosion hazard. The explosive effects are largely confined to the package and no projection of fragments is expected.

Division 1.5—very insensitive explosives. This division includes substances that have a mass explosion hazard but are so insensitive that there is very little probability of initiation under routine transport. This division includes blasting agents such as ammonium nitrate–fuel oil. The material is capable of exploding under very specialized conditions.

Division 1.6—extremely insensitive items.

Class 2—Gases. Gases are products that are cooled and compressed for ease in transportation. Gases pose dangers because they are stored under pressure. A compressed gas is defined as any material or mixture with an absolute pressure in a container of

- More than 40 psa at 70°F
- More than 140 psa at 130°F

Divisions of Class 2 are as follows:

Division 2.1—Flammable gas. A flammable, compressed gas has a lower explosive limit (LEL) concentration of 13% or less by volume in air, or has a flammable range (i.e., the difference between the LEL and UEL) more than 12%.
Division 2.2—Nonflammable, nonpoisonous, compressed gas. Includes compressed gas, liquefied gas, pressurized cryogenic gas, compressed gas in solution, asphyxiant gas, and oxidizing gas.
Division 2.3—Gas poisonous by inhalation.
Division 2.4—Toxic gas. The term "toxic gas" may be used in place of "poison gas" for domestic shipments. The term "toxic gas" must be used for international shipments.

Class 3—Flammable liquids. A flammable liquid refers to any liquid that has a closed-cup flashpoint below 37.8°C (100°F). The closed-cup test procedures are outlined in 40 CFR 261.21 and in EPA Method 1020B (U.S. EPA 1986). The term *flashpoint* refers to a temperature at which a substance generates sufficient vapors to sustain combustion. A combustible liquid is one with flashpoint between 37.8 and 75.6°C (100 and 200°F).

Class 4—Flammable solids. Flammable solid includes any solid material, other than explosives, which, under normal transport conditions, is liable to cause fire through friction, can retain heat from manufacturing, or can be ignited readily. When ignited, they burn so vigorously as to create a serious transportation hazard. Spontaneously combustible and water-reactive materials are included in this class. An example of a flammable solid is aluminum hydride.

Division 4.1—Materials that ignite easily and burn vigorously.
Division 4.2—Spontaneously combustible material. This includes *pyrophoric* materials. A pyrophoric material is a liquid or solid that, without an external ignition source, can ignite after coming in contact with air.
Division 4.3—Dangerous as wet material. A material that, by contact with water, becomes spontaneously flammable or releases flammable or toxic gas.

Class 5—Oxidizers and organic peroxides. An *oxidizer* is a substance such as a chlorate, permanganate, inorganic peroxide, or a nitrate, that yields oxygen readily to stimulate combustion of organic matter. The main hazard with oxidizing agents is contact with a combustible substance; for example, organic materials (even dust) may cause the substance to ignite or explode.

Division 5.1—Releases oxygen. These promote vigorous combustion of a substance.
Division 5.2—Organic peroxides. An organic peroxide is derived from hydrogen peroxide (H_2O_2). One or more hydrocarbon groups have replaced one of the hydrogen atoms. These substances may explode under certain conditions.

Class 6—Toxic or Poisonous materials. Poisonous materials are divided into three groups according to their degree of hazard in transportation.

Division 6.1, Packing Group I (PG I) and Packaging Group II (PG II)—Substances are "poisonous gases or liquids such that a very small amount of the gas, or vapor of the liquid,

mixed with air is dangerous to life." These are highly poisonous by inhalation, ingestion, or absorption through skin. Packing groups are discussed below.

Division 6.1, Packing Group III (PG III)—These materials are moderately toxic and must be stored away from contact with food items.

Division 6.2—An *etiologic agent* is "a viable microorganism, or its toxin, which causes or may cause human disease." Such agents include infected living tissue and microbiological materials.

Class 7—Radioactive materials. Radioactive materials are those that emit nuclear radiation. They are classified into three groups according to the controls needed to provide adequate safety during transportation.

Fissile Class I materials are the safest of these substances, do not require "nuclear criticality safety controls" during transportation, and may be shipped together in an unlimited number of packages.

Fissile Class II substances are more dangerous and can only be shipped in limited amounts when packages are shipped together.

Fissile Class III materials must be controlled to provide nuclear criticality safety in transportation.

Class 8—Corrosive materials. The DOT defines a *corrosive material* as "a liquid or solid that causes visible destruction or irreversible alterations in human skin tissue at the site of contact, or in the case of leakage from its packaging, a liquid that has a severe corrosion rate on steel." A liquid is considered to have "a severe corrosion rate" if it dissolves more than 0.6 cm (0.25 in.) of a steel sample at 54°C (130°F) over 1 year.

Class 9—Miscellaneous hazardous materials. The materials in this class have anesthetic, noxious, or other similar properties.

Other Regulated Materials—This includes a wide variety of hazardous materials shipped in limited quantities. There are five classes designated ORM-A, ORM-B, ORM-C, ORMD, and ORM-E.

The ten hazardous material classes, along with their divisions, are shown in Table 13.2. Further details regarding components of the HMT appear in Table 13.3, and the instructions for selecting the proper shipping name for a hazardous material appear in Table 13.4.

13.3.3.4 Packing Groups

After assigning a hazardous material to one of the classes listed above, the degree of risk must be noted. Most hazardous materials are assigned to one of three packing groups (49 CFR part 173, subpart D):

- PG I—great danger
- PG II—medium danger
- PG III—minor danger

The packing group will determine the type of packaging to be used for a material intended for transport. The more hazardous a material, the more stringent are the packaging requirements. Packing groups are assigned to all hazardous materials except Classes 2, 7, and ORM-D materials.

13.3.3.5 Identification Numbers

DOT has assigned a four-digit identification number to each of the hazardous materials regulated for transportation. When appearing in shipping papers and other documentation, the letters "UN" or "NA" precedes these numbers. The UN numbers, such as UN1823 for solid sodium hydroxide, were assigned in cooperation with the United Nations and are used for international shipments. The NA numbers are not used for international transportation except to and from Canada (49 CFR §172.101).

TABLE 13.2
DOT Hazard Classes and Divisions for Hazardous Materials Transportation

Label Code	Label Name
1	Explosive
1.1	Explosive 1.1
1.2	Explosive 1.2
1.3	Explosive 1.3
1.4	Explosive 1.4
1.5	Explosive 1.5
1.6	Explosive 1.6
2.1	Flammable gas
2.2	Nonflammable gas
2.3	Poison gas
3	Flammable liquid
4.1	Flammable solid
4.2	Spontaneously combustible
4.3	Dangerous when wet
5.1	Oxidizer
5.2	Organic peroxide
6.1	Poison inhalation hazard
6.2	Infectious substance
7	Radioactive
8	Corrosive
9	Class 9
ORM-D	Other regulated materials

Source: Code of Federal Regulations, Volume 49, *Department of Transportation*, U.S. Government Printing Office, Washington, DC, 2004.

TABLE 13.3
Details of the HMT

Column 1: Symbols

Column 1 of the Table contains six symbols ("A," "D," "G," "I," and "W") as follows:

A — Restricts the application to materials offered or intended for transportation by aircraft, unless the material is a hazardous substance or a hazardous waste.

D — Identifies proper shipping names which are appropriate for describing materials for domestic transportation but may be inappropriate for international transportation under international regulations (e.g., IMO, ICAO). An alternate proper shipping name may be selected when either domestic or international transportation is involved.

G — Identifies proper shipping names for which one or more technical names of the hazardous material must be entered in parentheses, in association with the basic description. (see Sec. 172.203(k))

I — Identifies proper shipping names which are appropriate for describing materials in international transportation. An alternate proper shipping name may be selected when only domestic transportation is involved.

W — Restricts the application to materials intended for transportation by vessel, unless the material is a hazardous substance or a hazardous waste.

If none of the above symbols appears in the Table, the substance is regulated for all modes of transportation.

Column 2: Hazardous materials descriptions and proper shipping names.

Column 2 lists the hazardous materials descriptions and proper shipping names of materials designated as hazardous materials. Proper shipping names are limited to those shown in Roman type (not italics).

Continued

TABLE 13.3 (*Continued*)
Details of the HMT

Hazardous substances. Proper shipping names for hazardous substances are in Table 1 to Appendix A, 49 CFR Sec. 172.101.

Hazardous wastes. If the word "waste" is not included in the hazardous material description in Column 2 of the Table, the proper shipping name for a hazardous waste must include the word "Waste" preceding the proper shipping name of the material. For example, "Waste acetone" is an appropriate shipping name.

Mixtures and solutions. A mixture or solution not identified specifically by name, composed of a hazardous material identified in the Table by technical name and nonhazardous material, must be described using the proper shipping name of the hazardous material and the word "mixture" or "solution."

A mixture or solution not identified in the Table specifically by name, composed of two or more hazardous materials in the same hazard class, must be described using an appropriate shipping description (for example, "Flammable liquid, n.o.s."). The name that most appropriately describes the material shall be used; for example, an alcohol not listed by its technical name in the Table shall be described as "Alcohol, n.o.s.," rather than "Flammable liquid, n.o.s." Some mixtures are more appropriately described according to their application, such as "Coating solution," rather than by an n.o.s. entry. The technical names of at least two components most predominately contributing to the hazards of the mixture or solution may be required along with the proper shipping name.

Column 3: Hazard class or Division.

Column 3 contains a designation of the hazard class or division corresponding to each proper shipping name, or the word "Forbidden." A forbidden material cannot be transported. This prohibition does not apply if the material is diluted or stabilized.

Column 4: Identification number.

Column 4 lists the identification number assigned to each proper shipping name. Those preceded by the letters "UN" are associated with proper shipping names considered appropriate for international transportation as well as domestic transportation. Those preceded by the letters "NA" are associated with proper shipping names not recognized for international transportation, except to and from Canada.

Column 5: Packing group.

Column 5 specifies one or more packing groups assigned to a material corresponding to the proper shipping name and hazard class for that material. Class 2, Class 7, Division 6.2 (other than regulated medical wastes), and ORM-D materials do not have packing groups. Packing Groups I, II, and III indicate that the degree of danger presented by the material is either great, medium or minor, respectively.

Column 6: Labels.

Column 6 specifies codes which represent the hazard warning labels required for a package filled with a material conforming to the associated hazard class and proper shipping name, unless the package is otherwise excepted from labeling by 49 CFR part 173.

The first code indicates the primary hazard of the material. Additional label codes are indicative of subsidiary hazards. Provisions in Sec. 172.402 may require that additional labels other than that specified in Column 6 be affixed to the package.

Column 7: Special provisions

Column 7 specifies codes for special provisions applicable to hazardous materials. The requirements of that special provision are as set forth in 49 CFR Sec. 172.102.

Column 8: Packaging authorizations.

Columns 8A, 8B, and 8C specify the applicable sections for exceptions, nonbulk packaging requirements, and bulk packaging requirements, respectively, in part 173. Columns 8A, 8B, and 8C are completed in a manner which indicates that "Sec. 173" precedes the designated numerical entry. For example, the entry "202" in Column 8B associated with the proper shipping name "Gasoline" indicates that for this material conformance to nonbulk packaging requirements prescribed in Sec. 173.202 is required. When packaging requirements are specified, they are in addition to the standard requirements for all packagings prescribed in Sec. 173.24.

Column 9: Quantity limitations.

Columns 9A and 9B specify the maximum quantities that may be offered for transportation in one package by passenger-carrying aircraft or passenger-carrying rail car (Column 9A) or by cargo aircraft only (Column 9B), subject to the following:

- "Forbidden" means the material may not be offered for transportation.
- The quantity limitation is "net" except where otherwise specified.

TABLE 13.3 (*Continued*)
Details of the HMT

- When articles or devices are specifically listed by name, the net quantity limitation applies to the entire article (less packaging) rather than only to its hazardous components.
- A package offered or intended for transportation by aircraft and which is filled with a material forbidden on passenger-carrying aircraft but permitted on cargo aircraft only, or which exceeds the maximum net quantity authorized on passenger-carrying aircraft, shall be labeled with the CARGO AIRCRAFT ONLY label specified in 49 CFR Sec. 172.448.

Column 10: Vessel stowage requirements.

Column 10A (Vessel stowage) specifies the authorized stowage locations on board cargo and passenger vessels. Column 10B (Other provisions) specifies codes for stowage requirements for specific hazardous materials. The meaning of each code in Column 10B is set forth in Sec. 176.84 of this subchapter. Section 176.63 sets forth the physical requirements for each of the authorized locations listed in Column 10A.

Source: Code of Federal Regulations, Volume 49, *Department of Transportation*, U.S. Government Printing Office, Washington, DC, 2004.

TABLE 13.4
Instructions for Selecting Proper Shipping Names for Hazardous Materials

1. Apply the most specific name listed in the hazardous materials table (49 CFR section 172.101). The DOT ranks the order of specificity as follows:
   - Specific chemical name (e.g., "Sulfuric Acid")
   - Chemical group or family (e.g., "Acid, liquid, n.o.s.")
   - End use of material (e.g., "Pigment")
   - Generic end use (e.g., "Medicines, n.o.s.")
   - Hazard class (e.g., "Corrosive liquid, n.o.s.")

   When hazardous waste is being shipped, the word "waste" must be included in the shipping name.
2. There are to be no additions or deletions to a shipping name except as explicitly allowed by DOT. When the term "n.o.s." (not otherwise specified) is used, additional information must be included which will identify at least two major constituents present in the waste which contribute to the hazard class.
3. Once the most appropriate name has been selected, it is assigned a specific ID number, that is, UN or NA followed by four unique digits. The information compiled thus far, that is, proper shipping name, hazard class, and the UN or NA number, comprise the U.S. DOT "Basic Description."

   The DOT description must be in the following order:
   - Proper shipping name, hazard class, and UN or NA number
   - Additional information
4. The packing group Roman numeral is assigned.
5. Reportable Quantity (RQ) values are assigned, if applicable. The RQ value for a constituent in the material is listed in the Appendix to 49 CFR Sec. 172.101, List of Hazardous Substances and Reportable Quantities. If the weight of the constituent meets or exceeds the RQ, then RQ must be added to the proper shipping name.
6. The completed form for shipping a hazardous waste is as follows:
   - RQ, proper shipping name, hazard class, UN/NA number, packing group
   - Additional information

Source: Code of Federal Regulations, Volume 49, *Department of Transportation*, U.S. Government Printing Office, Washington, DC, 2004.

Most of the numbers and material shipping names represent specific materials. However, DOT also permits some cargo to be identified generically. For example, the identification number UN1760 applies to Corrosive Liquid, n.o.s. The last three letters indicate "not otherwise specified."

13.3.3.6 Placards, Labels, and Markings

Hazard communication under DOT regulations includes the requirement of alerting regulators, emergency response personnel, and the general public of the contents of a truck, railcar, or similar vehicle. For example, DOT requires that placards be installed on railroad tank cars, highway tank trucks, and other large transport vehicles (Figure 13.3). Similarly, labels must appear on packages of hazardous materials. Placards and labels both serve to warn the public and emergency response personnel of the hazards associated with a specific material. The primary difference between placards and labels is that placards are larger and must be displayed on transport vehicles and other bulk packagings.

Placarding is required for the transportation of all hazardous waste, with few exceptions. The generator must placard the vehicle or provide the transporter with the appropriate placards. Many transporters, however, provide their own placards. A placard is required on each side or end of the vehicle (Figure 13.4). The placards must meet size, durability, color, and other requirements, and must be securely affixed to the vehicle.

How a hazardous waste or material is marked, labeled, and placarded will depend upon whether it is contained in nonbulk or bulk packaging. Nonbulk packagings are those that:

- Have a maximum capacity of 450 L (119 gal) or less (for liquids)
- Have a maximum net mass of 400 kg (882 lb) or less (for solids)
- Have a water capacity of 454 kg (1000 lb) or less (for gases)

Bulk packagings are those that:

- Have a capacity greater than 450 L (for liquids)
- Have a net mass greater than 400 kg or a capacity greater than 450 L (for solids)
- Have a water capacity greater than 454 kg (for gases)

13.3.3.7 Hazard Warning Labels

Each package of hazardous material must provide two types of communications, that is, *markings* and *labels*. Hazard warning labels provide an immediate alert to any hazards associated or precautions needed with a material. Two types of labels are in use:

- Primary labels, which indicate the most hazardous property of a material
- Subsidiary labels, which indicate other, less hazardous properties

Hazard class labels are diamond-shaped and indicate the hazard class of the material being shipped (e.g., flammable liquid). Primary labels include the appropriate hazard class or division number at the bottom, whereas subsidiary labels do not (Figure 13.5). In certain cases, both primary and subsidiary hazards must be labeled (e.g., a flammable liquid that is also poisonous). DOT also specifies certain special precaution labels, intended to indicate an extra hazard or precaution to be followed during transportation. Examples include the "Dangerous When Wet" label for materials that have water-reactive properties. The HMT (49 CFR 172.101) specifies the type of label required for a waste. Labels should be attached to at least two sides, with one near the opening point of the container. Hazardous material warning labels are listed in Figure 13.6.

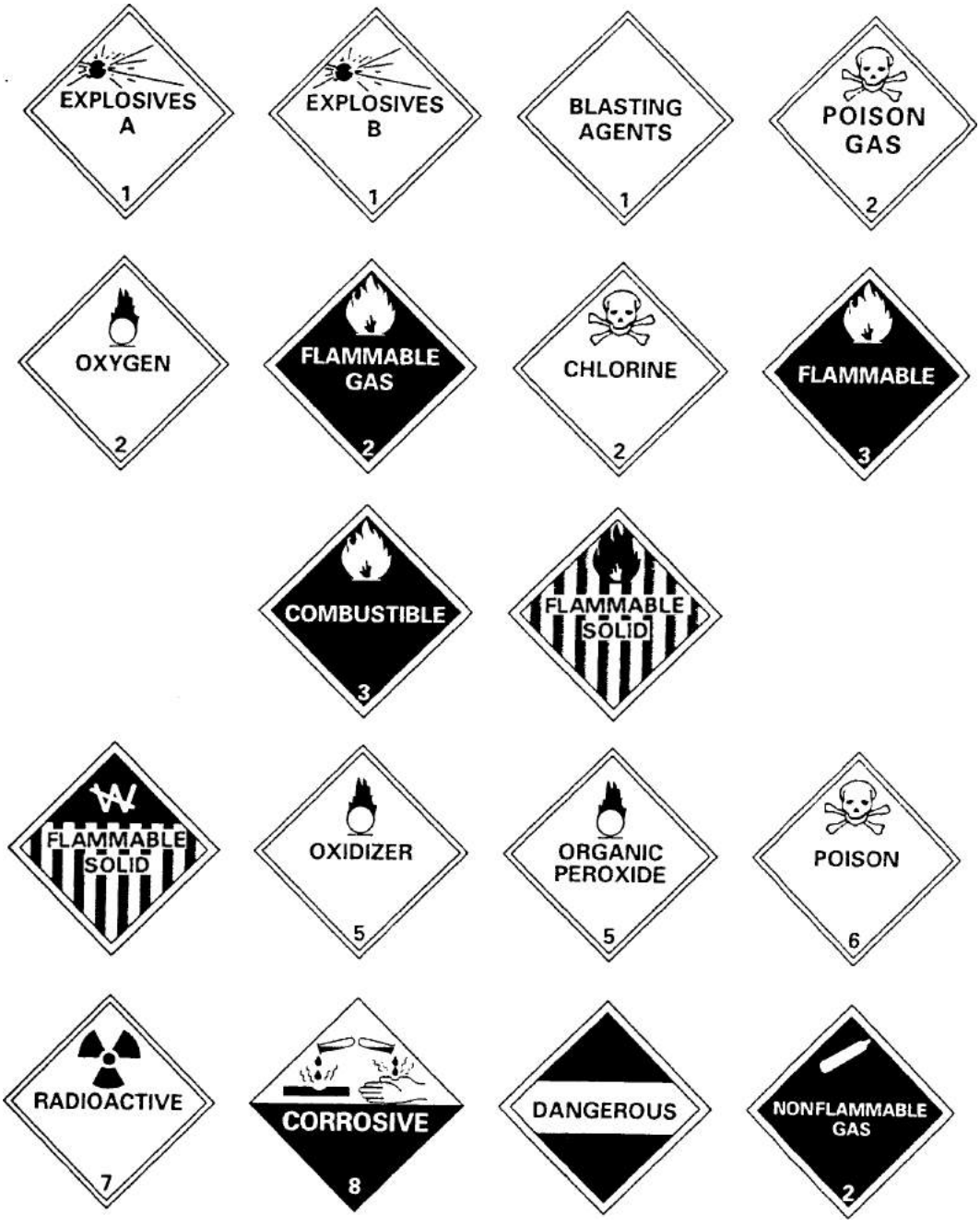


FIGURE 13.3 Types of placards required for transportation of hazardous materials.

13.3.3.8 Marking

Marking involves placing one or more of the following on the outside of a shipping container: the descriptive name, proper shipping name, hazard class, identification number, instructions, cautions, and weight. Markings must be durable, in English, on a background of sharply contrasting color, and away from other markings.



FIGURE 13.4 A placard is required on each side and end of the vehicle.



FIGURE 13.5 Primary and subsidiary labels for hazardous materials.

13.3.3.8.1 Nonbulk Markings

The proper markings for nonbulk hazardous materials include (Figure 13.7):

- Proper shipping name
- ID number of the material
- Consignee's or consignor's name and address

Other markings may be required depending on the type of material transported. For example:

- Packagings that contain materials designated "poisonous by inhalation" must be marked "INHALATION HAZARD."
- Packagings that contain a consumer commodity must be marked "ORM-D" immediately following the shipping name.

13.3.3.8.2 Bulk Markings

All bulk packagings must be marked with the ID number of the material. This is displayed across the primary hazard placard. Placement of the ID number depends on the type of packaging. For example, if the packaging has a capacity of 3785 L (1000 gal) or more and is a tube-trailer vehicle, the number must be displayed on each side and each end of the packaging. If the packaging has a capacity of less than 3785 L, the number must be displayed on two opposite sides. Additional markings may be required depending on the packaging and the material being transported.

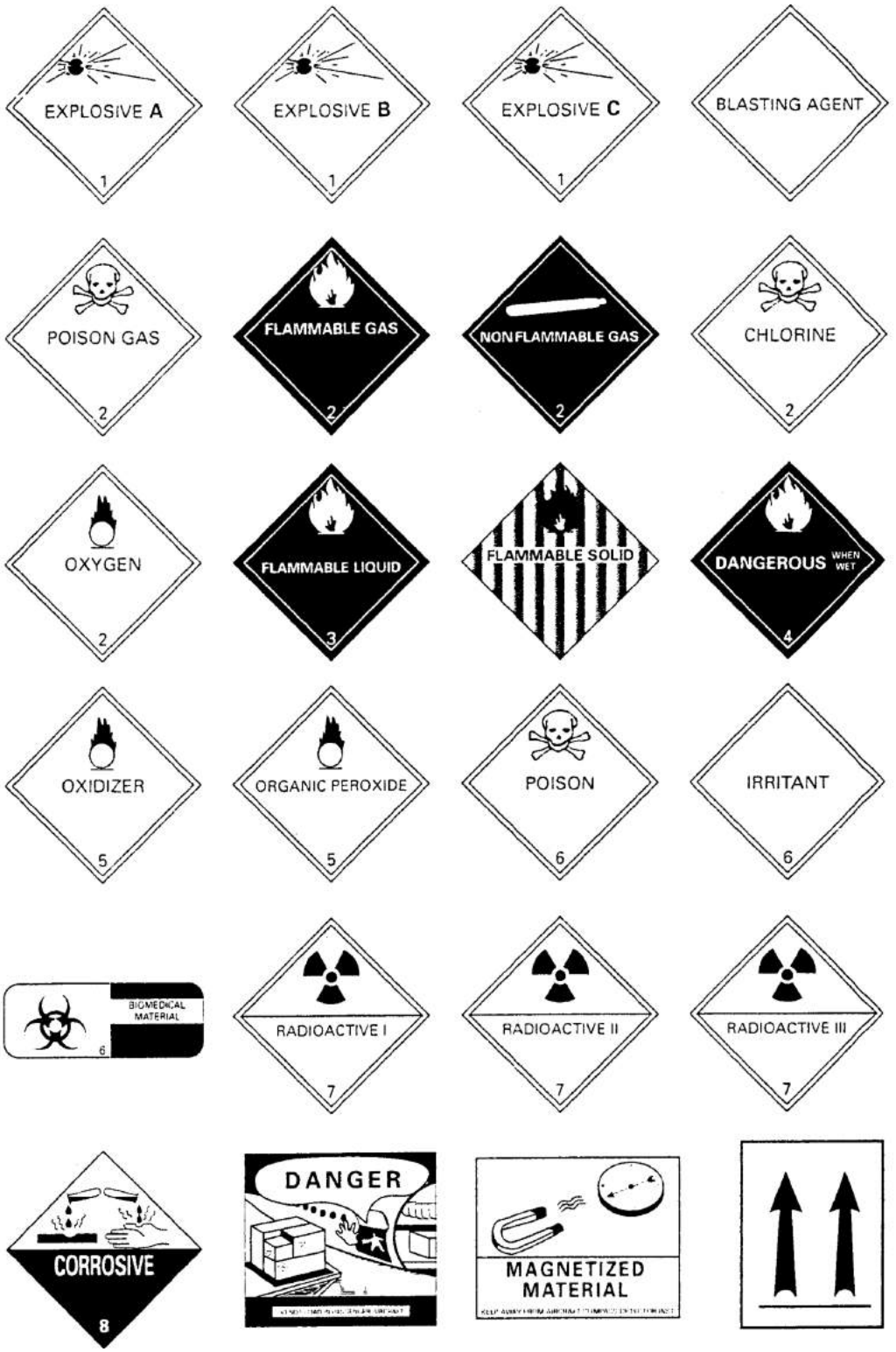


FIGURE 13.6 Hazardous materials warning labels.

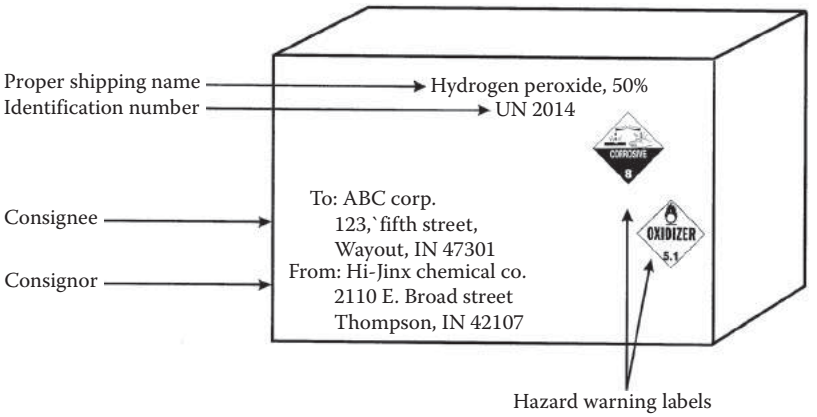


FIGURE 13.7 Markings for nonbulk hazardous materials.

13.3.3.9 Packaging

Two approaches are available for packaging shipments of hazardous waste. In the first approach, the generator can check with the TSD facility to determine the packaging the latter expects for a particular waste. The TSDF must recommend using a specific DOT specification packaging. The second approach is to determine the requirements directly from DOT regulations. Most hazardous waste will be contained in open- or closed-head drums or in bulk boxes.

The specific section for packaging a particular material is found by reference to column 8 of the HMT. In column 8, three subcolumns occur, indicating the specific sections in part 173 where the requirements are located for Exceptions (Column 8A), Nonbulk packaging (Column 8B), and Bulk packaging (Column 8C). Each of these columns is set up such that part 173 is the initial source, followed by the more specific subpart. For example, the entry "213" in column 8B associated with shipping name "ammonium chloride" indicates that for nonbulk packaging, the requirements of 49 CFR 173.213 must be followed. Whenever packaging requirements are specified, these are in addition to the standard requirements for all packaging described in part 173.

13.3.3.9.1 Examples of packaging

1. *Nonbulk packaging for liquid hazardous materials in PG I (section 173.201)*

DOT requirements are specific and stringent regarding selection of appropriate packaging material for a hazardous article. For example, when a liquid hazardous material is packaged under certain DOT sections, only nonbulk packagings may be used in transportation.

Packaging must conform to the general requirements of part 173, part 178, and §172.101 of the HMT. The following combination packagings are authorized for liquid hazardous materials in Packing Group I:

Outer packagings	
Steel drum	1A1 or 1A2
Aluminum drum	1B1 or 1B2
Metal drum other than steel or aluminum	1N1 or 1N2
Plywood drum	1D
Fiber drum	1G
Plastic drum	1H1 or 1H2
Steel jerrican	3A1 or 3A2
Plastic jerrican	3H1 or 3H2
Aluminum jerrican	3B1 or 3B2
Steel box	4A

Aluminum box	4B
Natural wood box	4C1 or 4C2
Plywood box	4D
Reconstituted wood box	4F
Fiberboard box	4G
Expanded plastic box	4H1
Solid plastic box	4H2

Inner packagings
Glass or earthenware receptacles
Plastic receptacles
Metal receptacles
Glass ampules

Except for transportation by passenger aircraft, the following single packagings are authorized:

Steel drum	1A1 or 1A2
Aluminum drum	1B1 or 1B2
Metal drum other than steel or aluminum	1N1 or 1N2
Plastic drum	1H1 or 1H2
Steel jerrican	3A1 or 3A2
Plastic jerrican	3H1 or 3H2
Aluminum jerrican	3B1 or 3B2
Plastic receptacle in steel, aluminum, fiber, or plastic drum	6HA1, 6HB1, 6HG1, 6HH1
Plastic receptacle in steel, aluminum, wooden, plywood, or fiberboard box	6HA2, 6HB2, 6HC, 6HD2, or 6HG2
Glass, porcelain, or stoneware in steel, aluminum, or fiber drum	6PA1, 6PB1, or 6PG1
Glass, porcelain, or stoneware in steel, aluminum, wooden, or fiberboard box	6PA2, 6PB2, 6PC, or 6PG2
Glass, porcelain, or stoneware in solid or expanded plastic packaging	6PH1 or 6PH2

2. Performance-oriented packaging

Performance-oriented packaging (POP) was introduced into international packaging regulations in 1989. After 1991, POP was phased into the domestic regulations (49 CFR) and has been in effect since 1996. All nonbulk quantities of hazardous materials are required to be shipped in POP. By definition, POP is packaging that meets design qualification testing. Package designs are subjected to drop, stack, vibration, leakproofness, and hydrostatic tests based on UN recommendations. A United Nations Certification marking may be applied to the packaging once the design passes the performance tests (Figure 13.8).

Identification codes are included in the standards for packaging in 49 CFR 178.504 through 178.523. The manufacturer must mark all packaging to indicate that it meets a UN standard, with other DOT-specified marks. The markings must be durable, legible, and placed in a readily visible location. Packaging conforming to a UN standard must be marked as follows:

1. The United Nations symbol as illustrated in Figure 13.8 or the letters "UN." A packaging identification code designating the type of packaging and material of construction.
2. A letter identifying the performance standard under which the packaging design type has been successfully tested, as follows:
   X for packagings meeting PG I, II, and III tests
   Y for packagings meeting PG II and III tests
   Z for packagings only meeting PG III tests

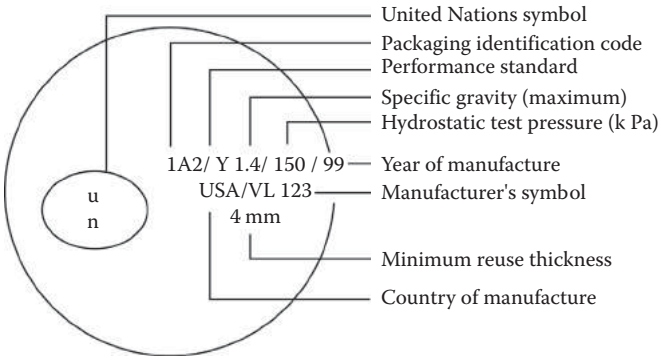


FIGURE 13.8 Performance-oriented packaging label.

3. A designation of the specific gravity or mass for which the packaging design type has been tested.
4. The last two digits of the year of manufacture. Packagings of types 1H and 3H must also be marked with month of manufacture.
5. The state authorizing allocation of the mark. The letters "USA" indicate that the packaging is manufactured and marked in the United States.
6. The name and address or symbol of the manufacturer or approval agency certifying compliance with DOT regulations.
7. For metal or plastic drums or jerricans intended for reuse or reconditioning, the thickness of the packaging material is expressed in millimeters.
8. The rated capacity of the packaging, expressed in liters, may also be marked.

3. *Performance-oriented packaging standards for nonbulk packagings*
Identification codes for designating nonbulk packagings consist of the following (section 178.502):

A numeral indicating the kind of packaging:

1. Drum
2. Wooden barrel
3. Jerrican
4. Box
5. Bag
6. Composite packaging
7. Pressure receptacle

A capital letter indicating the material of construction:

A Steel
B Aluminum
C Natural wood
D Plywood
F Reconstituted wood
G Fiberboard
H Plastic
L Textile
M Paper and multiwall
N Metal (other than steel or aluminum)
P Glass, porcelain, or stoneware

A third numeral provides additional packaging details. For example, for steel drums (1A), "1" indicates a nonremovable head drum (i.e., 1A1) and "2" indicates a removable head drum (1A2).

All of the above precautions and requirements have facilitated safe transportation of hazardous materials and hazardous wastes; however, industry has expressed some frustration over the regulations. DOT states that (49 CFR 173.24):

> Each package used for the shipment of hazardous materials under this subchapter shall be designed, constructed, maintained, filled, its contents so limited, and closed, so that under conditions normally incident to transportation—Except as otherwise provided in this subchapter, there will be no identifiable... release of hazardous materials to the environment.

The problem with the above requirement is that two different drums may pass the same POP tests; however, only one might survive a lengthy journey intact. Some argue that the problem is not with performance-based standards but with the actual tests, which do not adequately mimic real-world transportation conditions in the United States. The distance factor of an average transcontinental shipment multiplies the real-world problems of abrasion between drums, vibration, shock, puncture, external corrosion, and so on. Current POP tests do not address these problems.

13.4 EMERGENCY RESPONSE INFORMATION

The shipper is required to provide emergency response information for each hazardous material listed on the shipping paper (e.g., Bill of Lading). Information must include:

- Description of the hazardous material
- Immediate hazards to health
- Risks of fire or explosion
- Immediate precautions to be taken in the event of an incident
- Immediate methods for handling small or large fires
- Initial methods for handling spills or leaks
- Preliminary first aid measures

This information can be listed directly on the shipping papers. The shipper can also attach a copy of the appropriate guide from the DOT's *North American Emergency Response Guidebook* (U.S. DOT 2012) (Figure 13.9).

13.5 SEGREGATION (49 CFR PART 177, SUBPART C)

The generator and transporters must be aware of potential hazards if incompatible materials are loaded together. Certain materials may initiate reactions that can be dangerous to public health and property. To assist with safe loading and transport, DOT created the *Segregation Table* (Figure 13.10), which informs all parties as to which classes and divisions can be loaded together safely and which cannot.

The shipper is to locate the hazard classes or divisions of the material being transported, one in the vertical column, the other in the horizontal row. The codes at the intersection are defined as follows:

Code	Meaning
Blank	The materials may be loaded or stored together
X	The materials may not be loaded together
O	The materials may not be loaded together unless separated so that, in the event of leakage, there will be no mixing of materials
*	Class 1 (explosive) materials must be segregated in accordance with the Compatibility Table
A	An oxidizer may be loaded with Division 1.1 or 1.5 materials

If the classes or divisions are not listed in the table, there are no restrictions.



FIGURE 13.9 The North American Emergency Response Guidebook.

13.6 HAZARDOUS MATERIALS INCIDENTS (49 CFR PART 171)

From 2003 to 2012, hazardous waste incidents on the highway predominated over those for all other modes of transportation (Table 13.5). The number of reported incidents in 2011 and 2012 has increased markedly from those in 2005–2006. The total number of highway hazardous waste incidents totaled 1536 from 2003 to 2011. Rail incidents were second in number over this period, with incidents ranging between 7 and 24 per year. Two air-related incidents were reported over the same period (U.S. DOT 2013).

Carriers of hazardous materials are required to report certain unintentional releases that occur during transport (Figures 13.11 and 13.12). The requirements appear in 49 CFR, §§171.15 and 171.16. Requirements also appear in 49 CFR parts 174 to 177 that include reporting of incidents (49 CFR §§174.45 [rail], 175.45 [air], 176.48 [vessel], and 177.807 [highway]). Two phases of incident reporting are required in the regulations. Sec. 171.15 covers immediate telephone notification following an incident and part 171.16 outlines written reporting procedures (e.g., Incident Report Form 5800.1).

13.6.1 Immediate Notice of Certain Hazardous Materials Incidents (49 CFR 171.15)

Telephone notices are required immediately whenever there is a significant hazardous materials incident during transportation, during the course of transportation (including loading, unloading, and temporary storage), or storage related to transportation, in which the following occur:

1. As a direct result of hazardous materials:
   - A person is killed.
   - A person receives injuries requiring hospitalization.
   - Estimated carrier or other property damage exceeds $50,000.
   - An evacuation of the general public occurs lasting one or more hours.

SEGREGATION TABLE FOR HAZARDOUS MATERIALS

Class or division		Notes	1.1 1.2	1.3	1.4	1.5	1.6	2.1	2.2	2.3 gas zone A	2.3 gas Zone B	3	4.1	4.2	4.3	5.1	5.2	6.1 liquids PG I zone A	7	8 liquids only
Explosives	1.1 and 1.2	A	*	*	*	*	*	X	X	X	X	X	X	X	X	X	X	X	X	X
Explosives	1.3		*	*	*	*	*	X		X	X	X		X	X	X	X	X		X
Explosives	1.4		*	*	*	*	*	O		O	O	O		O				O		O
Very insensitive explosives.	1.5	A	*	*	*	*	*	X	X	X	X	X	X	X	X	X	X	X	X	X
Extremely insensitive explosives.	1.6		*	*	*	*	*													
Flammable gases	2.1		X	X	O	X				X	O							O	O	
Non-toxic, non-flammable gases.	2.2		X			X														
Poisonous gas Zone A	2.3		X	X	O	X		X				X	X	X	X	X	X			X
Poisonous gas Zone B	2.3		X	X	O	X		O				O	O	O	O	O	O			O
Flammable liquids	3		X	X	O	X				X	O					O		X		
Flammable solids	4.1		X			X				X	O							X		O
Spontaneously combustible materials.	4.2		X	X	O	X				X	O							X		X
Dangerous when wet materials.	4.3		X	X		X				X	O							X		O
Oxidizers	5.1	A	X	X		X				X	O	O						X		O
Organic peroxides	5.2		X	X		X				X	O							X		O
Poisonous liquids PG I Zone A.	6.1		X	X	O	X		O				X	X	X	X	X	X			X
Radioactive materials	7		X			X		O												
Corrosive liquids	8		X	X	O	X				X	O		O	X	O	O	O	X		

FIGURE 13.10 Segregation table for hazardous materials. (From Code of Federal Regulations, Volume 49, *Department of Transportation*, U.S. Government Printing Office, Washington, DC, 2004.)

TABLE 13.5
Hazardous Waste Incidents in the United States Listed By Mode and Incident Year

Mode of Transportation	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Total
Air	1				1						2
Highway	115	115	97	123	159	161	182	172	216	196	1536
Rail	24	24	15	12	16	7	22	13	16	7	156
Water			2		2		1	1			6
Total	140	139	114	135	178	168	205	186	232	203	1700

Source: U.S. Department of Transportation, 2013.



FIGURE 13.11 Hazardous materials incident on the highway.



FIGURE 13.12 Aftermath of a hazardous materials railway incident.

- One or more major transportation arteries or facilities are closed or shut down for one hour or more.
- The operational flight pattern of an aircraft is altered.

2. Fire, breakage, spillage, or suspected radioactive contamination occurs (see also 49 CFR 174.45, 175.45, 176.48, and 177.807).
3. Fire, breakage, spillage, or suspected contamination occurs involving shipment of infectious substances (etiologic agents).
4. Release of a marine pollutant exceeding 450 L (119 gal) for liquids or 400 kg (882 lb) for solids.
5. A situation exists (e.g., a danger to life exists at the scene of the incident) such that, in the judgment of the carrier, it should be reported to DOT.

Each notice must be provided to the National Response Center by telephone. Notice involving infectious substances (etiologic agents) may instead be given to the U.S. Centers for Disease Control, U.S. Public Health Service, Atlanta, GA. Each notice must include:

- Name of reporter and of carrier
- Telephone number where reporter can be contacted
- Date, time, and location of incident
- Extent of any injuries
- Classification, name, and quantity of hazardous materials involved, if such information is available
- Type of incident
- Whether a continuing danger to life exists at the scene

The Nuclear Regulatory Commission (NRC) is staffed around the clock. The Coast Guard Duty Officer notifies concerned organizations including the Research and Special Programs Administration (RSPA), modal administrations, CHEMTREC (a U.S. and Canadian chemical tracking system), and the National Transportation Safety Board to ensure prompt resolution of serious incidents. The telephone notices received by the NRC are accumulated and transmitted daily to the Hazardous Materials Information System (HMIS) host computer that is maintained at the Volpe National Transportation System Center in Cambridge, MA. At the Volpe Center, the information is made available on the same day in a telephone database.

13.6.2 Hazardous Materials Incidents Reports (49 CFR 171.16)

Within 30 days of the hazardous materials incident, the carrier must report in writing to the DOT on Form F 5800.1 (Figure 13.13). Each incident that occurred during transportation (including loading, unloading, and temporary storage) or any unintentional release of hazardous materials from a package must be reported. The report identifies the mode of transportation involved, name of reporting carrier, shipment information, results of the incident, hazardous materials involved, nature of packaging, cause of failure, and narrative description of the incident. This information is available in the incident database approximately 3 months after receipt of the report by RSPA.

If a report pertains to a hazardous waste discharge, a copy of the Uniform Hazardous Waste Manifest must be attached to the report. Also, an estimate of the quantity of the waste removed from the scene, the name and address of the facility to which it was taken, and the manner of disposition of any removed waste (e.g., treated off-site) must be entered in the report form (Form F 5800.1). The report is to be sent to the Research and Special Programs Administration, Department of Transportation, Washington, DC. A copy of the report must be retained for two years at the carrier's office.

The HMIS is a computerized information management system containing data that ensure safe transportation of hazardous materials by air, highway, rail, and water. The HMIS is the primary source of national data for the federal, state, and local governmental agencies responsible for the

DEPARTMENT OF TRANSPORTATION
HAZARDOUS MATERIALS INCIDENT REPORT

Form Approved OMB No. 2137-0039

INSTRUCTIONS: Submit this report in duplicate to the Information Systems Manager, Office of Hazardous Materials Transportation, DHM-63, Research and Special Programs Administration, U.S. Department of Transportation, Washington, D.C. 20590. If space provided for any item is inadequate, complete that item under Section IX, keying to the entry number being completed. Copies of this form, in limited quantities, may be obtained from the Information Systems Manager, Office of Hazardous Materials Transportation. Additional copies in this prescribed format may be reproduced and used, if on the same size and kind of paper.

I. MODE, DATE, AND LOCATION OF INCIDENT

1. MODE OF TRANSPORTATION: ☐ AIR ☐ HIGHWAY ☐ RAIL ☐ WATER ☐ OTHER _____

2. DATE AND TIME OF INCIDENT (Use Military Time, e.g. 8:30 am = 0830, noon = 1200, 6 pm = 1800, midnight = 2400). Date: ____/____/____ TIME: _____

3. LOCATION OF INCIDENT (Include airport name in ROUTES/STREET if incident occurs at an airport.)

CITY: _____ STATE: _____

COUNTY: _____ ROUTE/STREET: _____

II. DESCRIPTION OF CARRIER, COMPANY, OR INDIVIDUAL REPORTING

4. FULL NAME	5. ADDRESS (Principal place of business)

6. LIST YOUR OMC MOTOR CARRIER CENSUS NUMBER, REPORTING RAILROAD ALPHABETIC CODE, MERCHANT VESSEL NAME AND ID NUMBER OR OTHER REPORTING CODE OR NUMBER.

III. SHIPMENT INFORMATION (From Shipping Paper or Packaging)

7. SHIPPER NAME AND ADDRESS (Principal place of business)	8. CONSIGNEE NAME AND ADDRESS (Principal place of business)
9. ORIGIN ADDRESS (If different from Shipper address)	10. DESTINATION ADDRESS (If different from Consignee address)

11. SHIPPING PAPER/WAYBILL IDENTIFICATION NO.

IV. HAZARDOUS MATERIAL(S) SPILLED (NOTE: REFERENCE 49 CFR SECTION 172.101)

12. PROPER SHIPPING NAME	13. CHEMICAL/TRADE NAME	14. HAZARD CLASS	15. IDENTIFICATION NUMBER (e.g. UN 2764, NA 2020)

16. IS MATERIAL A HAZARDOUS SUBSTANCE? ☐ YES ☐ NO

17. WAS THE RQ MET? ☐ YES ☐ NO

V. CONSEQUENCES OF INCIDENT, DUE TO THE HAZARDOUS MATERIAL.

18. ESTIMATED QUANTITY HAZARDOUS MATERIAL RELEASED (Include units of measurement)	19. FATALITIES	20. HOSPITALIZED INJURIES	21. NON-HOSPITALIZED INJURIES
22. NUMBER OF PEOPLE EVACUATED			

23. ESTIMATED DOLLAR AMOUNT OF LOSS AND/OR PROPERTY DAMAGE, INCLUDING COST OF DECONTAMINATION OR CLEANUP (Round off in dollars)

A. PRODUCT LOSS	B. CARRIER DAMAGE	C. PUBLIC/PRIVATE PROPERTY DAMAGE	D. DECONTAMINATION/ CLEANUP	E. OTHER

24. CONSEQUENCES ASSOCIATED WITH THE INCIDENT: ☐ VAPOR (GAS) DISPERSION ☐ MATERIAL ENTERED WATERWAY/SEWER
☐ SPILLAGE ☐ FIRE ☐ EXPLOSION ☐ ENVIRONMENTAL DAMAGE ☐ NONE ☐ OTHER: _____

VI. TRANSPORT ENVIRONMENT

25. INDICATE TYPE(S) OF VEHICLE(S) INVOLVED: ☐ CARGO TANK ☐ VAN TRUCK/TRAILER ☐ FLAT BED TRUCK/TRAILER
☐ TANK CAR ☐ RAIL CAR ☐ TOFC/COFC ☐ AIRCRAFT ☐ BARGE ☐ SHIP ☐ OTHER: _____

26. TRANSPORTATION PHASE DURING WHICH INCIDENT OCCURRED OR WAS DISCOVERED:
☐ EN ROUTE BETWEEN ORIGIN/DESTINATION ☐ LOADING ☐ UNLOADING ☐ TEMPORARY STORAGE/TERMINAL

27. LAND USE AT INCIDENT SITE: ☐ INDUSTRIAL ☐ COMMERCIAL ☐ RESIDENTIAL ☐ AGRICULTURAL ☐ UNDEVELOPED

28. COMMUNITY TYPE AT SITE: ☐ URBAN ☐ SUBURBAN ☐ RURAL

29. WAS THE SPILL THE RESULT OF A VEHICLE ACCIDENT/DERAILMENT? ☐ YES ☐ NO
IF YES AND APPLICABLE, ANSWER PARTS A THRU C.

A. ESTIMATED SPEED:	B. HIGHWAY TYPE: ☐ DIVIDED/LIMITED ACCESS ☐ UNDIVIDED	C. TOTAL NUMBER OF LANES: ☐ ONE ☐ THREE ☐ TWO ☐ FOUR OR MORE	SPACE FOR DOT USE ONLY

FORM DOT F 5800.1 (Rev. 10/94) Supersedes DOT F 5800.1 (10/70) (9/1/76) 130-F (Rev. 10/94) THIS FORM MAY BE REPRODUCED

FIGURE 13.13 DOT form 5800.1, Incident Report.

VII. PACKAGING INFORMATION: If the package is overpacked (consists of several packages, e.g. glass jars within a fiberboard box), begin with Column A for information on the innermost package.

ITEM	A	B	C
30. TYPE OF PACKAGING, INCLUDING INNER RECEPTACLES (e.g. Steel drum, tank car)			
31. CAPACITY OR WEIGHT PER UNIT PACKAGE (e.g. 55 gallons, 65 lbs.)			
32. NUMBER OF PACKAGES OF SAME TYPE WHICH FAILED IN IDENTICAL MANNER			
33. NUMBER OF PACKAGES OF SAME TYPE IN SHIPMENT			
34. PACKAGE SPECIFICATION IDENTIFICATION (e.g. DOT 17E, DOT 105A100, UN 1A1 or none)			
35. ANY OTHER PACKAGING MARKINGS (e.g. STC, 18/16-55-88, Y1.4/150/87)			
36. NAME AND ADDRESS, SYMBOL OR REGISTRATION NUMBER OF PACKAGING MANUFACTURER			
37. SERIAL NUMBER OF CYLINDERS, PORTABLE TANKS, CARGO TANKS, TANK CARS			
38. TYPE OF LABELING OR PLACARDING APPLIED			
39. IF RECONDITIONED OR REQUALIFIED — A. REGISTRATION NUMBER OR SYMBOL			
39. IF RECONDITIONED OR REQUALIFIED — B. DATE OF LAST TEST OR INSPECTION			
40. EXEMPTION/APPROVAL/COMPETENT AUTHORITY NUMBER, IF APPLICABLE (e.g. DOT E1012)			

VIII. DESCRIPTION OF PACKAGING FAILURE: Check all applicable boxes for the package(s) identified above.

41. ACTION CONTRIBUTING TO PACKAGING FAILURE

	A	B	C		A	B	C	
a.	☐	☐	☐	TRANSPORT VEHICLE COLLISION	☐	☐	☐	CORROSION
b.	☐	☐	☐	TRANSPORT VEHICLE OVERTURN	☐	☐	☐	METAL FATIGUE
c.	☐	☐	☐	OVERLOADING/OVERFILLING	☐	☐	☐	FRICTION/RUBBING
d.	☐	☐	☐	LOOSE FITTINGS, VALVES	☐	☐	☐	FIRE/HEAT
e.	☐	☐	☐	DEFECTIVE FITTINGS, VALVES	☐	☐	☐	FREEZING
f.	☐	☐	☐	DROPPED	☐	☐	☐	VENTING
g.	☐	☐	☐	STRUCK/RAMMED	☐	☐	☐	VANDALISM
h.	☐	☐	☐	IMPROPER LOADING	☐	☐	☐	INCOMPATIBLE MATERIALS
i	☐	☐	☐	IMPROPER BLOCKING	☐	☐	☐	OTHER _____

42. OBJECT CAUSING FAILURE

	A	B	C	
a.	☐	☐	☐	OTHER FREIGHT
b.	☐	☐	☐	FORKLIFT
c.	☐	☐	☐	NAIL/PROTRUSION
d.	☐	☐	☐	OTHER TRANSPORT VEHICLE
e.	☐	☐	☐	WATER/OTHER LIQUID
f.	☐	☐	☐	GROUND/FLOOR/ROADWAY
g.	☐	☐	☐	ROADSIDE OBSTACLE
h.	☐	☐	☐	NONE
i.	☐	☐	☐	OTHER _____

43. HOW PACKAGE(S) FAILED

	A	B	C	
a.	☐	☐	☐	PUNCTURED
b.	☐	☐	☐	CRACKED
c.	☐	☐	☐	BURST/INTERNAL PRESSURE
d.	☐	☐	☐	RIPPED
e.	☐	☐	☐	CRUSHED
f.	☐	☐	☐	RUBBED/ABRADED
g.	☐	☐	☐	RUPTURED
h.	☐	☐	☐	OTHER _____

44. PACKAGE AREA THAT FAILED

	A	B	C	
a.	☐	☐	☐	END, FORWARD
b.	☐	☐	☐	END, REAR
c.	☐	☐	☐	SIDE, RIGHT
d.	☐	☐	☐	SIDE, LEFT
e.	☐	☐	☐	TOP
f.	☐	☐	☐	BOTTOM
g.	☐	☐	☐	CENTER
h.	☐	☐	☐	OTHER _____

45. WHAT FAILED ON PACKAGE(S)

	A	B	C	
a.	☐	☐	☐	BASIC PACKAGE MATERIAL
b.	☐	☐	☐	FITTING/VALVE
c.	☐	☐	☐	CLOSURE
d.	☐	☐	☐	CHIME
e.	☐	☐	☐	WELD/SEAM
f.	☐	☐	☐	HOSE/PIPING
g.	☐	☐	☐	INNER LINER
h.	☐	☐	☐	OTHER _____

IX. DESCRIPTION OF EVENTS: Describe the sequence of events that led to incident, action taken at time discovered, and action taken to prevent future incidents. Include any recommendations to improve packaging, handling, or transportation of hazardous materials. Photographs and diagrams should be submitted when necessary for clarification. ATTACH A COPY OF THE HAZARDOUS WASTE MANIFEST FOR INCIDENTS INVOLVING HAZARDOUS WASTE. Continue on additional sheets if necessary.

46. NAME OF PERSON RESPONSIBLE FOR PREPARING REPORT	47. SIGNATURE	
48. TITLE OF PERSON RESPONSIBLE FOR PREPARING REPORT	49. TELEPHONE NUMBER (Area Code)	50. DATE REPORT SIGNED

FIGURE 13.13 (*Continued*) DOT form 5800.1, Incident Report.

safety of hazardous materials transportation. The industry, news media, and the general public are also entitled to use data from the system. The major components of the HMIS concern (DOT, 2004):

- Incidents involving the interstate transportation of hazardous materials by various transportation modes
- Exemptions issued to hazardous materials regulations
- Interpretations of the regulations issued by the RSPA, as requested by concerned parties
- Approvals of specialized container manufacturers, reconditioners, and testers
- Compliance activities including inspections and enforcement proceedings
- Registrations filed by certain carriers, shippers, and other providers of hazardous materials

13.A.1 APPENDIX: HAZARDOUS WASTE MANAGEMENT SCENARIOS

13.A.1.1 Introduction

After reading each scenario, discuss what, if any, violations may have occurred. How would these violations be best addressed (i.e., via changes in engineering design, a modified storage or disposal program, some use of common sense, etc.)? These are open-ended situations.

13.A.1.2 Scenarios

1. A driver has spilled hazardous waste (baghouse dust, K061) on to the road within a secure land disposal facility (Figure 13.A.1). The driver dismisses the concerns of the inspector, stating the amount released was a "minimal" quantity of hazardous waste.
2. A company truck is used to transport bulk hazardous waste to a disposal facility. What is wrong with this picture (Figure 13.A.2)?
3. A machining facility uses trichloroethylene (TCE) to degrease machine parts. During lunch breaks and after work, four of the plant employees enjoy playing paintball in the back of company property, alongside Sparkling River (Figure 13.A.3). They recently moved drums, in Moe's pickup truck, to the river's edge to use as barriers for the game. All drums are at least half-filled with TCE. One employee occasionally uses the TCE-laden drums for target practice with live ammunition. (To repeat from Chapter 12, *these are true stories*.)

Based on a neighbor's complaint, an inspector visits the site and notices paint-spattered drums on the riverside, both rusting and punctured by bullet holes. She instructs the company's plant manager to return the drums to the facility immediately. Later that afternoon, Moe and Larry load the ten drums on to Moe's truck, where they are returned to the plant floor for storage.



FIGURE 13.A.1 Hazardous waste spilled on road adjacent to a secure landfill.



FIGURE 13.A.2 Truck transporting solid hazardous waste.

Back at the plant site, the inspector notices an underground storage tank vent line. The plant manager acknowledges that a UST is on the premises; however, he declares that it does not store hazardous waste, just mop water from cleaning shop floors at the end of the working day. After some questioning, however, the manager acknowledges that spills of TCE have occurred over the past few years, and TCE-contaminated mop water has been directed into the UST drain.



FIGURE 13.A.3 How *not* to manage drums of a listed hazardous waste.

13.A.1.3 Responses to Scenarios

1. (a) Regardless of quantity, this spill was cited as a "release to the environment" and was also a violation of the state operating permit, which required facility employees to regularly inspect their vehicles and document all inspections. The permitting issue was cited in the federal standards:

   > **Section 264.15 General inspection requirements.**
   > (a) The owner or operator must inspect his facility for malfunctions and deterioration, operator errors, and discharges which may be causing—or may lead to—(1) release of hazardous waste constituents to the environment or (2) a threat to human health. The owner or operator must conduct these inspections often enough to identify problems in time to correct them before they harm human health or the environment.

   (b) This vehicle was traveling solely on the property of the TSD facility, that is, from the stabilization unit to the secure landfill. If it had been traveling on a public road it would have also been subject to DOT regulations (49 CFR) for hazardous materials transportation.
2. According to the facility permit, transport vehicles "must be maintained in good condition."
   The truck bed shown in the photo has spaces that will allow some hazardous cargo to disperse to air and soil. This is a permit violation.
   In the preamble to subpart A of Standards Applicable to Transporters of Hazardous Waste (part 263):

   > In these regulations, EPA has expressly adopted certain regulations of the Department of Transportation (DOT) governing the transportation of hazardous materials. These regulations concern, among other things, labeling, marking, placarding, using proper containers, and reporting discharges. EPA has expressly adopted these regulations in order to satisfy its statutory obligation to promulgate regulations which are necessary to protect human health and the environment in the transportation of hazardous waste.

3. (a) The drums are leaking alongside and possibly into the river. This is a violation of the Clean Water Act.
   (b) Hazardous wastes are to be transported only in EPA-registered vehicles. Use of Moe's pickup truck for transport to and from the river is clearly unacceptable and is a violation of 40 CFR 262.12(c).
   (c) The truck will need to be de-contaminated.
   (d) Because TCE is a F001-listed hazardous waste, the contents of the entire UST, including the mop water, are also considered hazardous. The Mixture Rule, 40 CFR 261.3(b) and (d), states that hazardous waste mixed with nonhazardous waste constitutes hazardous waste.
   (e) The drums must be repacked into stable, nonrusting containers.

QUESTIONS

1. What are the differences, in terms of content, between the Bill of Lading for hazardous wastes and the Uniform Hazardous Waste Manifest? Who is responsible for initiating each document?
2. The uniform hazardous manifest is: (a) required under RCRA/HSWA, (b) to be completed where applicable by the waste generator, (c) to be utilized by all LQGs and SQGs, (d) essential in "cradle-to-grave" waste management, (e) all of the above.
3. The uniform hazardous waste manifest serves which of the following purposes? (a) certification of treatment and disposal, (b) tracking document for delivery to designated TSDF, (c) shipping document for hazardous materials per DOT regulations, (d) b and c only.
4. List the ten classes of DOT hazardous materials. Which of the classes do not contain divisions?
5. What is the purpose of a packing group? How many packing groups exist?
6. Which of the following is *not* one of DOT's hazard classes? (a) Class 1—explosive, (b) ORM-D, (c) ORM-F, (d) Class 9—miscellaneous material.
7. According to federal regulations, what is the primary purpose of transportation placards?
8. How do hazardous placards differ from labels and markings in terms of size, shape, and location to be affixed? Explain how the requirements for their use differ for bulk and nonbulk packaging.
9. For a truck transporting hazardous wastes, on which side(s) is (are) the placard(s) to be placed?
10. A citizen contacts the local emergency response agency with the following information from an overturned tank truck. Which information will best assist the agency in identifying its contents? (a) company name on the truck, (b) license plate number, (c) PG II, (d) UN 1272.
11. When shipping a truckload of 25 drums of the same hazardous material, what is the total number of drums that must be labeled?
12. What is the difference between primary and subsidiary hazard warning labels on nonbulk packages of hazardous waste?
13. What details can you provide about a container with the following information stamped on its base? (a) 1A2 UN X, (b) 4G UN Z.
14. The shipper is required to provide emergency response information for each hazardous material listed on the shipping papers (e.g., Bill of Lading). List the specific information that must be included on those papers.
15. Refer to the DOT waste compatibility table (Figure 13.10). State whether or not the following wastes be placed in the same shipment: (a) spent hydrochloric acid and a class 4.1 waste, (b) waste classes 1.1 and 4.1, (c) flammable gases and explosives.
16. Which of the following situations does *not* require an incident report involving hazardous materials to DOT? (a) a person is killed; (b) property damage exceeds $50,000; (c) a person is injured but does not require hospitalization; (d) fire, breakage, spillage, or suspected contamination involving shipment of a biohazardous material.

17. What is the name of the table that must be used to select the proper container for accumulation and transportation of hazardous waste?
18. Suppose a facility's hazardous waste is stored in a 55-gal metallic drum. Locate the regulation number where the drum is listed (i.e., which column?).
19. According to DOT regulations, containers used to accumulate and transport hazardous waste must be in good condition. In this context, what is the definition of "good condition"?
20. Refer to 49 CFR 172.101 and the HMT. Find the regulatory reference for drums (i.e., nonbulk containers) for storage of waste methyl ethyl ketone (MEK).
21. Insert the packing groups authorized for containers meeting the performance standards identified below

Performance Standard	For Packages Meeting Packing Groups
X	
Y	
Z	

22. The following labels and markings occur on a drum of hazardous waste:

RQ, Waste Corrosive Liquid, acidic, inorganic,

n.o.s., 8, UN 3264, PG I (EPA D002)

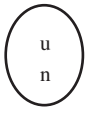
HAZARDOUS WASTE

Federal law prohibits improper disposal. If found, contact the nearest police station or public safety authority or the U.S. Environmental Protection Agency

Pristine Chemical Company, Inc.
555 Quiet Blvd.
Pristine, IL 50773

EPA #1D ILD098765432
Manifest # 012345
Start Date – Oct. 3, 2013

1H1/Y 1.6/165/02
USA/AB990
6 mm



Identify the following:

Hazardous Substance Designation
DOT Proper Shipping Name
Hazard class
DOT identification number
Hazardous waste warning
Generator name

23. Based on the manufacturer's mark, answer the following:
    (a) What is the minimum drum wall thickness for reuse of the drum?
    (b) What is the limit of specific gravity of the contents?
    (c) What is the drum type?
24. Who is responsible for ensuring that containers are properly marked and labeled (i.e., hazardous waste generator, transporter, TSDF, regulatory agency)?

REFERENCES

Blackman, W.C., Jr. 2001. *Basic Hazardous Waste Management*, 3rd ed. Boca Raton, FL: Lewis Publishing.

CFR (Code of Federal Regulations). 2004. *Volume 49*. Washington, DC: Department of Transportation, U.S. Government Printing Office.

Spraggins, H.B. 2007. Truck vs rail transportation of hazardous materials. *International Journal of Business Research. International Academy of Business and Economics*. http://www.freepatentsonline.com/article/International-Journal-Business-Research/178900207.html

U.S. DOT (U.S. Department of Transportation). 2004. *Guide for Preparing Hazardous Materials Incidents Reports. Washington, DC: Pipeline and Hazardous Materials Safety Administration*. http://phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Files/reporting_instructions_rev.pdf

U.S. DOT (U.S. Department of Transportation). 2012. *North American Emergency Response Guidebook. A Guidebook for First Responders During the Initial Phase of a Hazardous Materials/Dangerous Goods Incident*. 2012.

U.S. DOT (Department of Transportation). 2013. *Incidents by mode and incident year. Pipeline and Hazardous Materials Safety Administration office of Hazardous Material Safety.* https://hip.phmsa.dot.gov/analyticsSOAP/saw.dll?Dashboard&NQUser=HazmatWebsiteUser1&NQPassword=HazmatWebsiteUser1&PortalPath=/shared/Public%20Website%20pages/_portal/10%20Year%20Incident%20Summary%20Reports

U.S. EPA (U.S. Environmental Protection Agency). 1986. *Pensky-Martens Closed-Cup Method for Determining Ignitability), Method 1010*. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, EPA SW-846, Washington, DC: EPA.

U.S. Environmental Protection Agency, The National Biennial RCRA Hazardous Waste Report (Based on 1999 Data), EPA530-S-01-001, Solid Waste and Emergency Response PB2001-106318 (5305W), June 2001.

U.S. EPA (Environmental Protection Agency). 2011. *National Analysis, The National Biennial RCRA Hazardous Waste Report (Based on 2011 Data)*. Available from: http://www.epa.gov/epawaste/inforesources/data/br11/national11.pdf

SUGGESTED READINGS

Association of American Railroads/Bureau of Explosives. 2005. *Emergency Handling of Hazardous Materials in Surface Transportation*. Washington, DC: AAR/BOE.

Fox, M.A. 2000. *Glossary for the Worldwide Transportation of Dangerous Goods and Hazardous Materials*. Boca Raton, FL: CRC Press.

IATA (International Air Transport Association). 2009. *Dangerous Goods Regulations 2009*. Washington, DC: IATA.

Perry, D.M. and Klooster, D.J. 1992. *The Maquiladora Industry: Generation, Transportation and Disposal of Hazardous Waste at the California-Baja California, U.S. – Mexico Border: Second Maquiladora Report*. Los Angeles, CA: School of Public Health, University of California.

14 Treatment, Storage, and Disposal Facility Requirements

E'en from the tomb the voice of nature cries,
E'en in our ashes live their wonted fires.

Thomas Gray (1716–1771)
Elegy

14.1 INTRODUCTION

In the final phase of the cradle-to-grave waste management protocols under the Resource Conservation and Recovery Act (RCRA), hazardous wastes are to be treated and disposed. Treatment, storage, and disposal practices embrace many diverse systems; in addition, technologies are constantly changing and improving.

The regulatory requirements for treatment, storage, and disposal facilities (TSDFs) are more extensive as compared with those for generators and transporters. In this chapter, the regulatory requirements for TSDFs under RCRA will be presented. In subsequent chapters, specific practices for hazardous waste destruction and disposal are provided.

RCRA requires a part B permit for the treatment, storage, and disposal of hazardous waste at a facility. The relevant terms are defined in 40 CFR 270.2 as follows:

Treatment: Any method or process designed to change the physical, chemical, or biological character of any hazardous waste so as to: (1) neutralize such wastes, recover energy or material resources from the waste, or render such waste as nonhazardous or less hazardous; (2) make the waste safer to transport, store, or dispose; or (3) make the waste amenable for recovery, amenable for storage, or reduced in volume.

Storage: The holding of hazardous waste for a temporary period, at the end of which the hazardous waste is treated, disposed, or stored elsewhere.

Disposal: The discharge, deposit, injection, dumping, spilling, leaking, or placing of any hazardous waste into or on any land or water so that the waste may enter the environment or be emitted into the air or discharged into any water, including groundwater.

According to the U.S. Environmental Protection Agency (EPA), land disposal accounted for 62% of the management methods for hazardous waste. The quantities managed by land disposal include (U.S. EPA 2011):

Deep well or underground injection	22.8 million tons
Landfill/surface impoundment	1.3 million tons
Land treatment, application, and farming	16 thousand tons

Thermal treatment accounted for 6.6% of the national total. Thermal treatment methods include:

Energy recovery	1.6 million tons
Incineration	1.0 million tons

TABLE 14.1
Quantities of RCRA Hazardous Wastes Managed by Various Methods, 2011

Management Method	Tons Managed	Percentage of Quantity	Number of Facilities	Percentage of Facilities
Deep well or underground injection	22,852,829	58.6	41	3.0
Other disposal	3,612,247	9.3	341	24.6
Aqueous organic treatment	2,848,612	7.3	40	2.9
Other treatment	1,990,520	5.1	300	21.6
Energy recovery	1,563,267	4.0	68	4.9
Landfill and surface impoundment	1,291,650	3.3	53	3.8
Metals recovery	1,039,554	2.7	106	7.6
Incineration	1,009,814	2.6	132	9.5
Aqueous inorganic treatment	702,769	1.8	108	7.8
Fuel blending	651,974	1.7	90	6.5
Stabilization	613,251	1.6	79	5.7
Sludge treatment	395,316	1.0	26	1.9
Solvents recovery	255,219	0.7	384	27.6
Other recovery	184,533	0.5	64	4.6
Land treatment, application, or farming	16,376	0.0	14	1.0
Total	39,027,932	100.0	1389	100.0

Source: U.S. EPA, *National Analysis, The National Biennial RCRA Hazardous Waste Report (Based on 2011 Data)*, Solid Waste and Emergency Response, 2011, Available from: http://www.epa.gov/epawaste/inforesources/data/br11/national11.pdf.

Recovery operations represented 5.6% of the national total. The methods defined as recovery operations and the quantity managed by each include:

Fuel blending	652 thousand tons
Metals recovery (for reuse)	1.0 million tons
Solvents recovery	255 thousand tons
Other recovery	185 thousand tons

The remaining quantities were managed in other treatment and disposal units, including:

Other disposal	1.4 million tons
Stabilization	613 thousand tons
Sludge treatment	395 thousand tons

Details on hazardous waste management by method are shown in Table 14.1.

14.2 SUBPART A—GENERAL ISSUES REGARDING TREATMENT, STORAGE, AND DISPOSAL

All facilities involved in the treatment, storage, and disposal of hazardous wastes must comply with 40 CFR 264 and 265 regulations unless if they are excluded. The requirements do not apply to:

- A facility permitted to manage municipal or industrial solid waste, if the only hazardous waste the facility handles is from a conditionally exempt small quantity generator (SQG)

- A facility managing recyclable materials described in 40 CFR 261.6
- A generator accumulating waste on-site
- A farmer disposing of waste pesticides from his own use
- A totally enclosed treatment facility
- A neutralization unit or a wastewater treatment unit
- A person engaged in treatment or containment activities during immediate response to a discharge of a hazardous waste, or an imminent and substantial threat of a discharge of hazardous waste
- Addition of absorbent material to waste in a container
- A transporter storing manifested shipments of hazardous waste in containers at a transfer facility for ten days or less
- Universal waste handlers and universal waste transporters (40 CFR 260.10) handling the following wastes:
  - Batteries as described in 40 CFR 273.2
  - Pesticides as described in 40 CFR 273.3
  - Thermostats as described in 40 CFR 273.4
  - Lamps as described in 40 CFR 273.5

14.3 SUBPART B—GENERAL FACILITY STANDARDS

Hazardous waste TSDFs are subject to a permitting system dedicated to ensuring both safe operation and adequate protection of the environment. Under the permit system, facilities must meet both general standards for proper waste management, as well as requirements specific to the individual facility.

14.3.1 Notification of Hazardous Waste Activity

As is the case for generators of hazardous waste, every permitted TSDF is required to obtain an EPA identification number. EPA Form 8700-12, Notification of Hazardous Waste Activity (see Figure 12.1), must be submitted to EPA or the state regulatory agency. This is a one-time notification. A copy of the completed form should be maintained at the facility.

14.3.2 Waste Analysis

Before a facility manages any hazardous waste, it must obtain a detailed chemical and physical analysis of a representative sample of each waste. This analysis must ultimately provide all relevant information required for proper treatment, storage, and disposal of the waste in order to comply with regulatory requirements. Permitted facilities are required to develop and adhere to a waste analysis plan (WAP) that describes the procedures conducted to ensure that sufficient data are compiled about each waste stream. EPA or the state agency must approve the WAP as part of the facility permit application.

The WAP must include detailed parameters for hazardous waste analysis and the rationale for use of these parameters, including:

- Sampling methods used to obtain a representative sample of each waste.
- The frequency with which the waste analysis is reviewed to ensure accuracy.
- Procedures used to test for parameters.
- For facilities that accept waste from off-site, the plan must document all analyses that off-site waste generators provide.

Both sampling procedures and laboratory analytical methods listed in the WAP should be the same or equivalent to those documented in Test Methods for Evaluating Solid Waste, EPA publication SW-846 (U.S. EPA 1986).



FIGURE 14.1 Warning signs at the entrance to a TSDF.

14.3.3 Security

The TSDF operator must prevent the unauthorized entry of persons onto the active portion of the facility. Security features at a facility must include:

- A 24-h surveillance system (e.g., television monitoring or surveillance by guards), which continuously monitors and controls entry to the facility
- An artificial or natural barrier (e.g., fence or berms), which completely surrounds the active portion of the facility
- A means to control entry, at all times, through gates or other entrances (e.g., an attendant, television monitors, locked entrance, or controlled roadway access)

Signs with the warning "Danger—Unauthorized Personnel Keep Out" must be posted at each entrance (Figure 14.1). The warning must be written in English and in any other language predominant in the area surrounding the facility. Therefore, in northern Maine it may be suitable to post signs in French and in Texas to post signs in Spanish.

14.3.4 Inspections

The facility operator is required to inspect the facility for malfunctions, deterioration, and operator errors that may lead to a release of hazardous waste or pose a threat to public health. Inspections must be scheduled frequently to identify and correct problems on time. The schedule must identify potential problems to be checked, the date and time of each inspection, the name of the inspector, a list of observations, and the date and types of any repairs or other actions. A written schedule for inspecting monitoring equipment, safety and emergency equipment, security devices, and operating and structural equipment must be kept on file at the facility. The inspections must be recorded in an inspection log, and records must be maintained for at least 3 years.

Inspection frequency may vary for items on the schedule; however, frequency must be based on the rate of possible deterioration of the equipment and probability of an environmental or public health incident if the deterioration or malfunction goes undetected between inspections. Inspection frequencies for certain equipment, as specified in the regulations, are listed in Table 14.2. Because of its uniqueness, each facility should develop its own inspection logs that identify the specific items to be inspected and frequency of inspection.

TABLE 14.2
Inspection Frequencies for Selected Equipment at TSD Facilities

Item	Minimum Inspection Frequency
Loading and unloading areas	Daily
Container storage areas	Weekly
Tank systems	Daily
Surface impoundments	Weekly
Incinerators	Daily
Chemical, physical, biological treatment units	Weekly
Containment buildings	Weekly

14.3.5 Reactive and Ignitable Wastes

A TSDF is required to take precautions to prevent accidental ignition or reaction of ignitable or reactive waste. This waste must be separated and protected from sources of ignition. A facility that treats, stores, or disposes ignitable or reactive waste, or mixes incompatible wastes, must take precautions to prevent reactions that:

- Generate extreme heat, pressure, fire, or explosion
- Produce harmful quantities of toxic mists, fumes, dusts, or gases
- Produce harmful levels of flammable fumes or gases
- Damage the structural integrity of the device or facility

The operator must document compliance with the above requirements by citing published scientific literature, trial tests, waste analyses, or results of similar treatment processes.

14.3.6 Training

Training is required for facility personnel involved in management of hazardous waste. Training records are required to document that relevant personnel have successfully completed their required training. In the Hazardous Waste Operations and Emergency Response (HAZWOPER) regulations (29 CFR 1910.120) of the Occupational Safety and Health Act, all personnel who work at a permitted TSDF must complete a training program (minimum of 24 h) prior to conducting any activity that could expose them to hazardous waste.

14.4 SUBPART C—PREPAREDNESS AND PREVENTION

Portions of new facilities where treatment, storage, and disposal of hazardous waste will be conducted must not be located within 61 m (200 ft) of a fault that has experienced displacement in Holocene time. In addition, a facility located in a 100-year floodplain must be designed, constructed, and operated to prevent washout of any hazardous waste by a 100-year flood (40 CFR 264.18). The placement of any noncontainerized or bulk liquid hazardous waste in any salt dome formation, salt bed formation, underground mine, or cave is prohibited.

A construction quality assurance (CQA) program is required for all surface impoundments, waste piles, and landfill units. The program must be developed and implemented under the direction

of a CQA officer who is a registered professional engineer (40 CFR 264.19). The CQA program must address the following physical components:

- Foundations
- Dikes
- Low-permeability soil liners
- Geomembranes
- Leachate collection and removal systems and leak detection systems
- Final cover systems

The facility-written CQA plan must identify steps used to monitor the quality of construction materials and the manner of their installation. It must also identify applicable units and describe how they will be constructed. The plan identifies key personnel in the development and implementation of the CQA plan. It also provides a description of inspection and sampling activities for all unit components to ensure that construction materials and components meet design specifications. The description covers:

- Sampling size and locations
- Frequency of testing
- Data evaluation procedures
- Acceptance and rejection criteria for construction materials
- Plans for implementing corrective measures

The CQA program includes inspections, tests, and measurements sufficient to ensure the structural stability and integrity of all components of the unit. The program must ensure proper construction of all components of liners, leachate collection and removal system, leak detection system, and final cover system according to permit specifications.

14.4.1 Facility Design and Operation

Facilities must be designed, constructed, and operated to minimize the possibility of a fire, explosion, or any unplanned release of hazardous wastes to air, soil, or surface water. With limited exceptions, all TSDFs must be equipped with the following (40 CFR 264.32):

- An internal communications or alarm system capable of providing immediate emergency instruction (voice or signal) to facility personnel
- A telephone or hand-held two-way radio, capable of summoning emergency assistance from local police departments, fire departments, or emergency response teams
- Portable fire extinguishers, fire control equipment (including special extinguishing equipment, such as that using foam, inert gas, or dry chemicals), spill control equipment, and decontamination equipment
- Water of adequate volume and pressure to supply water hose streams, foam-producing equipment, automatic sprinklers, or water spray systems

All facility communications or alarm systems, fire protection apparatus, spill control materials, and decontamination equipment must be tested and maintained as necessary to assure their proper operation in time of emergency. The facility must maintain aisle space to allow unobstructed movement of personnel, fire protection equipment, spill control equipment, and decontamination equipment to any area of facility operation in an emergency (40 CFR 264.35).

14.4.2 Arrangements with Local Authorities

The facility must make arrangements with local authorities in preparation for any site emergency. The facility is to familiarize police, fire departments, and emergency response teams with the layout of the facility, properties of hazardous waste handled and associated hazards, places where facility personnel normally work, entrances to and roads inside the facility, and possible evacuation routes. In cases where more than one police and fire department might respond to an emergency, agreements are established designating primary emergency authority to a specific police and fire department, and agreements with others to provide support to the primary emergency authority. Agreements may also be established with state emergency response teams, emergency response contractors, and equipment suppliers. The facility is to familiarize local hospitals with the properties of hazardous waste handled at the facility and the types of injuries or illnesses that may result from fire, explosion, or releases at the facility.

14.5 SUBPART D—CONTINGENCY PLAN AND EMERGENCY PROCEDURES

14.5.1 Contingency Plan

Each facility must prepare and maintain a contingency plan. This document is designed to minimize hazards to human health or the environment from fire, explosion, or any unplanned release of hazardous waste (40 CFR 264.51). The provisions of the plan are carried out immediately whenever an event occurs that could threaten health or the environment. The plan describes response actions that facility personnel must take in response to a hazardous event at the facility. Included are arrangements agreed to by local police departments, fire departments, hospitals, contractors, and emergency response teams to coordinate emergency services. All persons qualified to act as emergency coordinators are listed.

The contingency plan lists all emergency equipment on-hand at the facility (such as fire extinguishing systems, spill control equipment, communications and alarm systems, and decontamination equipment). In addition, the location and physical description of each item and a brief outline of its capabilities are provided. The plan must also include an evacuation protocol for facility personnel. This includes signals to be used to begin evacuation, and provides evacuation routes and alternative routes, in cases where the primary exits are blocked by releases of hazardous waste or fires.

A copy of the contingency plan and all revisions must be maintained at the facility and submitted to local police departments, fire departments, hospitals, and emergency response teams that may be called upon to provide emergency services.

Real-world situations often do not occur according to our expectations; therefore, the contingency plan must be reviewed and amended whenever the following occurs (40 CFR 264.54):

- The facility permit is revised
- The plan fails in an emergency
- The facility changes its design, construction, or operation in a way that increases the potential for fire, explosions, or releases of hazardous waste, or changes the response in an emergency
- The emergency coordinators change
- The emergency equipment changes

There must be at least one employee either on the facility premises or on call at all times with the responsibility of coordinating emergency response measures. This individual must be thoroughly familiar with the facility contingency plan, all operations at the facility, the location and characteristics of waste handled, the location of all records within the facility, and the facility layout.

14.5.2 Emergency Procedures

Whenever there is an imminent or actual emergency situation, the emergency coordinator must immediately activate internal facility alarms or communication systems to notify all facility personnel. This individual must also notify appropriate state or local agencies if their assistance is needed. Whenever there is a release, fire, or explosion, the emergency coordinator must immediately identify the character, exact source, amount, and aerial extent of any released materials. This identification may be carried out by observation or by review of facility records and by chemical analysis. Concurrently, the emergency coordinator must assess possible hazards to human health or the environment that may result from the emergency. If evacuation of local areas is advisable, the coordinator must immediately notify appropriate local authorities. The coordinator must also notify either the government official designated as on-scene coordinator for that area or the National Response Center (24-h toll free number 800-424-8802).

If the facility must halt operations in response to an incident, the emergency coordinator must monitor for leaks, pressure buildup, gas generation, or ruptures in valves, pipes, or other equipment. Immediately after such an emergency, the coordinator must provide for the treatment, storage, and disposal of recovered waste, contaminated soil or surface water, or any other material that results from such an event.

14.6 SUBPART E—MANIFEST SYSTEM, RECORD KEEPING, AND REPORTING

When the TSDF receives hazardous waste, it must sign and date the Uniform Hazardous Waste Manifest to certify that the waste listed therein was received. It must also note any significant discrepancies in the manifest. The facility then provides the transporter with at least one copy of the signed document. Within 30 days after delivery, the TSDF must forward a copy of the manifest to the generator. It must also retain at the facility a copy of the manifest for at least 3 years from the date of delivery.

14.6.1 Manifest Discrepancies

Manifest discrepancies are differences between the quantity or type of hazardous waste designated on the manifest or shipping paper, and the quantity or type that the facility actually receives. Significant discrepancies in quantity are (40 CFR 264.72):

- For bulk waste, variations greater than 10% by weight
- For batch waste, any variation in piece count, such as a discrepancy of one drum in a truckload

Upon discovering a significant discrepancy, the TSDF must attempt to reconcile it with the waste generator or transporter. If the discrepancy is not resolved within 15 days after receiving the waste, the TSDF must submit a letter to the state regulatory agency describing the discrepancy and attempts to reconcile it, and a copy of the manifest in question.

14.6.2 Operating Record

The facility must maintain written records of regular operations. The following information must be recorded and maintained in the operating record:

- A description and the quantity of each hazardous waste received and the method(s) and date(s) of its treatment, storage, or disposal at the facility.

- The location of all hazardous wastes within the facility and the quantity at each location. For disposal facilities, the location and quantity of each waste must be recorded on a map of the disposal area.
- Records and results of waste analyses and waste determinations.
- Summary reports of all incidents that require implementing the contingency plan.
- Records and results of inspections.
- Monitoring, testing or analytical data, and corrective action where required.
- Records of the quantities and date of placement for each shipment of hazardous waste placed in land disposal units.

All records and plans must be available for inspection by a state regulatory inspector or EPA representative.

14.6.3 Biennial Report

The facility must submit a biennial report to the regulatory agency by March 1 of each even-numbered year. The biennial report must be submitted on EPA form 8700-13B. The report must cover facility activities during the previous calendar year and include:

- The EPA identification number of each hazardous waste generator from which the facility received hazardous waste during the year; for imported shipments, the name and address of the foreign generator
- A description and the quantity of each hazardous waste the facility received during the year
- The method of treatment, storage, and disposal for each hazardous waste
- The most recent closure cost estimate and, for disposal facilities, the most recent postclosure cost estimate
- For generators who treat, store, or dispose of hazardous waste on-site, a description of the efforts undertaken during the year to reduce the volume and toxicity of waste generated
- A description of the changes in volume and toxicity of waste actually achieved during the year in comparison with previous years

14.7 SUBPART F—RELEASES FROM SOLID WASTE MANAGEMENT UNITS

Facilities must implement a hazardous waste monitoring and response program. Whenever hazardous constituents released from a regulated unit are detected, the facility must institute a compliance monitoring program. Also, whenever the groundwater protection standard (40 CFR 264.92; see below) is exceeded, the facility must institute a corrective action program. The state regulatory agency specifies, in the facility permit, the specific components of the monitoring and response program.

14.7.1 Groundwater Protection Standard

The facility must ensure that hazardous constituents detected in the uppermost aquifer underlying the waste management area do not exceed specified concentration limits. The state agency establishes this groundwater protection standard in the facility permit. The agency specifies concentration limits in groundwater for hazardous constituents. The concentration of a hazardous constituent must not exceed the background level in the groundwater, or it must not exceed the value given in Table 14.3.

TABLE 14.3
Maximum Concentration of Constituents for Groundwater Protection

Constituent	Maximum Concentration (mg/L)
Arsenic	0.05
Barium	1.0
Cadmium	0.01
Chromium	0.05
Lead	0.05
Mercury	0.002
Selenium	0.01
Silver	0.05
Endrin (1,2,3,4,10,10-hexachloro-1,7-epoxy 1,4,4a,5,6,7,8,9a-octahydro-1,4-endo, endo-5,8-dimethano naphthalene)	0.002
Lindane (1,2,3,4,5,6-hexachlorocyclohexane, gamma isomer)	0.004
Methoxychlor (1,1,1-Trichloro-2,2-bis (*p*-methoxyphenylethane)	0.1
Toxaphene (technical chlorinated camphene, 67–69% chlorine)	0.005
2,4-D (2,4-dichlorophenoxyacetic acid)	0.1
2,4,5-TP Silvex (2,4,5-trichlorophenoxypropionic acid)	0.01

14.7.2 Groundwater Monitoring Requirements

The facility must comply with the following requirements for any groundwater monitoring program. The monitoring system must:

- Consist of a sufficient number of wells, installed at appropriate locations and depths to yield groundwater samples from the uppermost aquifer.
- Represent the quality of groundwater passing *the point of compliance*. The point of compliance is defined as the location where groundwater constituents are collected and measured.
- Allow for the detection of contamination when hazardous waste has migrated to the uppermost aquifer.

All monitoring wells must be cased, and the casing must be screened or perforated and packed with gravel or sand, where necessary, to enable collection of groundwater samples. The annular space (i.e., the space between the both bore hole and well casing) above the sampling depth must be sealed to prevent contamination of both samples and groundwater. At a minimum, the program must include procedures for sample collection, sample preservation and shipment, analytical procedures, and chain of custody control.

In detection monitoring (or in compliance monitoring), data on each hazardous constituent specified in the permit are collected from background wells and wells at the compliance points.

14.7.3 Detection Monitoring Program

A facility that establishes a detection monitoring program must install a groundwater monitoring system at the point of compliance (40 CFR 264.98). The facility must monitor for indicator parameters (e.g., specific conductance, total organic carbon, total organic halogens), waste constituents, or reaction products that indicate the presence of hazardous constituents in groundwater. The regulatory agency specifies the parameters to be monitored in the facility permit after considering factors such as the types, quantities, and concentrations of constituents in wastes being managed; the mobility, stability, and persistence of waste constituents or their reaction products in the unsaturated

zone beneath the waste management area; and the detectability of indicator parameters and waste constituents in groundwater.

The state agency will specify the frequencies for collecting samples and conducting statistical tests to determine whether there is statistically significant evidence of contamination for any hazardous constituent. A set of at least four samples from each well (both background and compliance wells) must be collected at least semiannually during detection monitoring.

If significant evidence of contamination is detected at any monitoring well at the compliance point, the facility must notify the state regulatory agency within 7 days. The TSD must also immediately sample all monitoring wells and determine whether waste constituents are present and, if so, in what concentration. Within 90 days, the TSDF must submit to the state regulatory agency an application for a permit modification to establish a compliance monitoring program.

14.7.4 Corrective Action Program

A TSDF required to establish a corrective action program is charged with numerous responsibilities; for example, it must take action to ensure that regulated units are in compliance with the groundwater protection standard under §264.92. The state regulatory agency will specify the groundwater protection standard in the facility permit, including a list of the hazardous constituents identified, concentration limits for each of the hazardous constituents, the compliance point, and the compliance period.

The facility must implement a corrective action program that prevents hazardous constituents from exceeding concentration limits at the compliance point by removing the constituents or treating them in place. The permit will specify the specific measures to be taken.

14.8 SUBPART G—CLOSURE AND POSTCLOSURE

14.8.1 Closure Plan (264.112)

The TSDF must prepare a written closure plan. The plan must be submitted with the permit application and approved by the state regulatory agency as part of the permit issuance procedure. The approved closure plan will become a condition of any RCRA permit.

The plan must identify steps necessary to perform partial or final closure of the facility at any point during its active life. The closure plan must include:

- A description of how each hazardous waste management unit (e.g., landfill cell) at the facility will be closed.
- An estimate of the maximum inventory of hazardous wastes on-site over the active life of the facility.
- Methods for removing, transporting, treating, storing, or disposing of all hazardous wastes and identification of the types of off-site hazardous waste management units to be used.
- A detailed description of the steps needed to remove or decontaminate all hazardous waste residues and contaminated containment system components, equipment, structures, and soils during partial and final closure, including procedures for cleaning equipment and removing contaminated soil.
- Methods for sampling and testing surrounding soils.
- Other activities necessary, including groundwater monitoring, leachate collection, and run-on and run-off control.
- A schedule for closure of each hazardous waste management unit and for final closure of the facility. The schedule must include the total time required to close each hazardous waste management unit.

The facility must notify the state regulatory agency in writing at least 60 days prior to the date on which it will begin closure of a surface impoundment, waste pile, land treatment, or landfill unit. The facility must notify the state agency in writing at least 45 days prior to the date of beginning final closure of a facility with only treatment or storage tanks, container storage, incinerator units, industrial furnaces, or boilers.

14.A.1 APPENDIX: HAZARDOUS WASTE MANAGEMENT SCENARIOS

14.A.1.1 Introduction

After reading each scenario, discuss what, if any, violations may have occurred. How would these violations be best addressed (i.e., via changes in engineering design, a modified storage or disposal program, some use of common sense, etc.)? These are open-ended situations.

14.A.1.2 Scenarios

1. The D. Lerious Lead Company processes off-specification and waste auto batteries for eventual recycling. At the facility, the batteries are crushed, and the lead plates are removed and smelted to recover and purify the lead. The plastic battery cases are shredded to approximately 1 cm × 1 cm (0.5 in. × 0.5 in.) and washed with dilute acid to remove residual lead. The plastic chips are shipped by truck to a battery manufacturing facility in another state to be used as feedstock for new battery housings. Upon arrival at the receiving facility, the chips are washed a second time.

   An inspector claims that the plastic chips are not completely cleaned of lead and are still wet. At least one truck trailer, filled with plastic chips, is leaking a reddish liquid, probably indicating corrosion of the trailer's interior (Figure 14.A.1).

   The company responds that the plastic chips are cleaned of lead and are therefore not hazardous waste. They furthermore claim that the chips cannot be considered waste, as they are *feedstock* for the manufacture of new batteries.
2. At a metal foundry, baghouse dusts are enriched with cadmium. They clearly fail the TCLP (172 mg Cd/L, whereas the RCRA limit is 1 mg/L [40 CFR 261.24]). In order to avoid the substantially higher costs associated with hazardous waste disposal, the company decides to apply a proprietary fixative agent to their process before the materials enter the furnace. The baghouse dust that exits the furnace has an average Cd value just below the TCLP limit. The inspector suggests that this procedure is *treatment* of a hazardous waste. The



FIGURE 14.A.1 Truck filled with plastic chips from battery casings.

company, however, argues that the fixative compound was added to *product*, not to waste; therefore, they are not engaging in treatment of a hazardous waste.

3. Storage area for bulk hazardous wastes at the Haz-R-Dus Chemical Company. What is wrong with this picture (Figure 14.A.2)?
4. Bogus Pesticides, Inc., manufactures and stores a range of pesticides and fumigants. A waste hauler collects solid waste from their facility in a conventional loader truck. The driver immediately notices a strong and unpleasant odor while driving and promptly diverts to the solid waste transfer station. Upon arrival, he is instructed to tip the wastes immediately upon the tipping floor. By this time, the waste is smoldering and begins to burn.

The fire department is called in, and attempts to extinguish the small blaze. Upon contact with water, the waste pile reacted violently, spewing flames and releasing gas and vapor. The emergency response team is subsequently called in to handle the incident.

State inspectors later visit Bogus Pesticides, where it is determined that containers of aluminum phosphide pesticide were placed in ordinary trash. This pesticide had subsequently decomposed in transit and during wetting by the fire department. An inspector was informed by the plant manager that this formulation is water-reactive. The reaction with water is as follows:

$$AlP + 3H_2O \rightarrow Al(OH)_3 + PH_{3(g)}$$

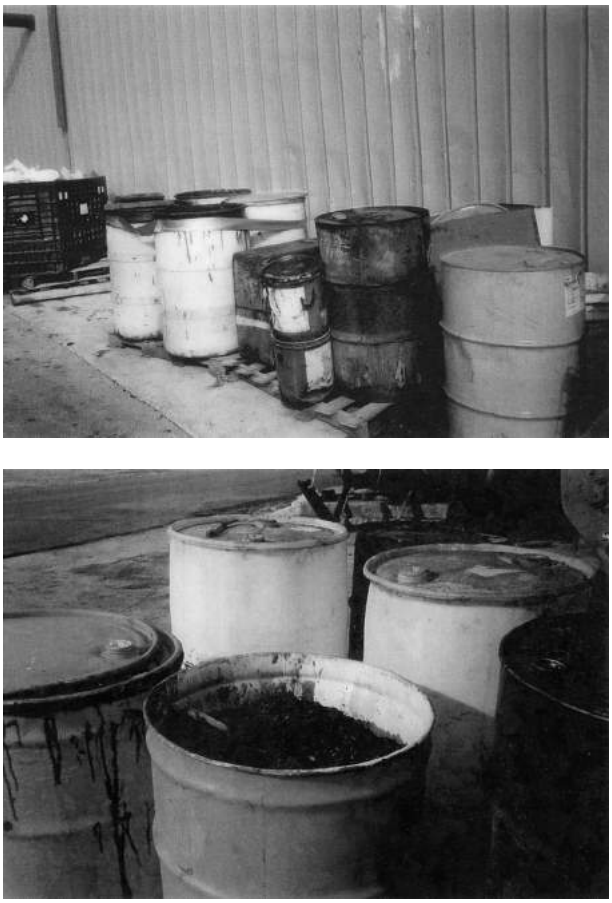


FIGURE 14.A.2 Storage area for bulk hazardous wastes.

The product, phosphine gas (PH_3), is highly toxic.

The inspector walked over the facility to find several aluminum phosphide containers stored in a large shed with a damaged roof (water was dripping inside the building from melting snow). The company manager made arrangements to repack the containers and transport them to a friend's farm field. There, it was planned, the fumigants would be reacted with water and allowed to decompose. The remaining residue would be landfilled. The manager contends that such a practice is acceptable as the fumigant is a *product* and not a *waste*.

14.A.1.3 Responses to Scenarios

1. (a) If the chips could be used in exactly the same form as when they were removed from the original battery casings, they are not necessarily a "waste." However, once they are processed, they become a waste. In the current situation, the chips must be washed (i.e., "processed, treated") at least twice.
   (b) If the chips are indeed contaminated with lead (and, this was later found to be true), the chips are also hazardous waste (The Mixture Rule). The transporter must therefore possess an EPA identification number; the shipments must be manifested (Uniform Hazardous Waste Manifest), and the chips must be sent to an EPA-approved treatment, storage, and disposal facility. The chips can be easily tested for the characteristic of toxicity by using the TCLP. If the lead concentration in a representative extract exceeds 5 mg/L lead, the chips have failed the toxicity test.
2. "Treatment" is defined in 40 CFR 270.2 as:

   > Any method, technique, or process, including neutralization, designed to change the physical, chemical, or biological character or composition of any hazardous waste so as to neutralize such wastes, or so as to recover energy or material resources from the waste, or so as to render such waste as nonhazardous, or less hazardous; safer to transport, store, or dispose of; or amenable for recovery, amenable for storage, or reduced in volume.

   Given that the new baghouse dust measures "just below" the TCLP limit, a number of samples have been required by the inspector for TCLP determination. Chemists within the agency carefully assessed all data. As of this writing, this argument continues. EPA is also being asked for guidance to settle this matter. (What is *your* assessment of the situation?)
3. Drums are not labeled (they require the yellow "Hazardous Waste" label); several drums are open. In addition, drums should be covered or stored indoors to limit the effects of weather on the containers. Finally, the four white polyethylene drums in the back of Figure 14.2.a have been held together with a single loop of duct tape. This is not adequate for preventing a drum from falling off the pallet.
4. Given that the fumigants were stored for long periods, the containers were in very poor condition, and the inspector required immediate removal; these materials are considered a solid waste. Furthermore, aluminum phosphide is a P006 hazardous waste (40 CFR 268.40).

   This waste is covered under the EPA Land Ban (see Chapter 17) so it is not to be land disposed.

   If the fumigants could be used immediately, for example, to fumigate several warehouses, the inspectors may have been willing to permit such an activity; however, there is little practical use for pesticides and soil fumigants in the middle of winter.

   Given that this is a hazardous waste, there are the obvious DOT and RCRA requirements for transportation (proper transporters, labeling, packaging, etc.). Furthermore, taking the waste to a field and reacting it is a form of treatment, and Bogus Pesticides would need a permit to do so. "Treatment" in the farmer's field would have been impractical; at temperatures below 49°F, at least 14 days are needed for aluminum phosphide to decompose. Given regional winter temperatures averaging 20–25°F, decomposition will take

even longer. According to 40 CFR 268.50, the appropriate treatment would be chemical oxidation, chemical reduction, or controlled incineration.

As of this writing, Bogus Pesticides has been cited for illegal disposal and the case is being sent to the State Office of Enforcement.

QUESTIONS

1. Which permitted TSDFs are required to obtain an EPA identification number? To whom is the completed EPA Form 8700-12, *Notification of Hazardous Waste Activity*, to be submitted? How frequently is the form to be sent to this agency?
2. Is a WAP required for all TSDFs? Which agency must approve the WAP as part of the permit application?
3. Provide the specific components of a facility WAP.
4. At the Hi-Jinx Corporation Central Waste Incineration facility, how often should the following areas be inspected by plant personnel? (a) loading areas, (b) tank systems, (c) incinerator units, (d) container storage buildings.
5. For what types of TSDFs is a CQA program required? Under whose direction is the program developed and implemented? Which physical components must the CQA program address?
6. The TSDF must develop and implement a written CQA plan. What is the overall purpose of the CQA plan? What must it include?
7. TSDFs must be equipped with internal communication systems and fire control equipment. What additional emergency equipment is required?
8. In preparation for any site emergency, the facility must make numerous arrangements with local authorities. List these arrangements.
9. Whenever there is a release, fire, or explosion, what specifics regarding the released materials is the emergency coordinator to identify immediately? How is the identification to be carried out? How are the findings to be reported?
10. What types of equipment must the TSDF be equipped with in order to minimize the possibility of fire, explosion, or the release of hazardous wastes?
11. What is the general purpose of a contingency plan? What are the major components of the plan? To whom in the community should copies of the plan be given?
12. Under what conditions are TSDF contingency plans revised?
13. The TSDF is the final stage of cradle-to-grave hazardous waste management. What are the responsibilities of the TSDF regarding the Uniform Hazardous Waste Manifest? For how long is the manifest to be kept on the premises? How are manifest discrepancies handled?
14. The groundwater monitoring program at a TSDF must include sampling and analysis procedures that provide a reliable indication of groundwater quality below the waste management area. List the minimum procedures to be included in the program.
15. In your community, is there a comprehensive household hazardous waste management program currently in place? How are household hazardous wastes collected, treated, and disposed? What agency or company is responsible for administering such a program?

REFERENCES

CFR (Code of Federal Regulations). 2012. *Volume 40 Part 264*, *Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities.* Washington, DC: U.S. Government Printing Office.

U.S. EPA (U.S. Environmental Protection Agency). 1986. *Test Methods for Evaluating Solid Waste*. Washington, DC: Publication SW-846, EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2011. *National Analysis, The National Biennial RCRA Hazardous Waste Report (Based on 2011 Data)*. Solid Waste and Emergency Response. Available from: http://www.epa.gov/epawaste/inforesources/data/br11/national11.pdf

SUGGESTED READINGS AND WEBSITES

EHSO (Environment, Health and Safety Online). n.d. RCRA Hazardous Waste Treatment Storage & Disposal Facilities. Available from: http://www.ehso.com/tsdfs.htm

EHSO (Environment, Health and Safety Online). 2003. The Hazardous Waste Permitting Process. Available from: http://www.ehso.com/ehshome/hazwaste_permitting.htm

Oregon DEQ (Oregon Department of Environmental Quality). n.d. Procedure and Criteria for Hazardous Waste Treatment, Storage or Disposal Permits. Available from: http://www.deq.state.or.us/wmc/hw/factsheets/HazardousWastePermits.pdf

Oregon DEQ (Oregon Department of Environmental Quality). n.d. RCRA Treatment, Storage, and Disposal Facility Permits. Available from: http://www.deq.state.or.us/pubs/permithandbook/hwrcra.htm

U.S. EPA (U.S. Environmental Protection Agency). 1998. *RCRA Organic Air Emission Standards for TSDFs and Generators*, EPA530-F-98-011. Washington, DC: Solid Waste and Emergency Response.

U.S. EPA (U.S. Environmental Protection Agency). 2002. Treat, Store, and Dispose of Waste. Available from: http://www.epa.gov/epaoswer/osw/tsd.htm#facts

15 Incineration of Hazardous Wastes

Troops harnessed in bright armor marched three times
In parade formation, and the cavalry
Swept about the sad cremation flame
Three times, while calling out their desolate cries.

Virgil (70–19 BCE)
The Aeneid

15.1 INTRODUCTION

Since the enactment of the Resource Conservation and Recovery Act (RCRA) in 1976, incineration technologies for the destruction of solid, liquid, and gaseous hazardous wastes have become increasingly sophisticated and effective. Aerobic thermal processes detoxify a wide range of organic compounds such as chlorinated pesticides, munitions wastes, chemical warfare agents, polymer residues, and petrochemical wastes. Incineration can be used for the destruction of contaminated soil and water; thus, the technology is not limited strictly to treatment of organic residuals from a single production process. Furthermore, hazardous waste destruction under RCRA is not limited solely to dedicated incineration facilities; for example, thermal destruction of certain hazardous wastes is permitted in industrial boilers and furnaces, with the resultant recovery of heat.

As was the case for the combustion of municipal solid waste (MSW) (Chapter 9), incineration of hazardous waste is defined as the *controlled* burning of a substance, where "controlled" refers to clearly defined temperature ranges, oxygen input, turbulence, atmospheric pressure, firebox design, and other aspects of the combustion environment. The regulatory definition of an incinerator is (40 CFR 260.10):

> any enclosed device that uses controlled flame combustion and does not meet the criteria for classification as a boiler, sludge dryer, carbon regeneration unit, or industrial furnace.

Typical incinerators include rotary kilns, liquid injectors, controlled air incinerators, and fluidized-bed incinerators. The definition also includes the infrared incinerator and plasma arc incinerator. An infrared incinerator is a device that uses electric-powered resistance as a source of heat. A plasma arc incinerator uses a high-intensity electrical discharge as a heat source (40 CFR 260.10). These two incinerator types will not be discussed here.

Other waste incineration devices include boilers and industrial furnaces. A boiler is composed of two primary components: the combustion chamber where hazardous waste is destroyed via the application of heat, and collection tubes that store a fluid, usually water, to produce energy as steam. Industrial furnaces are units within a manufacturing facility that use thermal treatment to recover materials or energy from hazardous waste. The following devices fulfill the definition of an industrial furnace (U.S. EPA 2002):

- Cement kiln
- Aggregate kiln

- Coke oven
- Smelting, melting, and refining furnace
- Methane reforming furnace
- Pulping liquor recovery furnace
- Lime kiln
- Phosphate kiln
- Blast furnace
- Titanium dioxide chloride process oxidation reactor
- Halogen acid furnace

15.2 COMBUSTION AND ITS RESIDUES

For incineration to be an effective method of eliminating the hazardous properties of a waste, combustion must be complete. Three critical factors ensure the completeness of combustion in an incinerator: (1) temperature of the combustion chamber (firebox), (2) length of time the wastes are maintained at high temperatures, and (3) turbulence, or degree of mixing, of the wastes and air. These parameters are often labeled "The Three T's of Combustion." In each incinerator permit, the operating conditions are clearly stipulated to ensure that these factors are optimized, ultimately assuring complete combustion of the waste feed.

During a controlled burn, wastes are fed continuously or in batch mode into the incinerator firebox. As the wastes are heated, they are physically converted from solids and liquids into gases. These gases, mostly organic, become sufficiently hot so that chemical bonds break. The atoms that are released combine with oxygen and hydrogen to form stable gases, primarily carbon dioxide and water, which are subsequently released from the system via the flue. In reality, however, the combustion of organic substances is a rather complex sequence of reactions that results in simple products. The combustion of ethane, a simple alkane, is as follows:

$$2C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6H_2O \tag{15.1}$$

Aromatic hydrocarbons are combusted in a similar fashion as demonstrated by the reaction for xylene:

$$C_6H_4(CH_3)_2 + 11.5\ O_2 \rightarrow 8\ CO_2 + 5H_2O \tag{15.2}$$

Incineration of halogenated hydrocarbons results in the formation of the corresponding halogen acids, which must be treated within the flue gas prior to release. An example of combustion of a chlorinated hydrocarbon is the reaction of dichloroethane:

$$2C_2H_4Cl_2 + 5O_2 \rightarrow 4CO_2 + 2H_2O + 4HCl \tag{15.3}$$

Depending on waste composition, various quantities of sulfur oxides, nitrogen oxides, and other gases are formed. Also, if combustion is not complete, compounds such as elemental carbon (C), benzopyrenes, and others may be emitted. This latter group is collectively referred to as products of incomplete combustion (PICs). RCRA regulations place strict limits on acceptable amounts of selected pollutants released from the flue (40 CFR part 264).

Another significant product of waste combustion is ash, an inert solid material composed primarily of salts, metals, and some carbon. During combustion, the heavier ash component is collected by gravity at the base of the combustion chamber (i.e., *bottom ash*). When the ash is removed from its hopper, it may be considered hazardous waste via the Derived-from Rule or because it exhibits one of the four hazard characteristics (ignitable, corrosive, reactive, and toxic) (see Chapter 11). A significant fraction of the ash may be very lightweight and become entrained with gases as particulate

matter. These particles, collectively referred to as *fly ash*, are collected in pollution control devices in accordance with RCRA regulations.

As a hazardous waste management technology, incineration has several unique attributes. If conducted under optimum conditions, controlled incineration permanently destroys toxic organic compounds within waste by converting them to stable molecules. Second, incineration reduces the volume of hazardous waste. Land disposal of ash, as opposed to the disposal of untreated hazardous waste, is therefore safer and should reduce long-term liability for the waste generator and extends the lifetime of the disposal facility. Incineration, however, does not destroy inorganic compounds such as metals. In fact, the residue becomes more concentrated with various nonburnables after the organic component has been destroyed. Ash from incinerators is subject to applicable RCRA standards and may need to be treated for metals or other inorganic constituents prior to land disposal.

15.3 OVERVIEW OF REGULATORY REQUIREMENTS

Emissions from hazardous waste combustors are regulated under two statutory authorities, RCRA and the Clean Air Act (CAA). Relevant RCRA regulations include 40 CFR part 264, subpart O; part 265, subpart O for incinerators; and 40 CFR part 266, subpart H for boilers and industrial furnaces (BIFs). RCRA permit requirements for these units are provided in 40 CFR part 270. All these units are subject to the general treatment, storage, and disposal facility (TSDF) standards under RCRA. Hazardous waste incinerators, hazardous waste-burning cement kilns, and aggregate kilns are also subject to the CAA maximum achievable control technology (MACT) emission standards. The MACT standards set emission limitations for polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), metals, particulate matter, total chlorine, hydrocarbons, carbon monoxide, and destruction and removal efficiency (DRE) for organic emissions. The combustion standards under RCRA and the MACT standards under the CAA are discussed below.

15.4 COMBUSTION STANDARDS UNDER RCRA, SUBPART O

To minimize potential harmful effects of incinerator gaseous emissions, EPA has developed *performance standards* to regulate four pollutant categories: organics, hydrogen chloride and chlorine gas, particulate matter, and metals (40 CFR 264.343). For each type of emission, the regulations establish compliance methods and alternatives.

The subpart O standards apply to facilities that destroy hazardous wastes; they also regulate various emissions from combustion. An incinerator burning hazardous waste must be designed, constructed, and operated so that the performance standards outlined below are met. Specifically, the RCRA regulations restrict gaseous emissions of organic compounds, hydrogen chloride (HCl), particulate matter, fugitive emissions, and metals. All hazardous waste incinerators must conform to the requirements of subpart O unless the waste is considered "low risk" (40 CFR 264.340). These include certain listed hazardous wastes (subpart D) or those characterized as hazardous due to ignitability or corrosivity.

15.4.1 Organic Compounds

To obtain an operating permit, an incineration facility must demonstrate that emission levels for selected hazardous organic constituents are within applicable limits. The main indicator of incinerator performance designated by EPA is the destruction and removal efficiency (DRE). An incinerator burning hazardous waste must achieve a DRE of 99.99% for each principal organic hazardous constituent (POHC) designated in the waste stream. The DRE is determined from the following equation:

$$\text{DRE} = (W_{in} - W_{out})/W_{in} \times 100\% \tag{15.4}$$

where W_{in} is the mass feed rate of a POHC into the incinerator and W_{out} the emission rate of that same POHC in the exhaust.

An incinerator burning the listed hazardous wastes F020–F023, F026, or F027 must achieve a DRE of 99.9999% for each. These are chlorinated hydrocarbon wastes that have the potential to contain PCDDs (40 CFR 264.343); therefore, combustion conditions must be more rigorous.

For many waste generators and TSDFs, it would be impractical and very costly to monitor DRE results for every organic constituent contained within the waste stream. In response to this reality, only certain POHCs are selected for monitoring and are designated in the permit. POHCs are selected if they are more likely to be present in large concentrations in the waste. Similarly, organic constituents that are the most difficult to destroy by incineration are likely to be designated as POHCs. If the incinerator achieves the required DRE for the selected POHCs, regulatory agencies conclude that the incinerator should achieve the same or better DRE for other, more easily combustible, organic compounds in the waste stream.

15.4.2 Hydrogen Chloride

HCl, an acidic gas, forms when chlorinated organic compounds in wastes are burned. An incinerator burning hazardous waste cannot emit more than 1.8 kg of HCl/h or more than 1% of the total HCl in the stack gas prior to entering any pollution control equipment, whichever is larger (40 CFR 264.343(b)).

Boilers and most industrial furnaces must follow a tiered system for regulation of both HCl and chlorine gas (U.S. EPA 2002). The facility determines the allowable feed or emission rate of total chlorine by selecting one of three approaches (tiers). Each tier differs in the amount of monitoring and, in some cases, air dispersion modeling (i.e., mathematically modeling the pathways through which air pollutants may travel) that the facility is required to conduct (Figure 15.1).

A facility can select any of the three tiers. Factors to consider in selecting a tier include the physical characteristics of the facility and the local environs, the anticipated waste composition and feed rates, and the resources available for conducting the analysis. The main distinction between tiers is the point of compliance, that is, the point at which the facility must ensure that chlorine concentrations will be below EPA's acceptable exposure levels. The facility must determine if the costs of

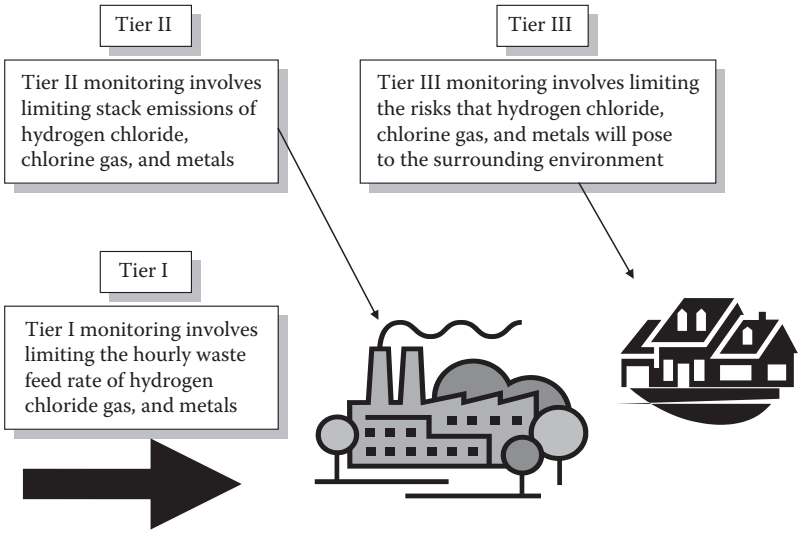


FIGURE 15.1 Performance standards for hydrogen chloride, chlorine gas, and metals. (From U.S. EPA, *RCRA Orientation Manual,* EPA530-R-02-016, Office of Solid Waste/Communications, Information, and Resources Management Division, U.S. EPA, Washington, DC, 2002.)

monitoring and modeling are worth the benefit of combusting waste with a higher concentration of chlorine (U.S. EPA 2002).

15.4.3 Particulate Matter

Particulate matter is composed of minute particles, solid or liquid, organic or inorganic, which are carried with combustion gases to the incinerator flue. Particulates are of regulatory concern because they occur in many sizes, some of which are readily inhaled and transported deep within the lungs. Some are additionally composed of hazardous constituents or possess hazardous coatings, for example, heavy metals that had condensed on a particle exterior. These effects are discussed in Chapter 9.

The subpart O requirements control metal emissions through the performance standard for particulates, since metals are often contained within or attached to particulate matter. An incinerator burning hazardous waste must not emit particulate matter in excess of 180 mg/dscm (milligrams per dry standard m^3) (0.08 grains per dry ft^3) according to the formula (40 CFR part 264)

$$P_c = P_m \times 14/(21 - Y) \tag{15.5}$$

where P_c is the corrected concentration of particulate matter, P_m the measured concentration of particulate matter, and Y the oxygen concentration in stack gas.

Example 15.1

A waste mixture consisting of benzene, xylene, and chlorophenol is being incinerated. The incinerator temperature is 1075°C and the stack gas flow rate is 410.82 dscm/min. Waste feed rate is given in the table below. Determine if the unit is in compliance for each compound.

Compound	Inlet(kg/h)	Outlet(kg/h)
Benzene (C_6H_6)	245	0.015
Xylene (C_8H_{10})	442	0.061
Chlorobenzene (C_6H_5OCl)	235	0.149
HCl	—	1.1
Particulates at 8.5% O_2	—	2.775

Solution

a. Calculate the DRE for each of the POHCs
DRE = $(W_{in} - W_{out})/W_{in} \times 100\%$

Benzene	DRE = (245 − 0.015)/245 × 100 = 99.9939%
Xylene	DRE = (442 − 0.041)/442 × 100 = 99.9907%
Chlorobenzene	DRE = (235 − 0.129)/235 × 100 = 99.945%

The DRE limit for chlorobenzene does not meet the regulatory requirement for DRE.

b. HCl emissions
The HCl emissions shown in the table do not exceed the federal limit of 1.8 kg/h.

c. Particulates
The outlet loading of the particulates is calculated by dividing the outlet mass rate by the stack flow rate:

$$W_{out} = [(2.775 \text{ kg/h})(10^6 \text{ mg/kg})]/[(410.82 \text{ dscm/min})(60 \text{ min/h})] = 112 \text{ mg/dscm}$$

Since the particulate concentration was measured at 8.5% oxygen, a correction factor is required.

$$P_c = P_m \times 14/(21 - Y)$$

$$= 112 \text{ mg/dscm} \times 14/(21 - 8.5)$$

$$= 125 \text{ mg/dscm}$$

This value is below the standard of 180 mg/dscm and is therefore in compliance with regard to particulate release.

15.4.4 Fugitive Emissions

Operating conditions regulated under subpart O are also formulated to control *fugitive emissions*, i.e., gases that escape from the combustion chamber and do not enter pollution control devices. An example of fugitive emissions is a gas that escapes through the inlet opening of the combustion chamber. Fugitive emissions are controlled by ensuring that the combustion zone is completely sealed or by maintaining combustion zone pressure lower than atmospheric pressure so that air is drawn out of the firebox and into the pollution control device.

15.4.5 Metals

For RCRA combustion units, both carcinogenic and noncarcinogenic metals are regulated under the same type of tiered system as for chlorine. The facility determines an appropriate tier for each regulated metal and must assure that the facility meets both the feed rate and emission standards. A different tier may be selected for each metal pollutant (Figure 15.2) (U.S. EPA 2002).

15.4.6 Waste Analysis

During operation, the facility must conduct sufficient waste analyses to verify that the waste feed is within the physical and chemical composition limits specified in the permit. This analysis may include a determination of waste heat value, viscosity, and content of hazardous constituents, including POHCs. Waste analysis is one component of the trial burn permit application (see Sec. 15.4.8). The EPA stresses the importance of proper waste analysis to ensure compliance with emission limits.

15.4.7 Operating Conditions and the RCRA Permit

Regulatory agencies must clearly delineate the operating conditions for hazardous waste incinerators to ensure compliance with the performance standards for organics, HCl, particulate matter, and fugitive emissions. The details of an incinerator permit are based upon results from trial burns of hazardous wastes (see section 15.4.8). The permit specifies the operating conditions that have been shown to meet these performance standards.

A RCRA permit for a hazardous waste incinerator sets operating conditions and allowable ranges for certain critical parameters, and also requires continuous monitoring of these parameters. Operation within this range ensures that combustion is performed in the most protective manner and that the performance standards are achieved. The parameters may include (U.S. EPA 1987, 2000, 2002):

- Maximum allowable carbon monoxide levels in stack emissions
- Allowable temperature ranges
- Maximum waste feed rates

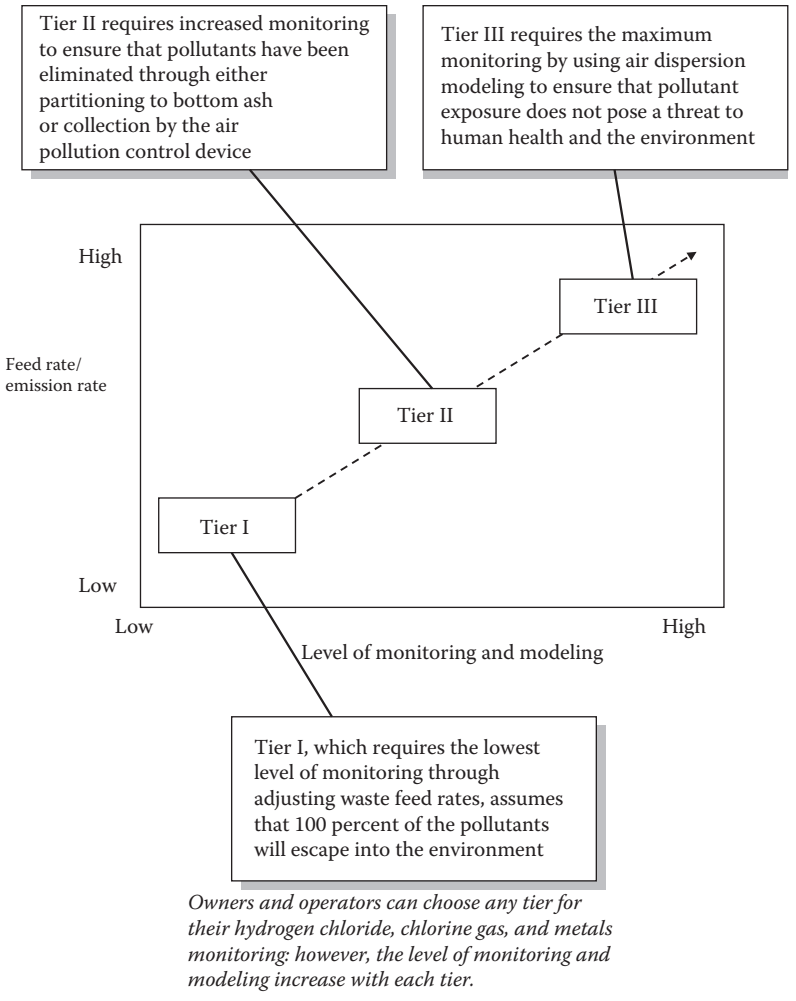


FIGURE 15.2 The tiered system of modeling and monitoring gaseous air pollutants. (From U.S. EPA, *RCRA Orientation Manual,* EPA530-R-02-016, Office of Solid Waste/Communications, Information, and Resources Management Division, U.S. EPA, Washington, DC, 2002.)

- Combustion gas velocity
- Control of the firing system
- Allowable variations of system design and operating procedures

In addition, during the startup and shutdown of an incinerator, hazardous waste must not be charged into the unit unless it is operating according to all conditions specified in the permit. The facility must stop operations when changes in waste feed, incinerator design, or operating conditions exceed any limits designated in the permit.

15.4.8 Obtaining the RCRA Permit

A facility planning to operate a new hazardous waste incinerator is required to obtain a RCRA permit prior to constructing the unit. The purpose of the permit is to allow the facility to establish incineration conditions that ensure the protection of public health and the environment. The incinerator permit covers aspects of pretrial burn, trial burn, posttrial burn, and final operating conditions.

The pretrial burn phase allows the incinerator to initiate all parameters for conducting the trial burn. This may include setting charging rates, fuel and airflow rates, and installing air monitoring equipment.

During the trial burn, the incinerator is prepared for operation. Operating conditions are monitored and adjusted, and gaseous emissions are measured. Test conditions are based on operating conditions indicated by the permit application. EPA establishes conditions in the permit necessary to conduct the trial burn; in other words, the burn should represent the expected incinerator operation. Physical and chemical analysis of the waste feed is also a necessary component of the trial burn permit application. The waste must be analyzed to verify that its composition is within the limits specified in the permit. This analysis may include determination of the content of hazardous constituents, including POHCs and the heat value of the waste.

The post trial burn period is devoted to completing the sampling, analysis, and calculation of trial burn results, and submission of results to EPA. During this period, EPA evaluates all data compiled during the trial burn. After reviewing the results, EPA may modify the permit conditions again to ensure compliance with incinerator standards and protection of health and the environment.

15.4.9 Monitoring and Inspections

In order to ensure safe operations in compliance with all permit specifications, the operator must perform the following during routine incineration of hazardous waste (U.S. EPA 2000):

- Monitor waste feed rate, combustion temperature, and combustion gas velocity on a continuous basis
- Monitor carbon monoxide emissions on a continuous basis at some point downstream of the combustion zone and prior to release to the atmosphere
- Sample and analyze waste and exhaust emissions to verify compliance with permit operating requirements
- Conduct daily visual inspections of the incinerator and associated equipment (e.g., pumps, valves, conveyors)
- Test the emergency waste feed cutoff system and associated alarms at least once weekly (40 CFR 264.347)

15.4.10 Management of Residues

According to the Derived-from Rule, if an incinerator burns a listed hazardous waste, the ash generated is also considered a listed waste. The Derived-from Rule states that any solid waste generated from the treatment, storage, or disposal of a listed hazardous waste, including any sludge, spill residue, ash, emission control dust, or leachate, remains a hazardous waste. The operator is also required to determine whether the ash exhibits any characteristics of a hazardous waste. If a facility incinerates a characteristic hazardous waste (ignitable, corrosive, reactive, or toxic), the operator must determine whether the ash exhibits any of the four characteristics, using the procedures outlined in 40 CFR part 261. If an ash sample fails the test (i.e., exhibits a characteristic), it must be managed as a hazardous waste.

15.4.11 Closure

At the time of closure, the facility operator must remove all hazardous waste and hazardous residues from the incinerator site. In addition, if the residues are hazardous waste, the operator becomes a generator of hazardous waste and must manage the residues in compliance with 40 CFR parts 262–266.

15.5 MACT STANDARDS UNDER THE CAA

Hazardous waste incinerators, cement kilns, and certain aggregate kilns must comply with emission limitations beyond those set by RCRA. The MACT emission standards are established within the CAA regulations. Instead of using specific operating requirements to ensure that the unit meets performance standards, combustion facilities subject to MACT standards are permitted to use a specific pollution control technology to achieve the stringent emission limits.

15.5.1 Organics

To control emissions of organics, combustion units must comply with DRE requirements similar to the RCRA requirements for hazardous waste combustion units. MACT combustion units must select POHCs and demonstrate a DRE of 99.99% for each POHC in the hazardous waste stream.

Facilities that combust F020–F023 or F026–F027 waste are required to achieve a DRE of 99.9999% for each designated POHC. In addition, for PCDDs and PCDFs, EPA has promulgated more stringent standards under MACT. MACT-regulated incinerators and cement kilns must not exceed an emission limit of either 0.2 ng of toxicity equivalence per dry standard cubic meter (TEQ/dscm) or 0.4 ng TEQ/dscm at the inlet to the particulate control device. This unit of measure is based on a method for assessing risks associated with exposure to PCDDs and PCDFs (U.S. EPA 2002).

15.5.2 HCl and Chlorine Gas

MACT combustion units do not use a tiered system to control HCl and chlorine gas emissions; rather, facilities must ensure that total chlorine emissions do not exceed specific limits; for example, the emission limit of total chlorine for a new incinerator is 21 ppmv. The facility may achieve this emissions level by controlling the amount of chlorine-containing waste entering the incinerator (U.S. EPA 2002).

15.5.3 Particulate Matter

EPA developed rather stringent standards for control of particulate matter in order to limit emissions of certain metals. For example, a new aggregate kiln cannot exceed an emission limit of 57 mg/dscm of particulate matter.

15.5.4 Metals

Hazardous waste incinerators, cement kilns, and aggregate kilns are not required to use the tiered approach to control the release of toxic metals into the atmosphere. The MACT rule established numerical emission standards for three categories of metals: mercury, low-volatile metals (arsenic, beryllium, and chromium), and semivolatile metals (lead and cadmium). Combustion units must meet emission standards for quantities of metals emitted. For example, a new cement kiln must meet an emission limit of 120 μg/dscm for mercury, 54 μg/dscm for the low-volatile metals, and 180 μg/dscm for the semi-volatile metals.

15.5.5 Operating Requirements

To ensure that an MACT combustion unit does not exceed MACT emission standards, the unit must operate under parameters demonstrated in a comprehensive performance test (CPT). Operating parameters such as temperature, pressure, and rate of waste feed are established based on the results of the CPT. Continuous monitoring systems are used to monitor the operating parameters.

The facility may also use a more advanced type of monitoring known as continuous emissions monitoring systems (CEMS). CEMS directly measure the pollutants that exit the stack at all times.

15.5.6 Additional Requirements

Because hazardous waste combustion units are a type of TSDF, they are also subject to the general TSDF standards as discussed in 40 CFR part 264, in addition to the above combustion unit performance standards and operating requirements.

15.6 INCINERATION DEVICES

The majority of hazardous wastes occur as liquids, either as hydrocarbon or aqueous mixtures. Under RCRA, land disposal of liquid hazardous wastes has been banned. A number of technologies are being promoted for chemical treatment of wastes in order to render them nonhazardous (Chapter 16); however, many waste streams are not suitable for chemical treatment due to their inherently hazardous nature. Incineration has thus been promoted as an appropriate technology for their destruction. Other wastes are designated as hazardous solely based on the characteristic of ignitability. Incineration, therefore, can serve as a means of energy generation from their destruction.

The physical form of the waste and its content of solid residues determine the optimal type of combustion chamber. Table 15.1 provides some of the general considerations for selection of the combustion chamber. The major subsystems that may occur in a hazardous waste incinerator include (Oppelt 1987):

- Waste preparation and feeding
- Combustion chamber(s)
- Air pollution control
- Ash handling and disposal

TABLE 15.1
Applicability of Major Incinerator Types to Physical Form of Waste

	Liquid Injection	Rotary Kiln	Fixed Hearth
Solids			
Granular, homogeneous		X	X
Irregular, bulky (pallets, etc.)		X	X
Low melting point (tars, etc.)	X	X	X
Organic compounds with fusible ash constituents		X	
Unprepared, large, bulky material		X	
Gases			
Organic vapor-laden	X	X	X
Liquids			
High, organic-strength aqueous wastes	X	X	
Organic liquids	X	X	
Solids/liquids			
Waste contains halogenated aromatic compounds (2200°F minimum)	X	X	
Aqueous organic sludge		X	

Source: Reproduced with kind permission from Oppelt, E.T., *JAPCA* 37, 558–586, 1987.

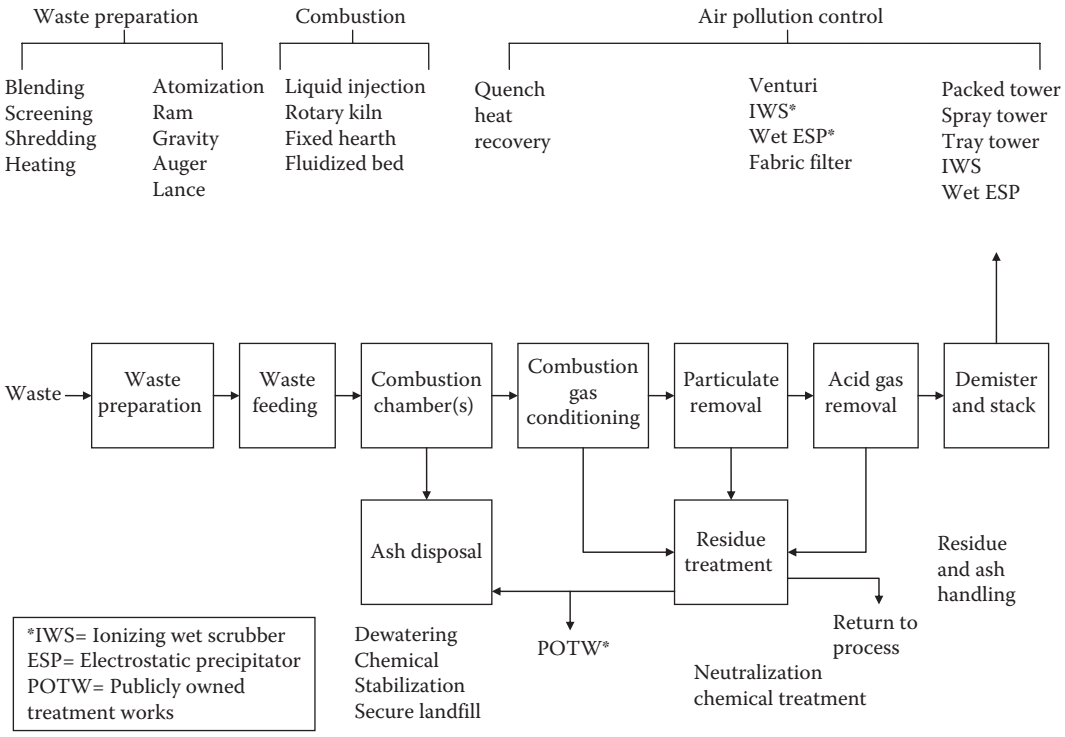


FIGURE 15.3 Schematic showing the orientation of incinerator subsystems and process component options. (Reproduced with kind permission from Oppelt, E.T., *JAPCA* 37, 558–586, 1987.)

The typical orientation of these subsystems appears in Figure 15.3. The selection of the particular combination of subsystems is based upon several variables, including the physical and chemical properties of the waste, regulatory requirements for atmospheric emissions, capital cost, and public acceptance.

15.6.1 Liquid Injection

The liquid injection incinerator (Figure 15.4) is a stationary system consisting of one or more refractory-lined combustion chambers operating under high temperature and equipped with a series of atomizing nozzles. The major units marketed are horizontally and vertically fired. The liquid injection incinerator is currently the most commonly used incinerator type for hazardous waste destruction. It is in daily use throughout the United States both at industrial facilities and at dedicated hazardous waste treatment facilities.

From a combustion standpoint, liquid wastes are classified as either combustible or partly combustible. The first category includes materials having sufficient calorific value (approximately 17,900 kJ/kg [8000 Btu/lb] or higher) to support combustion in a conventional firebox. Below this value, the material cannot maintain a flame—the waste contains a high percentage of noncombustible components, including water, and addition of auxiliary fuel may be necessary.

As the name of the technology implies, wastes are acceptable in a liquid injection incinerator as long as they exist as either pumpable liquids or slurries. A conventional liquid or gaseous fuel (e.g., propane) preheats the system to an equilibrium temperature of approximately 815°C (1500°F) before the introduction of waste. Liquid waste is then transferred from storage drums to a feed tank (Figure 15.5). Blending, which may be used to lower waste chlorine content or improve pumpability or combustibility of the waste, occurs in the tank. The tank may be pressurized with nitrogen

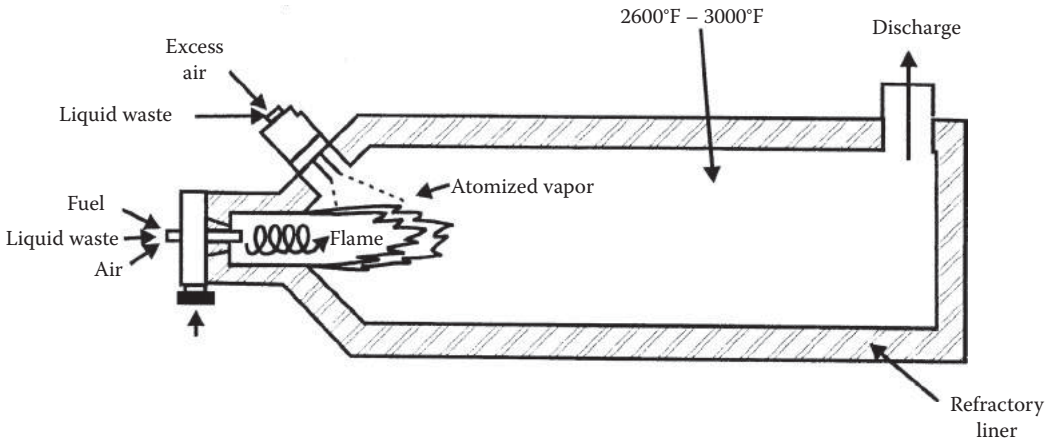


FIGURE 15.4 A liquid injection incinerator. (Reproduced with kind permission from Oppelt, E.T., *J JAPCA* 37, 558–586, 1987.)



FIGURE 15.5 Hazardous waste storage tanks. These tanks can store over 350,000 gal of hazardous waste.

or another inert gas, and waste is fed into the incinerator using a remote valve. After waste transfer, the fuel line is purged with nitrogen to eliminate any explosion hazard.

In the combustion chamber, liquids will react (combust) more readily when they possess a high surface area (e.g., present in the form of a fine mist). Thus, atomizing nozzles are used to inject waste liquids (Figure 15.6). Within the kiln, wastes are typically injected downstream of the fuel nozzle. However, if the waste possesses sufficient heat content (approx. 13,400 kJ/kg or 6000 Btu/lb), it can be injected directly into the fuel envelope. These wastes are said to burn *autogenously* (i.e., without the need for supplemental fuel).

Due to the use of nozzles, there is a limit as to how viscous a waste can be for incineration. The higher the viscosity, the more difficult it is to pump, inject through a nozzle, and ultimately combust. A substance can be pumped if its viscosity is less than 10,000 Saybolt-seconds universal (SSU) (Brunner 1993). For conventional nozzles, the viscosity should be less than 750 SSU for adequate atomization to occur. Atomization is also strongly affected by nozzle type. An ideal droplet size ranges between 40 and 100 μm, which is attained using gas–fluid nozzles and high pressure air or steam (Wentz 1995).

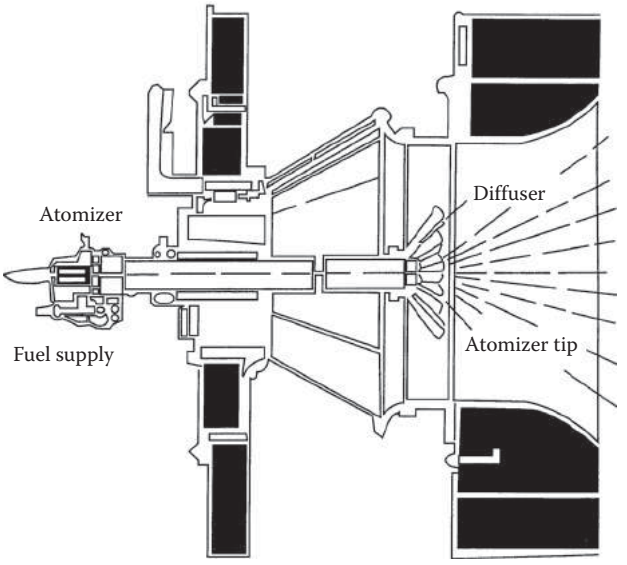


FIGURE 15.6 A mechanical atomizing burner, one of many possible nozzle designs for a liquid injection incinerator. (From Combustion Engineering Superheater, Inc.)

15.6.2 Air Requirements in Liquid Injectors

Whenever an organic material is to be incinerated, sufficient oxygen is necessary to complete combustion. Oxygen is provided via a supply of air. Air is required for several purposes, including:

- Primary air supply, to promote combustion of the waste stream
- Secondary air supply, injected downstream of the burner
- Atomization, to promote vaporization and efficient burning

Primary combustion air is that supplied at the fuel burner to combust the main fuel. Air is supplied through a burner register, a fan-shaped unit surrounding the burner nozzle that creates a circular motion in the airflow. The register is either fixed or adjustable. Secondary air is necessary for combustion of the waste feed and is normally introduced into the firebox downstream of the main flame. In liquid injection furnaces, the secondary air supply is used to shape the flame and divert it away from the walls. The secondary air creates turbulence within the furnace and provides a relatively cool flow on the refractory furnace surfaces, keeping them cooler than the center of the furnace. The primary and secondary airflows are also used to assist in fuel atomization and prevent unburned materials from contacting furnace linings (Brunner 1993).

As the droplets vaporize and combust, any inorganics present in the waste remain in the gas stream and are carried to the air pollution control equipment. The size of particles is determined in part by the size distribution of the original droplets. Larger droplets usually result in larger particles and vice versa. Smaller particles are less likely to be captured by air pollution control equipment, and are thus more likely to escape to the atmosphere. Particle size depends on other variables, including the form of the waste burned (i.e., solid, liquid, gas) and factors specific to the combustion device (e.g., temperature, turbulence, air flow). Only small quantities of bottom ash typically form in the liquid injection incinerator.

As for all incinerator types, the firebox temperature, waste residence time, and overall turbulence are adjusted to optimize destruction efficiencies. The liquid injector operates within a range

of temperatures, depending on waste type. Typical combustion chamber residence times and temperature ranges are 0.5–2 s and 700°C–1650°C (1300°F–3000°F), respectively. Feed rates measure up to 5000–6000 L/h of organic wastes.

15.6.3 Overview of Liquid Injection

The type, size, and shape of a furnace are a function of waste characteristics, burner design, air distribution, and furnace wall design. The furnace can be simple in design as in a vertical, refractory-lined chamber or it can be relatively complex, involving preheating of combustion air and firing of multiple fuels. Liquid injection systems are capable of burning virtually any combustible waste that can be pumped. They are usually designed to burn specific waste streams and consequently are not used in multipurpose facilities. Liquid injection facilities routinely destroy a variety of wastes, including phenols, PCBs, solvents, polymer wastes, herbicides, and pesticides.

The advantages in using a liquid injection incinerator include (Freeman et al., 1987):

- Fewer moving parts result in less downtime and less maintenance
- Capability to incinerate a wide range of wastes
- Low maintenance costs due to the few moving parts in the system

Disadvantages include:

- Only capable of combusting pumpable liquids and slurries
- Feed nozzles tend to clog, resulting in downtime

15.6.4 Rotary Kilns

The key component of the rotary kiln incinerator (Figure 15.7) is a refractory-lined rotating cylinder mounted at a slight incline from ground level. Wastes in the form of liquids, slurries, or bulk solids are fed into entry port(s) (Figure 15.8) and are agitated under elevated temperatures for a

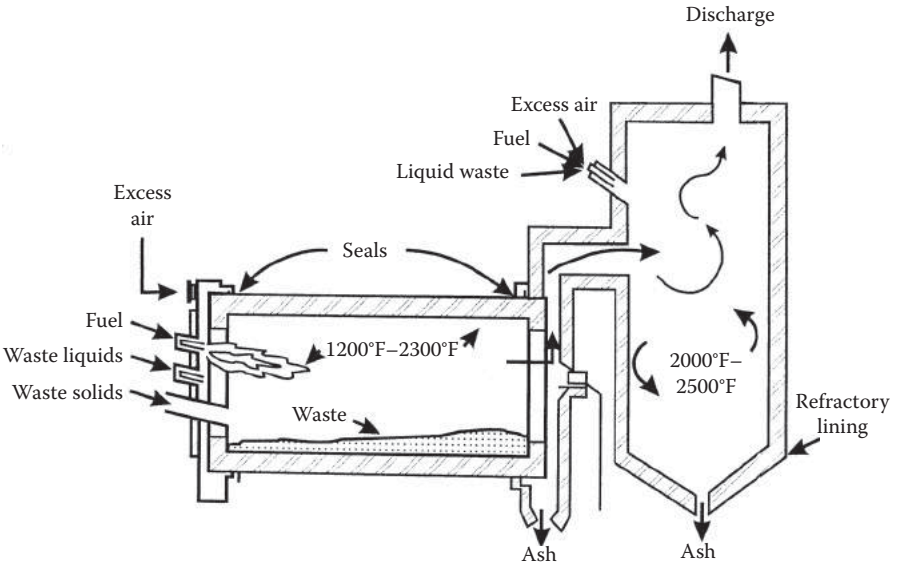


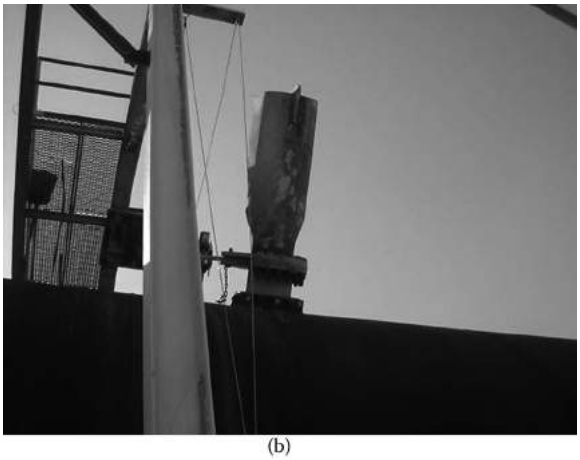
FIGURE 15.7 Rotary kiln incinerator. (Reproduced with kind permission from Oppelt, E.T., *JAPCA* 37, 558–586, 1987.)



FIGURE 15.8 Injection ports for the introduction of liquid hazardous wastes to a rotary kiln.



(a)



(b)

FIGURE 15.9 Mechanical feeding of containerized hazardous wastes into a kiln. (a) Picking up 5 gal container of hazardous waste; (b) charging 5 gal container.

predetermined length of time, depending on waste and kiln characteristics. Waste liquids may be pumped in through a nozzle, thus atomizing the charge. A screw feed mechanism will inject slurries, and bulk solids may enter by a ram feed or similar mechanical system. Many rotary kilns are charged discretely; often, entire packages are fed into a kiln in a single charge (Figure 15.9). Such charging results in a cyclical temperature distribution inside the kiln.

The waste is expected to burn to ash by the time it reaches the kiln exit. Kiln rotation speed varies in the range of ¾ to 4 rpm (Brunner 1993). Most kilns possess a smooth inner surface; however, some are equipped with internal baffles to promote turbulence of the waste charge. The residence time for solid wastes in the kiln is at least 30 min, which is based on the rotational speed and angle of the kiln (Wentz 1995). A long residence time is preferred because the solids bed in the kiln is not thermally uniform. Solids retention time may be several hours and can be estimated from (U.S. WPCF 1988):

$$\theta = 0.19L/(NDS) \tag{15.6}$$

where θ is the retention time (min), L the kiln length (m), N the kiln rotational velocity (r/min), D the kiln diameter (m), and S the kiln slope (m/m). The coefficient 0.19 is based on empirical data.

Example 15.2

Determine the waste retention time for a rotary kiln operating at 0.9 rpm with a kiln length of 5 m, a diameter of 2.2 m, and a slope of 0.1 m/m.

Solution

$$\theta = 0.19L/(NDS)$$

$$\theta = 0.19 \times 5/(0.9 \times 2.2 \times 0.1)$$

$$\theta = 4.8 \text{ min}$$

If the desired retention time is actually to be 7.5 min, what should the rotational velocity be adjusted to?

Solution

Rearrange the equation to solve for rpm:

$$N = 0.19L/(\theta\ D\ S)$$

$$N = 0.19 \times 5/(7.5 \times 2.2 \times 0.1)$$

$$= 0.58 \text{ rpm}$$

The gas retention time for 99.99% destruction of a compound is given by (Kiely 1996):

$$\ln t_g = (\ln 9.21/A) + (E/RT) \tag{15.7}$$

where A is the Arrhenius pre-exponent frequency (s^{-1}), E the energy of activation (J/kg mol), R the universal gas constant = 8314 J/kg mol, and T the absolute temperature (K). The variables A and E are typically known for a specific compound.

A source of heat is required to bring the system to operating temperatures and to maintain the desired combustion temperature. Supplemental fuel (e.g., natural gas) is injected into the kiln through a nozzle. Excess air is also provided. Negative pressure (i.e., suction) is applied to the kiln via an induced draft fan to remove particulate matter and noncombusted vapors.

Two modes of kiln gas flow are available. In the co-current mode, the burner is installed at the entrance to the kiln, and gas flow is in the same direction as waste flow. In the counter-current mode, the burner is placed near the kiln exit, and gas flow is opposite to the direction of waste flow. The counter-current system has been demonstrated to be effective for combustion of aqueous wastes—gases near the kiln entrance serve to dry the incoming aqueous waste.

Organic gases and particulates may be drawn into a second, stationary chamber, labeled the *afterburner*. Here, temperatures are higher compared with the kiln and permit more complete destruction of remaining organic particles or vapors. The gases discharged from the afterburner are subsequently directed to an air pollution control system, such as an electrostatic precipitator, baghouse, or scrubber.

Rotary kilns experience a high entrainment of particulate matter. Entrainment occurs because solids are continuously tumbling within the kiln and are reintroduced to the gas stream. Particle size ranges are similar for both rotary kiln incinerators and liquid injectors. In rotary kilns, entrained particles tend to be larger than 10 μm.

In some cases, it is desirable to operate a kiln in the so-called *slagging mode*. At temperatures of approximately 1090°C–1200°C (2000°F–2200°F), ash will liquefy. Ash fusion temperature is influenced by waste composition as well as incinerator conditions (e.g., oxygen concentration). When ash occurs in molten form, salt-laden wastes and metal drums are more easily incorporated. Production of particulates is also minimized. However, temperatures must be maintained in a higher range in a slagging kiln, resulting in higher energy costs and possible accelerated wear of components; temperatures may average 1425°C–1540°C (2600°F–2800°F), compared with less than 2000°F in a nonslagging kiln. The construction of a slagging kiln is also more complex. Finally, maintenance tends to be more frequent with a slagging kiln (Brunner 1993).

Several sites occur within the kiln where leakage of gases may occur. Critical points include inlet ports and kiln seals. Efficient kiln operation requires the limited introduction of unwanted air into the system. During a phenomenon known as *puffing*, the introduction of a volatile organic waste will result in the instantaneous production of gases with consequent expansion and rapid pressure increase at the inlet end of the kiln. This pressure may be sufficient to weaken kiln seals. In order to limit such a pressure increase, the kiln atmosphere is maintained with a negative pressure draft.

15.6.5 Overview of Rotary Kiln Incineration

The rotary kiln is one of the more popular incineration systems for hazardous wastes. These devices operate under a wide range of conditions and handle a variety of waste types. No single temperature is characteristic of a rotary kiln.

Advantages of the rotary kiln include (Brunner 1993):

- Applicability for a number of waste types (liquids, slurries, sludges, and bulk solids)
- High turbulence provides for thorough mixing of the waste charge
- Minimal preprocessing of waste
- Many types of feed mechanisms available
- Readily controlled waste residence time in the kiln

Disadvantages include:

- High initial capital costs
- Significant costs for maintenance
- Separate afterburner required for destruction of volatile components
- Damage to kiln linings due to abrasion from solids such as drums
- Damage to rotary seals
- High particulate carryover into the afterburner
- Conditions along the length of the kiln are difficult to control
- Ash production may be significant

15.6.6 Boilers and Industrial Furnaces

A boiler is composed of the combustion chamber used to heat hazardous waste, and tubes that hold water for production of steam. The regulatory definition of a boiler requires that these two

components be situated close to one another to ensure effective energy recovery. In addition, the unit must export or use the recovered energy for some beneficial purpose.

Industrial furnaces are enclosed units installed within a manufacturing facility, and they use thermal treatment to recover materials or energy from hazardous waste. These units may use hazardous waste as a fuel to heat raw materials to make a commodity (e.g., a cement kiln which manufactures cement) or the unit may recover materials from the hazardous waste (e.g., a smelter which recovers silver or lead).

Not all units that meet the definition of boiler or industrial furnace are subject to the 40 CFR part 266, subpart H, BIF standards. Each individual unit is evaluated against a list of possible exemptions from the BIF requirements. For several reasons (e.g., to avoid duplicate regulation), EPA exempted the following units from the BIF regulations (U.S. EPA 2002):

- Units burning used oil for energy recovery
- Units burning gas recovered from hazardous or solid waste landfills for energy recovery
- Units burning hazardous wastes that are exempted from RCRA regulation, such as household hazardous wastes
- Units burning hazardous waste produced by a conditionally exempt small quantity generator
- Coke ovens burning only K087 decanter tank tar sludge from coking operations
- Certain units engaged in precious metals recovery
- Certain smelting, melting, and refining furnaces processing hazardous waste solely for metal recovery

15.6.7 Industrial Boilers

Many industrial and commercial facilities are equipped with boilers that are fired by coal, heating oil, or natural gas. Heat is transferred by means of either a boiler adjacent to the firebox or via tubes lining the combustion chamber. The heat from the combustion gas is transferred to the water within the boiler or waterwall tubes.

Hazardous wastes may be combusted in industrial boilers, provided that the wastes are designated hazardous based solely on the characteristic of ignitability. Wastes combusted in this manner usually occur as liquids that are generated on-site. Examples include aliphatic and aromatic solvents, alcohols, and other highly volatile hydrocarbons. EPA requires field tests of operating facilities for destroying hazardous wastes in standard boilers.

During day-to-day operations, the interior of a boiler becomes dirty due to accumulation of particulate matter on surfaces or on waterwall tubes. Such coatings result in reduced heat transfer. To control the accumulation of particles, high-velocity air or steam is periodically blown into the unit to scour surfaces. This process is known as *soot blowing* and is an important consideration when designing a trial burn. During soot blowing, a combination of previously deposited metals, soot, and particulate matter is released. This pulse of particulates enters the air pollution control system. Part of the trial burn must be conducted under soot blowing conditions in order to assess its effects on air quality (U.S. EPA 1993).

The advantage of hazardous waste disposal via combustion in a boiler is reduced cost to the waste generator compared with on- or off-site incineration. The facility obtains a fuel value from the waste, and cost savings are accrued from not having to dispose the waste in an RCRA-regulated process. Also, the waste does not have to be transported to a disposal facility. One disadvantage of incineration in boilers is that the process is not closely regulated and may be subject to accidents or misuse.

15.6.8 Cement Kilns

In a cement kiln, combustion conditions are more severe than those present in many waste incinerators. During cement manufacture, limestone and other additives are exposed to temperatures of

1375°C–1540°C (2500°F–2800°F) in a large rotary kiln heated with fossil fuels (Figures 15.10 and 15.11). The gas temperature may be several hundred degrees higher. The end-product of this process, and the primary component of cement, is a solid material called *clinker* (U.S. EPA 1993).

Cement kilns are a promising disposal option for many organic wastes. They are particularly beneficial for destruction of chlorinated wastes, since most will decompose to their component elements within this temperature range. In burns carried out in the United States, Sweden, and elsewhere, recalcitrant wastes such as pesticides and PCBs have been successfully combusted in cement kilns (Mournighan 1985; Karstensen et al. 2006). Furthermore, newly formed HCl, HBr, and HF gases are neutralized during the clinker production process, which is normally alkaline.

The metal concentration of the raw input of cement kilns can exceed that of both the waste and fuel. Therefore, the metal content of raw materials must be monitored to control metal emissions.

The cement matrix affects the volatility of the metals within the kiln. Cement contains a suite of compounds that form complexes with metals, with a resultant decrease in metal volatility.

A valuable practical attribute of cement kilns is their ability to recycle particulate matter. Volatile metals are also recycled as they vaporize, condense, and attach to particles. As with the rotary kiln, cement kilns use counter-current processes in which fuel and air are introduced from one end while raw materials enter the opposite end. As the hot burning fuel and air pass through the kiln, heat is transferred to the input materials. In this zone, the volatile metals vaporize, but as they are entrained with the airflow, they cool and condense onto particle surfaces. Metals that escape with the gas stream are carried to a baghouse or electrostatic precipitator for collection.

Advantages of cement kilns for hazardous waste incineration include:

- Destruction of organic wastes, including a number of chlorinated and recalcitrant wastes
- Reclamation of energy value of the waste
- Capacity to destroy large quantities of waste

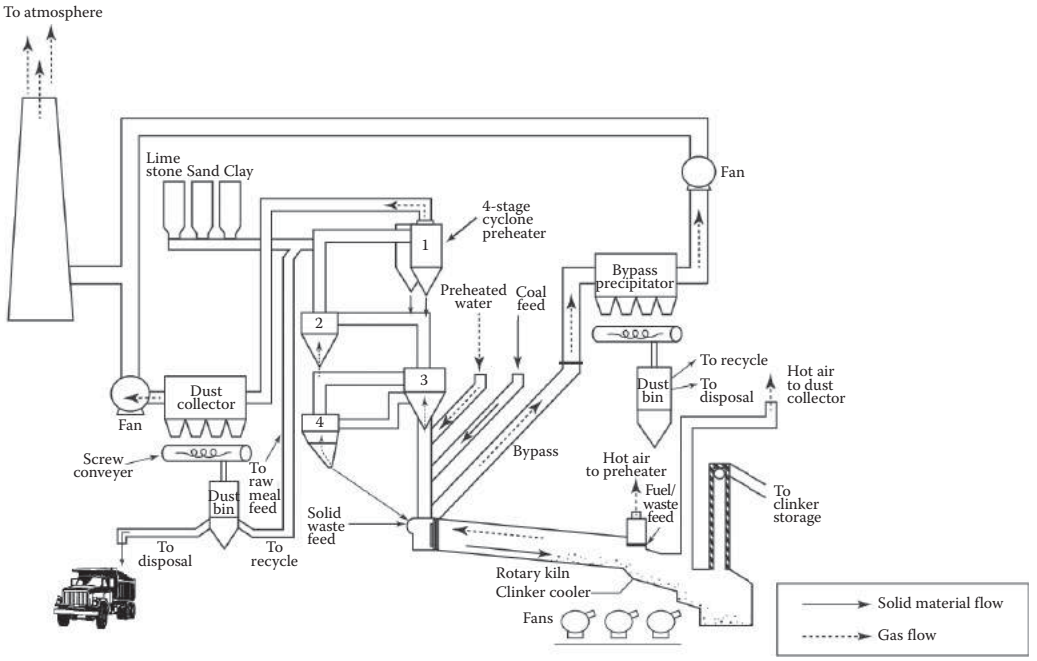


FIGURE 15.10 Cement kiln schematic. (From U.S. EPA, 2012, Cement Kiln Dust Waste. Cement Kiln Overview, Available from: http://www.epa.gov/osw/nonhaz/industrial/special/ckd/rtc/chap-2.pdf)



FIGURE 15.11 Dual cement kilns, each measuring 450 ft in length with a 1 in. steel shell lined with 9–12 in. of firebrick. This facility handles 25 million gal of hazardous waste per year.

Disadvantages include:

- A large quantity of particulates is produced, requiring extensive pollution control.

15.7 AIR POLLUTION AND ITS CONTROL

A major regulatory concern associated with hazardous waste incineration (and a popular justification for the NIMBY [Not in My Backyard] syndrome) is the emission of air pollutants. For a simple hydrocarbon compound (e.g., methane), the primary end-products from combustion, given adequate amounts of air, are carbon dioxide, water vapor, and heat. When complex hazardous wastes are incinerated, however, gaseous wastes that pose an acute threat to public health or the environment often result. The types and amounts of emissions from hazardous waste incineration depend upon a number of variables, including the chemical composition of the waste, waste incineration rate, incinerator type, incinerator operating parameters, and air pollution control equipment.

15.7.1 Atmospheric Products from Combustion

The greatest mass of air contaminants consists primarily of particulate matter and oxides of sulfur and nitrogen. Acid gases such as HCl, HBr, and HF may be produced in significant quantities, depending on feedstock. Trace levels of various other oxides, hydrocarbons (including chlorinated hydrocarbons), and heavy metals are also generated. Particulate matter consists of metal salts from the waste, metal oxides formed by combustion, fragments of incompletely burned material (primarily carbonaceous), and condensed gaseous contaminants (i.e., droplets). Metals and other toxic by-products condense as, or on, fine particles as the exhaust gas stream cools.

Sulfur oxides, mostly sulfur dioxide (SO_2) but also including small amounts of sulfur trioxide (SO_3), originate from sulfur-containing compounds present in the waste or fuel mixture. Nitrogen

oxides (NO_x) originate from nitrogen in combustion air, from organic nitrogen compounds present in the waste, or both. HCl and chlorine (Cl_2) are derived from the incineration of chlorinated hydrocarbons such as polyvinyl chloride. Phosphorus pentoxide and phosphoric acid are formed from the incineration of organophosphorus compounds such as malathion or parathion.

15.7.2 Products of Incomplete Combustion

Even in a well-designed incinerator, the firebox may contain areas of incomplete oxygen incorporation or other, similar, *quench zones*. At temperatures common to hazardous waste incinerators, hydrocarbons may not oxidize in these zones but will decompose pyrolytically, forming PICs. The primary PICs include carbon monoxide, carbon soot, hydrocarbons, organic acids, and polycyclic aromatic hydrocarbons (PAHs). In well-designed and well-operated incinerators, these incomplete combustion products are emitted only in trace amounts.

In a study by EPA (1986), combustion by-products were examined from 23 emissions tests at thermal destruction facilities, including eight incinerators, nine industrial boilers, and six industrial kilns. Emissions were compared with those from facilities burning coal only, and with MSW incinerators. A total of 28 volatile and 27 semivolatile compounds were detected in stack emissions. The compounds were emitted at rates that spanned five orders of magnitude, i.e., 0.09–13,000 ng/kJ of combustor heat input. Emission rates for 12 compounds emitted from the three sources are shown in Table 15.2.

Metals occurring in hazardous wastes being combusted are usually collected as bottom ash or are emitted as particulate matter. In some cases, however, some of the more volatile elements (e.g., Hg, Cd, and Se) are emitted as vapors. Emission rates for a number of metals from hazardous waste combustion appear in Table 15.3.

Example 15.3

A waste mixture of 40% xylene, 35% toluene, 23% n-pentane, and 2% water is to be combusted in a liquid injection incinerator at 550 kg/h. There is 18% excess air in the combustion chamber.

Properties of the waste constituents are as follows:

Compound	Chemical Formula	MW	Heat Content, kJ/kg
Xylene	$C_6H_4(CH_3)_2$	106.16	42,989
Toluene	$C_6H_5CH_3$	92.13	42,527
Pentane	C_5H_{12}	72.14	49,142
Water	H_2O	18.01	0

1. Calculate the total heat release in the incinerator.
2. Calculate the percent by volume of each component in the flue gas.

Solution

1. Heat release in the incinerator.

Xylene heat release =	0.40 × 42,989 = 17,196 kJ/kg
Toluene heat release =	0.35 × 42,527 = 14,884 kJ/kg
Pentane heat release =	0.23 × 49,142 = 11,303 kJ/kg
Water heat release =	0 kJ/kg
Heat release/kg of mixture	43,382 kJ/kg
Total heat release in the incinerator	550 kg/h × 43,382 kJ/hg = 23,860,100 kJ/h

2. Calculate the percent by volume of each component in the flue gas.

a. Xylene $C_8H_{10} + 11.5\ O_2 \rightarrow 8\ CO_2 + 5H_2O$

Mass of xylene = 0.40 × 550 kg/h = 220 kg/h

220/106 = 2.08 moles/h of xylene

Component	MW	Moles/h
Xylene	106	2.08
O_2	32	23.92
CO_2	44	16.64
H_2O	18	10.4

0.18 × 23.92 = 4.31 moles/h of O_2

23.92 + 4.31 = 28.32 moles/h of O_2

Note that air is 79% N and 21% O_2, so 79/21 × 28.23 = 106.20 moles N_2

b. Toluene $C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O$

Mass of toluene = 0.35 × 550 kg/h = 192.5 kg/h

192.5/92 = 2.09 moles/h of toluene

Component	MW	Moles/h
Toluene	92	2.09
O_2	32	18.81
CO_2	44	14.63
H_2O	18	8.36

Given 18% excess air,

0.18 × 18.81 = 3.39 moles/h of O_2 in addition to that calculated above.

18.81 + 3.39 = 22.2 moles/h of O_2

Note that air is 79% N and 21% O_2, so

79/21 × 22.2 = 79.72 moles N_2

c. Pentane $C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O$

Mass of pentane = 0.23 × 550 kg/h = 126.5 kg/h

126.5/72.14 = 1.75 moles/h of pentane

Component	MW	Moles/h
Pentane	72	1.75
O_2	32	14.00
CO_2	44	77.00
H_2O	18	31.50

Given 18% excess air,

$0.18 \times 14.00 = 2.52$ moles/h of O_2 in addition to that calculated above.

$14.00 + 2.52 = 16.52$ moles/h of O_2

Note that air is 79% N_2 and 21% O_2, so

$79/21 \times 16.52 = 62.15$ moles N_2

Beyond the above data for hydrocarbon combustion, there is also 2% water in the waste. This amounts to $.02 \times 550$ kg/h = 11 kg/h

$11/18 = 0.61$ moles H_2O.

Add the moles of each component generated in the flue gas to determine the total moles.

	CO_2	H_2O	O_2	N_2
Xylene	16.64	10.4	23.92	106.20
Toluene	14.63	8.36	18.81	79.72
Pentane	77.00	31.50	14.00	62.15
Water		0.61		
Total	108.27	50.87	56.73	248.07

Total moles = 463.94

Given that the mole% is equivalent to the volume%, the flue gas contains the following:

23.34% CO_2

10.97% H_2O

12.23% O_2

53.47% N_2

15.7.3 Air Pollution Control

Four classes of air pollution equipment are commonly used for particulate control in hazardous waste incinerators: electrostatic precipitators, venturi scrubbers, ionizing wet scrubbers, and baghouses. The removal of acid gases is accomplished using technologies identical to those for MSW incinerators (see Chapter 9). For example, wet scrubbers and packed-tower absorbers are highly effective for the condensation and removal of HCl and SO_x.

Most hazardous waste incinerator facilities use one of three possible schemes for overall air pollution control:

- Venturi scrubber (for particulates) followed by a packed tower absorber (for gases)
- Ionizing wet scrubber (for particulates) combined with a packed tower absorber (for gases)
- Dry scrubber (for acid gases) followed by a baghouse or an electrostatic precipitator (for particulates).

TABLE 15.2
Emission Rates of Specific Compounds for Incinerators, Boilers, and Kilns, ng/kJ[a]

	Incinerators		Boilers		Kilns	
	Mean	Range	Mean	Range	Mean	Range
Benzene	87	2–980	30	0–300	580	290–1000
Toluene	1.6	1.5–4.1	280	0–1200	No data	
Carbon tetrachloride	0.8	0.3–1.5	1.8	0–7.2	No data	
Chloroform	3.8	0.5–8.4	120	0–1700	No data	
Methylene chloride	2.2	0–9.6	180	0–5800	No data	
Trichloroethylene	1.2	2.3–9.1	1.2	0–13	1.3	0.7–2.8
Tetrachloroethane	0.3	0–1.3	63	0–780	No data	
1,1,1-Trichloroethane	0.3	0–1.3	7.5	0–66	2.4	(One value)
Chlorobenzene	1.2	1–6.0	63	0–1000	152	33–270
Naphthalene	44	0.7–150	0.6	0.3–2.1	No data	
Phenol	7.8	0–16	0.3	0–0.8	0.02	0–0.05
Diethylphthalate	3.7	2.8–4.8	0.4	0.04–1.6	No data	

Source: Reproduced with kind permission from Oppelt, E.T., *JAPCA* 37, 558–586, 1987.
* Expressed as ng of emission per kJ of combustor heat input (1 ng/kJ = 2.34×10^{-6} lb/MM Btu).

TABLE 15.3
Average Stack Emissions of Metals from Five Hazardous Waste Incinerators

	Emission Rate (g/kJ)					
Metals	Plant A	Plant B Uncontrolled	Plant B Controlled	Plant C	Plant D	Plant E
Sb	0.32	0.26	BDL	BDL	–	–
As	–	BDL	BDL	BDL	–	[a]
Be	0.052	0.19	0.011	BDL	0.056	0.050
Be	–	5	BDL	BDL	–	[a]
Cd	0.055	0.11	0.019	BDL	0.012	0.36
Cr	0.14	0.73	0.19	2.5	[a]	0.094
Pb	5.4	2.3	0.64	BDL	0.24	9.0
Ni	0.024	0.50	0.087	2.7	0.052	[a]
Se	–	7.0	0.45	BDL	0.29	–
Ag	0.0008	BDL	BDL	0.33	0.0076	–
Ti	0.0089	BDL	BDL	BDL	–	–

Source: Adapted from Oppelt, E.T., *JAPCA* 37, 558–586, 1987.
Note: BDL = All values below detection limit.
[a] Some values were below detection limits; thus, average not calculated.

Example 15.4

A hazardous waste incinerator is operating for the destruction of a mixed, nonchlorinated solvent waste. The flue gas is passed through a lime (CaO) slurry in a dry scrubber where acid gases are partially neutralized and the gases cooled. The gases then pass through a baghouse for particulate removal and are released via the flue.

The flue gas contains 410 kg/h of SO_2 and 325 kg/h of HCl. The dry scrubber lime feed rate is 1.2 × stoichiometric rate, and it is 75% efficient in removing SO_2 and 88% efficient in HCl removal.

1. Calculate the lime feed rate in kg/h.
2. Determine how many kg/h of SO_2 and HCl will be in the flue gas following the dry scrubbing process.

Assume that CO_2 in the flue gas does not react with the lime.

$$CaO + SO_2 \rightarrow CaSO_3$$

$$CaO + 2HCl \rightarrow CaCl_2 + H_2O$$

(Molecular weights: CaO = 56; SO_2 = 64; HCl = 36.5)

Solution

410 kg/h/64 kg/mole = 6.4 moles/h SO_2 in flue gas

325 lb/h/36.5 kg/mole = 6.71 moles/h HCl in flue gas

SO_2 requires 6.4 moles/h CaO × 1.2 = 7.68 moles/h

HCl requires 6.71 moles/h CaO × 1.2 = 8.05 moles/h

Total CaO required = 15.73 moles/h

1. Total lime usage = 15.7 moles/h × 56 kg/mole = 879.2 kg/h
2. 0.25 × 410 kg/h = 103 kg/h SO_2 in flue gas
   0.12 × 245 kg/h = 29 kg/h HCl in flue gas

Note: Additional treatment of this flue gas to remove additional acid gases is warranted.

QUESTIONS

1. Which two major sets of regulations are included in the federal standards for hazardous waste thermal technologies? How do they differ in terms of regulatory coverage?
2. Combustion involves chemical transformations in which solid materials are converted to gases and solid residues. What factors, with regard to both incinerator design and operation and waste properties, affect the composition and quantities of gases produced? What factors will influence the quantity of solid residues generated, both carbonaceous and inorganic?
3. Whenever an organic material is to be incinerated, air (oxygen) is necessary to complete combustion. For what other purposes is air required? Be specific.
4. List the engineering and design factors that serve to enhance combustion in an incinerator.
5. Discuss how each of the major types of gaseous emissions from an incinerator may be effectively removed from flue gas.
6. Compare and contrast the rotary kiln injection system and the liquid injection incinerator in terms of overall design, efficiency, and problems during use. Which is most suited to the destruction of organic sludges, organic solids, liquid solvents, and metal-enriched acidic solutions?
7. A waste mixture consisting of benzene and chlorophenol is being incinerated. Is the unit in compliance for each compound?

Compound	Inlet (kg/h)	Outlet (kg/h)
Benzene (C_6H_6)	953	0.081
Chlorobenzene (C_6H_5OCl)	950	0.149
Xylene (C_8H_{10})	442	0.061
HCl	–	0.95
Particulates (8.8% O_2)	–	48.1

Note: Flow rate 16,250 dscfm.

8. For the data in the previous question, determine if the emissions meet federal requirements for particulates.
9. Calculate the solids retention (θ) time in a rotary kiln incinerator with the following data:
   kiln length = 6 m
   kiln rotational velocity = 0.8 r/min
   kiln diameter = 1.8 m
   kiln slope = 0.085 m/m
10. For question number 9, if the desired retention time is actually 12.0 min, what should the rotational velocity be adjusted to?
11. In a regulatory sense, how might hazardous waste incinerator ash be designated "hazardous"? Consider both listed and characteristic hazardous wastes.
12. Boilers and most industrial furnaces must follow a tiered system for the regulation of both hydrogen chloride and chlorine gas. How do the tiers differ in terms of monitoring requirements, dispersion modeling, and point of compliance? Which factors may be considered when a facility selects a tier?
13. Provide two examples of incinerator fugitive emissions. How can their releases to the environment be controlled?
14. A RCRA permit for a hazardous waste incinerator sets operating conditions and allowable ranges for certain critical parameters, and also requires their continuous monitoring. List the important parameters.
15. Suppose there are several facilities in your county that generate liquid organic hazardous waste that must be shipped off-site for treatment or disposal. Based on economic and practical factors for the generator, incineration is considered the safest and most effective disposal option. Locate the hazardous waste incinerator nearest to your state or community. Are there special routes that the hazardous waste transporter must follow in order to make a delivery?
16. Flue gas from a liquid injection incinerator contains 550 kg/h of SO_2 and 475 kg/h of HCl. The dry scrubber lime feed rate is 1.5 × stoichiometric rate and is known to be about 82% efficient in removing SO_2 and 90% efficient in HCl removal. Calculate the lime feed rate in kg/h. How many kg/h of SO_2 and HCl will remain in the flue gas following dry scrubbing?
17. A liquid waste mixture of 64% xylene, 32% acetone, and 4% water is to be combusted in a liquid injection incinerator at 1275 kg/h. There is 35% excess air in the combustion chamber. Properties of the waste constituents are as follows:

Compound	Chemical Formula	MW	Heat Content, kJ/kg
Xylene	$C_6H_4(CH_3)_2$	106	42,989
Acetone	CH_3COOCH_3	74	13,120
Water	H_2O	18	0

(a) Calculate the total heat release in the incinerator.
(b) Calculate the percent by volume of each component in the flue gas.

REFERENCES

Brunner, C.D. 1993. *Hazardous Waste Incineration*. New York: McGraw-Hill.

CFR (Code of Federal Regulations). 2012. *Volume 40 Part 261, Identification and Listing of Hazardous Waste*. Washington, DC: U.S. Government Printing Office.

CFR (Code of Federal Regulations). 2012. *Volume 40 Part 264, Standards for Owners and Operators of Hazardous Waste Treatment*. Washington, DC: Storage, and Disposal Facilities, U.S. Government Printing Office.

Freeman, H.M., Olexsey, R.A., Oberacker, D.A., and Mournighan, R.E. 1987. Thermal destruction of hazardous waste—A state-of-the-art review. *J Hazard Mater* 14, 103–117.

Haas, C.N. and Vamos, R.J. 1995. *Hazardous and Industrial Waste Treatment*. Englewood Cliffs, NJ: Prentice-Hall.

Karstensen, K., Kinh, N.K., Thang, L.B., Viet, P.H., Tuan, N.D., Toi, D.T., Hung, N.H., Quan, T.M., Hanh, L.D., and Thang, D.H. 2006. Environmentally sound destruction of obsolete pesticides in developing countries using cement kilns. *Environ Sci Pol* 9(6), 577–586.

Kiely, G. 1997. Environmental Engineering. The McGraw-Hill Companies, New York, NY.

Manahan, S.E. 1994. *Environmental Chemistry*, 6th ed. Boca Raton, FL: Lewis Publishing.

Mournighan, R.E. 1985. Hazardous Waste in Industrial Processes. Cement and Lime Kilns. *First International Congress on New Frontiers of Hazardous Waste Management*, EPA 600-9-85-025, Pittsburgh, PA, p. 533–549.

Oppelt, E.T. 1987. Incineration of hazardous waste: A critical review. *JAPCA* 37, 558–586.

U.S. EPA (U.S. Environmental Protection Agency). 1987. *Permitting Hazardous Waste Incinerators,* EPA/625/4-87/017. Cincinnati, OH: Center for Environmental Research Information, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1993. *Operational Parameters for Hazardous Waste Combustion Devices,* EPA/625/R-93/008. Cincinnati, OH: Office of Research and Development, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2000. *Introduction to Hazardous Waste Incinerators (40 CFR Parts 264/265, Subpart O), RCRA, Superfund and EPCRA Hotline Training Module*, EPA530-R-99-052. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2002. *RCRA Orientation Manual*. EPA530-R-02-016. Washington, DC: Office of Solid Waste/Communications, Information, and Resources Management Division, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2012. Cement Kiln Dust Waste. Cement Kiln Overview. Available from: http://www.epa.gov/osw/nonhaz/industrial/special/ckd/rtc/chap-2.pdf

U.S. WPCF (U.S. Water Pollution Control Federation). 1988. *Hazardous Waste Site Remediation*. Alexandria, VA: U.S. Water Pollution Control Federation.

SUGGESTED READINGS

Forster, P., Ingram, C., and Kriznic, P. 2009. Energy recovery from hazardous waste – The new generation of incineration based waste treatment systems. *SSEE 2009: Solutions for a Sustainable Planet*. Engineers Australia, Barton, ACT, 289–296.

Löthgren, C.-J. and van Bavel, B. 2005. Dioxin emissions after installation of a polishing wet scrubber in a hazardous waste incineration facility. *Chemosphere* 61(3), 405–412.

Ma, P., Ma, Z., Yan, J., Chi, Y., Ni, M., and Cen, K. 2011. Industrial hazardous waste treatment featuring a rotary kiln and grate furnace incinerator: A case study in China. *Waste Manag Res* 29(10), 1108–1112.

National Research Council. 2002. *Waste Incineration and Public Health*. Washington, DC: National Academy Press.

Rivera-Austrui, J., Borrajo, M.A., Martinez, K., Adrados, M.A., Abalos, M., Van Bavel, B., Rivera, J., and Abad, E. 2011. Assessment of polychlorinated dibenzo-*p*-dioxin and dibenzofuran emissions from a hazardous waste incineration plant using long-term sampling equipment. *Chemosphere* 82(9), 1343–1349.

Roberts, S.M., Teaf, C.M., and Bean, J.A. 1999. *Hazardous Waste Incineration: Evaluating the Human Health and Environmental Risks*. Boca Raton, FL: Lewis Publishing.

Schuhmacher, M., Domingo, J.L., Agramunt, M.C., Bocio, A., and Müller, L. 2002. Biological monitoring of metals and organic substances in hazardous-waste incineration workers. *Int Arch Occup Environ Health* 75, 500–506.

16 Hazardous Waste Treatment

> Because the newer methods of treatment are good, it does not follow that the old ones were bad; for if our honorable and worshipful ancestors had not recovered from their ailments, you and I would not be here today.
>
> **Confucius (551–478 BCE)**

16.1 INTRODUCTION

Congress updated the Resource Conservation and Recovery Act (RCRA) in 1984 by prohibiting land disposal of certain hazardous wastes, with the consequent enactment of the Land Disposal Restrictions (LDR) program by the Environmental Protection Agency (EPA). The LDR program requires that toxic constituents within hazardous waste be adequately treated prior to disposal on land. Since the enactment of the LDR program became mandatory, technology-based treatment standards have been formulated that must be met before hazardous waste is disposed to land. These standards have been most valuable in minimizing threats to human health and the environment.

16.2 LAND DISPOSAL RESTRICTIONS

By May 8, 1990, the Hazardous and Solid Waste Amendments to RCRA (HSWA) prohibited all untreated hazardous waste from landfill disposal. Many wastes were restricted from being disposed in or on the land due to the probability of severe groundwater or soil contamination. HSWA also required EPA to formulate treatment standards for all hazardous wastes by five specific deadlines. The treatment standards established maximum contaminant levels that a hazardous waste cannot exceed in order for it to be disposed in a hazardous waste landfill. The specific goals of the treatment standards are to (U.S. EPA 2001c):

- Identify wastes with similar physical and chemical characteristics
- Establish treatability groups based on these characteristics
- Identify the Best Demonstrated Available Technology (BDAT) to treat a hazardous waste.

Three types of treatment standards were included:

- *Concentration-based.* The waste must be treated to a level at which only permissible quantities of toxins remain in the waste.
- *Technology-based.* The waste must be treated by a specific technology to a level below the limit at which it is prohibited from land disposal.
- *No land disposal*
  - The waste can be recycled without generating a prohibited residue
  - The waste is not currently being disposed
  - The waste is no longer being generated

Wastes that meet these treatment standards may be disposed in EPA-approved hazardous waste landfills.

The LDR program contains three major components that address hazardous waste disposal, dilution, and storage. *The Disposal Prohibition* states that before a hazardous waste can be

land-disposed, treatment standards specific to that waste must be met. A facility may meet such standards by either (U.S. EPA 2001c):

- Treating hazardous chemical constituents in the waste to meet required treatment levels. Any method of treatment can be used to bring concentrations to the appropriate level (except dilution); or
- Treating hazardous waste by using a treatment technology specified by EPA. Once the waste is treated with the required technology, it can be land-disposed.

The *Dilution Prohibition* states that waste must be properly treated and not simply diluted in concentration by adding large volumes of water, soil, or nonhazardous waste. Dilution does not reduce the toxicity of the hazardous constituents but only increases total volume.

The *Storage Prohibition* states that waste must be treated and cannot be stored indefinitely. This prohibition prevents treatment, storage, and disposal facilities (TSDFs) and generators from "warehousing" hazardous waste for long periods to avoid treatment. Waste may be stored, subject to the LDR, in tanks, containers, or containment buildings, but only to accumulate quantities necessary to facilitate proper recovery, treatment, or disposal.

16.3 WASTE TREATMENT PRIOR TO LAND DISPOSAL

Chemical treatment of hazardous waste is carried out via the application of one or a series of chemical reactions. Chemical processes may be applied for the treatment of soluble contaminants (e.g., wastewaters), or mixtures of solids and liquids (sludges) containing hazardous constituents. Table 16.1 lists common chemical and physical processes for the treatment of hazardous wastes.

16.3.1 Neutralization

Neutralization is used for the treatment of acidic or alkaline wastes, many of which are designated as RCRA corrosive wastes. A waste that exhibits the characteristic of corrosivity as defined in 40 CFR 261.22 is aqueous with a pH ≤ 2 or ≥ 12.5, or is a liquid that corrodes steel at a rate greater than a specified rate (see Chapter 11). Some listed hazardous wastes (e.g., spent pickle liquor generated by steel finishing operations, K062) are also corrosive wastes and must be neutralized.

It is important to conduct a waste characterization early in the design of a waste neutralization process. The overall chemical composition of the waste, including variations in strength, must be known to ensure correct design of the treatment system. Similarly, waste flow rate will affect the size of the system. Waste characterization is a requirement for hazardous waste generators (see Chapter 12) and can be accomplished using established laboratory procedures or by considering

TABLE 16.1
Common Chemical Treatment Processes for Hazardous Wastes

Process	Specific Applications
Neutralization	Neutralization of acidic or basic properties of a liquid waste to reduce its corrosive properties.
Precipitation	Removal from solution of dissolved hazardous inorganic contaminants by chemical reaction.
Oxidation and reduction	Changing the valence of an element via addition or removal of electron(s). The reaction renders that element less toxic and/or amenable to other treatment processes.
Sorption	Physical adhesion of soluble hazardous contaminant molecules to the surface of a solid sorbent.
Stabilization	Stabilization and solidification of metal-containing waste sludges by precipitation with Portland cement, fly ash, or similar fixative agent.

the nature of the facility's processes. Waste strength (i.e., concentration of acidity or alkalinity) is determined by collecting representative samples and performing a simple titration.

Depending on waste properties, pretreatment may be necessary prior to neutralization. Pretreatment can include filtration, sedimentation, and equalization. Other pretreatment steps include cyanide destruction, chromium reduction, and removal of oil and grease.

Neutralization of acidic wastes is carried out by reaction with a base, which raises pH to an acceptable range (Figure 16.1). Neutralization is conducted on a batch basis or as a continuous-flow process. Methods of neutralizing acidic wastes include:

- Adding appropriate volumes of strong or weak base to the waste
- Mixing acidic waste with lime slurries
- Passing acidic waste through limestone beds
- Mixing acidic waste with a compatible alkaline waste

Reagents used to neutralize acidic wastes include sodium hydroxide (caustic soda), sodium carbonate (soda ash), ammonia, limestone, and lime (Table 16.2). The choice of neutralizing agent is based upon several factors, including neutralizing ability, production of reaction products, and cost. For wastes having mineral acid acidity more than 5000 mg/L, high calcium lime or caustic soda are often used, whereas for more dilute acid wastes, limestone treatment may be economically feasible (Camp Dresser and McKee 1984).

Sodium hydroxide (NaOH) is relatively expensive compared with many common neutralizing agents; however, its popularity is based on ease of storage and delivery (i.e., low equipment costs), rapid reaction rate, uniformity of composition, and relatively low volumes of sludge produced (Haas and Vamos 1995). Sodium hydroxide is quite reactive and poses a serious hazard to workers. The reagent itself is highly corrosive to skin and materials. Rapid, vigorous reactions produce excessive amounts of heat.

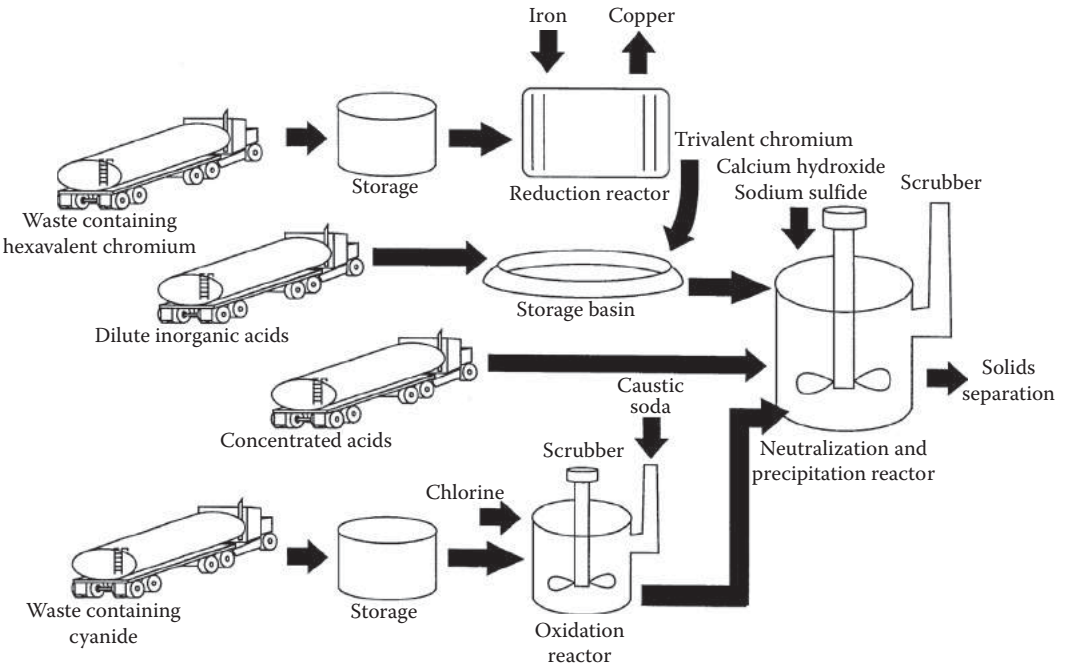


FIGURE 16.1 Chemical treatment of hazardous wastes: neutralization, precipitation, and oxidation–reduction. (Reproduced with kind permission from Blackman, W.J. Jr., *Basic Hazardous Waste Management,* 3rd ed., Lewis Publishers/CRC Press, Boca Raton, FL, 2001.)

TABLE 16.2
Common Acid Neutralizing Agents

Common Name	Chemical Formula
Calcitic limestone	$CaCO_3$
Dolomitic limestone	$Ca{\cdot}Mg(CO_3)$
Quicklime	CaO
Hydrated lime	$Ca(OH)_2$
Soda ash	Na_2CO_3
Caustic soda	NaOH
Potassium hydroxide	KOH
Magnesium hydroxide	$MgOH_2$
Ammonia	NH_3
Slags, industrial	
Blast furnace slag	Calcium silicate
Powerplant fly ash	Varied, alkaline

Sodium carbonate (Na_2CO_3) is a weak base and is safer to use than NaOH; however, it is less reactive and more expensive to use. This base is applied in slurry form due to its low solubility in water. Sodium carbonate has the advantage of buffering the pH of the waste mixture. However, evolution of CO_2 gas can cause foaming problems.

Ammonia (NH_3) is a strong alkali and is very reactive. Neutralization of acidic wastes with ammonia has the advantage of ease of handling; in addition, it provides modest buffering capacity. Ammonia is quite toxic and special precautions are required for its use. For example, neutralization reactions should be carried out in well-ventilated units with continuous atmospheric monitoring and controls. Ammonia-neutralized waste may contain high levels of dissolved nitrogen compounds.

Acidic waste can be neutralized by mixing with limestone ($CaCO_3$), either by adding pulverized or granular material to a reaction basin or by passing acidic liquid wastes over a granular limestone bed. Limestone-based neutralization is popular because of its availability and low cost. Unfortunately, limestone has a modest neutralizing potential compared with other alkali reagents. Also, low reactivity results in long treatment times (45 min or more). Another practical concern involves the production of large volumes of sludge. The reaction of sulfuric acid (H_2SO_4) with limestone is given by

$$H_2SO_4 + CaCO_3(s) \rightarrow CaSO_4 \cdot H_2O(s) + CO_2 \tag{16.1}$$

The presence of sulfate in acidic wastes will result in large quantities of gypsum sludge. In addition, the sludge produced in Equation 16.1 is difficult to settle. When treating concentrated acidic wastes, limestone particles can become coated with precipitates, thus rendering them inactive, and the coated particles end up as sludge. In order to circumvent this problem, particle diameters of less than 0.074 mm are recommended for limestone bed neutralization. An additional difficulty in limestone bed treatment is that the carbon dioxide gas produced during neutralization reactions can gas-bind the beds (Haas and Vamos 1995).

Acidic wastes can also be neutralized by the addition of lime slurries. A slaked lime ($Ca(OH)_2$) slurry, produced by reacting lime (CaO) with water, usually has a solids concentration of about 10%–35%. Acid neutralization requires 15–30 min (Wilk et al. 1988; Haas and Vamos 1995). Lime has an advantage over limestone in that it is a more soluble and more concentrated neutralizing reagent. As with limestone, a disadvantage of using lime slurries is the formation of insoluble salts, especially when the waste contains sulfate. The insoluble salts can coat pH electrodes, valves, pipes, and pumps. Also, handling lime releases large amounts of lime dust.

Alkaline industry wastes can neutralize an acidic waste stream. However, supplemental neutralizing agents should be available to account for any incomplete reaction. Mixing alkaline waste

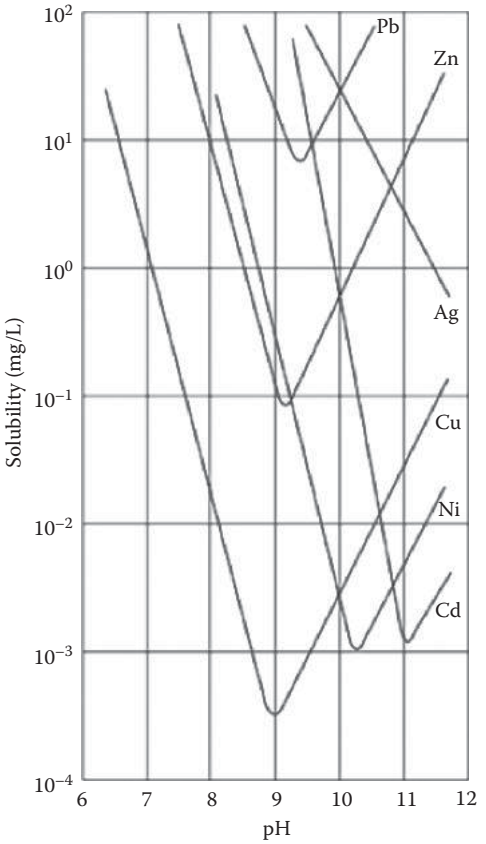


FIGURE 16.2 Precipitation of metals as a function of solution pH. (From U.S. EPA, *Corrective Action: Technologies and Applications, Seminar Publication*, EPA/625/4-89/020, Center for Environmental Research Information, U.S. EPA, Cincinnati, OH, 1989. With permission.)

with metal-containing acidic waste will produce heavy metal hydroxide sludges. Figure 16.2 shows the behavior of soluble metals as a function of solution pH. Wastes containing cyanide are not suitable for neutralization processes because of the potential for the evolution of hydrogen cyanide gas.

Example 16.1

At a wire processing facility, a precipitation system is being installed to remove copper from the processing solution. A pH meter will be used to control the feed of the hydroxide solution to the mix tank. To what pH should the instrument be set to achieve a Cu effluent concentration of 0.5 mg/L?

Solution

The K_{sp} of $Cu(OH)_2 = 2.0 \times 10^{-19}$

And the copper hydroxide reaction is

$$Cu^{2+} + 2OH^- \rightarrow Cu(OH)_{2(s)}$$

$$K_{sp} = [Cu^{2+}][OH^-]^2$$

Convert mg/L Cu to moles/L Cu:

$$[Cu^{2+}] = (0.50 \text{ mg/L})/[(63.54 \text{ g/mol})(1000 \text{ mg/g})] = 7.87 \times 10^{-6} \text{ moles/L}$$

The solubility product equation above is rearranged to solve for the hydroxide concentration.

$$[OH^-]^2 = (2.0 \times 10^{-19})/(7.87 \times 10^{-6}) = 2.54 \times 10^{-14}$$

$$[OH^-] = (2.54 \times 10^{-14})^{1/2}$$

$$= 1.59 \times 10^{-7}$$

$$pOH = -\log (1.59 \times 10^{-7})$$

$$= 6.80$$

$$pH = 14 - pOH$$

$$= 14 - 6.8$$

$$= 7.20$$

Thus, the pH should be set to 7.20 to reduce the soluble copper to 0.5 mg/L.

Neutralization of alkaline waste is achieved by reaction with an adequate quantity of an acid to bring solution pH within the desired range. Methods of neutralizing alkaline wastes include (Haas and Vamos 1995):

- Adding appropriate quantities of strong or weak acid to the waste
- Blowing compressed carbon dioxide gas into the waste
- Blowing acidic flue gas (e.g., from coal combustion or municipal solid waste [MSW] incineration) through the waste
- Mixing acidic waste with the alkaline waste

Alkaline wastes are most commonly neutralized by reaction with mineral acids, typically H_2SO_4 and hydrochloric acid (HCl). H_2SO_4 is popular by virtue of its relatively low cost. Neutralization residence times of 15–30 min are recommended with H_2SO_4 (Wilk et al. 1988; Haas and Vamos 1995). A disadvantage of using H_2SO_4 is that it will form sludge when reacted with calcium-containing alkaline waste.

HCl is more expensive than H_2SO_4; however, HCl neutralization does not produce sludge when neutralizing calcium-enriched alkaline wastes. Neutralization residence times of 5–20 min are recommended. A disadvantage of using HCl is that it can form a corrosive and irritating acid mist upon reaction. Nitric acid (HNO_3) may also be used for neutralization; however, it is dangerous because it is a powerful oxidizing agent.

16.3.2 Chemical Precipitation

During chemical precipitation of a hazardous waste stream, a soluble hazardous species is removed from solution by addition of a precipitating reagent; an insoluble compound subsequently forms that contains the hazardous constituent (Equation 16.2). The precipitate is removed from solution by using a physical separation technique such as sedimentation or filtration. Coagulants or flocculants may be added to the mixture to enhance separation of the precipitate from the soluble phase. Examples of common inorganic coagulants are aluminum sulfate (alum), $(Al_2(SO_4)_3 \cdot 18H_2O)$ and ferric sulfate $(Fe_2(SO_4)_3)$.

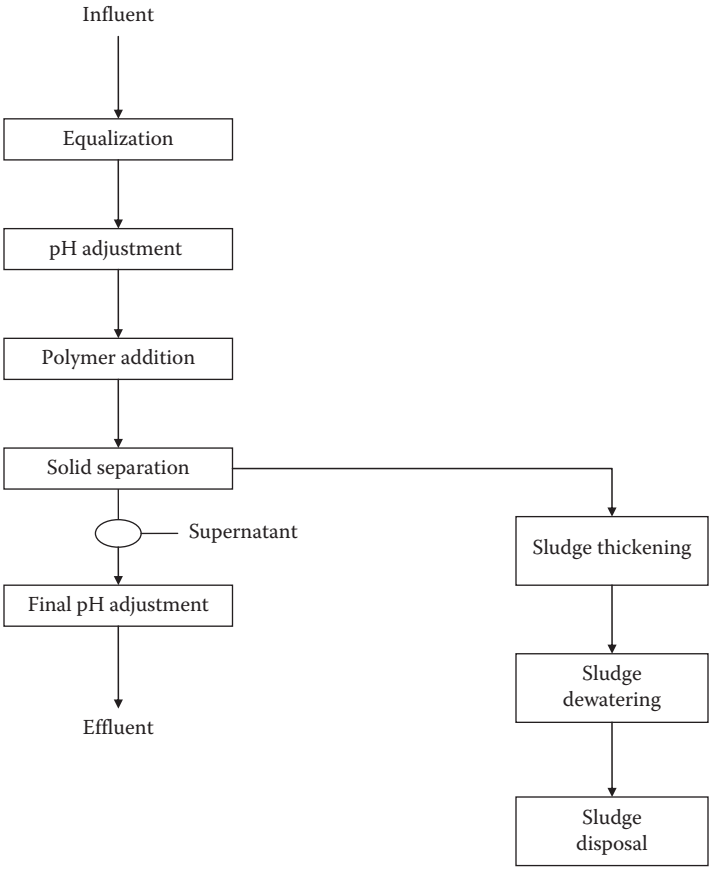


FIGURE 16.3 Schematic of a precipitation process. (Reproduced with kind permission of Water Environment Federation, Alexandria, VA.)

A schematic of a typical precipitation process is provided in Figure 16.3.

Precipitation treatment is typically focused on the removal of dissolved inorganic ions, particularly metals:

$$Cd^{2+}(aq) + HS^{-}(aq) \rightarrow CdS(s) + H^{+}(aq) \tag{16.2}$$

A number of counter anions are suitable for reaction with the metal. These anions vary widely in terms of rate of reaction, inherent toxicity, and cost. A common means of precipitating soluble metal ions is by hydroxide formation, as in the example of zinc(II) hydroxide:

$$Zn^{2+} + 2OH^{-} \rightarrow Zn(OH)_2(s) \tag{16.3}$$

The hydroxide ion source can be a common alkali such as NaOH, Na_2CO_3, or ($Ca(OH)_2$). When reacted with such alkalis, most metal ions produce basic salt precipitates. Lime is the most common reagent for precipitation of metals as hydroxides and basic salts. Sodium carbonate is used to form hydroxides ($Cr(OH)_3$), carbonates ($CdCO_3$), or basic carbonate salts ($2PbCO_3 \cdot Pb(OH)_2$) (Manahan 2009). The carbonate anion produces hydroxide as a result of hydrolysis with water:

$$CO_3^{2-} + H_2O \rightarrow HCO_3^{-} + OH^{-} \tag{16.4}$$

The hydroxide anion subsequently reacts with the metal.

Several heavy metal sulfides have extremely low solubilities; therefore, precipitation by hydrogen sulfide (H_2S) or other sulfides serves as a very effective treatment. Unfortunately, H_2S is a toxic gas and a hazardous waste, listed as a U135 waste. A safer source of sulfide that produces metal–sulfide precipitates is iron(II)sulfide (FeS).

A disadvantage of producing sulfide precipitates is that H_2S can evolve if metal sulfide wastes come into contact with acid:

$$MS_{(s)} + 2H^+ \rightarrow M^{2+} + H_2S_{(g)} \tag{16.5}$$

Metals can also be precipitated from solution by action of a reducing agent such as sodium borohydride (Manahan 1990):

$$4Cu^{2+} + NaBH_4 + 2H_2O \rightarrow 4Cu_{(s)} + NaBO_2 + 8H^+ \tag{16.6}$$

Precipitation reactions result in the formation of a treated effluent and a sludge containing most of the contaminants originally present in solution. After precipitation, the volume of the sludge should be substantially less than the volume of original solution. Therefore, the precipitation process is considered a volume-reduction process and not a destruction process. The sludge may contain mostly water and must be dewatered before disposal. Dewatered sludges are often characteristic hazardous wastes based upon TCLP results or are listed hazardous wastes based on the industrial process from which the wastes were generated. Such sludges may require further treatment prior to landfilling as required by the LDR.

The formation and settling of inorganic precipitates (commonly termed *flocculation* and *sedimentation*) can also entrap dissolved and colloidal organic contaminants via physical and chemical mechanisms. The removal of organic contaminants by precipitation is viewed as a beneficial side reaction of the process (Haas and Vamos 1995).

Industries producing wastewaters amenable to precipitation include metal plating and finishing, steel and nonferrous, inorganic pigments, mining, and electronics. Landfill leachate and contaminated groundwater can also contain hazardous species that are suitable for chemical precipitation.

16.3.3 Oxidation and Reduction

Oxidation and reduction reactions are applied for the treatment of a variety of inorganic and organic wastes. By definition, an oxidation reaction increases the valence of an element due to removal of electrons; conversely, a reduction reaction decreases an element's valence because electrons are added to its shell.

For oxidation to proceed, an oxidizing agent is reacted with the waste. A number of useful oxidizing agents are listed in Table 16.3. Common ones include ozone (O_3), hydrogen peroxide (H_2O_2), and chlorine gas (Cl_2). Ozone, used at levels of 1–2 wt% in oxygen and 2–5 wt% in air, has been used to treat a variety of effluents and wastes, including wastewater and sludges (Manahan 2009). Ozone is a strong oxidant and decomposes rapidly; therefore, it is generated on-site by an electrical discharge through dry air or oxygen. Ozone must be used with caution as it is a nonselective and rapid oxidant. Similarly, H_2O_2 and Cl_2 are nonselective and highly reactive depending on their initial concentration.

Cyanide-bearing wastewater generated by the metal-finishing industry is often oxidized with alkaline chlorine or hypochlorite solutions. The cyanide contaminant is initially oxidized to a less toxic cyanate and then to carbon dioxide and nitrogen in the following reactions (U.S. EPA 2000a):

$$2NaOH + Cl_2 \rightarrow NaOCl + NaCl + H_2O \tag{16.7}$$

TABLE 16.3
Commonly Used Oxidizing and Reducing Agents

Oxidizing agents
Cl_2
F_2
O_2
O_3
Permanganate (MnO_4^-)
Chromate (CrO_4^{2-})
Dichromate ($Cr_2O_7^{2-}$)
Nitric acid (HNO_3)
Perchloric acid ($HClO_4$)
Sulfuric acid (H_2SO_4)
Reducing agents
Sodium
Magnesium
Aluminum
Zinc
Metal hydrides: NaH, CaH_2, $LiAlH_4$

$$NaCN + Cl_2 \rightarrow CNCl + NaCl \quad (16.8)$$

$$CNCl + 2NaOH \rightarrow NaCNO + NaCl + H_2O \quad (16.9)$$

$$2NaCNO + 3Cl_2 + 4NaOH \rightarrow 2CO_2 + N_2 + 6NaCl + 2H_2O \quad (16.10)$$

In these reactions, the free chlorine concentration is concurrently reduced. Oxidation of cyanide may also be accomplished with hydrogen peroxide, ozone, and electrolysis (Dawson and Mercer 1986; Blackman 2001).

Example 16.2

A metal processing industry produces 95,000 L per day of a waste stream containing 325 mg/L cyanide as NaCN. Calculate the stoichiometric quantity of Cl_2 required daily to destroy the cyanide.

Solution

Combining reactions 16.7 through 16.10, we obtain:

$$2NaCN + 5Cl_2 + 12\ NaOH \rightarrow N_2 + Na_2CO_3 + 10NaCl + 6H_2O \quad (16.11)$$

From this reaction, we can see that a total of 2.5 moles of Cl_2 is required to completely react with one mole of NaCN.

The total mass of NaCN generated daily is

$$(95{,}000\ L/day)\ (1\ kg/L)\ (325\ parts/10^6\ parts) = 30.88\ kg\ NaCN/day$$

The kg-moles of NaCN generated per day is

$$(30.88\ kg/day)/(49\ kg/kg\text{-}mole) = 0.630\ kg\text{-}mole\ NaCN/day$$

The amount of Cl_2 required daily is

$$2.5\ (0.63) = 1.576 \text{ kg-mole } Cl_2$$

$$= (1.576)\ (70.9 \text{ kg/kg-mole})$$

$$= 111.7 \text{ kg/d } Cl_2 \text{ required}$$

Note: Due to reaction with other contaminants, Cl_2 concentrations beyond the stoichiometric amount will be required to complete the process.

Example 16.3

For the waste stream in example 16.2, determine the stoichiometric amount of NaOH required to oxidize the cyanide to N_2. Refer to Equations 16.8 through 16.10 for the conversion of CN^- to N_2.

The molecular weight of CN^- = 26; Cl_2 = 70.9; NaOH = 40.

Solution

From Equation 16.9, the molar ratio of CNO^-/CN^- = 1
From Equation 16.10, the molar ratio of $NaOH/CNO^-$ = 4/2 = 2
Therefore, the molar ratio $NaOH/CN^-$ = 2.
The mass ratio $NaOH/CN^-$ = 2 × 40/26 = 3.08 kg/kg
The mass of NaOH required daily is 111.7 × 3.08 kg/kg = 344.0 kg/day

Hexavalent chromium-containing wastewater is generated during chromium electroplating and in metal-finishing operations carried out on chromium as the base material. Chromium wastes are typically treated in a two-stage batch process. In the initial stage, the highly toxic hexavalent chromium (Cr^{6+}) is reduced to the less toxic trivalent form (Cr^{3+}). Several reagents reduce hexavalent to trivalent chromium, including sulfur dioxide, bisulfate, or ferrous sulfate. The Cr^{3+} is then precipitated as chromic hydroxide and removed. Most processes use caustic soda (NaOH) to generate chromium hydroxide. Hydrated lime [$Ca(OH)_2$] may also be used. Key reactions are as follows:

$$SO_2 + H_2O \rightarrow H_2SO_3 \tag{16.12}$$

$$3H_2SO_3 + 2H_2CrO_4 \rightarrow Cr_2(SO_4)_3 + 5H_2O \tag{16.13}$$

Addition of NaOH results in Cr precipitation:

$$6NaOH + Cr_2(SO_4)_3 \rightarrow 2Cr(OH)_3(s) + 3Na_2SO_4 \tag{16.14}$$

Some generic oxidation and reduction reactions are depicted in Table 16.4.

16.3.4 Sorption

Sorption involves the use of a *sorbent* to remove a soluble hazardous contaminant (*the sorbate*) from an aqueous waste solution. Sorption is not a chemical process; rather, it involves the physical adhesion of molecules or particles to the surface of a solid sorbent. Sorption is solely a surface phenomenon.

One of the most popular sorbents for the removal of both organic and some inorganic substances from aqueous waste is activated carbon. Carbon possesses a high surface area and hydrophobic surface characteristics, thus making it an excellent sorbent for removing contaminants from water (Figure 16.4).

TABLE 16.4
Examples of Oxidation and Reduction Reactions Used to Treat Wastes

Waste Type	Reaction with Oxidant or Reductant
Oxidation of organics	
Organic matter, (CH_2O)	$\{CH_2O\} + 2\{O\} \rightarrow CO_2 + H_2O$
Aldehyde	$CH_3CHO + \{O\} \rightarrow CH_3COOH$
Oxidation of inorganics	
Cyanide	$2CN^- + 5OCl^- + H_2O \rightarrow N_2 + 2HCO_3^- + 5\ Cl^-$
Iron(II)	$4Fe^{2+} + O_2 + 10H_2O \rightarrow 4Fe(OH)_3 + 8H^+$
Sulfur dioxide	$2SO_2 + O_2 + 2H_2O \rightarrow 2H_2SO_4$
Reduction of inorganics	
Chromate	$2CrO_4^{2-} + 3SO_2 + 4H^+ \rightarrow Cr_2(SO_4)_3 + 2H_2O$
Permanganate	$MnO_4^- + 3Fe^{2+} + 7H_2O \rightarrow MnO_2(s) + 3Fe(OH)_3(s) + 5H^+$

Source: Reproduced with kind permission of Manahan, S.E., *Environmental Chemistry,* 9th ed., CRC Press, Boca Raton, FL, 2009.

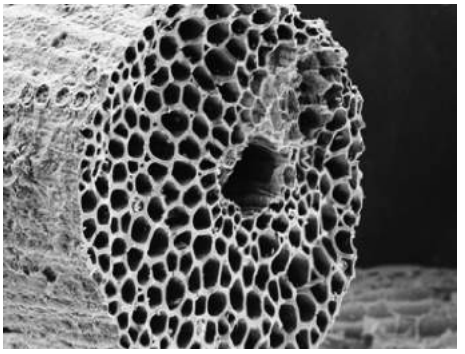


FIGURE 16.4 Electron micrograph of activated carbon. (Available from: http://chemical.eng.usm.my/bassim/)

Activated carbon is used in either granular or powdered form. Different raw materials and processing techniques are used to produce a range of carbon types with different sorption characteristics. Activated carbon is prepared from coconut shells, wood, bituminous coal, or lignite. The carbon is first dehydrated by heating at 170°C; the temperature is increased further, resulting in *carbonization*, that is, transforming the material to a charcoal-like substance. The final step is activation or the addition of superheated steam, which enlarges pores, removes ash, and increases surface area. The resulting activated carbon has an extremely high surface area, in excess of 1000 m^2/g. At the microscopic level, an activated carbon particle possesses a porous structure with a large internal surface (Figure 16.4).

Sorption of an organic molecule to a surface site requires four separate phenomena: bulk fluid transport, film transport, intraparticle (or pore) diffusion, and actual physical attachment. The driving forces that control adsorption of the organic solute include electrical attraction, a chemical affinity of a particular organic molecule for the adsorbent, van der Waal's forces (weak attractive forces acting between molecules), and the hydrophobic nature of the organic solute (Tchobanoglous et al. 1993). Most adsorption processes are physical processes resulting from van der Waal's molecular forces.

The adsorption equilibrium may be represented by the Freundlich isotherm,

$$x/m = kC^{1/n} \tag{16.15}$$

where x is the mass of solute adsorbed (g), m the mass of carbon adsorbent (g), k an empirical constant, n an empirical constant, and C the equilibrium concentration of solute (g/L).

An adsorption isotherm is essentially a plot of the quantity of contaminant adsorbed per unit of mass of carbon (x/m) against the concentration of contaminant in the fluid (C). Several different mathematical forms of isotherms are available for determining sorption. Another popular isotherm is the Langmuir isotherm,

$$x/m = (kCb)/(1 + kC) \tag{16.16}$$

where b is the maximum quantity of adsorbate that can be adsorbed.

16.3.5 Sorption Systems

Activated carbon has a number of applications; for example, in industrial and wastewater treatment, activated carbon is used to remove undesirable organic substances. Carbon sorption is also used as a polishing step for treatment of drinking water. Some of the organic compounds amenable to sorption by activated carbon are shown in Table 16.5.

Many process configurations have been designed for treatment of aqueous waste streams, such as upflow and fluidized-bed systems; however, the most common process configuration is gravity flow through a packed-bed column. The carbon contactor consists of a lined steel column or a steel or concrete rectangular tank in which the carbon is packed to form a filter bed. Process water is initially applied to the top of the column and contaminants are sorbed at the top of the bed. Process water exits the bottom of the column via an underdrain. Eventually, these sorption sites become saturated and the contaminants are sorbed further down the column. The saturated zone migrates all the way down until the entire column is saturated. At this point, *breakthrough* occurs and the column loses its effectiveness.

After the carbon has been spent (i.e., exhausted), it must be regenerated. Regeneration takes place by heating in an oxygen-rich environment. If sorbed organic material is volatile, the carbon bed may be regenerated with the use of steam. More typically, however, the carbon is removed from the chamber and regenerated in a controlled furnace. In a large activated carbon unit, a regeneration furnace is often installed as one component of the carbon treatment system. In smaller installations the

TABLE 16.5
Organic Compounds Suitable for Sorption Treatment by Activated Carbon

Class	Example
Aromatic solvents	Benzene, toluene, xylene
Polynuclear aromatics	Naphthalene, biphenyl
Chlorinated aromatics	Chlorobenzene, PCBs, Endrin, toxaphene, DDT
Phenolics	Phenol, cresol, resorcinol, nitrophenols, chlorophenols, alkyl phenols
Aromatic amines and high molecular weight aliphatic amines	Aniline, toluene diamine
Surfactants	Alkyl benzene sulfonates
Soluble organic dyes	Methylene blue, textiles, dyes
Fuels	Gasoline, kerosene, oil
Chlorinated solvents	Carbon tetrachloride, percholoroethylene
Aliphatic and aromatic acids	Tar acids, benzoic acids
Pesticides and herbicides	2,4-D, atrazine, simazine, aldicarb, alachlor, carbofuran

Source: U.S. EPA, *Granular Activated Carbon Systems Problems and Remedies*, EPA 800/490/9198, U.S. EPA, Washington, DC, 1984.

carbon is removed and returned to the supplier for reprocessing. Such regeneration processes cause the carbon to lose some of its sorptive qualities. In addition, about 10% of the carbon is lost with each regeneration. All carbon contactors must be equipped with carbon removal and loading mechanisms to allow spent carbon to be collected and virgin or regenerated carbon to be added. Spent, regenerated, and virgin carbon are typically transported hydraulically by pumping as a slurry (U.S. EPA 2000b).

Carbon adsorption is generally cost-effective only when the contaminants are present in dilute quantities. Carbon adsorption is typically used to treat dilute aqueous streams with organic contaminants in the low ppm range. For wastewater streams that contain a significant quantity of industrial flow, activated carbon adsorption is a proven, reliable technology to remove dissolved organics. Space requirements are small—granular activated carbon (GAC) adsorption can be easily incorporated into an existing wastewater treatment facility.

Disadvantages occur with use of activated carbon for sorption. Under certain conditions, granular carbon beds may generate hydrogen sulfide from bacterial growth, creating odors and corrosion problems. Spent carbon which is not regenerated may present a land disposal problem. Wet GAC is highly corrosive and abrasive. Finally, variations in pH, temperature, and flow rate may adversely affect carbon sorption (U.S. EPA 2000b).

16.3.6 Stabilization

Stabilization processes are accomplished by mixing hazardous waste with a binding agent to form a crystalline or polymeric matrix that incorporates the entire waste. Inorganic binders include cement, cement kiln dust, fly ash, and blast furnace slag. Organic wastes are immobilized by addition of organic binders such as bitumen (asphalt) or polyethylene. Stabilization converts contaminants into a less- or a nonreactive form, typically by chemical processes. Contaminants are furthermore physically immobilized within a solid matrix in the form of a monolithic block. Thus, stabilization serves to physically sorb, encapsulate, or alter the physical or chemical form of the contaminants, producing a less leachable material.

Stabilization techniques also improve the handling characteristics of waste for transport. Stabilization techniques designed to limit the solubility or mobility of hazardous constituents are required for RCRA hazardous wastes containing heavy metals.

The ideal stabilization agent is inert, readily available, and nondegradable. In selecting a stabilization agent, considerations should include the quantity required to eliminate free liquid, compatibility with the waste, and binding properties.

Pozzolanic materials such as fly ash form a solid monolithic mass when mixed with hydrated lime. The stabilization of waste using lime and pozzolanic material requires that the waste be mixed with water to create an optimal consistency. Numerous treatment processes incorporate Portland cement as a binding agent combined with pozzolans to improve the strength and chemical resistance of the solidified waste. Soluble silicates may be added to a pozzolan–cement mixture to further enhance performance and to reduce interference from metals. Emulsifiers may be added to better incorporate organic liquids. Solidification and fixation processes are generally adjusted for the waste on a case-by-case basis.

To reduce the final volume of stabilized waste for disposal, wastes should be dewatered before stabilization reactions. Pretreatment such as a chemical process to scavenge toxic materials may contribute to a more cost-effective treatment of the waste.

Example 16.4

An aqueous sludge containing high amounts of free liquids is stabilized with a cement–slag mixture at a secure landfill. The wastes are mixed with the cement–slag by using a front-end loader. The blended material is then transported to the secure landfill and spread in uniform lifts with a bulldozer. Waste properties are as follows: 45 mg/kg Cd, 1055 mg/kg Pb, and 575 mg/kg Zn.

In order to optimize stabilization, the required ratio of fly ash to waste is estimated at 1.5:1. Calculate the reduction in contaminant concentrations due to dilution.

Solution

$$C_o \times W_w = C_f (W_w + W_{FA}) \tag{16.17}$$

where C_o is the original containment concentration, W_w the weight of waste, C_f the final concentration, and W_{FA} the weight of fly ash.

$$C_o/C_f = (W_w + W_{FA})/W_w = (1.0 + 1.5)/1 = 2.5/1 = 2.5$$

$$C_f/C_o = W_w/(W_w + W_{FA}) = 1.0/(1.0 + 1.5) = 1/2.5 = 0.40$$

Contaminant concentrations are reduced by 60%.

(Adapted from LaGrega, M.D. et al., *Hazardous Waste Management*, Waveland Press, Long Grove, IL, 2010.)

A major drawback to stabilization processes is the significant increase in volume of material to be disposed. Waste mixtures may require several pretreatment steps that may render the process cost-prohibitive (Wentz 1995).

QUESTIONS

1. List some of the key reagents used to neutralize acidic wastes. What factors are involved in choosing a neutralizing agent? What hazards may be involved in the use of certain agents?
2. Which of the neutralizing agents discussed in this chapter have the benefit of buffering the reaction medium?
3. Precipitation processes are typically focused on the removal of what types of compounds or elements? List the common counter-ions involved in precipitation.
4. What are the drawbacks to using an oxidizing agent such as O_3 to treat a waste stream consisting of numerous organic and inorganic components, only one of which is deemed hazardous?
5. What is the principle of stabilization of hazardous waste? Is stabilization solely a physical process or are chemical reactions also possible?
6. In order to remove hexavalent chromium from a waste stream, what pretreatment step is necessary?
7. A metal plating solution contains 32.2 mg/L of zinc. Calculate the concentration (mol/L) of [OH^-] needed to precipitate all but 0.80 mg/L of the copper. The K_{sp} of zinc hydroxide is 7.68×10^{-17}. What is the final pH?
8. Can aerobic thermophilic composting be used to treat hazardous waste? Explain.
9. At a metal plating facility, a precipitation system is being installed to remove zinc from the process solution. A pH meter will be used to control the feed of the hydroxide solution to the mix tank. To what pH should the instrument be set to achieve a Zn effluent concentration of 1.0 mg/L?
10. Aqueous sodium cyanide wastes at a metal processing industry are to be treated with chlorine and NaOH. Calculate the stoichiometric quantity of Cl_2 required daily to remove the cyanide from 5 kg of NaCN.

REFERENCES

Blackman, W.J. Jr. 2001. *Basic Hazardous Waste Management*, 3rd ed. Boca Raton, FL: Lewis Publishing.

Camp Dresser & McKee, Inc. 1984. *Technical Assessment of Treatment Alternatives for Wastes Containing Corrosives*, U.S. EPA 68–01–6403. Boston, MA: Camp Dresser & McKee, Inc.

Dawson, G.W. and Mercer, B.W. 1986. *Hazardous Waste Management*. New York: Wiley.

Haas, C.N. and Vamos, R.J. 1995. *Hazardous and Industrial Waste Treatment.* Englewood Cliffs, NJ: Prentice-Hall.
LaGrega, M.D., Buckingham, P.L., and Evans, J.C. 2010. *Hazardous Waste Management.* Long Grove, IL: Waveland Press.
Manahan, S.E. 1990. *Hazardous Waste Chemistry, Toxicology and Treatment.* Chelsea, MI: Lewis Publishing.
Manahan, S.E. 2009. *Environmental Chemistry,* 9th Ed. Boca Raton, FL: CRC Press.
Tchobanoglous, G., Theisen, H., and Vigil, S. 1993. *Integrated Solid Waste Management: Engineering Principles and Management Issues.* New York: McGraw-Hill.
U.S. EPA (U.S. Environmental Protection Agency). 1984. *Granular Activated Carbon Systems Problems and Remedies*, EPA 800/490/9198. Washington, DC: U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 1989. *Corrective Action: Technologies and Applications, Seminar Publication*, EPA/625/4-89/020. Cincinnati, OH: Center for Environmental Research Information, U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 2000a. *Managing Cyanide in Metal Finishing, Capsule Report*, EPA/625/R-99/009. Washington, DC: Office of Research and Development, U.S. EPA.
U.S. EPA (U.S. Environmental Protection Agency). 2000b. *Granular Activated Carbon Absorption and Regeneration, Wastewater Technology Fact Sheet*, EPA 832-F-00-017. Washington, DC: Office of Water, U.S. EPA.
U.S. EPA (Environmental Protection Agency). 2001c. Land Disposal Restrictions: Summary of Requirements. EPA530-R-01-007. Offices of Solid Waste and Emergency Response & Enforcement and Compliance Assurance. Washington, DC.
Water Pollution Control Federation. 1981. Pretreatment of Industrial Wastes. Alexandria, VA. p. 100.
Wentz, C.A. 1995. *Hazardous Waste Management*, 2nd ed. New York: McGraw-Hill.
Wilk, L., Palmer, S., and Breton, M. 1988. *Technical Resource Document: Treatment Technologies for Corrosive-Containing Wastes*, Vol. II, EPA/600/S-87-099. Cincinnati, OH: U.S. Environmental Protection Agency.

SUGGESTED READINGS

Chen, J.P. 2012. *Decontamination of Heavy Metals: Processes, Mechanisms, and Applications (Advances in Industrial and Hazardous Wastes Treatment)*. Boca Raton, FL: CRC Press.
Hung, Y.-T., Wang, L.K., and Shammas, N.K. 2013. *Waste Treatment in the Service and Utility Industries (Advances in Industrial and Hazardous Wastes Treatment)*. Boca Raton, FL: CRC Press.
Roy, A., Eaton, H.C., Cartledge, F.K., and Tittlebaum, M.E. 1992. Solidification/stabilization of hazardous waste: Evidence of physical encapsulation. *Environ Sci Technol* 7, 1349–1353.
Sedlak, D.L. and Andren, A.W. 1991. Aqueous phase oxidation of polychlorinated biphenyls by hydroxyl radicals. *Environ Sci Technol* 25, 1419–1427.
Tang, W.Z. 2003. *Physicochemical Treatment of Hazardous Wastes*. Boca Raton, FL: CRC Press.
Wang, L.K., Chen, J.P., Hung, Y.-T., and Shammas, N.K. 2009. *Heavy Metals in the Environment (Advances in Industrial and Hazardous Wastes Treatment)*. Boca Raton, FL: CRC Press.
Wang, L.K., Hung, Y.-T., Lo, H.H., and Yapijakis, C. 2005. *Waste Treatment in the Process Industries*. Boca Raton, FL: CRC Press.
Wang, L.K., Hung, Y.-T., Lo, H.H., and Yapijakis, C. 2006. *Hazardous Industrial Waste Treatment*. Boca Raton, FL: CRC Press.
Wang, L.K., Hung, Y.-T., and Shammas, N.K. 2009. *Handbook of Advanced Industrial and Hazardous Wastes Treatment (Advances in Industrial and Hazardous Wastes Treatment)*. Boca Raton, FL: CRC Press.
Wang, L.K., Shammas, N.K., and Hung, Y.-T. 2006. *Advances in Hazardous Industrial Waste Treatment (Advances in Industrial and Hazardous Wastes Treatment)*. Boca Raton, FL: CRC Press.
Wang, L.K., Shammas, N.K., and Hung, Y.-T. 2008. *Waste Treatment in the Metal Manufacturing, Forming, Coating, and Finishing Industries (Advances in Industrial and Hazardous Wastes Treatment)*. Boca Raton, FL: CRC Press.

17 Land Disposal of Hazardous Waste

Farther off, farther off, the burying ground.
I wish you peace.
I wish the labyrinth of byways may one day be lost
beneath the new green of Spring.

Gu Cheng (1956–1993)
Yes, I go also

17.1 INTRODUCTION

About 2 million tons of hazardous wastes are land-disposed each year (U.S. EPA 2013). Land disposal can take place on or slightly below ground surface, that is, in a landfill or other land-based unit, or can occur deep under the earth's surface, for example, by deep-well injection.

Modern land-based disposal systems for hazardous wastes are designed and equipped with numerous safeguards and are closely regulated; however, if a hazardous waste is not properly treated before disposal, it can still contaminate local soil, groundwater, and surface water. In addition, rainwater, snowmelt, and groundwater can penetrate a landfill, including emplaced hazardous waste, and can potentially mobilize hazardous substances.

17.2 LAND DISPOSAL RESTRICTIONS REVISITED

The land disposal restrictions (LDRs) were originally divided into five deadlines, or phases, mandated by federal law. Each phase restricted different types of hazardous waste from land disposal by a specific deadline. Phase One, for PCDD-containing wastes and spent solvents, was put into effect by 1986 (40 CFR 268.30 and 268.31). These were the first wastes restricted from land disposal because they are generated in the greatest quantities and can be extremely hazardous. These wastes include F001–F005 solvents and F020–F023 plus F025–F028 dioxin wastes listed in 40 CFR 261.31.

Phase Two, the so-called *California List*, was put into effect in 1987. This title was created because California was the first state to restrict land disposal of these wastes. Phase Two restricts land disposal of untreated, liquid hazardous waste containing:

- Polychlorinated biphenyls (PCBs)
- Corrosives with pH < 2 or free cyanides
- Arsenic, cadmium, chromium (VI), lead, mercury, nickel, selenium, and thallium

The California List also restricts hazardous waste containing halogenated organic compounds in liquid or nonliquid form (40 CFR 268.32). After the Phase One wastes, California List wastes are the next most abundant and hazardous.

Phases Three, Four, and Five address LDRs for all remaining hazardous wastes listed by EPA in the hazardous waste regulations (40 CFR part 261). Wastes in Phases Three, Four, and Five include F-, K-, P-, and U-coded wastes.

17.2.1 General Requirements

LDRs apply to: (1) hazardous waste generators (including cleanup waste); (2) hazardous waste transporters; (3) hazardous waste treatment, storage, and disposal facilities (TSDFs); and (4) hazardous waste recycling facilities. The restrictions do not apply to generators of less than 100 kg of hazardous waste per month (conditionally exempt small quantity generators).

Under the LDRs, hazardous waste generators, TSDFs, and recycling facilities must meet specific requirements for waste analysis, record keeping, notification, and certification. The Uniform Hazardous Waste Manifest for LDR wastes must be accompanied by an LDR notification. The LDR is a one-time notification form that is signed by the generators and it indicates that they understand that this waste cannot be land-disposed. It is the responsibility of the generator to provide the manifest and the LDR. Most hazardous waste disposal contractors supply one or both forms.

Treated wastes can only be disposed in a landfill meeting EPA minimum technology standards for hazardous waste landfills. These standards are found in the federal regulations in 40 CFR 264.301.

17.3 SECURE LANDFILL

17.3.1 Regulatory Requirements

According to federal requirements, a secure landfill must possess a liner system that is constructed and installed to prevent any migration of waste out of the landfill during its active life and throughout the closure period. A subtitle D landfill for MSW disposal is required to possess a single liner system; however, the requirements for a subtitle C (i.e., RCRA hazardous waste) landfill are much more stringent. For example, there is to be a double-liner system equipped with two leachate collection and removal systems (LCRs) (Figures 17.1 and 17.2). The liner system must include:

- A top liner (primary liner) constructed of materials (e.g., a geosynthetic liner or flexible membrane liner) to prevent migration of hazardous constituents during the active life and postclosure care period.
- A composite bottom liner (secondary liner) consisting of at least two components. The upper component is typically a geosynthetic liner. The lower component must be constructed of materials to minimize the migration of hazardous constituents if a breach in the upper component were to occur. The lower component must be constructed of at least 91 cm (3 ft) of compacted soil material with a hydraulic conductivity of 1×10^{-7} cm/s or less.

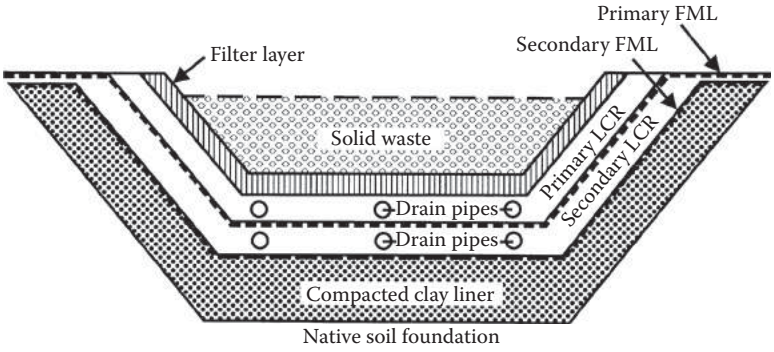


FIGURE 17.1 Schematic of a landfill base showing liners and leachate collection and removal systems (not to scale). (From U.S. EPA, *Requirements for Hazardous Waste Landfill Design, Construction, and Closure*, Seminar Publication, EPA/625/4-89/022, Center for Environmental Research Information, U.S. EPA, Cincinnati, OH, 1989. With permission.)



FIGURE 17.2 Geosynthetic landfill liner being installed. (Reproduced with kind permission of Tenax, Baltimore, MD, Available from: http://www.tenax.net/geosynthetics/products/geocomposite-mdp.htm.)

The LCR system is installed immediately above the top (primary) liner to collect and remove leachate during the active life and postclosure care period of the landfill. A secondary LCR system is placed above the composite liner. The secondary LCR serves also as a leak detection system and must be capable of detecting, collecting, and removing leaks of hazardous constituents through the top liner as early as possible. The state regulatory agency specifies the design and operating conditions in the permit to ensure that the leachate depth over the liner does not exceed 30 cm (1 ft). The requirements for a leak detection system include that it be (40 CFR 264):

- Constructed with a bottom slope of 1% or more.
- Constructed of granular drainage materials with a saturated hydraulic conductivity of 1×10^{-2} cm/s or more and a thickness of 30.5 cm (12 in.) or more; or constructed of synthetic or geonet drainage materials with a transmissivity of 3×10^{-5} m^2/s or more.
- Constructed of materials that are chemically resistant to the waste present in the landfill and the leachate expected to be generated, and of sufficient strength and thickness to prevent collapse under the pressures exerted by overlying wastes, waste cover materials, and heavy equipment used.
- Designed and operated to minimize clogging during the active life and postclosure care period.
- Constructed with sumps and pumps of sufficient size to remove liquids from the sump and prevent liquids from backing up into the drainage layer. Each unit must have its own sump. All pumpable liquids must be removed in the leak detection system sumps to minimize the head on the bottom liner.

Alternative designs and operating practices are allowed by the permitting agency if they adequately prevent the migration of hazardous constituents into groundwater or surface water. Factors to consider with alternative designs include the characteristics and quantity of the wastes, and the hydrogeologic setting of the facility, including the ability of liners and soils to attenuate any

contaminants which may leach. The double-liner requirement may be waived for a hazardous waste facility under certain conditions, for example, if the landfill:

- Contains only hazardous wastes from foundry furnace emission controls or metal casting molding sand
- Has at least one intact liner
- Is located more than one-quarter mile from an underground source of drinking water (USDW)
- Is in compliance with applicable groundwater monitoring requirements

Precautions are also required for the proper management of surface liquids, including run-on and run-off. The facility must design, construct, and operate a run-on control system capable of preventing flow onto the active portion of the landfill during peak discharge from at least a 25-year storm. Also, a run-off management system must be installed to collect and control the water volume resulting from a 24-h, 25-year storm. These design aspects will be discussed below.

17.3.2 Secure Landfill Design, Construction, and Operation

Many of the requirements for secure landfill design and construction are similar to those for subtitle D (sanitary) landfills; therefore, several sections will be discussed briefly below. Details appear in Chapter 10.

17.3.3 Liner Materials

17.3.3.1 Clay Liners

As discussed in Chapter 10, clay is a critical component of soil liners due to its ready availability and its tendency to be accommodating to mechanical and other stresses. Clay materials, being natural, incorporate readily with native soil materials and are obviously very durable. In addition, clay-rich soil ensures low hydraulic conductivity. For the secure landfill, EPA requires that clay liners be constructed so that hydraulic conductivity is less than 1×10^{-7} cm/s.

17.3.3.2 Synthetic Liner Materials

Synthetic liner materials (geomembrane liners) are composed of polymers that are either natural or synthetic compounds of high molecular weight. Polymeric materials commonly used in construction of geomembranes include:

- Thermoplastics—polyvinyl chloride (PVC)
- Crystalline thermoplastics—high-density polyethylene (HDPE) and linear low-density polyethylene (LLDPE)
- Thermoplastic elastomers—chlorinated polyethylene (CPE) and chlorolsulfonated polyethylene (CSPE)
- Elastomers—neoprene and ethylene propylene diene monomer (EPDM)

Additional liner materials are discussed in Chapter 10.

Membranes contain various oils and fillers that aid in geomembrane manufacture; these additives furthermore affect overall performance. Chemical compatibility, stress-strain characteristics, survivability, and permeability are critical issues that must be addressed when selecting a geomembrane.

As discussed in Chapter 10, the polymers most commonly used in geomembranes are HDPE, LLDPE, PVC, flexible polypropylene (fPP), and CSPE. The preferred formulations for HDPE and PVC geomembranes are shown in Table 17.1. EPA regulations require a thickness of 30 mil (1 mil = 1/1000 in.) for PVC and 60 mil for HDPE geomembranes. A thicker HDPE geomembrane is required for a number of reasons, including the ability to weld without damage to the liner,

TABLE 17.1
Example Formulations for Geomembranes

Polymer
Butyl rubber
Chlorosulfonated polyethylene
Elasticized polyolefin
Epichlorohydrin rubber
Ethylene propylene rubber
Neoprene (chloroprene rubber)
Nitrile rubber
Polyethylene
Chlorinated
High density
Low density
Linear low density
Very low density
Polypropylene
Flexible
Reinforced
Polyvinyl chloride
Elasticized
Polyvinylidene fluoride

increased strain to tensile yield, greater stress crack resistance, and less susceptibility to folding, which can lead to stress cracking.

A primary advantage of HDPE membranes is their higher chemical resistance to hydrocarbons and solvents (Vandervoort 1992). Differences in chemical resistance between HDPE and PVC may be significant for aliphatic and aromatic hydrocarbons, and chlorinated, oxygenated, and crude petroleum solvents. The semicrystalline nature of HDPE may make it more susceptible to stress cracking when under stress in the presence of leachate (PGI 1999). Manufacturers continue to develop resins that are more resistant to stress cracking, chemical attack, and oxidation, and that are more cost-effective.

17.3.3.3 Composite Liners

A composite liner system is one fitted with a highly impermeable liner, for example, a geomembrane situated directly above another impermeable liner such as compacted clay. A composite liner system should, therefore, outperform either liner alone. In accordance with Darcy's law (see Chapter 10), leachate that ponds directly on top of a clay liner will percolate downward at a rate controlled by the hydraulic conductivity of the liner, the head of leachate on the liner, and the liner's total area. With placement of a geomembrane directly above the clay and sealed against its surface, leachate moving through a hole or defect in the geomembrane does not spread out significantly between geomembrane and clay (see Figure 17.3). The composite liner system allows much less leakage than a clay liner acting alone because the area of flow through the clay is much smaller.

As discussed above, clay liners, synthetic liners, or combinations of both are required in secure landfills. Figure 17.1 presents the synthetic composite double liner system that appears in the EPA minimum technology guidance.

17.3.4 Compatibility of Liners with Wastes

The chemical compatibility of a geomembrane with waste leachate is a critical consideration regarding choice of material. A secure landfill is considered a permanent repository for hazardous wastes;

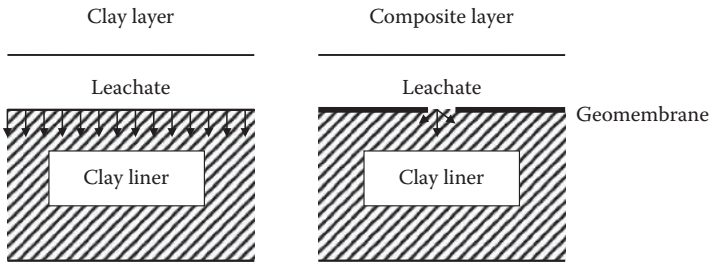


FIGURE 17.3 Leachate infiltration in a clay and a composite liner system.

therefore, materials used in its construction must be expected to withstand a wide range of natural stresses for very long periods. Many materials deteriorate over time when exposed to chemicals occurring in both hazardous and nonhazardous leachate. Landfill owners and operators must anticipate the composition of leachate that a site will generate and select the appropriate liner materials. The chemical resistance of any geomembrane materials, as well as LCR pipes, should be thoroughly assessed prior to installation. Several tests for geomembranes are outlined in Chapter 10.

17.3.5 Leachate Management

A liner that is completely sealed at the base requires an efficient means of removing accumulated leachate; otherwise, head pressure will damage the geomembrane. As mentioned in Chapter 10, the best quality material will eventually allow liquids to penetrate. Even if a liner is perfectly sealed and without holes or other disturbances, molecular diffusion will cause some liquids ponded on top of the liner system to leach through the geomembrane.

The first "line of defense" in collection of leachate is the primary LCR situated directly beneath the waste and above the primary geomembrane (Figures 17.1 and 17.4). The primary LCR is designed and constructed on a site-specific basis in order to optimize performance.

The secondary LCR is installed between the primary and secondary liners and is also termed the *leak detection network*. The leak detection, collection, and removal system can consist of either granular soils (i.e., gravel) or synthetic geonets. The primary purpose of this system is to manage leakage of any liquids through the primary liner. Under optimum conditions, the secondary LCR will collect negligible quantities of leachate; nevertheless, it must be designed on the basis of a worst-case scenario.



FIGURE 17.4 Photograph of an LCR system. (From Seneca Meadows Landfill, *Solid Waste Management*, 2014. A available from: http://www.senecameadows.com/facilities_waste.php. Reproduced with kind permission from Duprey Video Productions, Waterloo, NY.)

17.3.6 Drainage Materials

Drainage materials for the leachate management system must allow for unimpeded flow of liquids. Drains may consist of pipes, coarse soil such as gravel, or geonets (see Figure 10.23). Perforated drainage pipes are commonly used in a number of industrial and other (e.g., agricultural) systems. Such pipes transmit fluids rapidly. They do, however, require considerable vertical space and are susceptible to particulate clogging, biological clogging, and creep (deflection). *Creep* is a potential problem with both PVC and HDPE pipe materials. The crushing strength of pipes should also be tested. Events have been documented where landfill pipes have collapsed and failed. The ASTM D2412 test is used to measure the strength of pipe materials (ASTM 2002).

Geonets are synthetic materials that require less space than perforated pipe or gravel, promote rapid transmission of liquids, and, because of their relatively large openings, are less likely to clog (see Chapter 10). They do, however, require placement of geotextile filters above them, and they can experience problems with creep and intrusion.

Natural drainage materials should be tested to ensure that they will not dissolve in the leachate or form a precipitate that might clog the system. ASTM D2434 evaluates the ability of porous materials to retain permeability characteristics (ASTM 1968), whereas ASTM D1883 tests for bearing ratio, that is, the ability of the material to support the waste unit (ASTM 1999).

17.3.7 Leachate Removal Systems

A sump is needed in the lowest portion(s) of the landfill to remove accumulated leachate. The leachate removal standpipe must be extended through the entire landfill from the lowest liner to the cover, and then through the cover itself. It must be maintained for the entire postclosure care period of 30 years or longer.

17.3.8 Closure of the Secure Landfill

Once a secure landfill or a cell is completed, it must be sealed off from its surroundings. Under the Hazardous and Solid Waste Amendments (HSWA), there are numerous requirements for preventing water entry into the landfill and for diverting and removing surface liquids.

A secure landfill cover consists of several layers. A dense clay cover is placed directly over the waste. This is compacted by heavy machinery in order to decrease pore sizes and thus slow down hydraulic conductivity. After grading, a geomembrane cap is installed over the clay layer. A surface water collection and removal (SWCR) system is placed above this composite liner system. Finally, a soil layer that supports shallow-rooted vegetation is installed as the topmost layer.

17.3.9 Geomembrane Caps

Geomembrane caps are synthetic membranes with chemical and physical properties similar to those of geomembrane liners. The geomembrane cap is placed over the low permeability clay cap and below the SWCR system (Figure 17.5). Geomembrane caps function primarily by preventing surface water, including precipitation, from entering the landfill. In selecting materials for the geomembrane cap, operators should keep in mind some practical differences between liners and caps. Unlike a liner, a geomembrane cap is usually not exposed to leachate, so chemical compatibility is not a significant issue. Membrane caps also have lower stresses acting on them in comparison with liners. An advantage geomembrane caps have over liners is that they are much easier to repair due to their proximity to the landfill surface. Geomembrane caps will, however, be subject to other strains due to the settlement of waste.

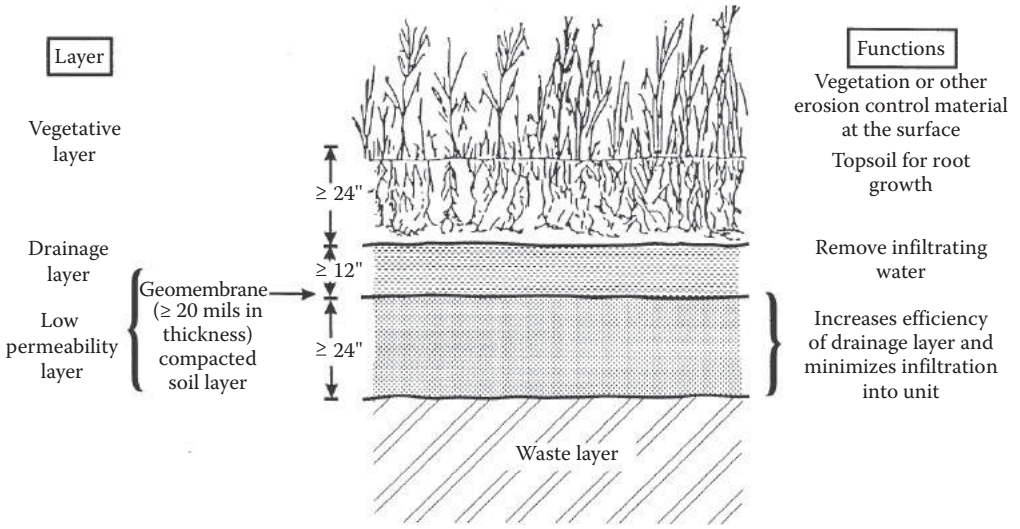


FIGURE 17.5 SWCR system, humid climate. (From U.S. EPA, *Requirements for Hazardous Waste Landfill Design, Construction, and Closure*, Seminar Publication, EPA/625/4-89/022, Center for Environmental Research Information, U.S. EPA, Cincinnati, OH, 1989.)

17.3.10 SWCR System

The SWCR system is installed directly above the geomembrane cap (Figure 17.5). The purpose of the SWCR system is to prevent infiltration of surface water by diverting and removing any liquid that comes into contact with it. Rainwater that percolates through the topsoil and vegetative cover is carried off to an upper drainage system.

Surface water drainage systems can be composed of granular soils, geonets, or geocomposites, but the majority of drainage systems use granular soil. This is significant in frost-susceptible regions, where a 1 to 2 m (3 to 6 ft) soil layer is needed above the geomembrane liner to protect against frost damage. In such cases, a 0.3 m (1 ft) layer of granular soil serves as the surface water collector. If natural drainage materials are not available or if the site is too large, a synthetic geonet or geocomposite can be used. The advantage of drainage geocomposites is their higher flow rate capabilities compared with geonets or granular soils. All geocomposite systems are designed with polymer cores protected by a geotextile filter. Many of the polymers cannot withstand highly reactive leachates; however, in a surface drainage collector, the only contact is with water and leachate will not be encountered.

Figure 17.6 shows a typical landfill profile designed to meet EPA minimum technology guidance requirements. The upper part of the profile includes the soil cover, a 1 ft lateral drainage layer, and a low permeability cap of barrier soil (clay), which must be more than 2 ft thick. This three-layer system also includes a geomembrane cap. A gas control layer is optional. In designing an SWCR system, three highly practical issues must be considered: (1) cover stability, (2) puncture resistance, and (3) the ability of the system to withstand considerable stresses due to the impact of settlement. Geomembrane caps must resist penetration by construction equipment, rocks, roots, and other natural phenomena. Traffic by operational equipment can cause tearing. In a subtitle C landfill, a geomembrane is always underlain by a clay liner, which will protect against puncture. In addition, a geotextile placed on top or beneath a membrane increases its puncture resistance by three or four times. The impact of settlement is a major concern in the design of the SWCR system. A number of facilities have settled 6 ft in a single year and 40 ft or more over a period of years (U.S. EPA 1989).

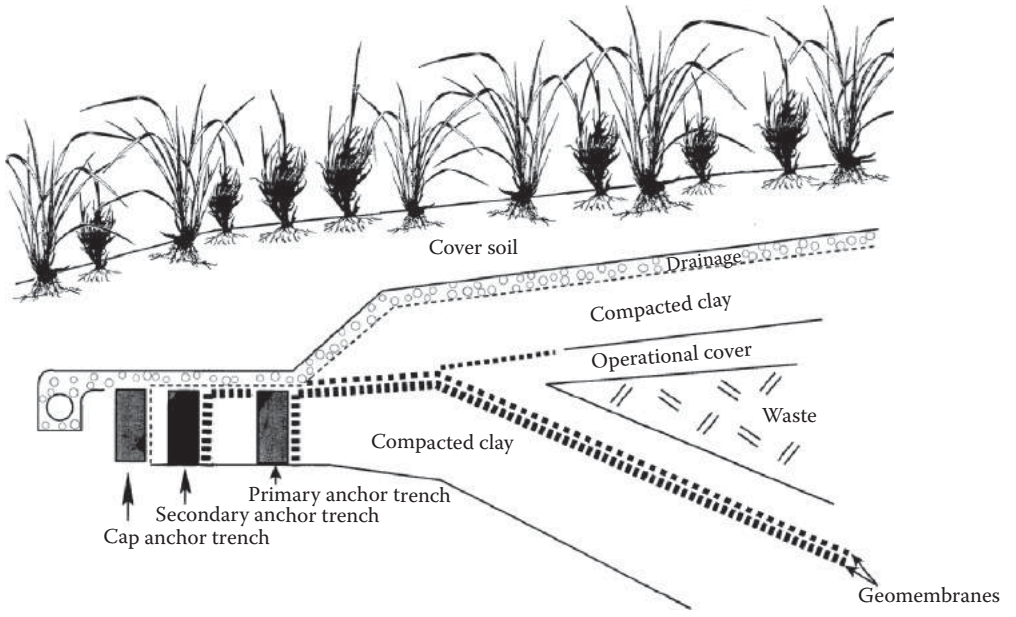


FIGURE 17.6 Profile of a subtitle C hazardous waste landfill. (From U.S. EPA, *Requirements for Hazardous Waste Landfill Design, Construction, and Closure*, Seminar Publication, EPA/625/4-89/022, Center for Environmental Research Information, U.S. EPA, Cincinnati, OH, 1989.)

17.3.11 Gas Control Layer

Gas collection systems are typically not used in subtitle C landfills—gas is rarely detected in these systems. This is attributed to the fact that most wastes are received in stabilized or solid form, and there are no putrescible materials present as would be found in a conventional MSW landfill. Because the long-term effects of gas generation are not known and costs are minimal, EPA recommends installation of gas collector systems. In the subtitle C landfill, the gas collection system is installed directly beneath the low permeability clay cap.

17.3.12 Biotic Barrier

A biotic barrier is a gravel and rock layer designed to prevent the intrusion of burrowing animals into the landfill. Animals cannot generally penetrate a geomembrane cap, but they can widen an existing hole or tear the material where it has wrinkled (U.S. EPA 1989).

17.3.13 Vegetative Layer

The uppermost layer in the closed landfill profile is the vegetative cover. This layer is often planted with a bed of dense-rooted grasses and legumes. The vegetative cover protects against wind and water erosion, minimizes percolation of surface water into the waste layer, and maximizes evapotranspiration. The vegetative cover also enhances aesthetics and promotes a self-sustaining ecosystem on top of the landfill.

Problems are sometimes reported in maintaining a vegetative layer on top of a landfill, especially in arid or semiarid regions. A vegetative cover built upon a SWCR system composed of well-drained stone or synthetic material may be unable to support plants of any kind because insufficient soil moisture is available. In arid regions, a continuous sprinkler system may be required to maintain plant growth, even if the soil is sufficiently deep and fertile.

17.4 DEEP WELL INJECTION OF HAZARDOUS WASTES

Deep well injection, also known as underground injection, involves pumping liquid hazardous wastes into confined geologic formations deep below the surface. A geologic formation considered suitable for injection is one having sufficient permeability and porosity surrounded by thick impermeable strata.

Injection well disposal places treated or untreated liquid waste into geologic formations that are considered to have no potential for migration of contaminants into potential potable water aquifers. Injection wells have been used for the disposal of industrial and hazardous wastes since the 1950s; therefore, the equipment and methods are readily available and well known. Use of injection wells, however, continues under strict regulatory control. The overriding environmental concern regarding underground disposal of hazardous wastes is the potential for contamination of drinking water. For this reason, legislation was enacted under the Safe Drinking Water Act (SDWA) of 1974 to protect underground sources of drinking water (USDW) from contamination that may be caused by disposal of hazardous liquids in injection wells (U.S. ACE, n.d.).

17.4.1 Underground Injection Control Program

One component of the SDWA required EPA to develop minimum federal requirements for injection practices that protect public health, by preventing wells from contaminating an USDW. An USDW is defined as an aquifer that:

- Supplies any public water system or contains sufficient water to supply a public water system
- Currently supplies drinking water for public consumption
- Contains fewer than 10,000 mg/L total dissolved solids and is not an exempted aquifer

EPA established the Underground Injection Control Program (UIC) to set minimum federal requirements for all injection wells that discharge hazardous and nonhazardous liquids above, below, or into USDW. The requirements affect siting, construction, operation, maintenance, monitoring, testing, and closure of injection wells. The program is also designed to provide a safe and cost-effective means for industries, municipalities, and small businesses to dispose their wastewater, extract mineral resources, and store water for the future. All operational wells require authorization under general rules or specific permits.

Under the UIC program, a well is defined as

- A bored, drilled, or driven shaft whose depth is greater than the largest surface dimension
- A dug hole whose depth is greater than the largest surface dimension
- An improved sinkhole
- A subsurface fluid distribution system

17.4.2 Well System Design

A typical injection well (Figure 17.7) consists of a series of concentric pipes that may extend thousands of feet from the ground surface into highly saline, permeable strata that are confined above and below by impermeable layers. The outermost pipe (surface casing) extends below the base of any underground sources of drinking water and is cemented to surface soil to prevent contamination of drinking water. Immediately inside the surface casing is a long pipe that extends to the injection zone. The waste is injected through tubing inside the long pipe, either through perforations or in an opening at the bottom of the tube. The space between the inner pipe and the injection tube,

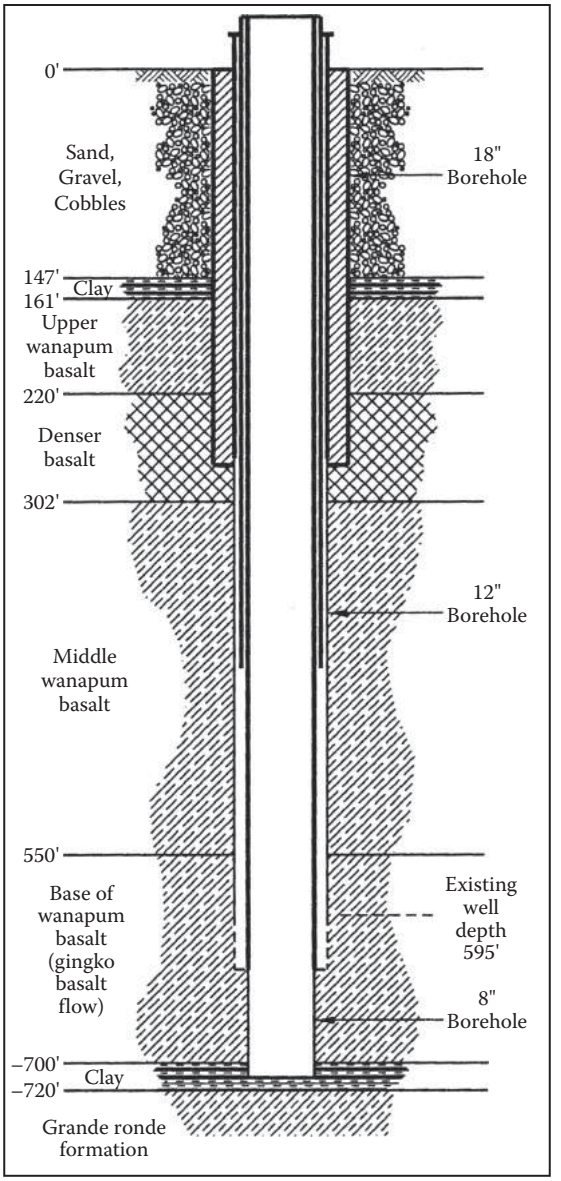


FIGURE 17.7 Schematic of a deep well for injecting hazardous liquid wastes. Not to scale. (From U.S. EPA, *Protecting Drinking Water through Underground Injection Control*, Pocket Guide #2, EPA 816-K-02-001, Office of Ground Water and Drinking Water, U.S. EPA, Washington, DC, 2002.)

the annulus, is filled with a fluid, for example, diesel fuel under pressure, and is sealed at the bottom by a removable packer, which prevents injected wastewater from backing up into the annulus.

At the disposal facility, the wastes are stored in large-capacity tanks for blending, diluting, or other processing (Figure 17.8). In some injection facilities handling very hazardous (e.g., caustic) wastes, there is no pretreatment except for simple filtering to remove particulates that may plug the well. Wastes are pumped to the pump house, which transfers them to the well house, a simple structure that houses the injection well head (Figure 17.9).



FIGURE 17.8 Tanks for storage and blending of liquid hazardous wastes.



FIGURE 17.9 Well head at deep-well injection facility.

Wastes commonly disposed by deep well injection have included caustics, volatile organic compounds (VOCs), semivolatile organic compounds (SVOCs), fuels, explosives, pharmaceutical wastes, and pesticides. However, existing permitted deep-well injection facilities are limited to a narrow range of specific wastes.

17.4.3 Classes of Injection Wells

Injection wells regulated under the UIC program are divided into five classes (Table 17.2).

TABLE 17.2
U.S. EPA Injection Well Classification System

Well Class	Injection Well Description	Approximate Inventory
Class I	Inject hazardous wastes beneath the lowermost USDW Inject industrial nonhazardous liquid beneath the lowermost USDW Inject municipal wastewater beneath the lowermost USDW	680
Class II	Dispose of fluids associated with the production of oil and natural gas Inject fluids for enhanced oil recovery Inject liquid hydrocarbons for storage	172,068
Class III	Inject fluids for the extraction of minerals	22,131
Class IV	Inject hazardous or radioactive waste into or above a USDW This activity is banned These wells can only inject as part of an authorized cleanup	33
Class V	Wells not included in the other classes Inject nonhazardous liquid into or above a USDW	400,000 to >650,000
Class VI	Inject carbon dioxide (CO_2) for long-term storage, also known as Geologic Sequestration of CO_2.	6–10 commercial wells expected to come online by 2016

Source: U.S. EPA, *Classes of Wells*, 2012, Available from: http://water.epa.gov/type/groundwater/uic/wells.cfm.

17.4.3.1 Deep Wells (Class I)

Class I injection wells are designed for the disposal of industrial hazardous waste, industrial nonhazardous waste, and municipal nonhazardous waste. Approximately 680 Class I injection facilities are operating nationwide. Of these, the majority dispose nonhazardous waste (U.S. EPA 2012a). Class I hazardous waste wells operate in ten states, with the majority being in Texas and Louisiana. These wells dispose wastes from the following industries:

- Petroleum refining
- Metal production
- Chemical manufacture
- Pharmaceutical manufacture
- Commercial disposal
- Municipal disposal
- Food production

Examples of wastes injected include:

- Hydrochloric acid
- Sulfuric acid
- Chromic acid
- Nitric acid
- Hydrofluoric acid
- Phosphoric acid
- Mixed acids
- Caustics
- Ammonium wastes
- Metal plating and galvanizing solutions
- The Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) (Superfund site) wastes

- Aqueous solutions of pesticides and pharmaceuticals
- Boiler and tank cleanouts

Although a number of toxic and hazardous wastes are acceptable for Class I injection wells, many wastes or characteristics are restricted or not accepted at all, for example:

- Reactive cyanides
- Reactive sulfides
- Flashpoint (e.g., must be greater than 100°C or 212°F)
- PCBs
- High oil content
- Radioactive wastes
- Shock-sensitive wastes
- Infectious wastes

Class I injection wells are regulated under the SDWA (UIC program) and RCRA subtitle B (40 CFR 146.11–146.14). Class I injection wells are sited and designed such that they inject below the lowermost drinking water source with a confining zone situated above the injection zone. Injection zone reservoirs range in depth from 1700 to over 10,000 ft below the surface. Specific requirements delineate siting, construction, operating, monitoring and testing, reporting and record keeping, permitting, and closure for all Class I wells. The two main categories of Class I wells are hazardous and nonhazardous waste wells.

17.4.3.1.1 Hazardous Waste Injection Wells

The injection of hazardous waste into deep wells began in the United States in the 1960s. The technology originated with the oil and gas industry. By far, the majority of the hazardous waste that is land-disposed is through Class I wells (U.S. EPA 2002a). Wells in this grouping are mainly used by industries such as petroleum refining and metal, chemical, and pharmaceutical manufacture.

The majority of the Class I hazardous waste injection wells are located in Texas and Louisiana. A fraction of these are commercial hazardous waste injection facilities. These are the only facilities that can accept hazardous waste generated off-site for injection.

The HSWA made UIC regulations more stringent for Class I hazardous wells. This resulted in strict no-migration standards and a petition approval process for continued operation of the wells. To receive a no-migration petition, the facility must be capable of demonstrating that injected waste will not impact groundwater or surface water for 10,000 years. Such a demonstration is often conducted using highly conservative mathematical and computer modeling, in addition to scientific and engineering data.

17.4.3.1.2 Nonhazardous Waste Injection Wells

Nonhazardous deep wells inject industrial, low radiation, and municipal wastewater. These wells must meet all technical requirements of hazardous waste wells. Some states include mining wells within this group and require that wells meet all the requirements of other deep wells.

Class I nonhazardous injection wells occur across 19 states; however, most are found in Texas, Louisiana, Kansas, and Wyoming. Approximately 48% of Class I wells inject nonhazardous industrial waste, and 30% serve as municipal wastewater disposal wells (U.S. EPA 2012a).

EPA submitted to Congress a study of Class I wells that describes the current Class I UIC program; documents past compliance incidents involving Class I wells; and summarizes studies of human health risks associated with Class I injection conducted for past regulatory efforts. The program is described in *Class I Underground Injection Control Program: Study of the Risks Associated with Class I Underground Injection Wells* (U.S. EPA 2001).

17.4.3.2 Oil and Gas Injection Wells (Class II)

Class II wells exist where there is production of oil and gas. The oil and gas production industry accounts for a large proportion of liquids injected via deep wells. When oil and gas are extracted, large quantities of salt water (brine) are brought to the surface. About 38 L (10 gal) of brine is produced for each gallon of oil recovered. This brine is often saltier than seawater and may contain toxic metals and radioactive substances. As a result, this water cannot be discharged to surface water; rather, states have implemented rules that prevent the disposal of brine to surface water bodies and soil, thereby making deep well injection a preferred form of disposal. The brine must be injected into formations similar to those from which it was extracted. Over 2 billion gal of brine is injected daily into injection wells in the United States (U.S. EPA 2012b).

The largest proportions of oil and gas field brines are injected into formations that contain trace quantities of extractable oil and gas. Therefore, brine injection may enhance extraction of oil and gas. Approximately 172,000 oil and gas injection wells are in use in the United States (U.S. EPA 2012a–e), most of which are used for this so-called secondary recovery of oil. In a common configuration, one injection well is surrounded by four or more extraction wells. Water is pumped into the formation. Some hydrocarbons are recovered, along with the injected water, by extraction wells. The recovered fluid is treated to remove most of the hydrocarbons by using an oil–water separator.

The second type of oil and gas injection well is a disposal well. Here, excess fluids from production and related activities are injected solely for the purpose of disposal.

Class II well facilities are required to adhere to strict construction standards, except when historical practices in the state and geology allow for different standards. A Class II well that follows EPA standards is constructed with specifications similar to those for a Class I well. In 1980, Congress added section 1425 to the SDWA that controls underground injection, relieving Class II well programs from having to meet the technical requirements in the UIC regulations. Instead, they can make a demonstration that the state has an

> …effective program (including adequate record-keeping and reporting) to prevent underground injection which endangers drinking water sources.

Most of the oil and gas injection wells are located in the West and Southwest, with Texas, California, Oklahoma, and Kansas having the largest numbers (U.S. EPA 2012b). More than 700 million gallons of liquids is injected annually into Class II wells.

17.4.3.3 Mining Wells (Class III)

A number of minerals are mined using injection wells. The technology involves injection of a fluid termed a *lixiviant*, which comes into contact with the desired ore. Minerals within the ore dissolve, and the saturated lixiviant fluid is pumped to the surface where the mineral is removed in situ. Leaching of uranium is the practice of injecting a fluid to leach out uranium salts, and pumping it to the surface where the uranium is extracted. About 80% of the uranium extracted in the United States is produced using this technique (U.S. EPA 2012c).

There are about 165 mining sites with approximately 18,500 Class III wells in operation across the nation.

EPA protects drinking water from contamination from mining wells by implementing regulations that set minimum standards. These regulations require mining well operators to

- Case and cement their wells to prevent migration of fluids into an underground drinking water source
- Never inject fluid between the outermost casing and the well bore
- Test the well casing for leaks at least once every 5 years

17.4.3.4 Shallow Hazardous and Radioactive Injection Wells (Class IV)

Class IV wells are defined in 40 CFR 146.5(d) as

> Wells used by generators of hazardous waste or of radioactive waste, by owners or operators of hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to dispose of hazardous waste or radioactive waste into a formation which within one quarter mile of the well contains an underground source of drinking water.

A second category includes wells that:

> … dispose of hazardous waste or radioactive waste above a formation which within one quarter mile of the well contains an underground source of drinking water.

Class IV wells are prohibited unless injection wells are used to inject contaminated groundwater that has been treated and is being injected into the same formation from which it was drawn.

These wells are authorized by rule for the life of the well if EPA or a state, pursuant to provisions in CERCLA or RCRA, approves emplacement of fluids. An estimated 32 waste clean-up sites in the United States are currently using Class IV wells (U.S. EPA 2012d).

17.4.3.5 Shallow Injection Wells (Class V)

Class V wells comprise a diverse grouping; wells not included in the previous four classes that inject nonhazardous fluids fall into Class V. This category came about after all the easily definable wells were placed into Classes I–IV; EPA did not have comprehensive information on these wells when it published the UIC regulations in the late 1970s.

The Class V designation includes shallow wells such as septic systems and dry wells used to place nonhazardous fluids directly below the land surface. However, Class V wells also can be deep, highly sophisticated wells. EPA estimates that there are more than 650,000 Class V wells in the United States, although some estimates place the number as high as 1 million. Class V wells are located in every state, especially in unsewered areas where the population depends on groundwater as its source of drinking water (U.S. EPA 2001).

Class V wells provide a convenient and inexpensive means of disposing of a variety of nonhazardous fluids. Some examples of Class V wells are

- Agricultural drainage wells
- Storm water drainage wells
- Large-capacity septic systems
- Sewage treatment effluent wells
- Spent brine return flow wells
- Mine backfill wells
- Aquaculture waste disposal wells
- Solution mining wells
- In situ fossil fuel recovery wells
- Experimental wells
- Aquifer remediation wells
- Geothermal electric power wells
- Geothermal direct heat wells
- Heat pump or air conditioning return flow wells
- Salt water intrusion barrier wells
- Aquifer recharge and aquifer storage and recovery wells
- Subsidence control wells
- Industrial wells
- Radioactive waste disposal wells other than Class IV

The majority of Class V well owners are small businesses and municipalities; Class V wells are mostly stormwater drainage and large-capacity septic systems (U.S. EPA 2002b). For facilities that generate nonhazardous waste, Class V wells provide for disposal when there is no access to a sewer system. Class V wells are also an alternative to discharges to surface water.

The effective management of Class V wells is critical because of their large number, the wide variety of fluids discharged, and because most accessible fresh water is stored in aquifers.

Aquifers serve as drinking water sources for about 90% of public water systems in the United States (U.S. EPA 2001). Regulation of Class V wells continues to pose a problem; many owners of Class V wells are not aware of the UIC regulations and furthermore may not consider their facility (e.g., a heat pump system well) to be a regulated injection well.

17.4.3.6 Carbon Dioxide Injection Wells (Class VI)

Class VI wells are wells used for injection of carbon dioxide into subsurface formations for long-term storage or geologic sequestration. These wells do not relate to disposal of hazardous waste and will not be discussed.

17.4.4 Practical Considerations of Deep-Well Injection

The primary purpose of the UIC program is to protect current and potential drinking water supplies by keeping injected liquids within the well and the intended injection zone. Injected liquids can contaminate USDWs by several major pathways (Table 17.3).

A range of factors limit the applicability and effectiveness of deep well injection (FRTR 2003):

- It is not feasible in areas of seismic activity.
- Injected wastes must be compatible with the components of the injection well system and with water occurring in natural formations.
- The waste generator may be required to perform physical, chemical, biological, or thermal treatment of the waste to modify its character and ensure its compatibility.
- High concentrations of suspended solids (typically > 2 ppm) can cause plugging of the injection equipment and injection zone.
- Corrosive media may react with injection well components, the injection zone formation, or confining strata.
- Equipment will last longer if wastes are neutralized prior to injection.
- High Fe concentrations may cause fouling when conditions alter the valence state and convert soluble to insoluble species.
- The presence of significant amounts of organic carbon may result in rapid microbial growth and subsequent fouling.

TABLE 17.3
Major Pathways of Contamination of Underground Sources of Drinking Water

Faulty well construction	Leaks in well casing or fluid escaping between well's outer casing and well bore
Nearby wells	Fluids from pressurized area in injection zone may escape through wells in injection area
Faults or fractures in confining strata	Fluids may leak out of pressurized area through faults and fractures in confining beds
Direct injection	Inject fluids into or above USDWs
Displacement	Fluid may be displaced from injection zone into hydraulically connected USDWs

Source: U.S. EPA, *Class II Wells – Oil and Gas Related Injection Wells (Class II)*, 2002, Available from: http://water.epa.gov/type/groundwater/uic/class2/index.cfm.

- Waste streams containing organic contaminants above their solubility limits may require pretreatment before injection.
- Site assessment and aquifer characterization are required to determine the suitability of the site for wastewater injection.

QUESTIONS

1. The LDR program includes treatment standards for all hazardous wastes scheduled for land disposal. It has three major components that address hazardous waste disposal, dilution, and storage. Discuss these components.
2. What waste types are restricted from secure landfills under current federal regulations? Be specific.
3. Under what conditions may the double liner requirement be waived for a hazardous waste facility?
4. List the advantages of clay liner materials as compared with synthetics. What are the relative disadvantages of using clay?
5. What is an advantage of HDPE liners over PVC and other polymers? Are there any significant disadvantages with the use of HDPE?
6. Discuss three tests commonly used for assessing the integrity of a synthetic landfill liner material.
7. If a synthetic liner is perfectly sealed and without holes or other disturbances, molecular diffusion will allow some of the organics from the liquids ponded on top of the liner to leach through. True or false?
8. Is chemical compatibility with wastes of equal concern regarding installation of geomembrane caps and geomembrane liners? Explain.
9. What are the major purposes of layered landfill caps? How do they function?
10. What is the significance of saturated hydraulic conductivity (K_s) in assessing soils for landfill liners, caps, and as a soil base? How is K_s influenced by soil texture? By engineering practices (e.g., compaction)? What is the RCRA limit for liner K_s?
11. Geomembrane installation practices significantly influence potential leachate losses from a landfill. List and discuss those factors that must be considered for successful geomembrane design and installation.
12. Discuss the five major classes of waste injection wells. What are the primary types of wastes acceptable in each?
13. Discuss the UIC program. What is its overall scope and purpose?
14. Under what conditions (and in what class[es] of wells) are dioxin-containing wastes permitted for injection?

REFERENCES

ASTM (American Society for Testing and Materials). 1968. *Standard Test Method for Permeability of Granular Soils (Constant Head) ASTM D2434-68*. West Conshohocken, PA: ASTM.

ASTM (American Society for Testing and Materials). 1999. *Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils, ASTM D1883-99*. West Conshohocken, PA: ASTM.

ASTM (American Society for Testing and Materials). 2002. *Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading ASTM D2412-02*. West Conshohocken, PA: ASTM.

FRTR (Federal Remediation Technologies Roundtable). 2003. *Deep Well Injection*. Available from: http://www.frtr.gov/matrix2/section4/4_57.html

PGI. 1999. *Comparison of 30 mil PVC and 60 mil HDPE Geomembranes*. Urbana, IL: PGI Technical Bulletin.

Tenax. n.d. *Leachate Collection and Removal System* (LCRS). Baltimore, MD. Available from: http://www.tenaxus.com/landfills/applications/leachate.html

U.S. ACE (U.S. Army Corps of Engineers). n.d. *Commercial Deep Well Injection Facilities*. Available from: http://www.environmental.usace.army.mil/library/pubs/tsdf/sec4-3/sec4-3.html

U.S. EPA (U.S. Environmental Protection Agency). 1989. *Requirements for Hazardous Waste Landfill Design, Construction, and Closure*, Seminar Publication, EPA/625/4-89/022. Cincinnati, OH: Center for Environmental Research Information, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2001. *Safe Drinking Water Act, Underground Injection Control (UIC) Program*, EPA 816-H-01-003. Washington, DC: Office of Water, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2002a. *Underground Injection Control (UIC) Program*. Available from: http://www.epa.gov/safewater/uic/classii.html

U.S. EPA (U.S. Environmental Protection Agency). 2002b. *Protecting Drinking Water through Underground Injection Control*, Pocket Guide #2, EPA 816-K-02-001. Washington, DC: Office of Ground Water and Drinking Water, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2012a. *Industrial & Municipal Waste Disposal Wells (Class I)*. Available from: http://water.epa.gov/type/groundwater/uic/wells_class1.cfm

U.S. EPA (U.S. Environmental Protection Agency). 2012b. *Class II Wells – Oil and Gas Related Injection Wells (Class II)*. Available from: http://water.epa.gov/type/groundwater/uic/class2/index.cfm

U.S. EPA (U.S. Environmental Protection Agency). 2012c. *Mining Wells (Class III)*. Available from: http://water.epa.gov/type/groundwater/uic/wells_class3.cfm

U.S. EPA (U.S. Environmental Protection Agency). 2012d. *Shallow Hazardous and Radioactive Injection Wells (Class IV)*. Available from: http://water.epa.gov/type/groundwater/uic/wells_class4.cfm

U.S. EPA (U.S. Environmental Protection Agency). 2012e. *Classes of Wells*. Available from: http://water.epa.gov/type/groundwater/uic/wells.cfm

U.S. EPA (U.S. Environmental Protection Agency). 2013. *2011 State Fact Sheet, TRI Explorer*. Available form: http://iaspub.epa.gov/triexplorer/tri_broker_statefs.broker?p_view = STCO&SFS = YES&trilib = TRIQ1&state = US&year = 2011

Vandervoort, J. 1992. *The Use of Extruded Polymers in the Containment of Hazardous Wastes.* The Woodlands, TX: Schlegel Lining Technology, Inc.

SUGGESTED READINGS

Hix, K. 1998. *Leak Detection for Landfill Liners, Overview of Tools for Vadose Zone Monitoring*. Washington, DC: U.S. Environmental Protection Agency, Technology Innovation Office.

Richardson, G.N., and R.M. Koerner. 1988. *Geosynthetic design Guidance for Hazardous Waste Landfill Cells and Surface Impoundments. US Environmental Protection Agency. Office of Research and Development.* Cincinnati, OH.

Simonds, F.W. 2002. *Simulation of Ground-water and Potential Contaminant Transport at Area 6 Landfill, Naval Air Station Whidbey Island, Island County, Washington*. Tacoma, WA: U.S. Dept. of the Interior, U.S. Geological Survey, Information Services.

Streissguth, T. 2001. *Nuclear and Toxic Waste*. San Diego, CA: Greenhaven Press.

Part IV

Special Categories of Waste

The final section of this book serves as an amalgamation of topics, covering management of those wastes that may not fit well in a regulatory or management context with either municipal or hazardous wastes. Universal Wastes, used motor oil, medical waste, construction and demolition debris, and electronics waste are included. Some of these residuals, for example, medical or infectious wastes and certain electronics wastes, may be inherently hazardous; others have the reputation of being simply nuisance materials (e.g., construction and demolition debris) and are generated in large volumes. Many had not been adequately managed in the past. Regulations regarding their management have evolved over the past two decades and continue to be updated with the advent of new waste types and new technologies for treatment and disposal.

18 Universal Wastes

How much of the Source escapes with thee
How chief thy sessions be
For thou hast borne a universe
entirely away.

Emily Dickinson (1881)

18.1 INTRODUCTION

Routine management of hazardous waste in accordance with Resource Conservation and Recovery Act (RCRA) requirements has earned a reputation among certain industries as being a costly, cumbersome, and time-consuming ball-and-chain. In response to the requests of generators to ease regulatory burdens on businesses, the Environmental Protection Agency (EPA) formulated the Universal Waste Rule (40 CFR part 273), first published in the May 1995 *Federal Register*. The primary purpose of the rule is to promote appropriate recycling and disposal of several potentially hazardous wastes generated in large quantities by businesses regulated under RCRA.

The wastes addressed in the new rule include batteries, pesticides, thermostats, and certain types of lamps. Until recently, such wastes were managed solely as RCRA hazardous waste. As a consequence, disposal costs for many businesses were substantial. There were also the inevitable episodes of improper disposal (Figure 18.1). Streamlined recycling and disposal of these wastes substantially reduces the quantity of hazardous wastes in the municipal solid waste (MSW) stream. Removing them from MSW landfills and incinerators furthermore decreases the threat to public health and the environment. For example, in 1989, in the United States, 643,000 kg (1.4 million lb) of mercury was discarded in MSW and 84% of this was landfilled (Building Green 2004). Household batteries were by far the largest contributors of mercury in MSW in 1989, with other sources including thermostats and thermometers (3.9%), and mercury-containing lamps (3.8%). The EPA Office of Solid Waste estimates that roughly 600 million fluorescent lamps are discarded each year.

By reducing administrative requirements, the Universal Waste Rule saves companies from compliance costs and reduces the amount of time spent on paperwork. Specifically, the rule streamlines requirements related to notification, labeling of packaging, accumulation time limits, employee training, response to releases, off-site shipments, tracking, exports, and transportation. For example, under the Universal Waste Rule, a waste generator may transport these wastes with a standard carrier instead of a hazardous waste transporter. In addition, the Uniform Hazardous Waste Manifest is not required. Conditionally exempt small quantity generators (CESQGs) are not affected by the Universal Waste Rule. EPA encourages CESQGs to participate voluntarily in collection and recycling programs by bringing universal wastes to collection centers for proper treatment and disposal.

Universal wastes are also generated by households, which are not regulated under RCRA and are permitted to dispose these items in ordinary trash. Although MSW landfills designed under RCRA can handle small amounts of hazardous wastes, they are better managed in a recycling program or transferred to collection centers for proper bulking and disposal. In states that adopt the Universal Waste Rule, communities can work with both businesses and residents to facilitate proper recycling or disposal of these wastes. Municipalities can establish collection programs or cooperate with collection and management programs established by local businesses.



FIGURE 18.1 Clearly *not* the proper method to manage universal waste lamps.

18.2 UNIVERSAL WASTES DEFINED

Universal wastes are limited to a small group of wastes generated in relatively large quantities by businesses, institutions, and private homes. The specific wastes are defined by the 40 CFR 272 regulations and examples are provided.

Battery is defined as (40 CFR 273.0):

> a device consisting of one or more electrically connected electrochemical cells which is designed to receive, store, and deliver electric energy. An electrochemical cell is a system consisting of an anode, cathode, and an electrolyte, plus such connections (electrical and mechanical) as may be needed to allow the cell to deliver or receive electrical energy. The term battery also includes an intact, unbroken battery from which the electrolyte has been removed.

Batteries such as nickel–cadmium (Ni–Cd) and small lead–acid batteries found in household and commercial items, including electronic equipment, portable computers, mobile telephones, and emergency backup lighting, are included in this definition.

Pesticide means:

> any substance intended for preventing, destroying, repelling, or mitigating any pest, or intended for use as a plant regulator, defoliant, or desiccant …

Agricultural pesticides that have been banned from use, are obsolete, have become damaged, or are no longer needed due to changes in agricultural practices fall in this category.

Thermostat means:

> a temperature control device that contains metallic mercury in an ampule attached to a bimetal sensing element, and mercury-containing ampules that have been removed from these devices.

Many thermostats contain as much as 3 g of liquid mercury and are located in commercial, industrial, agricultural, community, and household buildings.

Lamp, also referred to as "universal waste lamp," is defined as

> the bulb or tube portion of an electric lighting device. A lamp is specifically designed to produce radiant energy.

Examples of common universal waste electric lamps include fluorescent, high-intensity discharge, neon, mercury vapor, high pressure sodium, and metal halide lamps. Such universal waste lamps contain mercury and sometimes lead, and are found in homes and businesses.

18.3 CATEGORIES OF UNIVERSAL WASTE HANDLERS

Management of universal wastes is similar for large- and small quantity handlers. Differences occur primarily with respect to notification, documentation, and employee training.

18.3.1 Large Quantity Handlers

A *large quantity handler* of universal wastes is defined as a facility that generates more than 5000 kg (approx. 11,000 lb) of universal waste comprising batteries, pesticides, thermostats, and lamps during a calendar year. A large quantity handler must provide written notification of universal waste management to the state or federal environmental regulatory agency and must receive an EPA Identification Number. Notification must include:

- The handler's name and mailing address
- The name and business telephone number of a contact person at the facility
- The location of universal waste management activities
- A list of the types and amounts of universal waste managed by the handler

18.3.2 Small Quantity Handlers

A *small quantity handler* of universal waste is permitted to generate no more than 5000 kg of universal wastes per calendar year. The small quantity handler does not need to provide written notification of universal waste management to the state regulatory agency. Similarly, there is no requirement to receive an EPA Identification Number. Additional details about generator types and requirements are provided below.

18.4 MANAGEMENT OF UNIVERSAL WASTES

18.4.1 Universal Waste Batteries

In 2010, 1.5 million tons of nonferrous materials other than aluminum were recovered (U.S. EPA 2011a), most being composed of lead (Pb) recovered from batteries. Automotive batteries are considered hazardous because they contain both Pb, in the form of metallic Pb and PbO pastes,

and sulfuric acid. Since the 1980s, the lead–acid battery has been one of the most highly recycled products in the United States. About 1.3 million tons of lead is recycled in the United States every year (Journal Sentinel 2012). It is estimated that 96% of battery lead was recovered in 2010 (U.S. EPA 2011b).

About 2.9 billion batteries are discarded annually in the United States alone (Randall 2013). Demand for batteries in the United States is projected to increase by 5.8% every year due to technological advances in the battery industry and the convenience and portability of battery-operated equipment (Sova and Mueller, n.d.). As a consequence, demand for these metals, whether as virgin ore or recycled, will continue to increase.

Under 40 CFR 273, a large quantity handler of universal waste is required to properly manage batteries in order to prevent releases to the environment. Specific requirements are comparatively simple and include transferring and containing batteries that are leaking or damaged to a suitable container. The container must be compatible with battery contents and must be kept closed. In addition, a large quantity handler is permitted to carry out the following activities with universal waste batteries:

- Sort batteries by type
- Mix battery types in one container
- Discharge batteries to expel the electric charge
- Regenerate used batteries
- Disassemble batteries into individual cells
- Remove batteries from consumer products
- Remove electrolyte from batteries

A large quantity handler who removes electrolyte from batteries must determine whether the electrolyte fails any characteristic test for a hazardous waste (40 CFR part 261). If a characteristic of hazardous waste is expressed, the electrolyte must be managed in compliance with 40 CFR parts 260 through 272 (Standards Applicable to Management of Hazardous Wastes). The handler is thus designated a generator of hazardous waste.

A large quantity handler of universal waste must label waste containers to identify contents. Universal waste batteries or their containers must be labeled with one of the following: “Universal Waste—Batteries,” “Waste Batteries,” or “Used Batteries.”

18.4.2 Lead–Acid Battery Recycling

Spent (dead) batteries are broken apart manually or mechanically in a hammermill and the lead, plastic, and acid are separated. The metallic and plastic battery pieces fall into a vat where the lead and other heavy components fall to the bottom, whereas the plastic floats. The floating polypropylene pieces are skimmed off and the liquids are drawn away, leaving the heavier components behind.

The Pb grids, lead oxide (PbO), and other lead components are melted together in smelting furnaces. Molten lead is poured into ingot molds to form either large ingots weighing 900 kg (2000 lb), called *hogs*, or smaller ingots weighing 30 kg (65 lb), called *pigs*. Impurities (*dross*) float at the top of the molten lead mixture in the molds. The dross is removed and the ingots are allowed to cool. The solid ingots are removed from the molds and shipped to battery manufacturers, where they are remelted and used in the production of new lead plates and other parts for new batteries (Figure 18.2).

Spent battery acid is managed in two ways. The acid is neutralized with an industrial alkali that forms a simple inert salt solution. The solution is tested for chemical composition and may be discharged to a publicly owned treatment works. Acid is also treated by conversion to sodium sulfate, an odorless and harmless salt, which is used in certain industrial and manufacturing processes. The plastic casing is shredded and the polypropylene pieces are washed, dried in a stream of air, and shipped to a plastics recycler where the pieces are melted together to a near-liquid state. The molten

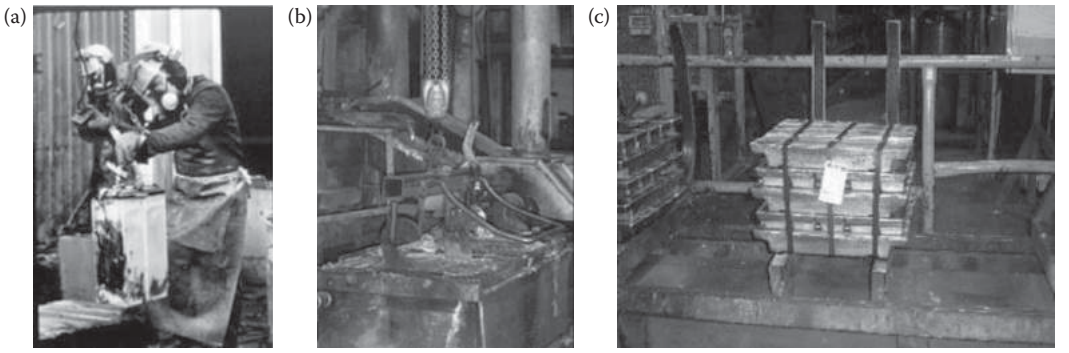


FIGURE 18.2 Recycling of spent lead–acid batteries: (a) manual breaking of industrial batteries; (b) reverbatory furnace for lead smelting; (c) lead ingots (pigs). (From OSHA, *Battery Breaking and Separating*, n.d., Available from: http://www.osha.gov/SLTC/etools/leadsmelter/credits.html.)

plastic is forced through an extruder that produces small pellets of uniform size. The pellets are sold to a battery case manufacturer for eventual reuse.

18.4.3 Nickel–Cadmium Battery Recycling

Nickel (Ni)–cadmium (Cd) battery recycling occurs through a high-temperature metal recovery process. The batteries are first shredded using a hammermill. Consumer-type battery packs are placed in a natural gas-fired thermal oxidizer where the plastic is vaporized, leaving the clean Ni–Cd cells. Gases from the thermal oxidizer are directed to a rotary hearth furnace where they are combusted for heat value. The clean Ni–Cd cells are placed in a cadmium recovery furnace. Cadmium is reduced using carbon, vaporized and condensed, thereby producing elemental cadmium, Cd^{o}. This cadmium is eventually used in the manufacture of new Ni–Cd batteries. The remaining nickel and iron become feedstocks for a metal recovery plant—the material is used to produce nickel, chromium, and iron remelt alloy that is used in stainless steel production (Sova and Mueller, n.d.).

18.4.4 Universal Waste Pesticides

A large quantity handler must contain universal waste pesticides in either its original container, a container overpacked in another container, a tank (40 CFR part 265), or a vehicle. These must be closed, structurally sound, and compatible with the pesticide. A container, tank, transport vehicle, or vessel that holds universal waste pesticides must include the product label and the words "Universal Waste—Pesticides" or "Waste—Pesticides."

Many states have enacted programs to promote drop-off and recycling of agricultural and other pesticides (Figure 18.3), and many have been highly successful in preventing improper disposal.

18.4.5 Universal Waste Thermostats

Mercury is a public health and environmental concern because it is a potent neurotoxin with the potential to accumulate in the food chain.

The Thermostat Recycling Corporation (TRC) recycles used mercury-switch thermostats in the 48 continental U.S. states. TRC is a private corporation established by thermostat manufacturers Honeywell, General Electric, and White-Rod*ge*rs. To date, TRC has collected over 1.4 million thermostats and 7.4 tons of mercury.



FIGURE 18.3 Recycling of pesticides and pesticide containers. (Courtesy of South Dakota Department of Agriculture.)

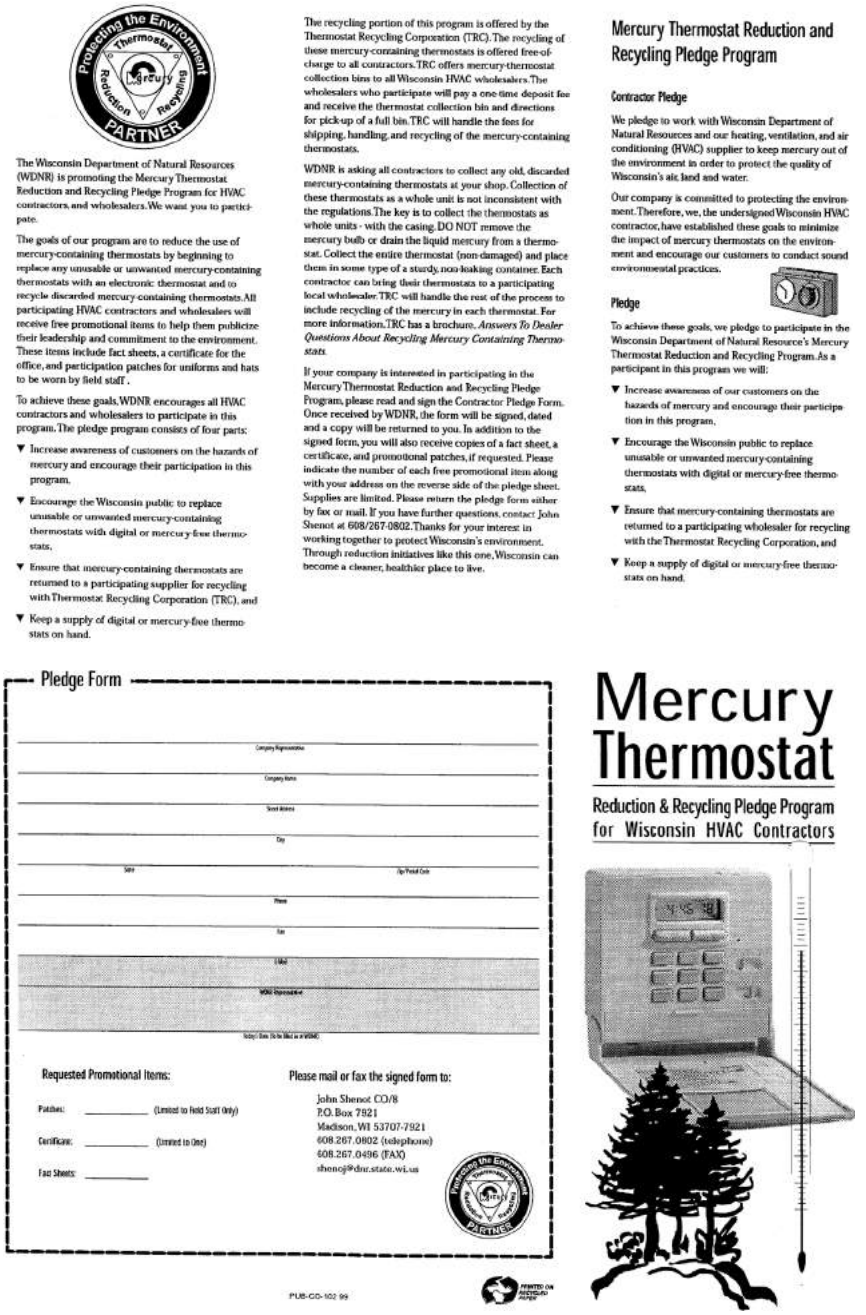
Under this voluntary, industry-sponsored effort, heating and cooling contractors relinquish old mercury-switch thermostats at participating wholesalers who collect them in protective bins supplied by TRC. Full bins are sent to TRC's recycling center where the switches are removed and forwarded to a mercury recycler.

TRC devotes much of its attention to heating and air-conditioning contractors and wholesalers, as these entities sell and install the majority of thermostats, and because the industry already has the infrastructure to support an effective recycling program. Many states encourage cooperation with the TRC program, urging contractors to sign a pledge of cooperation (Figure 18.4). Some local governments have established separate programs to manage recycling or disposal of used thermostats directly from homeowners.

A large quantity handler managing universal waste thermostats is required to contain any thermostat that is leaking or damaged. The container must be closed and compatible with the contents of the thermostat. A large quantity handler may remove mercury-containing ampules from thermostats, provided they are handled to prevent breakage and opened over a containment device. Also, the handler must ensure that a mercury cleanup system is available and the work area is well ventilated to ensure compliance with Occupational Safety and Health Administration (OSHA) exposure levels for mercury. The facility must train employees in proper mercury handling and emergency procedures. A large quantity handler who removes mercury-containing ampules from thermostats must determine whether any residues are characteristic hazardous wastes described in 40 CFR part 261. If the residues are not hazardous, the waste may be managed according to solid waste regulations. Universal waste thermostats must be labeled with "Universal Waste—Mercury Thermostats," "Waste Mercury Thermostats," or "Used Mercury Thermostats."

18.4.6 Universal Waste Lamps

Fluorescent lamps work by passing an arc of electricity through mercury vapor. The charged mercury atoms emit ultraviolet (UV) light, which is absorbed by a phosphor powder coating on the inside of the cylindrical glass lamp. The energized phosphors subsequently emit a white light. To generate the mercury vapor, a small amount of elemental (liquid) mercury is added to each lamp during manufacture. The mercury instantly vaporizes when the lamp is turned on and it recondenses when



The Wisconsin Department of Natural Resources (WDNR) is promoting the Mercury Thermostat Reduction and Recycling Pledge Program for HVAC contractors, and wholesalers. We want you to participate.

The goals of our program are to reduce the use of mercury-containing thermostats by beginning to replace any unusable or unwanted mercury-containing thermostats with an electronic thermostat and to recycle discarded mercury-containing thermostats. All participating HVAC contractors and wholesalers will receive free promotional items to help them publicize their leadership and commitment to the environment. These items include fact sheets, a certificate for the office, and participation patches for uniforms and hats to be worn by field staff.

To achieve these goals, WDNR encourages all HVAC contractors and wholesalers to participate in this program. The pledge program consists of four parts:

- Increase awareness of customers on the hazards of mercury and encourage their participation in this program.
- Encourage the Wisconsin public to replace unusable or unwanted mercury-containing thermostats with digital or mercury-free thermostats.
- Ensure that mercury-containing thermostats are returned to a participating supplier for recycling with Thermostat Recycling Corporation (TRC), and
- Keep a supply of digital or mercury-free thermostats on hand.

The recycling portion of this program is offered by the Thermostat Recycling Corporation (TRC). The recycling of these mercury-containing thermostats is offered free-of-charge to all contractors. TRC offers mercury-thermostat collection bins to all Wisconsin HVAC wholesalers. The wholesalers who participate will pay a one-time deposit fee and receive the thermostat collection bin and directions for pick-up of a full bin. TRC will handle the fees for shipping, handling, and recycling of the mercury-containing thermostats.

WDNR is asking all contractors to collect any old, discarded mercury-containing thermostats at your shop. Collection of these thermostats as a whole unit is not inconsistent with the regulations. The key is to collect the thermostats as whole units - with the casing. DO NOT remove the mercury bulb or drain the liquid mercury from a thermostat. Collect the entire thermostat (non-damaged) and place them in some type of a sturdy, non-leaking container. Each contractor can bring their thermostats to a participating local wholesaler. TRC will handle the rest of the process to include recycling of the mercury in each thermostat. For more information, TRC has a brochure, *Answers To Dealer Questions About Recycling Mercury Containing Thermostats*.

If your company is interested in participating in the Mercury Thermostat Reduction and Recycling Pledge Program, please read and sign the Contractor Pledge Form. Once received by WDNR, the form will be signed, dated and a copy will be returned to you. In addition to the signed form, you will also receive copies of a fact sheet, a certificate, and promotional patches, if requested. Please indicate the number of each free promotional item along with your address on the reverse side of the pledge sheet. Supplies are limited. Please return the pledge form either by fax or mail. If you have further questions, contact John Shenot at 608/267-0802. Thanks for your interest in working together to protect Wisconsin's environment. Through reduction initiatives like this one, Wisconsin can become a cleaner, healthier place to live.

Mercury Thermostat Reduction and Recycling Pledge Program

Contractor Pledge

We pledge to work with Wisconsin Department of Natural Resources and our heating, ventilation, and air conditioning (HVAC) supplier to keep mercury out of the environment in order to protect the quality of Wisconsin's air, land and water.

Our company is committed to protecting the environment. Therefore, we, the undersigned Wisconsin HVAC contractor, have established these goals to minimize the impact of mercury thermostats on the environment and encourage our customers to conduct sound environmental practices.

Pledge

To achieve these goals, we pledge to participate in the Wisconsin Department of Natural Resource's Mercury Thermostat Reduction and Recycling Program. As a participant in this program we will:

- Increase awareness of our customers on the hazards of mercury and encourage their participation in this program.
- Encourage the Wisconsin public to replace unusable or unwanted mercury-containing thermostats with digital or mercury-free thermostats,
- Ensure that mercury-containing thermostats are returned to a participating wholesaler for recycling with the Thermostat Recycling Corporation, and
- Keep a supply of digital or mercury-free thermostats on hand.

Pledge Form

Company Representative

Company Name

Street Address

City

State Zip/Postal Code

Phone

Fax

E-Mail

WDNR Representative

Notes: (Use To Be Filled in at WDNR)

Requested Promotional Items:

Patches: _____ (Limited to Field Staff Only)

Certificate: _____ (Limited to One)

Fact Sheets: _____

Please mail or fax the signed form to:

John Shenot CO/8
P.O. Box 7921
Madison, WI 53707-7921
608.267.0802 (telephone)
608.267.0496 (FAX)
shenoj@dnr.state.wi.us

PUB-CO-102 99

PRINTED ON RECYCLED PAPER

Mercury Thermostat

Reduction & Recycling Pledge Program for Wisconsin HVAC Contractors

FIGURE 18.4 Pledge program form for mercury thermostat reduction. (Reproduced with kind permission of Wisconsin Department of Natural Resources, Available from: http://www.uwex.edu/erc/doc/hhw/MerThermPatch.pdf.)

the lamp is turned off. Most types of high-intensity discharge lamps, that is, mercury vapor, metal halide, and high-pressure sodium lamps, also contain mercury.

The quantity of mercury in fluorescent lamps is highly variable (3–46 mg) depending on the type of lamp and year of manufacture (UNEP 2005). T-12 lamps (measuring 38 mm or 12/8 in. in diameter) contain significantly more mercury than T-8 lamps (25 mm or 1 in. in diameter). The mercury

content per lamp has declined substantially over the past 25 years, however. Most 1.2 m (48 in.) T-12 fluorescent lamps in use today contain an average of 22 mg of mercury (NJMTF 2002); however, some contain as little as 4 mg (Philips 2007).

For years, EPA considered mercury-containing lamps to be ordinary MSW that generators could dispose along with everyday MSW. Landfilling had been the traditional means of disposing spent lamps (NEMA 2001). Due to their relatively low mercury content, lamps had historically accounted for only 3.8% of all the mercury deposited in municipal landfills (Truesdale et al. 1993). Debate has ensued as to the extent of hazard such disposal may create. Although some studies claim that there is little to no mercury in landfill leachate, others argue that the mercury content may be substantial (U.S. EPA 1988; Massachusetts DEP 1996; Aucott 2006).

Until recently, most municipal waste incinerators were not equipped with the necessary controls to reduce mercury emissions. Incineration of mercury-containing lamps released up to 90% of their mercury component into the air. By 2000, most incinerators added stringent new EPA-mandated mercury controls, significantly reducing the amount of mercury that incinerators released from any mercury-containing product.

In 1990, EPA revised the test required to identify a hazardous waste, i.e., the EP-Tox test was replaced by the TCLP (see Chapter 11). Under the new test, many spent mercury-containing lamps failed and were classified as hazardous waste. In response, the industry developed numerous types of lamps having reduced mercury content that could pass the TCLP and that were, therefore, no longer classified as hazardous waste. Federal law exempts households and CESQGs from handling spent lamps that fail the TCLP. A few states ban the disposal of all lamps in solid waste, however.

Both large- and small quantity handlers of universal waste must contain lamps in containers that are structurally sound, adequate to prevent breakage, and compatible with the contents of the lamps. Such containers and packages must remain closed and must show no evidence of leakage.

Safe recycling of fluorescent lamps involves the separation of its three primary components: glass, aluminum end-caps, and phosphor powder (where most of the mercury resides). These components are crushed and separated, thus reclaiming nearly all of the mercury. The recovered mercury is triple-distilled and sold on the commodity market. Other recovered materials can also be marketed. The Philips Company uses substantial amounts of recycled phosphor in its new lamps (Wilson 1997).

Recycling has the advantage of reusing potentially hazardous materials from fluorescent lamps, including mercury. Studies indicate that mercury releases into the air from well-managed lamp recycling facilities are low. However, the reclaimed glass often contains some residual mercury that can be released as the glass is distributed through commerce and processed at high temperatures to make new products. In some areas of the United States, the number of lamp recycling operations is still limited. In addition, the market value of the reclaimed materials from lamps is negligible such that lamp recycling is not overly profitable and waste generators or government programs must pay for recycling (NEMA 2001).

18.5 RESPONSE TO RELEASES

A handler of universal waste must contain releases of universal wastes and its residues. The handler must determine whether any material resulting from the release is hazardous waste and, if so, must manage the waste in compliance with 40 CFR parts 260 through 272.

18.6 TRACKING UNIVERSAL WASTE SHIPMENTS

A large quantity handler must maintain records of each shipment of universal waste received at the facility. The record for each shipment received must include:

- The name and address of the originating waste handler from whom the waste was sent
- The quantity of each type of universal waste received
- The date of receipt of waste shipment

A large quantity handler must keep records of each shipment of waste sent from the handler to other facilities. The record must include:

- The name and address of the destination facility to whom the universal waste was sent
- The quantity of each type of universal waste sent
- The date the shipment of universal waste left the facility

A large quantity handler must retain the records for 3 years from the receipt of waste shipment. Similarly, the handler must retain the records of all wastes shipped off-site for at least 3 years from the shipping date.

18.7 SMALL QUANTITY HANDLERS OF UNIVERSAL WASTE

The small quantity handler of universal waste must manage universal waste batteries, pesticides, and thermostats in order to prevent releases to the environment. Operating requirements are essentially identical to those of large quantity handlers. A small quantity handler may accumulate universal waste for no longer than 1 year from the date the waste is generated or received. The handler must be able to demonstrate the length of time that the waste has been accumulated.

A small quantity handler is prohibited from sending or taking universal waste to a location other than another universal waste handler, a destination facility, or a foreign destination. If a small quantity handler self-transports universal waste off-site, it becomes a universal waste transporter and must comply with universal waste transporter requirements. A small quantity handler of universal waste is not required to maintain records of universal waste shipments.

A small quantity handler must provide adequate information regarding universal waste hazards to all employees who are responsible for managing the waste. The information must describe proper handling and emergency procedures appropriate to the types of universal waste handled at the facility.

A summary of the differences in regulatory requirements between large and small quantity handlers of universal waste is given in Table 18.1.

18.8 UNIVERSAL WASTE TRANSPORTERS

A universal waste transporter is responsible for the safe transport of universal waste. Restrictions on transporter operations include:

- Prohibitions from disposing universal waste
- Prohibitions from diluting or treating universal waste, except when responding to releases

A universal waste transporter must comply with U.S. DOT regulations in 49 CFR parts 171 through 180 for the transport of any universal waste that meets the definition of "hazardous material" in 49 CFR 171.8. Some universal wastes are regulated by DOT as hazardous materials because they meet the criteria for one or more hazard classes listed in 49 CFR §173.2. As universal waste shipments do not require a manifest, they are not described by the DOT shipping name "hazardous waste."

A universal waste transporter is permitted to store the universal waste at a transfer facility for a maximum of 10 days. If wastes are stored for more than 10 days, the transporter becomes a universal waste handler and must comply with the requirements for handlers. A universal waste transporter must immediately contain all releases of universal wastes. It must be determined whether any of the release is hazardous waste, and, if so, it is subject to 40 CFR parts 260 through 272.

TABLE 18.1
Differences in Regulatory Requirements for Handlers of Universal Wastes and RCRA Hazardous Wastes

	Small Quantity Handler of Universal Waste	Large Quantity Handler of Universal Waste	CESQG	SQG	LQG
Quantity handled by category	Accumulate <5000 kg (11,000 lb) on-site at any one time; §273.9	Accumulate >5000 kg (11,000 lb) or more on-site at any one time; §273.9	Generate <100 kg (220 lb) per month; <1 kg acute per month; §261.5(a) & (e)	Generate <1000 kg (2200 lb) per month; §260.10	Generate >1,000 kg per month; >1 kg acute per month; part 262 and §261.5(e)
EPA identification number	Not required; §273.12	Required; §273.32	Not required; §261.5	Required; §262.12	Required; §262.12
On-site accumulation limit	<5000 kg; §273.9	No quantity limit	<1000 kg; <1 kg acute; <100-kg spill; residue from acute; §§261.5(f)(2) & (g)(2)	<6000 kg; §262.34(d)(1)	No quantity limit
Storage time limit (without a storage permit)	1 year, unless for proper recovery, treatment, or disposal; §273.15	1 year, unless for proper recovery, treatment, or disposal; §273.25	None; §261.5	<180 days or <270 days; §§262.34(d) & (e)	<90 days; §262.34(a)
Manifest	Not required; §273.19	Not required but must keep basic shipping records; §273.39	Not required; §261.5	Required; §262.20	Required; §262.20
Personal training	Basic training; §273.16	Basic training geared toward employee responsibilities; §273.36	Not required; §261.5	Basic training; §262.34(d)	Full training; §262.34(a)

Source: U.S. EPA, *Proposed CRT Rule*, 2002, Available from: http://www.epa.gov/epaoswer/osw/meeting/pdf02/goode.pdf.

18.9 DESTINATION FACILITIES

A universal waste destination facility is defined as one that treats, disposes, or recycles a particular category of universal waste. The operator of a destination facility is subject to the requirements of parts 264, 265, 266, 268, 270, and 124, and the notification requirement under section 3010 of RCRA.

The formal requirements for a Universal Waste Destination Facility are limited. This contrasts with the extensive body of requirements for RCRA-regulated TSDFs managing hazardous waste (40 CFR parts 265 and 265). The destination facility is prohibited from sending universal waste to a site other than a universal waste handler, another destination facility, or a foreign destination. If the destination facility receives a shipment containing hazardous waste that is not universal waste, the operator must notify the state regulatory office of the shipment.

TABLE 18.2
Significant Differences between Universal Waste and Hazardous Waste Rules

	Universal Waste Transporters	Hazardous Waste Transporters
	40 CFR part 273 subpart D	**40 CFR part 263**
Compliance with DOT	Yes §273.52(a) cites DOT requirements *49 CFR parts 171-180*	Yes §263.10 cites DOT requirements *49 CRF parts 171-179*
EPA ID Number	None	Yes; §263.11
Allow to store up to 10 days at transfer facility	Yes; §273.53	Yes; §263.12
Manifest Requirements	None	Yes; §263.20-22
Response to Releases	Yes; §273.54	Yes, with more complex requirements; §263.30-31

Source: U.S. EPA, *Proposed CRT Rule*, 2002, Available from: http://www.epa.gov/epaoswer/osw/meeting/pdf02/goode.pdf.

The destination facility must keep a record of each shipment of universal waste received. The record for each shipment received must include:

- The name and address of the universal waste handler, destination facility, or foreign shipper from whom the universal waste was sent
- The quantity of each type of universal waste received
- The date of receipt of the shipment

Records must be retained by the destination facility for at least 3 years from the receipt of the shipment.

As should be obvious by this point, the Universal Waste Rules were designed to coincide with the RCRA regulations for management of hazardous wastes; however, the former were designed to be more business-friendly in order to promote recycling and streamline waste management. The differences between the universal waste and hazardous waste rules are highlighted in Tables 18.1 and 18.2.

18.10 RESPONSIBILITY OF THE STATES

When EPA issues a new rule, states authorized to implement the RCRA program are expected to adopt the rule as well. A state rule–making procedure is required in order to implement the new rule. EPA encourages state adoption of the Universal Waste Rule to encourage improved management of universal wastes. State adoption facilitates a number of interstate issues, such as import and export between states. Similar Universal Waste programs among states facilitate the implementation of regional collection and disposal programs.

If states adopt the rule, they are also allowed to add wastes to their universal waste programs. States can also establish requirements that are more stringent compared with federal regulations. Universal wastes specific to states are listed in Table 18.3, and the overall status of state programs is depicted in Figure 18.5.

TABLE 18.3
Universal Wastes[a] Specific to States

Waste	State(s)
Aerosol cans	California, Colorado
Antifreeze	Louisiana, New Hampshire
Ballasts	Maine, Maryland, Vermont
Barometers	New Hampshire, Rhode Island
Cathode ray tubes (CRTs)	Maine, New Hampshire, Rhode Island
Electronics	Arkansas, California, Colorado, Connecticut, Louisiana, Michigan, Nebraska, New Jersey
Oil-based finishes	New Jersey
Paint and paint-related wastes	Texas
Hazardous waste pharmaceuticals	Michigan

Source: U.S. EPA, *State-Specific Universal Waste Regulations*, 2012, Available from: http://www.epa.gov/epaoswer/hazwaste/id/univwast/uwsum.htm.

[a] These wastes are also referred to as "State-only Universal Wastes."



FIGURE 18.5 Universal waste programs in the United States. (From U.S. EPA, *State-Specific Universal Waste Regulations*, 2012, Available from: http://www.epa.gov/epaoswer/hazwaste/id/univwast/uwsum.htm.)

QUESTIONS

1. What is the overall rationale for the Universal Waste Rule? What are the advantages to waste generators in complying with this rule rather than with RCRA subtitle C?
2. What types of facilities must comply with the Universal Waste Rule?
3. Are universal waste handlers and universal waste transporters required to comply with 40 CFR 264 and 265 regulations? What types of operations are exempted from the regulations?
4. List and describe the different classes of universal wastes. In your opinion, are other waste types appropriate for classification as universal waste? Would personal computers fit well in this category? Give reasons.
5. How do large- and small quantity handlers of universal waste differ from large and small quantity generators of hazardous waste in terms of weight limitations, notification requirements, and storage requirements? Which of these categories of handler or generator requires an EPA identification number?
6. How long can a facility accumulate a universal waste? How does this differ from small and large quantity generators of hazardous waste?
7. When are batteries considered a universal waste and what are their handling requirements?
8. If a large quantity handler removes electrolyte from automotive batteries, are there any requirements to determine hazardous waste characteristics? Discuss.
9. How do tracking requirements differ for large quantity handlers of universal wastes compared with large quantity generators of hazardous waste? Is a manifest system required for the former? Explain.
10. How are mixtures of universal waste and hazardous waste regulated?
11. If a company has several locations at which universal waste is generated, how should each location be managed in a regulatory sense, that is, is each considered a separate handler?
12. If a small quantity handler of universal waste generates 6250 kg of universal waste in one month in a year, does the handler's classification change?
13. According to the Universal Waste Rule, if a transporter stores universal waste for more than 10 days, what will the transporter be classified as?
14. If an authorized state adds a waste to its universal waste category, would this designation be applicable in other states?
15. Because a manifest is not required for compliance with the Universal Waste Rule, how will handlers know when their universal waste finally arrives at an appropriate destination facility?
16. A handler who transports universal waste is considered a universal waste transporter. Does this rule apply for *any* quantity of universal waste?

REFERENCES

Aucott, M. 2006. The fate of heavy metals in landfills: A review. Industrial Ecology, Pollution Prevention and the NY-NJ Harbor, New York: New York Academy of Sciences.

Building Green. 2004. *Disposal of Fluorescent Lamps and Ballasts*. Available from: http://www.buildinggreen.com/features/ds/disposal.cfm

CFR (Code of Federal Regulations). 2000a. *Volume 40 Part 273, Standards for Universal Waste Management*. Washington, DC: U.S. Government Printing Office.

CFR (Code of Federal Regulations). 2000b. *Volume 40 Part 279, Standards for the Management of Used Oil*. Washington, DC: U.S. Government Printing Office.

Journal Sentinel. 2012. *Lead-Recycling Business has More than Shot at Success*. Available from: http://www.jsonline.com/business/lead-recycling-business-has-more-than-shot-at-success-7q6k0qf-168328976.html

Massachusetts DEP (Massachusetts Department of Environmental Protection). 1996. *Mercury in Massachusetts: An Evaluation of Sources, Emissions, Impacts and Controls*. Available from: www.state.ma.us/dep/files/mercury/appb.htm

NEMA (National Electrical Manufacturers Association). 2001. *Fluorescent Lamps and the Environment: Mercury Use, Environmental Benefits, Disposal Requirements*. NEMA01BR, Washington, DC: NEMA.
NJMTF (New Jersey Mercury Task Force Report). 2002. *Sources of Mercury in New Jersey*, Vol. III. Available from: http://www.state.nj.us/dep/dsr/Vol3-chapter1.pdf
OSHA (Occupational Health and Safety Administration). n.d. *Battery Breaking and Separating*. Available from: http://www.osha.gov/SLTC/etools/leadsmelter/credits.html
Philips. 2007. *Upgrade to a High PerformingT12 Lamp*. Available from: http://www.lighting.philips.com/pwc_li/us_en/connect/tools_literature/downloads/p-5769.pdf
Randall, M. 2013. *Remote Power Transfer – the End of Batteries!* Childlikes Inc. Available from: http://www.childlikes.com/battery.htm
South Dakota Department of Agriculture. 2012. *Container recycling and waste pesticide collection.* http://sdda.sd.gov/farming-ranching-agribusiness/container-recycling-waste-pesticide-collection-program/
Sova, C. and Mueller, H. n.d. *Battery Recycling Makes Sense in the Second Millennium*. South Brighton, MI: Battery Solutions Inc.
TRC (The Thermostat Recycling Corporation). n.d. *Answers to Dealer Questions about Recycling Mercury Containing Thermostats*. Rosslyn, VA: TRC.
Truesdale, R.S., Beaulieu, S.M., Pierson, T.K. 1993. *Management of used fluorescent lamps: Preliminary risk assessment*. Prepared by Research Triangle Institute, Research Triangle Park, North Carolina, for the office of Solid Waste, U.S. Environmental Protection Agency. Revised May 1993.
UNEP (UN Environment Programme). 2005. *Toolkit for Identification and Quantification of Mercury Releases*. Available from: http://www.chem.unep.ch/MERCURY/Toolkit/UNEP-final-pilot-draft-toolkit-Dec05.pdf
U.S. EPA (U.S. Environmental Projection Agency). 1988. *Summary of data on municipal solid waste landfill leachate characteristics*. EPA/530-SW-88-038. Washington, DC: Office of Solid Waste.
U.S. EPA (U.S. Environmental Protection Agency). 2002. *Proposed CRT Rule*. Available from: http://www.epa.gov/epaoswer/osw/meeting/pdf02/goode.pdf
U.S. EPA (U.S. Environmental Protection Agency). 2011a. *Municipal Solid Waste Generation, Recycling, and Disposal in the United States, Tables and Figures for 2010*. Available from: http://www.epa.gov/osw/nonhaz/municipal/pubs/2010_MSW_Tables_and_Figures_508.pdf
U.S. EPA (U.S. Environmental Protection Agency). 2011b. *Municipal Solid Waste Generation, Recycling, and Disposal in the United States, Facts and Figures for 2010*. Available from: http://www.epa.gov/wastes/nonhaz/municipal/pubs/msw_2010_rev_factsheet.pdf
U.S. EPA (U.S. Environmental Protection Agency). 2012. *State-Specific Universal Waste Regulations*. Available from: http://www.epa.gov/epaoswer/hazwaste/id/univwast/uwsum.htm
Wilson, A. 1997. Disposal of fluorescent lamps and ballasts. *Environ Build News* 6(9). Available from: http://www.buildinggreen.com/features/ds/disposal.cfm
Wisconsin Department of Natural Resources. 1999. *Mercury thermostat reduction and recycling pledge program for Wisconsin HVAC contractors*. http://infohouse.p2ric.org/ref/09/08356.pdf

FURTHER READINGS AND WEBSITES

California Department of Toxic Substance and Control. 2000. *Final Regulations: Universal Waste Rule*. Available from: http://www.dtsc.ca.gov/LawsRegulationsPolicies/UWR/UWR_final_regs.html
Colorado Department of Public Health and Environment. 2003. *Compliance Bulletin, Hazardous Waste Universal Waste Rule*. Available from: http://www.cdphe.state.co.us/hm/UWRgeneral.pdf
Illinois Environmental Protection Agency. 2003. *Used Fluorescent and High-Intensity-Discharge Lamps as Universal Wastes*. Available from: http://www.epa.state.il.us/land/fluorescent-lamps/
Michigan Department of Environmental Quality. 2003. *Universal Wastes (Including Electric Lamps) and Lead Acid Batteries*. Available from: http://www.michigan.gov/deq/1%2C1607%2C7-135-3585_4130_4192-12659—%2C00.html
North Carolina Division of Pollution Prevention and Environmental Assistance. n.d. *Fluorescent Lights and Mercury*. Available from: http://www.p2pays.org/mercury/lights.htm
Wuf Technologies. n.d. *Capabilities of Recycling Universal Wastes*. Concord, NH. Available from: http://www.wuftech.com/CapabilitiesUniversals.htm

19 Management of Used Oil

Petroleum is a jealous mistress.

Paul Carusoe, 1957–

19.1 INTRODUCTION

An estimated 1.3 billion gallons of used oil is generated each year in the United States alone (USGS 2013). Automotive maintenance facilities, do-it-yourself (DIY) oil-changing practices, manufacturing companies, electric generating stations, and mining and smelter operations are among the primary sources of used oil. Prior to Resource Conservation and Recovery Act (RCRA) regulations, a significant portion of used oil was used and disposed improperly; for example, used oil had routinely been applied to control road dust and kill roadside weeds. New regulations, however, have banned certain uses and encouraged others. For example, under RCRA, about 1.9 billion L (500 million gal) of used oil is burned in 30,000 boilers and industrial furnaces (Mouche 1995). Unfortunately, large quantities of oil continue to be improperly disposed; about 200 million gallons is dumped onto the land, discarded in ordinary household trash, and poured down storm sewers and drains (U.S. EPA 2012). The persistent components of these oils are transported via sewers and large water bodies where they sink into sediments. Pollution due to used motor oil occurs worldwide and reaches several million tons yearly.

The Used Oil Management Standards (40 CFR part 279) impose requirements affecting the storage, transportation, burning, processing, and re-refining of used oil by commercial facilities. For facilities that generate used oil, the regulations establish storage standards. For a used oil marketer (i.e., one that sells directly to a burner facility), there are additional tracking and paperwork requirements. Transporters of used oil are responsible for determination of the chemical analysis of used oil shipments and for compliance with both RCRA and Department of Transportation (DOT) requirements. Finally, recyclers and burners of used oil must comply with requirements for analysis of the oil, furnace type, and air pollution control measures.

19.2 PRODUCTION AND PROPERTIES OF LUBRICATING OILS

Petroleum refining is designed to extract a wide range of fuels and lubricating oils as a function of their respective boiling points. Within the refining tower, a number of lubricating oils are recovered, including engine oil, industrial transmission oils, hydraulic oils, heat-transfer oils, cutting oils, electrical oils, and others. Lubricating oils are distinguished from other fractions of crude oil by their high (>400°C [750°F]) boiling point and viscosity. Compounds separated for the production of lubricating oils are hydrocarbons containing as many as 40 carbons per molecule. In these oils, there is a predominance of *normal* (i.e., straight chain) and branched paraffins. There are also polycycloparaffins, with rings commonly condensed. Mono-, di-, and trinuclear aromatics, for example, naphthalene and phenanthrene, are the main components of the aromatic portion. Lubricating oils also possess a high additive content. These compounds are included in an oil blend to improve physical and chemical properties. Additive content can be as high as 20%, the most important being detergents and dispersants (Table 19.1) (Yukon, n.d). The technology used in the fabrication of different lubricating oils, including type and quantity of additives, is unique for each manufacturer.

TABLE 19.1
Typical Formulation of Engine Oils

Ingredient	Percent by Volume
Hydrotreated heavy paraffinic petroleum distillates	<70
Solvent-dewaxed heavy paraffinic distillate	<70
Detergent or dispersant	5–10
Viscosity modifier	<10
Pour point depressant	<2

Source: Yukon Water Board, n.d, *Material Safety Data Sheet, Quaker State® Peak Performance Conventional Motor Oil – All Grades*, Available from: http://www.yukonwaterboard.ca/registers/municipal/MN10-55/1-3-5.pdf.

19.3 CHEMICAL COMPOSITION OF USED MOTOR OIL

Used motor oil may originate from monograde or multigrade automotive engine oil, mineral-based crankcase oil, and railway diesel oil. There is no consistent chemical composition of used motor oil since it is based upon the crude oil source, refining processes, presence of additives, and length of time in use (ATSDR 1997a). In general, used motor oil contains small amounts of gasoline, additives (detergents, dispersants, oxidation inhibitors, rust inhibitors, and viscosity improvers); N and S compounds; metals such as Pb, Zn, Ca, Ba, and Mg; and a broad range of aromatic and aliphatic hydrocarbons with chain lengths ranging from C15 to C50 (Dominguez 2002). Cotton et al. (1977) were unable to determine a single predominant organic compound in 30 samples of used motor oil examined. However, several broad classes of compounds were commonly present, including saturated aliphatic, mono-, di-, tri-, and polyaromatic ring products.

Aliphatic compounds comprise about 73%–80% of the total weight of used motor oil. This fraction is composed of alkanes and cycloalkanes of 1–6 rings. Monoaromatics and diaromatics make up another 11%–15% and 2%–5% of the weight, respectively (Vazquez-Duhalt 1989). The percentages of hydrocarbons in crankcase oil are shown in Figure 19.1.

Examples of common monoaromatic structures in used motor oil include benzene and its derivatives: toluene, xylene, and ethylbenzene (Figure 19.2). Used motor oil contains higher percentages of polycyclic aromatic hydrocarbons (PAHs) and additives compared with fresh oil (Vazquez-Duhalt 1989; Hewstone 1994; Dominguez 2002). The concentration of PAHs in used oil may range from 34 to 190 times higher than that in fresh motor oil (Grimmer et al. 1982). These compounds represent a direct hazard to the environment and human health. Hydrocarbons have low solubility in water and high solubility in fat. Material Safety Data Sheets of used motor oil indicate a specific gravity of 0.9 and low vapor pressure. Used motor oil is defined as a stable material; however, it may be incompatible with oxidizing agents.

The concentration of heavy metals in used oil is much higher than in fresh oils. Metals may originate in crude petroleum, in motor oil additives, from engine wear, or after contact with fuel. In decades past, high concentrations of lead could have arisen from contact of lead-based gasoline vapors with motor oil during engine operation (Chen et al. 1994); fortunately, however, this is no longer an issue due to the phaseout of leaded fuels in the late 1970s. Rauckytea et al. (2006) found used motor oil to contain lead, barium, and chromium in the ranges of 88–140, 13–24, and 5–6 mg/L, respectively, and all oil samples failed the TCLP for lead. In an early study, Raymond et al. (1975) found 13 metals in used motor oil with concentrations ten times higher than that in crude oil.

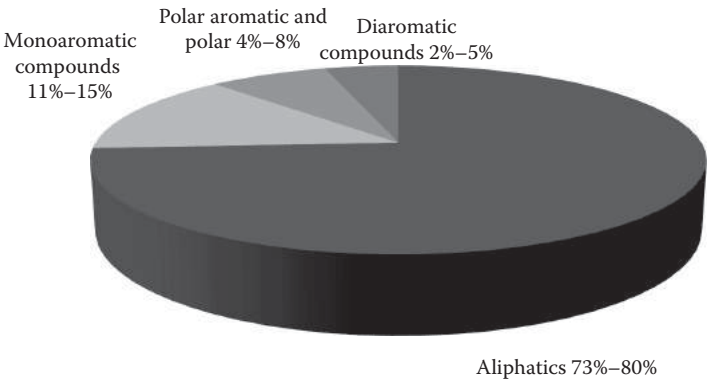


FIGURE 19.1 Chemical composition of hydrocarbons in used motor oil. (Reprinted from *Total Environ*, 79, Vazquez-Duhalt, R., Environmental impact of used motor oil, 1–23, Copyright 1989, with permission from Elsevier.)

19.4 CHEMICAL AND PHYSICAL CHANGES OF OIL DURING ENGINE OPERATION

In general, fresh oil is transformed by oxidation, nitration, cracking of polymers, decomposition of organometallics, and other processes. These chemical changes are brought about during motor operation, in part from the high temperatures and mechanical strains occurring within the engine. The main chemical changes experienced by lubricating oils are caused by heating and oxidation. The minimum decomposition temperature range for most hydrocarbons in motor oils is about 300°C–315°C (575°F–600°F). Oxidation products such as acids and esters, PAHs, and resins and asphaltenes are formed at lower temperatures. The oxidation products are more easily cracked by heat and the cracked materials are readily oxidized (Gruse 1967). New motor oils are usually light in color and subsequently darken during use because of oxidation reactions, contamination from the combustion chamber, and wear from the piston. Generally, oxidation of oils in engines produces soluble acidic compounds and semisolid to solid insoluble materials. Laboratory studies have shown that oxidation of paraffin is as follows:

$$\text{Paraffin hydrocarbon} \rightarrow \text{hydroperoxide} \rightarrow \text{water} + \text{ketone} \rightarrow \text{carboxylic acid} + \text{aldehydes}$$

Aldehydes of low molecular weight include formaldehyde, acetaldehyde, or propionaldehyde. These compounds may be oxidized, producing acids that are soluble in water. The carboxylic acid produced as a result of the above reaction is water soluble; therefore, the oil will become more corrosive.

Water constitutes a contaminant of oil, entering the crankcase and fuel tanks by natural "breathing," and may condense there. Some water, as a vapor, will migrate to the crankcase, and condensation may produce rust.

19.5 POTENTIAL HAZARDS WITH USED OIL

The presence of cleaning and dispersing substances, along with chemical transformations of all oil components, result in the production of a range of contaminants. In a study of 1000 samples of used oil, significant concentrations of toxic compounds such as 1,1,1-trichloroethane, trichloroethylene, tetrachloroethylene, toluene, and naphthalene were detected (Bergeson 1985). PAHs are of particular public health and environmental relevance because of their carcinogenic properties, and a total of 140 different PAHs have been detected in used motor oil. PAHs occur in fresh oil; however, quantities are significantly lower. They originate primarily from the combustion process.

The mutagenic effects of used engine oil have been determined by the Ames toxicity test (Ames et al. 1973), among others. The Ames test was developed to determine whether a specific chemical

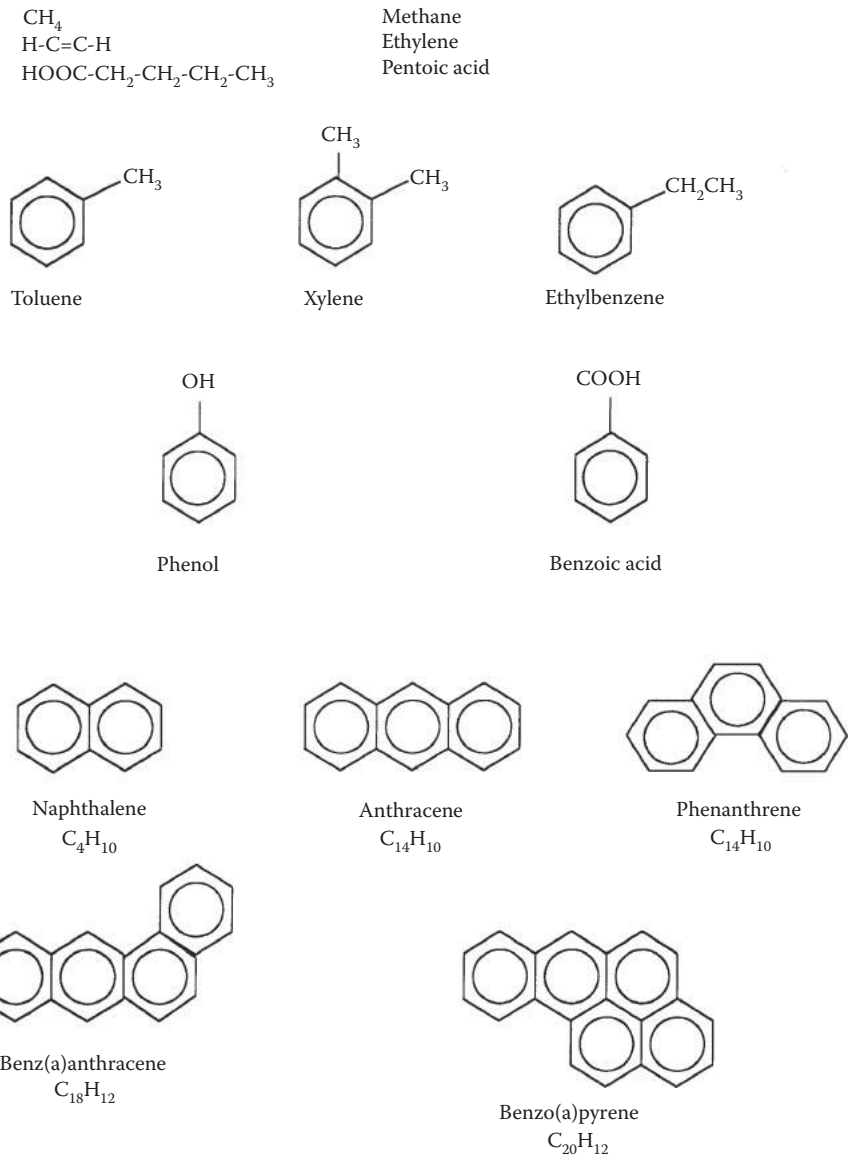


FIGURE 19.2 The chemical structures of some important aliphatic and aromatic compounds in used oil.

is a mutagen. The test is based on the assumption that any substance that is mutagenic to a specific strain of the bacterium *Salmonella typhimurium* may also be carcinogenic to humans. A large number of industrial chemicals test positive in the Ames test. Many chemicals are not carcinogenic in themselves but become converted into carcinogens as they are metabolized by the body. It is for this reason that the Ames test includes a mixture of liver enzymes.

In one study, up to 70% of the carcinogenic effects of used oil were caused by PAHs with more than three rings. This fraction represented less than 1% of the total volume of the oil. Of this fraction, 18% of the effects were caused by benzo[*a*]pyrene. Few mutagenic effects were caused by the PAH-free portion of the used oil. Schulte et al. (1993) found a significant increase in lung tumors and a dose-dependent increase in malignant lung tumors for mice exposed to PAH-enriched exhausts containing 0.05 or 0.09 mg/m^3 benzo[*a*]pyrene. Thyssen et al. (1981)

TABLE 19.2
Contaminants of Potential Public Health and Environmental Concern Occurring in Used Oil

Contaminant	Probable Source	Approximate Concentration Range
Aromatic hydrocarbons[a]	Petroleum base stock	
PAHs		
Benzo[a]pyrene		360–62,000
Benz[a]anthracene		870–30,000
Pyrene		1670–33,000
Monoaromatics alkylbenzenes		900,000
Diaromatic naphthalenes		440,000
Chlorinated hydrocarbons[a]		
Trichloroethanes	May be formed during use of	18–1800
Trichloroethylenes	contaminated oil	18–2600
Perchloroethylene		3–1300
Metals[b]		
Ba	Additives, engine wear	60–690
Zn		630–2500
Al		4–40
Cr		5–24
Pb	Contamination from leaded gasoline	3700–14,000

Source: Adapted from U.S. EPA, *Listing of Oil as a Hazardous Waste Pursuant to section (8)(2)*, Public Law 96–463, U.S. EPA, Washington, DC, 1981.

[a] Units of µg/L.

[b] Units of mg/kg.

showed evidence of a dose–response relationship between inhaled benzo[*a*]pyrene particles (most occurring between 0.2 and 0.54 µm in diameter) and respiratory tract tumorigenesis. Respiratory tract tumors were induced in the nasal cavity, pharynx, larynx, and trachea in a dose–related trend in hamsters exposed to 9.5 or 46.5 mg/m^3 for 109 weeks (ATSDR 1997b). Studies have shown an increase in the carcinogenic effect of engine oil with mileage in gasoline-powered engines (Hewstone 1994). Regardless of these and similar findings, however, The Department of Health and Human Services, the International Agency for Research on Cancer, and EPA have not classified used crankcase oil with regard to its mutagenicity or carcinogenicity in humans (ATSDR 1997b). Furthermore, used motor oil is not considered hazardous waste under RCRA.

As a result of friction within a metallic cylinder, metals are scoured from pistons and cylinder walls. Therefore, used oil commonly contains high levels of heavy metals such as Pb, Zn, Cu, Cr, Ni, and Cd. All are toxic to biota. Contaminants of potential concern in used oils are listed in Table 19.2.

19.6 HISTORY OF USED OIL MANAGEMENT

In 1980, the U.S. Congress directed EPA through the Used Oil Recycling Act to determine a suitable classification for used oil in order to ensure its appropriate management. The used oil regulations are codified in 40 CFR part 279. Used oil is defined as

> any oil that has been refined from crude oil, or any synthetic oil, that has been used and as a result of such use is contaminated by physical or chemical impurities.

TABLE 19.3
Examples of Used Oil according to 40 CFR Part 260.10

Used Oil	Not Used Oil
• Engine oil (gasoline; diesel engine; crankcase oils; piston engine oils for cars, trucks, boats, airplanes, locomotives, and heavy equipment) • Synthetic oil (from coal, shale or polymer-based starting material) • Transmission fluid • Refrigeration oil • Compressor oil • Metalworking fluids and oils • Industrial and hydraulic fluid • Copper and aluminum wire drawing solution • Electrical insulating oil • Industrial process oils • Oils used as buoyant	• Waste oil, that is, bottom clean-out waste from virgin fuel storage tanks, fuel oil spill cleanups, or other oil wastes that have not been used • Products such as antifreeze and kerosene • Vegetable and animal oil, even when used as a lubricant • Petroleum distillates used as solvents

Source: U.S. EPA, *Managing Used Oil: Advice for Small Businesses*, EPA530-F96-004, 2003, Available from: http://www.epa.gov/epaoswer/hazwaste/usedoil/usedoil.htm#what.

This definition does not include crude oil or fuel oils spilled onto land or water, wastes from petroleum refining operations, mineral oils, or oils derived from animal or vegetable fats. Examples of used oil according to the EPA definition are shown in Table 19.3 (U.S. EPA 2003).

Based on data for chemical composition such as that described earlier in this chapter, there are significant concerns regarding the effects of used oil on public health and the environment. Congress therefore directed EPA to determine whether used oil should be designated a RCRA hazardous waste, and to formulate regulations for its appropriate management and disposal. In 1985, EPA proposed a rule to list all used oil as hazardous waste (U.S. EPA 1994). Standards were proposed for recycling of used oil, and restrictions were established regarding the burning of used oil. The rule raised concerns, however, that the new restrictions and associated increased costs for management may discourage recycling. By the following year, EPA rescinded the rule (RCRA 1999). In 1986, EPA designated used oil as a nonhazardous waste.

Based on reviews of toxicological and other data, a court decision in 1988 required EPA to reconsider their most recent designation of used oil. In response to these conflicting factions, three options for used oil management were published in the 1991 *Federal Register*:

- To designate all used oil as listed hazardous waste under RCRA
- To designate only certain used oils (primarily nonindustrial oils) as hazardous
- To formulate management standards for used oil and classify used oil as RCRA hazardous material when disposed (RCRA 1999)

In 1992, a final ruling stated that used oil destined for disposal would not be listed as a hazardous waste. EPA reasoned that used oil has the potential to be recycled or re-refined. Used oil could then be used as a fuel or recycled as a lubricant instead of being disposed in a landfill. Also under the final ruling, drained used oil filters could be disposed as nonhazardous waste (40 CFR 261.4). On September 10, 1992, the Used Oil Management Standards were published in

the *Federal Register* (U.S. EPA 1999). The standards (40 CFR part 279) regulate used oil generators, collection centers, transporters and transfer facilities, re-refiners, used oil burners that burn off-specification used oil, facilities that use the oil as a dust suppressant, and facilities that dispose of used oil.

19.7 REQUIREMENTS OF THE USED OIL MANAGEMENT STANDARDS

19.7.1 Used Oil Generators

Any business that generates used oil as a result of commercial or industrial operations, or collects used oil from these operations or private households, is classified as a *used oil generator.* Examples include industrial facilities that use lubricated machinery; taxi, bus, and delivery companies; government and military motor pools; and shipyards. Household used oil generators, also known as DIY operations, are not regulated under the management standards; however, DIY collection centers are considered generators.

Used oil generators are required to engage in "good housekeeping practices in handling used oil." Some important requirements include:

- Storage containers and tanks at generator facilities must be labeled "Used Oil."
- Fill pipes used to transfer used oil into underground storage tanks must be labeled "Used Oil."
- Storage is to occur only in containers or tanks in good condition (no severe rusting, structural defects, and leakage).
- Used oil spills and leaks must be immediately stopped, contained, and cleaned.

Used oil generators are subject to the Spill Prevention, Control and Countermeasures (SPCC) program as listed in 40 CFR part 112. The SPCC consists of plans for emergency response in the event of a spill or release. Plans are specified by the Oil Pollution Act of 1990, which was promulgated to address spills into surface water. Industries managing used oil, except those located where a release will not reach a navigable waterway, must comply with SPCC specifications. Used oil generators are also subject to the Underground Storage Tank standards (40 CFR part 280). There is no requirement for generators to have secondary containment for containers or tanks of used oil.

19.7.2 Used Oil Collection Centers

A *used oil collection center* accepts and stores used oil from generators that deliver no more than 55 gal. Collection centers may also accept used oil from household DIYs. Collection centers must:

- Comply with the used oil generator standards, subpart C (40 CFR 279.20–279.24)
- Be registered, licensed, or permitted by a state, county, or municipal government to manage used oil

19.7.3 Marketers of Used Oil

Used oil marketers are defined as generators, processors, re-refiners, transporters, or burners of used oil. They must comply with additional management standards, such as conducting analyses, to ensure that the used oil has the suitable burning specifications, and to maintain these analysis reports for 3 years.

19.7.4 Transporters and Transfer Facilities

Used oil transporters are subject to more stringent requirements than are generators. Transporters are required to obtain an EPA identification number when shipping used oil off-site in amounts greater than 55 gal, and are permitted to deliver used oil only to

- Another used oil transporter, a used oil processing and re-refining facility, or an off-specification used oil burner facility that has obtained an EPA identification number
- An on-specification used oil burner facility (no EPA identification number required)

A key responsibility of a used oil transporter is to determine whether or not used oil is hazardous by measuring total halogen content. Transporters can apply the analytical Test Method for Evaluating Solid Waste (SW-846) (U.S. EPA 1986) for total halogen content. If concentrations of individual halogenated constituents are found to be insignificant, the used oil is not considered hazardous waste. If, however, more than 1000 mg/kg of halogenated compounds are measured, the used oil is considered hazardous waste and must be handled under RCRA subtitle C (Standards for Management of Hazardous Waste). Analytical reports are to be maintained by the transporter for 3 years.

The transporter is required to maintain records for used oil shipments for 3 years. Transfer facilities are required to abide by the same storage, labeling, and release response specifications as generators. In addition, tanks and storage containers must be equipped with impermeable secondary containment. This includes an impermeable floor and may include dikes, soil berms, or retaining walls.

19.7.5 DOT Requirements

The Hazardous Materials Transportation Act (HMTA) regulates the transportation of used oil. DOT has established its own definition of a hazardous material (49 CFR 171.8); DOT considers used oil a hazardous material if it is a combustible liquid (flash point of 38°C–75°C [100°F–200°F]) or a flammable liquid (flash point ≤ 38°C [100°F]). Persons transporting used oil that meets the definition of a hazardous material must comply with DOT requirements in 49 CFR parts 171 through 180.

In the event of a discharge of used oil during transportation, the transporter must take immediate action to protect human health and the environment (e.g., notify local authorities, dike the discharge area). A regulatory official may authorize the removal of the oil by transporters who do not have EPA identification numbers.

19.7.6 Used Oil Recycling

An estimated 380 million gallons of used oil is recycled each year. The basis of the decision to focus the Used Oil Management Standards on recycling was to protect public health and the environment, for conserving energy resources, and for economic benefits. For example, re-refining used oil consumes one-third the energy of refining crude oil to lubricant quality. In addition, about 3.8 L (1 gal) of used oil processed for fuel contains about 147,700 kJ (140,000 Btu) of energy. A discussion of used oil recycling technologies appears below.

Generation and handling are subject to the management standards until the used oil is shipped away for recycling or disposal. Used oil recyclers must comply with the following requirements:

- Tanks and storage containers must be equipped with impermeable secondary containment. This includes an impermeable floor and may include dikes, soil berms, or retaining walls.
- Used oil mixed with listed hazardous waste is to be treated as hazardous waste.

- Used oil mixed with characteristic hazardous waste is under hazardous waste regulations, if the mixture fails one of the four characteristic tests.
- Used oil containing more than 1000 mg/kg total halogens is designated a hazardous waste, because EPA concludes that such oil has been mixed with listed hazardous waste.
- Used oil containing chlorofluorocarbons (CFCs) removed from refrigerators where the CFCs are reclaimed are exempt.
- Persons who change their own oil and farmers generating less than 95 L (25 gal) per month are not regulated by the same requirements (40 CFR 279.53).

Used oil processors and re-refiners must have an EPA identification number and must develop practices that reduce the risk of fire, explosion, or release. Communications, emergency, and spill control equipment must be maintained at the facility. A contingency plan for prevention of health and environmental damage must be formulated. Operating records must be kept on file until the re-refiner is closed. Shipment records must be maintained for 3 years.

Used oil processing and re-refining facilities must develop a written analysis plan describing the procedures to comply with the analysis requirements listed above (e.g., total halogen content). The plan must specify whether sample analyses or knowledge of the halogen content (for example, by an understanding of the relevant industrial processes involved) is used to make the determination. If laboratory analyses are used to make the determination, the following information is required:

- Sampling method used to obtain representative samples
- Frequency of sampling to be performed
- Whether the analysis is performed on-site or off-site
- Methods used to analyze used oil for the necessary parameters

The analysis plan must be kept on file at the facility.

19.8 USED OIL RECYCLING METHODS

Recycling is loosely defined as the reuse of a substance in a beneficial way. The most commonly used oil recycling methods approved under the Used Oil Management Standards include:

- Re-refining for use as a base for lubricating oil
- Slipstreaming during refining of crude petroleum
- Processing
- Direct burning

The first two methods convert used oil to a lubricating oil or similar product; the last two are designed to recover heat energy from combustion of the used oil.

19.8.1 Re-Refining

During *re-refining*, used oil is subjected to a series of physical and chemical treatments to remove impurities. The resulting product is blended with virgin oil and additives to produce new lubricating oil. The recycled product is typically of a quality equivalent to that of a product derived from virgin oil. Re-refining uses vacuum distillation and hydrotreating (Figure 19.3). The used oil is first subjected to filtering, heating, and settling to remove water and large solids. A vacuum is then established within a column of oil, which strips out organic contaminants. The oil is subsequently treated with hydrogen, which bonds with certain contaminants that subsequently settle. Finally, the heavier lubricating oil is separated from the lighter fuel oil. With re-refining, the production

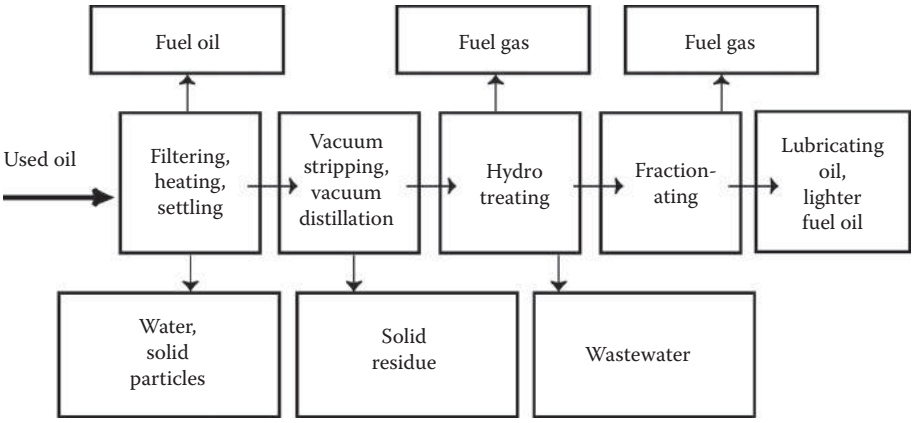


FIGURE 19.3 A vacuum distillation or hydrotreatment re-refining system for used oil. (From U.S. EPA, *Environmental Regulations and Technology: Managing Used Motor Oil*, EPA/625/R-94/010, Office of Research and Development, EPA, Cincinnati, OH, 1994.)

of hazardous waste is minimized, and residuals can be burned as fuel or used to produce asphalt (EERC et al. 1988).

Re-refining possesses several advantages. First, unlike other recycling options, re-refining allows used oil to be reused many times. In addition, re-refining used oil into lubricating oil is simpler and less expensive than refining crude oil into lubricating oil. The process saves energy—approximately 50%–85% less energy is needed to re-refine used oil than to refine virgin oil into lubricating oil (Byrne et al. 1989). A disadvantage of re-refining is that it is more complicated than other recycling options. Another disadvantage is that only a few re-refiners are currently in operation in the United States. As a result, costs of transporting used oil to a re-refiner may be substantial.

19.8.2 Slipstreaming

With *slipstreaming*, small quantities of used oil (approximately 1% of the feed) are mixed with crude oil and introduced into the standard refining process (Arner 1992). The used oil does not require pretreatment before it is mixed with the crude oil because the refining process removes contaminants that might impair the quality of the final product.

The major advantage of slipstreaming is that the heat or lubrication value of the used oil is realized without complicated processing methods. Slipstreamed used oil could serve as a base for several petroleum products, including fuel oil, gasoline, and lubricating oil. In addition, slipstreaming poses no greater environmental risk than refining crude oil. Used oil channeled into the refining process after distillation or catalytic cracking is exempt from the Used Oil Management Standards, provided that it is on-specification used oil (U.S. EPA 1994).

19.8.3 Processing

Processing involves treating used oil to improve its fuel characteristics. Relevant contaminants to be removed include water, sediment, and ash (e.g., metals). Once removed, the quality of the used oil is similar to that of virgin fuel oil (Mueller Associates 1989; Arner 1992). Physical treatment methods such as settling, filtering, and centrifuging remove water or solid contaminants (e.g., metallic fragments from engine wear) (Figure 19.4). During settling, used oil is retained in large tanks for relatively long periods. Heavy contaminants eventually sink and light contaminants rise to the top. Filtering screens out solids and captures lighter particles that do not settle. During high-speed centrifugation, the oil is separated from substances with different densities, such as water and solids.

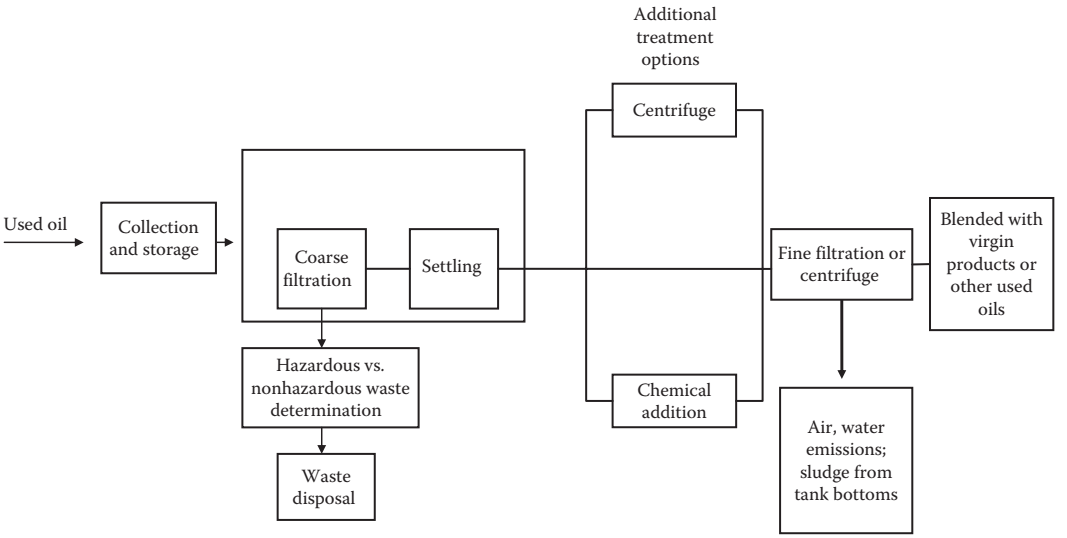


FIGURE 19.4 A used-oil processing schematic.

Processing also includes chemical treatment to remove contaminants and improve burning characteristics. For example, simple reagents can be added to neutralize acids. During processing, used oil may be blended with crude oil to adjust its viscosity or improve its fuel quality.

The major advantage of processing is that it improves the burning quality of used oil. Processing can also allow off-specification used oil to be upgraded to on-specification grade so that it can be burned by a greater number of facilities (see below). Processing used oil is a widespread industry in the United States. Most facilities are small operations that service local markets. Processing is therefore a more readily available recycling option for used oil generators than is re-refining.

19.8.4 Direct Burning

Direct burning is, as the name implies, burning used oil without prior processing to remove contaminants.

19.8.5 Off- vs. On-Specification Used Oil

Under the Used Oil Management Standards, if used oil exceeds allowable levels of any of the constituents and properties listed in Table 19.4, it is designated *off-specification used oil*, and restrictions are implemented as to its use, including burning for energy recovery. Limits are provided for concentrations of certain metals, flashpoint, and total halogens. Used oil that does not exceed any of these values may be burned for energy recovery, and any fuel produced from used oil by processing or other treatment is not subject to regulation. If it complies with all specifications, it is deemed *on-specification used oil.*

Off-specification used oil may be burned for energy recovery in the following:

- Industrial furnaces
- Industrial boilers (such as asphalt plants and cement kilns), located on the site of a manufacturing facility
- Utility boilers used to produce electric power, steam, heated, or cooled air
- Hazardous waste incinerators subject to 40 CFR parts 264 or 265

TABLE 19.4
Used Oil Specifications Limit

Constituent or Property	Allowable Level
Arsenic	5 mg/kg
Cadmium	2 mg/kg
Chromium	10 mg/kg
Lead	100 mg/kg
Flashpoint	100°F (minimum)
Total halogens	4000 mg/kg

Source: Code of Federal Regulations, Vol. 40, Part 279, *The Used Oil Management Standards*, U.S. Government Printing Office, Washington, DC, 2004.

- Used oil fired space heaters provided that: (a) the used oil is generated on the facility site or is received from household DIY used oil generators, (b) the heater is designed for a maximum capacity of 0.5 million Btu/h or less, and (c) combustion gases are vented outside (U.S. EPA 1992).

Off-specification used oil is effectively burned in the above systems because their operating temperatures are much higher than those for space heaters and other small heaters. The high temperatures result in effective combustion of the oil and most organic contaminants, thus reducing concerns regarding potential atmospheric contaminants. In addition, large burners are usually equipped with pollution control equipment that further reduces emissions.

Burners of off-specification used oil are required to obtain an EPA identification number. Facilities must demonstrate that the oil will be burned in a suitable device; for example, combustors must possess equipment that adequately reduces atmospheric emissions. Storage specifications are the same as those for transporters, and burners are required to follow the same procedures to treat releases to the environment (Booz Allen Hamilton Inc. 1999).

The major advantage of direct burning is that it allows the heat value of used oil to be gained without the need for additional processing. The advantage is greater when used oil is directly burned on-site, thus averting transportation costs. Another advantage is that numerous facilities in the United States are capable of directly burning used oil. Unlike re-refining, therefore, direct burning is a readily available recycling option for generators that are also off-specifications burners.

For service stations, quick-lube shops, fleet operations, DIY collection centers, and retailers, the major advantage of directly burning used oil on-site comes from utilizing the generated waste oil as a heating fuel. During seasons when heating is not required, used oil must be removed from the premises unless sufficient storage capacity is available for colder months.

One disadvantage of direct burning of off-specification used oil relates to its chemical analysis (or, more specifically, the lack thereof). Under the Used Oil Management Standards, generators who burn used oil in space heaters are not required to test if it meets specifications, as long as it is generated on-site or collected from DIYs. Consequently, generators could potentially burn off-specification used oil, and resultant emissions may pose a health hazard.

On-specification used oil can be burned in space heaters, boilers, and industrial furnaces without being subject to the Used Oil Management Standards. Burning on-specification oil is not expected to pose any greater risk to human health and the environment than burning virgin fuel oil; as a result, there are no special burning requirements (U.S. EPA 1994). Burning in small heaters is a common method of recycling—approximately 110 million gallons of used oil is burned in 75,000 small space heaters annually (Arner 2012). In many areas of the country, facilities (service stations,

quick-lube shops, fleet operations, DIY collection centers, and retailers) that wish to directly burn on-specification used oil must obtain local or state air pollution control permits.

Periodic maintenance of space heaters is necessary, and the ash from space heaters must be removed and disposed properly. Prior to disposal, a generator must determine whether the ash is regulated as a hazardous waste. The ash should be tested using the EPA characteristic tests to determine ignitability, corrosivity, reactivity, and toxicity. If the ash fails any one of these tests, it must be disposed in a permitted facility.

19.9 DISPOSAL

Under some circumstances, the cost of recycling used oil is exorbitantly high such that it is not a practical option. For example, used oil may be generated in very small quantities and too far from a recycling facility. Disposal may therefore be the only cost-effective option for the generator. The first step is to determine if the used oil is hazardous. The generator must test the oil to determine if it has been mixed with a hazardous waste or if it exhibits the characteristics of a hazardous waste. The used oil must be disposed as hazardous waste under subtitle C if it contains 1000 mg/kg or more total halogens, or if it exhibits a characteristic of a hazardous waste.

The used oil can be disposed as a solid waste under subtitle D if it contains less than 1000 mg/kg total halogens and does not exhibit the characteristics of a hazardous waste. If it is to be disposed as solid waste, the generator must identify either a subtitle D industrial landfill or an incinerator that will accept the oil. Different states have promulgated different regulations concerning whether or not solid waste facilities can accept used oil. If no subtitle D facilities can be identified that will accept the oil, the generator must identify a hazardous waste facility to accept it.

Irrespective of whether or not the used oil has a halogen content of 1000 mg/kg or more or exhibits other hazardous characteristics, it is considered a hazardous substance under DOT's HMTA regulations when transported. Consequently, the used oil generator must meet all HMTA requirements for a hazardous waste generator. This includes preparing a Uniform Hazardous Waste Manifest, properly labeling the used oil, using DOT-approved packaging, and hiring a transporter that meets DOT requirements. Details for hazardous materials transportation are provided in Chapter 13.

19.9.1 Prohibitions

Used oil is not permitted for storage or disposal in surface impoundments or waste piles. The use of used oil as a dust suppressant is prohibited except when such activity takes place in a state permitted by EPA. A state may petition EPA to allow application of used oil as a dust suppressant. It must be demonstrated that the used oil is not mixed with hazardous waste and does not exhibit a hazardous characteristic other than ignitability. The state is also required to minimize the local environmental impacts of its use as a dust suppressant.

19.9.2 Exemption from CERCLA Liability

Service stations, government-run DIY collection centers, and quick-lube shops may be considered *service station dealers* (defined by the Comprehensive Environmental Response, Compensation, and Liability Act [CERCLA or Superfund]) (see Chapter 3) if DIY used oil is accepted for recycling. The service station dealer is exempted from CERCLA liability. However, the Used Oil Management Standards must be complied with. If the used oil is mixed with hazardous waste, it is not exempt from CERCLA liability (Booz Allen Hamilton Inc. 1999).

19.A.1 APPENDIX: SCENARIOS

This chapter includes several situations that are intended to apply the regulatory foundation provided in previous chapters. All situations are based on actual events and inspections experienced



FIGURE 19.A.1 Drum storage area.



FIGURE 19.A.2 Drum storage in a facility basement.

by hazardous waste regulatory personnel. Names of companies and individuals have been changed.

After reading each scenario, discuss what, if any, violations may have occurred. How may these violations be best addressed (via changes in engineering design, a modified storage or disposal program, use of common sense, etc.)?

1. What is wrong with Figure 19.A.1?
2. At a wire-coating facility, an employee alleges that F002 solvent was mixed with used oil and that the mixture was stored in the facility basement. An inspector found the drums in question to be leaking (Figure 19.A.2), and cracks were apparent in the floor and along the walls.

19.A.1.1 Responses to Scenarios

1. (a) Containers must be labeled "Used Oil," not "Waste Oil" (40 CFR 279.22(c)(1)).
   (b) Clearly, this is not the proper method to store drums, regardless of whether they contain hazardous waste or used oil. Some of the drums have experienced corrosion and rust damage, and some appear to have leaked. Drums should be protected from weather and be kept away from water in order to prevent damage. According to federal regulations:

Containers and aboveground tanks used to store used oil at generator facilities must be:
(1) In good condition (no severe rusting, apparent structural defects, or deterioration)
(2) Not leaking (no visible leaks) (40 CFR 279.22(b))

(c) In some facilities, hazardous wastes such as chlorinated solvents have been stored mixed with used oil. If the inspector is suspicious, a waste determination of the drum contents can be ordered.
(d) Federal regulations do not limit the quantity of used oil in storage at a facility; however, local fire departments or state agencies may establish their own limits.

2. A waste determination should be carried out by the generator to ascertain the presence of hazardous waste solvent in the used oil.

Before the results of the waste determination were provided, the inspector stated in his report that "poor housekeeping was apparent at the facility, which creates the potential for a release to the environment." According to 40 CFR 264.31:

> Facilities must be designed, constructed, maintained, and operated to minimize the possibility of a fire, explosion, or any unplanned sudden or nonsudden release of hazardous waste or hazardous waste constituents to air, soil, or surface water which could threaten human health or the environment.

QUESTIONS

1. To what aspects of used oil handling (e.g., generator requirements, transportation) do the Used Oil Management Standards (40 CFR part 279) apply? Be specific.
2. Discuss the general chemical composition of used oil in terms of the presence of aliphatics, aromatics, PAHs, metals, and so on. How has the oil chemically changed compared with fresh oil?
3. Although used oil cannot be used as a weed killer on fencerows, can it be utilized to burn brush and other unwanted vegetation? Check 40 CFR part 279.
4. Based on the used oil regulations, is it acceptable for a DIY oil changer to place used oil in the trash?
5. Is it permissible for farmers to immerse pigs or cattle in used oil in order to remove lice and mites? Check 40 CFR part 279.
6. Used oil generators are required to engage in "good housekeeping practices in handling used oil." List and discuss some important requirements.
7. At least three bodies of federal regulations govern some aspect of used oil management. List them. Provide the appropriate citations from the Code of Federal Regulations.
8. Is it required that used oil be transported to permitted recycling facilities with EPA identification numbers?
9. What are the inspection requirements for used oil storage tanks?
10. What are the storage and secondary containment requirements for used oil storage tanks?
11. In what ways are the requirements for used oil processors and re-refiners similar to those for TSDFs as managed under RCRA subtitle C?
12. Discuss the most common used oil recycling methods approved by the Used Oil Management Standards. What are the advantages and disadvantages of each?
13. How does on-specification used oil differ from off-specification used oil in terms of composition? Where can off-specification used oil be burned for energy recovery? What is the rationale for the use of these systems?
14. The ash from used oil-burning space heaters must be removed and disposed properly. Prior to disposal, is the generator responsible for any special management of the ash?
15. Under what condition(s) must used oil be disposed as a subtitle C hazardous waste?

16. What is an approved procedure for rendering used oil filters acceptable for disposal? Can drained and crushed oil filters be disposed in a subtitle D landfill?
17. Where in your community can you bring used oil for recycling? How is the oil managed (how is it stored, where is it shipped for processing, etc.)? Can used oil filters be brought to this facility?
18. Trace the chronology of the Used Oil Management Standards. How did the waste classification for used oil evolve?

REFERENCES

Ames, B., Lee, F., and Durston, W. 1973. An improved bacterial test system for the detection and classification of mutagens and carcinogens. *Proc Natl Acad Sci* 70, 782–786.

Arner, R. 1992. *Used Oil Recycling Markets and Best Management Practices in the United States*. Boston, MA: National Recycling Congress.

Arner, R. 2012. Used Oil Recycling in America. *Twenty-Second International Conference on Solid Waste Technology and Management*. Philadelphia, PA, March 19, 2007. Available from: http://www.robarner.com/usedoil.html

ATSDR (Agency for Toxic Substances and Disease Registry). 1997a. Total Petroleum Hydrocarbons. Available from: http//www.atsdr.cdc.gov/toxprofiles/tp123-c-3.pdf

ATSDR (Agency for Toxic Substances and Disease Registry). 1997b. *Toxicological Profile for Used Mineral-Based Crankcase Oil*. Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service.

Bergeson, L. 1985. Legal lookout, EPA to list used oil as a hazardous waste. *Pollut Eng* 17, 58–59.

Booz Allen Hamilton Inc. 1999. Used Oil (40 CFR Part 266, Subparts E, and Part 279), RCRA, Superfund and EPCRA, Hotline Training Module.

Byrne, J.P., Cody, C.A., Doyle, P.J., MacKinnon, J.S., Mayor, A.H., Reid, A.M., Rosner, S.K., and Talbot, C.J. 1989. Used Motor Oil in Massachusetts: A Prioritization of End Uses based on Human Health and Environmental Risk. *Prepared for the Commonwealth of Massachusetts Department of Environmental Protection*. Medford, MA: Tufts University Department of Civil Engineering.

CFR (Code of Federal Regulations). 2004. *Volume 40, Part 279*, *The Used Oil Management Standards*. Washington, DC: U.S. Government Printing Office.

Chen, C.S.-H., Delfino, J., and Suresh, P. 1994. Partitioning of organic and inorganic components from motor oil into water. *Chemosphere* 28(7): 1385–1400.

Cotton F.O., Whisman, M.L., Gowtzinger, S.W., and Reynolds, J.W. 1977. Analysis of 30 used motor oils. *Hydrocarbon Process* 56, 131–140.

Dominguez, E. 2002. Phytoremediation of Soils Contaminated by Used Motor Oil. M.S. thesis, Ball State University, Muncie, IN.

EERC (Energy and Environmental Research Corporation) and Robert H. Salvesen Associates, Evergreen Oil, Inc. 1988. *Guide to Oil Waste Management Alternatives for Used Oil, Oily Wastewater, Oily Sludge, and Other Wastes Resulting from the Use of OilProducts*, Final Report. Diane Pub, Darby PA.

Grimmer, G., Naujack, K.W., Dettbarn, G., Brune, H., Deuschwenzel, R., and Mifeld, J. 1982. Studies on the carcinogenic action of use engine lubricating motor oil. *Erdol Kohle* 35, 466–472.

Gruse, W.A. 1967. *Motor Oils: Performance and Evaluation.* New York: Reinhold Publishing Corporation.

Hewstone, R.K. 1994. Health, safety and environmental aspects of used crankcase lubricating oils. *Sci Total Environ* 156, 255–268.

Mouche, C. 1995. Managing used motor oil. *Pollut Eng* 27, 40–43.

Mueller Associates. 1989. *Waste Oil: Reclaiming Technology, Utilization and Disposal.* Park Ridge, NJ: Noyes Data Corp.

Rauckytea, T., Hargreaves, D.J., and Pawlaka, Z. 2006. Determination of heavy metals and volatile aromatic compounds in used engine oils and sludges. *Fuel* 85, 481–485.

Raymond, R.L., Hudson, J. O., and Jamison, V.W. 1975. Oil degradation in soil. *Appl Environ Microbiol* 31, 522–535.

RCRA. 1999. Superfund and EPCRA Hotline Training Module, Used Oil, 40 CFR Part 266, Subpart E, and Part 279. Washington, DC.

Schulte, A., Ernst, H., and Peters, L. 1993. Induction of squamous cell carcinomas in the mouse lung after long-term inhalation of polycyclic aromatic hydrocarbon-rich exhausts. *Exp Toxicol Pathol* 45, 415–421.

Thyssen, J., Althoff, J.K.G., and Mohr, U. 1981. Inhalation studies with benzo[a]pyrene in Syrian golden hamsters. *J Natl Cancer Inst* 66, 575–577.

U.S. EPA (U.S. Environmental Protection Agency). 1981. *Listing of Oil as a Hazardous Waste Pursuant to Section (8)(2)*, Public Law 96– 463. Washington, DC: U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency).1986. *Method 9040, Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, EPA SW-846. Washington, DC: U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1992. *Environmental Fact Sheet: Management Standards Issued to Control Potential Risks from Recycled Used Oil—No Hazardous Waste Listing*, EPA/530-F-92-018. Washington, DC: Office of Solid Waste and Emergency Response, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1994. *Environmental Regulations and Technology: Managing Used Motor Oil*, EPA/625/R-94/010. Cincinnati, OH: Office of Research and Development, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1999. *Used Oil Management.* U.S. EPA Publications. Available from: http://www.ehso.com/usedoil.htm

U.S. EPA (U.S. Environmental Protection Agency). 2003. *Managing Used Oil: Advice for Small Businesses*, EPA530-F96-004. Available from: http://www.epa.gov/epaoswer/hazwaste/usedoil/usedoil.htm#what

U.S. EPA (U.S. Environmental Protection Agency). 2012. *Wastes – Resource Conservation – Common Wastes & Materials, Basic Information*. Available from: http://www.epa.gov/osw/conserve/materials/usedoil/oil.htm

USGS (U.S. Geological Survey). 2013. Used Motor Oil a Potential Source of MTBE in Ground Water. Available from: http://toxics.usgs.gov/highlights/waste_oil.html

Vazquez-Duhalt, R. 1989. Environmental impact of used motor oil. *Sci Total Environ* 79, 1–23.

Yukon Water Board. n.d. *Material Safety Data Sheet, Quaker State® Peak Performance Conventional Motor Oil – All Grades*. Available from: http://www.yukonwaterboard.ca/registers/municipal/MN10-55/1-3-5.pdf

SUGGESTED READINGS

Abdulkareem, A.S., Muzenda, E., and Afolabi, A.S. 2013. Optimization of treatment parameters on the recycling of used lubricating oil. *Adv Mat Res* 699, 735–741.

Energy and Environmental Research Corp. 2003. *Guide to Oil Waste Management Alternatives Used for Oil, Oily Wastewater, Oily sludge, and other Wastes Resulting from the Use of Oil Products*, Irvine, CA: Energy and Environmental Research Corp.

Gourgouillon, D. and Shrive, L. 2000. An environmentally friendly process for the regeneration of used oil. *Environ Sci Technol* 34, 3469–3474.

Inyang, H.I. 2003. Framework for recycling of wastes in construction. *J Environ Eng* 129, 887–899.

Kayode, O., Olowoyo, O., and Oyedeji, A. 2009. The effects of used engine oil pollution on the growth and early seedling performance of *Vigna uniguiculata* and *Zea mays*. *Res J Soil Bio* 1(1), 15–19.

Rincon, J., Canizares, P., Garcia, M.T., and Gracia, I. 2003. Regeneration of used lubricant oil by propane extraction. *Ind Eng Chem Res* 42, 4867–4874.

Schroder, J.L., Basta, N.T., Payton, M., Wilson, J.A., Carlson, R.I., Janz, D.M., and Lochmiller, R. L. 2003. Ecotoxicological risks associated with land treatment of petrochemical wastes; residual soil contamination and bioaccumulation by cotton rats. *J Toxicol Environ Health* 66, 305–326.

Sengupta, P., Sarkia, N., and Borthakur, P.C. 2002. Bricks from petroleum effluent treatment, plant sludge, properties and environmental characteristics. *J Environ Eng* 128, 1090–1095.

20 Medical and Infectious Wastes

Nearly all men die of their medicines, not of their diseases.

Moliere (1622–1672)

20.1 INTRODUCTION

Each year, more than 3.5 million tons of medical wastes is generated in the United States (Lee et al. 2004). For comparison, about 249 million tons of municipal solid waste (MSW) is generated annually (see Table 1.3). The majority of medical waste is generated during administration of healthcare, research by medical institutions, and home healthcare activities. The institutions generating most of the medical waste include hospitals, laboratories, physicians, dentists, veterinarians, long-term healthcare facilities, clinics, blood banks, and funeral homes. The majority (approximately 77%) of regulated medical waste (RMW), however, is generated by hospitals. Most of the remaining classes of generators produce relatively small quantities (<23 kg or 50 lb per month) of RMW. The distribution of waste types from various sources is presented in Figure 20.1.

Before 1988, the waste category termed "medical waste" received little attention from regulators or the public. In that year, however, syringes, blood vials, laboratory rats, and other medical-related debris began washing up on the beaches of the Atlantic coast and Great Lakes. In 1990, medical waste began appearing on the beaches near San Francisco and San Diego. Many beaches were closed because of potentially dangerous public health conditions. Although there was little chance of this medical detritus causing illness, public fears of possible contact with hepatitis B and HIV viruses led to a corresponding collapse in local tourist industries. It was subsequently determined that much of the beach washups consisted of garbage and other debris attributed to malfunctioning solid waste management systems, rather than to illegal dumping. A small portion of the waste consisted of syringes, medical vials, or other wastes of medical origin. This debris was not linked to hospitals but more likely the result of home injections (insulin and medications), drug users, recreational boaters, cruise ships, and U.S. Navy ships (Lipman 1992).

Federal agencies with the authority to establish medical and infectious waste regulations, such as the Environmental Protection Agency (EPA) and the U.S. Centers for Disease Control, had previously developed guidelines or best management practices, rather than promulgate regulations for managing medical wastes. Up to the late 1980s, state and local authorities regulated the management of medical waste. Regulations varied from one locality to another, and up to 1988, several states had no formal definition for medical waste. A number of states did not regulate medical and infectious wastes, thereby allowing hospitals and other medical facilities to dispose all wastes collectively as municipal waste.

20.2 MEDICAL WASTE TRACKING ACT

Congress passed House Bill 3515, the Medical Waste Tracking Act (MWTA), in November 1988, which directed EPA to develop protocols for dealing with infectious waste disposal. The EPA was required to publish an interim final rule for a 2-year demonstration medical waste management and tracking program. The Resource Conservation and Recovery Act (RCRA) was amended by adding subtitle J.

In a fashion analogous to RCRA, the Act established a cradle-to-grave medical waste tracking protocol; however, this program was implemented in only a limited number of states. New York, New Jersey, and Connecticut were required to participate. The program was open to any state wishing to

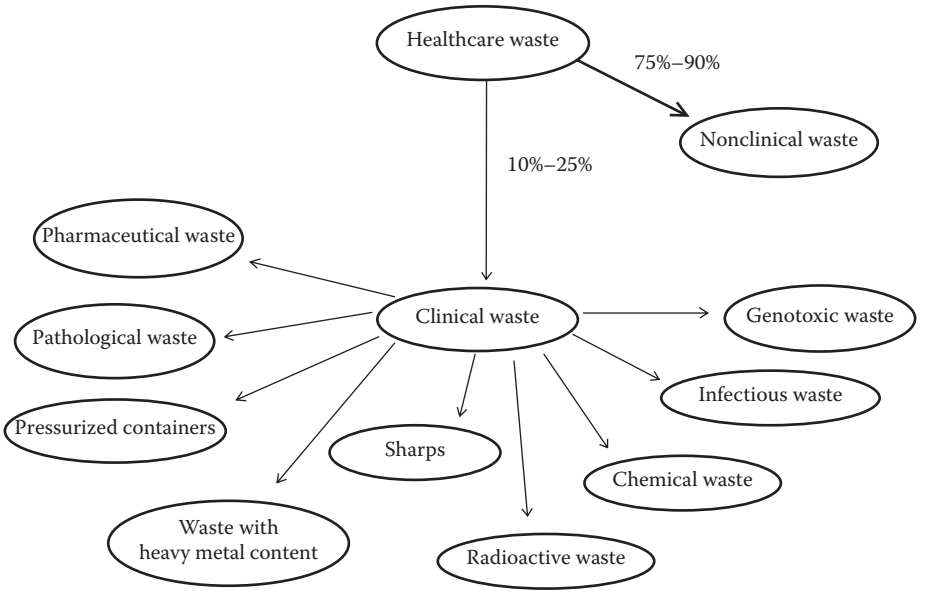


FIGURE 20.1 Categories of wastes from medical facilities. (Reproduced with kind permission of Water, Engineering and Development Centre, Loughborough University, UK, Available from: http://ec.europa.eu/echo/files/evaluation/watsan2005/annex_files/WEDC/es/ES08CD.pdf.)

petition EPA for inclusion. The Commonwealth of Puerto Rico petitioned for participation. States contiguous to the Great Lakes were designated by the MWTA to participate in the program; however, the act provided the option for them to voluntarily withdraw. These states did indeed choose to opt out.

The medical waste tracking program expired in June 1991 without being reauthorized by Congress; however, the course of medical waste management in the United States changed significantly as a result of this legislation. With increasing fear of the AIDS epidemic among the American public, along with washups of medical waste on beaches, medical waste policy shifted in order to respond to the potential risks associated with this waste stream. At present, no federal EPA tracking regulations are in effect for medical waste; however, many states have adopted their own programs.

20.3 DEFINITIONS AND SOURCES OF MEDICAL WASTE

As is the case for municipal and hazardous waste, one of the first steps in managing medical waste is to identify its sources. A logical next step is to determine the types and quantities of waste generated. The third step is determining as to whether the waste should be classified as solid, potentially infectious, hazardous, radioactive, and so on. Definitions of medical waste to be managed and disposed as potentially infectious will vary depending on which regulation or guideline is chosen.

Definitions for *infectious waste* also vary widely in different federal regulations and from state to state; there is no national standard defining which wastes comprise infectious wastes. Some federal designations of infectious waste include those established by the CDC (1985), the EPA *Guide for Infectious Waste Management* (U.S. EPA 1986), the *Medical Waste Tracking Act of 1988* (U.S. EPA 1988), and others. The CDC definition of infectious waste is any waste from microbiology laboratories, pathological waste, sharps, and blood or blood-product waste (CDC 1985). The definitions provided in the EPA *Guide* were more specific (U.S. EPA 1986):

> Isolation waste, cultures and stocks of infectious agents, human blood and blood products, pathological waste, contaminated sharps (e.g., hypodermic needles, syringes, Pasteur pipettes, scalpel blades, blood vials) and contaminated animal carcasses, body parts, and bedding.

Optional infectious waste is also listed in the *Guide* and includes surgery and autopsy waste, miscellaneous laboratory waste, dialysis unit wastes, and contaminated equipment. These are not considered to pose a risk, and the decision as to whether optional waste should be handled as infectious is left to an authorized representative at the facility.

The MWTA defined RMW to include cultures and stocks of infectious agents, human pathological wastes, human blood and blood products, sharps (used and unused), contaminated animal wastes, and isolation wastes. These are described further below. Based on the MWTA definition of medical waste, sources were identified as: (1) hospitals, (2) physicians' offices, (3) dentists' offices, (4) biomedical research facilities, (5) clinical laboratories, (6) manufacturing facilities, (7) veterinary offices and clinics, (8) funeral homes, (9) in-home medical care, (10) other healthcare and residential care facilities, (11) illicit intravenous drug use, and (12) other sources (e.g., cruise ships and naval vessels).

Because medical and infectious wastes are defined in many ways, because the general public tends to consider all medical wastes as potentially infectious, and because off-site disposal contractors may define any medical waste as potentially infectious, some institutions categorize all patient contact wastes as potentially infectious. Each healthcare facility must formulate its own definition of medical and infectious wastes based on definitions established at federal and state levels.

20.3.1 Potentially Infectious Waste

A portion of the medical waste stream from healthcare and similar institutions is categorized as being potentially infectious. Other terms for infectious waste are biohazardous waste, biological waste, biomedical waste, contaminated waste, pathogenic waste, pathological waste, red bag waste, and RMW. Regardless of regulatory definition, however, a waste is infectious when all of the following conditions are met simultaneously (U.S. EPA 1989a, 1989b, 1989c, 1991):

- Presence of a virulent pathogen
- Sufficient concentration of the pathogen
- Presence of a host
- Portal of entry is available
- Host susceptibility

20.3.2 Regulated Medical Waste (40 CFR Part 259.30)

The MWTA of 1988 defined RMW as:

> … any solid waste which is generated in the diagnosis, treatment (e.g., provision of medical services), or immunization of human beings or animals, in research pertaining thereto, or in the production or testing of biologicals.

Mixtures of hazardous waste and medical waste were subject to this part. Specific classes of medical wastes include:

Class 1—Cultures and stocks: Cultures and stocks of infectious agents and associated biological materials, including cultures from medical and pathological laboratories, cultures and stocks of infectious agents from research and industrial laboratories, wastes from the production of biological materials, discarded live and attenuated vaccines, and culture dishes and devices used to transfer, inoculate, and mix cultures.

Class 2—Pathological wastes: Human pathological wastes, including tissues, organs, body parts, and body fluids, that are removed during surgery, autopsy, or other medical procedures, and specimens of body fluids and their containers.

Class 3—Human blood and blood products: Waste human blood and blood products; items saturated, dripping with human blood or both; or items now caked with dried human blood, including serum, plasma, and other blood components and their containers, which were used in either patient care, testing and laboratory analysis, or development of pharmaceuticals. Intravenous bags are included in this category.

Class 4—Used sharps: Sharps that have been used in animal or human patient care or in medical, research, or industrial laboratories, including hypodermic needles, syringes, Pasteur pipettes, scalpel blades, blood vials, test tubes, and culture dishes. Other types of glassware that were in contact with infectious agents such as used slides and cover slips are also included.

Class 5—Animal waste: Contaminated animal carcasses, body parts, and the bedding of animals exposed to infectious agents during research; the production of biological materials; or the testing of pharmaceuticals.

Class 6—Isolation wastes: Biological waste and discarded materials contaminated with blood, excretion, exudates, or secretions from humans who are isolated to protect others from highly communicable diseases; or isolated animals known to be infected with highly communicable diseases.

Class 7—Unused sharps: Unused, discarded sharps including hypodermic needles, suture needles, syringes, and scalpel blades.

20.3.3 Exemptions to the Definition of RMW

According to 40 CFR part 259, several wastes were not to be regulated as medical waste. This ruling was in effect because some waste were already managed under other regulations; in other cases, for example, household waste, regulation is simply impractical. The following wastes were not to be regulated as medical waste under 40 CFR part 259:

- Hazardous waste identified or listed in 40 CFR part 261
- Household waste
- Ash from incineration of RMW
- Residues from treatment and disposal of medical waste
- Human remains intended for interment or cremation

20.3.4 RCRA Hazardous Waste

Hazardous wastes are defined in RCRA subtitle C and are either listed or meet the characteristics of ignitability, corrosivity, reactivity, or TCLP toxicity (see Chapter 11). Quantities of hazardous waste generated by hospitals compared with industry are small; however, some may be acutely toxic. Many chemotherapy wastes may be defined by RCRA as hazardous and are therefore regulated by 40 CFR parts 260 through 265. Other hazardous wastes include antineoplastic drugs (used to treat certain forms of cancer and malignant hematological diseases), formaldehyde, solvents, mercury, and waste anesthetic gases (U.S. EPA 1990a; 1990b). Sources of potentially hazardous chemical wastes include clinical and research laboratories, patient care activities, pharmacies (spills and expired items), and physicians' offices (outdated items) (U.S. EPA 1991).

If a container holds less than 3% (by weight) of the original quantity of hazardous material, it is considered empty and does not require disposal as hazardous waste (40 CFR 261.7). This exemption does not apply to seven chemotherapy drugs listed by EPA as acutely toxic (40 CFR 261.33f).

20.3.5 Radioactive Waste

Radioactive waste, specifically low level, is generated through a number of healthcare activities, including those associated with research laboratories, clinical laboratory procedures, and nuclear medicine procedures such as diagnostic and therapeutic applications. Low-level waste includes

items that have become contaminated with radioactive material or have become radioactive through exposure to radiation. This waste consists of contaminated clothing, rags, mop heads, filters, swabs, injection needles, syringes, and laboratory animal carcasses and tissues. Liquid radioactive wastes include scintillation fluids and research chemicals. Radioactivity can range from just above background levels found in nature to highly radioactive. In a study of one university hospital, radioisotopes included ^{125}I (25.5%), ^{32}P (19.1%), ^{3}H (14.5%), ^{14}C (8.7%), ^{35}S (6.2%), ^{131}I (1.1%), ^{51}Cr (0.8%), and several others (Emery et al. 1992).

Low-level waste is stored on-site by the generator either until it has decayed sufficiently and can be disposed as ordinary trash, or until amounts are large enough for shipment to a low-level waste disposal site in containers approved by Department of Transportation.

20.3.6 Mixtures

Mixtures of solid waste and RMW are also regulated as medical waste. Similarly, mixtures of listed or characteristic hazardous waste and RMW are considered medical waste.

20.4 MANAGEMENT OF MEDICAL WASTES PRIOR TO TRANSPORT

20.4.1 Handling and Packaging

The handling of medical wastes depends largely upon state regulations, disposal method, and location of the disposal facility. Medical wastes intended for transport off-site should be segregated into the following categories whenever possible: sharps (used and unused), fluids (>20 mL), and other RMW. Generators must ensure that all RMW is placed in containers that are

- Rigid
- Leak-resistant
- Impervious to moisture
- Of sufficient strength to prevent tearing under normal handling conditions
- Sealed to prevent leakage during transport

In addition, generators must package used and unused sharps in puncture-resistant packaging (Figure 20.2). Fluids are to be placed into break-resistant and tightly lidded packaging.



FIGURE 20.2 Puncture-resistant packaging for used sharps.

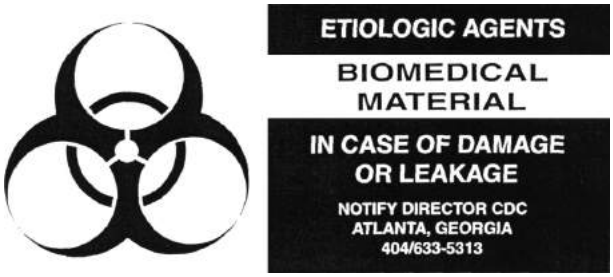


FIGURE 20.3 Biohazard symbol for the labeling of infectious wastes.

If medical wastes (excluding sharps and fluids) are to be incinerated off-site, they are generally packaged in plastic bags at the point of generation. Bags are usually red or labeled with a biohazard symbol for easy identification (Figure 20.3). The waste may be single- or double-bagged.

All nonrigid packaging and inner liners must be managed as RMW and cannot be reused. Any storage containers designated for reuse must be decontaminated after being emptied. If contamination cannot be removed from the container, it is to be managed as medical waste.

Medical waste must be stored in a location that maintains the integrity of the packaging and provides protection from the effects of weather. The location should also be protected from entry by animals. The waste is to be maintained in a nonputrescible state (i.e., not rotten or putrefied), using refrigeration if necessary. Areas containing dumpsters, sheds, and tractor-trailers are to be locked in order to prevent unauthorized entry. On-site storage areas are limited to access by facility employees only.

20.4.2 Labeling and Marking Medical Waste

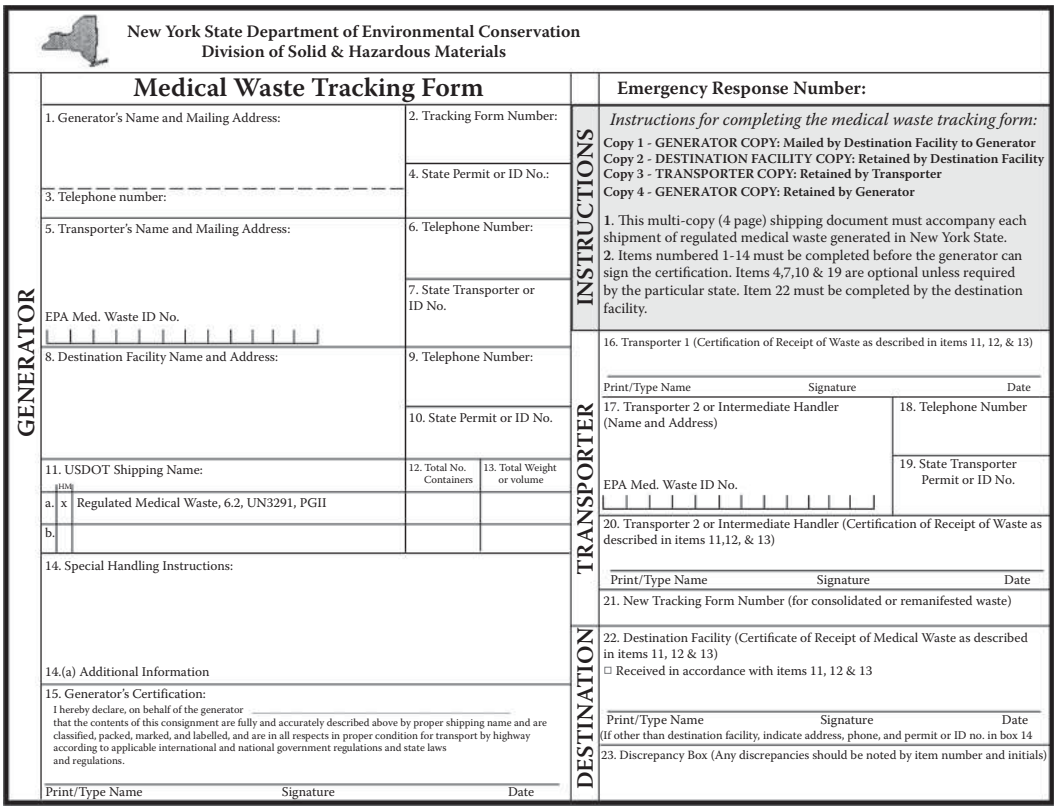
Packages containing untreated medical waste must have a water-resistant label attached to the outside of the containers. The label must include the words "Medical waste" or "Infectious waste," or display the universal biohazard symbol. Red plastic bags used as inner packaging need not be labeled. The outermost surface of each waste package must be marked with a water-resistant identification tag with the following information:

- Generator name
- Generator's state permit number or address
- Transporter's name
- Transporter state permit number or address
- Date of shipment
- Identification of contents as medical waste

20.4.3 Generator Requirements

Many states require that a facility that generates medical waste determine whether that waste is RMW. A generator must determine the quantity of RMW generated in a calendar month and the quantity transported off facility property.

A generator that transports medical waste for off-site treatment or disposal must prepare a tracking form (see Figure 20.4). This form is analogous to the Universal Hazardous Waste Manifest required for shipments of RCRA hazardous waste (Chapter 12). The generator is responsible for preparing copies of the form for each transporter, any intermediate handlers, and the destination facility. The generator is to keep a copy of the form, signed by all parties involved in storage, transport,



New York State Department of Environmental Conservation
Division of Solid & Hazardous Materials

Medical Waste Tracking Form

Emergency Response Number:

GENERATOR

1. Generator's Name and Mailing Address:
2. Tracking Form Number:
3. Telephone number:
4. State Permit or ID No.:
5. Transporter's Name and Mailing Address:
6. Telephone Number:
7. State Transporter or ID No.
EPA Med. Waste ID No.
8. Destination Facility Name and Address:
9. Telephone Number:
10. State Permit or ID No.
11. USDOT Shipping Name:
12. Total No. Containers
13. Total Weight or volume
a. x [HM] Regulated Medical Waste, 6.2, UN3291, PGII
b.
14. Special Handling Instructions:
14.(a) Additional Information
15. Generator's Certification:
I hereby declare, on behalf of the generator _____ that the contents of this consignment are fully and accurately described above by proper shipping name and are classified, packed, marked, and labelled, and are in all respects in proper condition for transport by highway according to applicable international and national government regulations and state laws and regulations.
Print/Type Name Signature Date

INSTRUCTIONS

Instructions for completing the medical waste tracking form:

Copy 1 - GENERATOR COPY: Mailed by Destination Facility to Generator
Copy 2 - DESTINATION FACILITY COPY: Retained by Destination Facility
Copy 3 - TRANSPORTER COPY: Retained by Transporter
Copy 4 - GENERATOR COPY: Retained by Generator

1. This multi-copy (4 page) shipping document must accompany each shipment of regulated medical waste generated in New York State.
2. Items numbered 1-14 must be completed before the generator can sign the certification. Items 4,7,10 & 19 are optional unless required by the particular state. Item 22 must be completed by the destination facility.

TRANSPORTER

16. Transporter 1 (Certification of Receipt of Waste as described in items 11, 12, & 13)
Print/Type Name Signature Date
17. Transporter 2 or Intermediate Handler (Name and Address)
18. Telephone Number
19. State Transporter Permit or ID No.
EPA Med. Waste ID No.
20. Transporter 2 or Intermediate Handler (Certification of Receipt of Waste as described in items 11,12, & 13)
Print/Type Name Signature Date
21. New Tracking Form Number (for consolidated or remanifested waste)

DESTINATION

22. Destination Facility (Certificate of Receipt of Medical Waste as described in items 11, 12 & 13)
□ Received in accordance with items 11, 12 & 13
Print/Type Name Signature Date
(If other than destination facility, indicate address, phone, and permit or ID no. in box 14
23. Discrepancy Box (Any discrepancies should be noted by item number and initials)

FIGURE 20.4 Tracking form (State of New York) to accompany medical waste shipments off-site.

and disposal. This form is to be kept on file by the generator for at least 3 years from the date that the waste was accepted by the transporter.

Generators of <23 kg (50 lb) of RMW per month are typically exempt from a number of requirements.

20.4.4 Transporter Requirements

Transporters must notify the state regulatory agency in writing of their intent to transport RMW. Notification must include the transporter's name, address, and EPA hazardous waste identification number (if applicable); location of each transfer facility that the transporter will operate from; and a state permit to handle medical or infectious waste.

Waste that is transported by commercial haulers is often prepared for off-site transport in reusable drums or in cardboard boxes. Transport vehicles may be compactor trucks, depending on state or local regulations. Secondary containers or additional packaging may be required. Vehicles that transport RMW must possess a fully enclosed, leak-resistant cargo-carrying body which must also be maintained in good sanitary condition. The transporter must ensure that the waste is not subject to mechanical stress or compaction during transit, loading, or unloading.

Transport vehicles must have the following identification on both sides and the back of the cargo body: transporter name, transporter state identification number, and a sign with the words "Medical waste" or "Regulated medical waste." Also, as per the Mixture Rule for medical wastes, a transporter cannot ship RMW mixed with solid waste unless both are designated as RMW.

TABLE 20.1
Medical Waste Types Appropriate for Treatment by Technology

Technology	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Radioactive	Hazardous and Cytotoxic
Incineration	X	X	X	X	X	X	X	X[a]	X[a]
Steam autoclave	X	X[b]	X	X	X[b]	X	X		
Chemical treatment	X	X[b]	X	X	X[b]	X	X		
Microwave	X	X[b]	X	X	X[b]	X	X		
Radio frequency	X	X[b]	X	X	X[b]	X	X		
Gamma irradiation	X	X[b]	X	X	X[b]	X	X		

Source: Reproduced with kind permission from RTI, *Guidance for Evaluating Medical Waste Treatment Technologies,* Final Report, 94U-5400-005/01-F, Research Triangle Park, NC, 1993.

[a] The radioactive, antineoplastic, and hazardous waste that are mixed with medical wastes can be treated with incineration; however, special permits are usually required for this type of treatment. In addition, incineration does not inactivate radioactive waste. Thus, the ash from these processes may be radioactive, may contain hazardous constituents, or both.

[b] Technology not recommended for treatment of body parts because the density of the waste may prevent adequate treatment. Grinding the waste may increase treatment efficacy; however, the grinding process may be aesthetically unacceptable.

20.4.5 Treatment and Disposal of Medical Waste

There is a wide range of methods available for the treatment and disposal of medical waste based on the original chemical and physical properties of the waste, regulatory issues, public concerns, and economics, among other factors. Incineration and steam sterilization are currently the most popular technologies for the destruction of microbiological cultures. For years, incineration has been the method of choice because it can be carried out on-site, and disposal involves only the removal of residual bottom ash. Other methods, less commonly used, include chemical disinfection, pulverization with chemical disinfection, microwave (thermal) inactivation, gas-vapor sterilization, and ionizing radiation. There is also the option of conventional landfilling, which is likely to be combined with one of the methods listed above. When the waste occurs in liquid form, it may be possible to dispose directly to a publicly owned treatment works. Such disposal is contingent upon local and state regulations.

Table 20.1 presents the medical waste types appropriate for treatment by each of the major medical waste treatment technologies.

20.4.6 Requirements for the Destination Facility

The destination facility for RMW is analogous to a treatment, storage and disposal (TSD) facility for RCRA hazardous wastes. When medical wastes arrive at the facility, the operator must review the tracking form for discrepancies. Discrepancies may include a variation in the count of drums, boxes, or containers; discrepancies in the number of containers for each category of medical waste; damaged packaging; regulated waste that arrives without the tracking form; or an incomplete (e.g., unsigned) tracking form. Upon discovery of the discrepancy, it is the responsibility of the destination facility to resolve the issue with the generator or transporter.

20.4.7 Record Keeping

The destination facility must maintain several records for at least 3 years from the date the waste was accepted. Records must include copies of all tracking forms, the name and state permit number of all generators who delivered waste to this destination, and copies of all discrepancy reports.

20.4.8 Disposal Options for Medical Waste

Presently, there are several treatment and disposal technologies available for managing medical wastes in the United States. As mentioned above, the primary technologies are incineration, autoclaving (steam sterilization), and shredding with chemical disinfection. Several innovative technologies are either in the test phase or are experiencing limited use in some facilities.

20.4.9 Incineration of Medical Waste

Of the disposal methods available for medical wastes, incineration is the most widely used—according to EPA, 90% of medical waste is incinerated. Several incinerator types are in use within the healthcare industry.

20.4.10 Regulatory Requirements for Medical Waste Incinerators

Based on discussions in other chapters, there is a great deal of concern on the part of the public and regulators regarding proper operation of incineration units. Concern tends to revolve around daily facility operations, atmospheric emissions, and ash disposal. As a consequence, federal regulations were promulgated that place strict emission limits on medical waste incinerators. Regulations may vary based upon age of the unit. For example, EPA formulated 40 CFR subpart Ec—Standards of performance for hospital, medical and infectious waste incinerators for which construction had commenced after June 20, 1996. Presented below is an overview of some of the more significant regulations for operation of a new medical waste incinerator.

20.4.11 Siting Requirements

A medical waste incineration facility for which construction began after September 15, 1997, is required to prepare an analysis of the impacts of the facility (40 CFR 60.54c). The analysis considers air pollution control alternatives that minimize potential risks to public health and the environment. In assessing such alternatives, the analysis considers costs, energy impacts, and additional environmental impacts.

20.4.12 Operator Training and Qualification Requirements

Fully trained and qualified incinerator operators must either be accessible at all times at the incineration facility or available within 1 hour. Training is obtained by completing an operator training course that includes the following provisions:

A. Training on the following subjects:
- Environmental concerns, including pathogen destruction and types of emissions
- Basic combustion principles, including products of combustion
- Operation of the type of incinerator to be used at the facility, including proper startup, waste charging, and shutdown procedures
- Combustion controls and monitoring

- Operation of air pollution control equipment
- Methods to monitor pollutants and equipment calibration procedures
- Inspection and maintenance of the incinerator, air pollution control devices, and emission monitoring systems
- Actions to correct malfunctions or conditions that may lead to malfunction
- Bottom and fly ash characteristics and handling procedures
- Applicable federal, state, and local regulations
- Safety procedures
- Pre-startup inspections
- Record keeping requirements

B. Completion of an examination. Qualification for incinerator operation is obtained by completion of a training course combined with experience as an operator. To maintain qualification, the qualified operator must pass an annual refresher course covering the following:

- An update of relevant regulations
- Incinerator operation, including startup and shutdown procedures
- Inspection and maintenance
- Responses to malfunctions or conditions that may lead to malfunction
- Discussion of operating problems encountered

20.5 FACILITY OPERATIONS

20.5.1 Waste Management Plan

There are numerous documented cases in which toxic materials such as nickel–cadmium batteries have been collected and commingled with combustibles and disposed in a hospital incinerator. In order to limit such contamination episodes, the incineration facility must prepare a waste management plan. The purpose of the plan is to identify the means of separating certain components of solid waste from the healthcare waste stream in order to reduce toxic emissions from incinerated waste. A waste management plan may include aspects such as paper, plastics, glass, battery, and metal recycling; or the purchase of recycled or recyclable products. A waste management plan may include different goals or methods for different departments at the facility. The plan should identify additional management measures, taking into account the costs of those measures, the emission reductions expected to be achieved, and any other environmental or energy impacts they might cause.

20.5.2 Compliance and Performance Testing

The facility must conduct an initial performance test (40 CFR 60.8) to determine compliance with emission limits (see below). All performance tests consist of a minimum of three test runs conducted under representative operating conditions. The minimum sample time is 1 h per test run.

Following the initial performance test, the facility must:

- Determine compliance with opacity limits by conducting an annual performance test
- Determine compliance with particulate matter, CO, and HCl emission limits by conducting an annual performance test

Table 20.2 contains the EPA Reference Methods for measurement of the above parameters.

TABLE 20.2
U.S. EPA Reference Methods for Incinerator Compliance and Performance Testing

EPA Reference Method	Purpose
1	Select the sampling location and number of traverse points.
3, 3A, or 3B	Gas composition analysis, including measurement of oxygen concentration.
3, 5, or 29	To measure particulate matter emissions.
9	To measure stack opacity.
10 or 10B	To measure CO emissions.
23	To measure total dioxin and furan emissions. The minimum sample time is 4 h per test run.
26 or 26A	To measure HCl emissions.
29	To measure Pb, Cd, and Hg emissions.
22	To determine compliance with the fugitive ash emission limit under 40 CFR 60.52c(c). The minimum observation time is a series of three 1 h observations.

Source: Code of Federal Regulations, Vol. 40, Part 259, *Standards for the Tracking and Management of Medical Waste*, U.S. Government Printing Office, Washington, DC, 2002, section 60, appendix A.

20.5.3 Emission Limits

After an initial performance test of the incinerator is completed, the facility is not permitted to discharge any gases that contain stack emissions in excess of the limits presented in Table 20.3. In addition, there are to be no discharges that exhibit greater than 10% opacity. There are also requirements for large incineration facilities regarding discharge of visible emissions of combustion ash from an ash conveying system (EPA Reference Method 22, Table 20.2).

Extensive requirements apply to those facilities equipped with a dry scrubber, fabric filter, wet scrubber, or similar air pollution control device. In addition, there are numerous requirements for the use and maintenance of sorbents for HCl, Hg, chlorinated dibenzodioxins, and furans (40 CFR 60.56c).

TABLE 20.3
Emission Limits for Small, Medium, and Large Medical Waste Incinerators

	Emission Limits		
	Incinerator size		
Pollutant, Units[a]	Small	Medium	Large
Particulate matter, mg/scm (grains per dscf)	69 (0.03)	34 (0.015)	34 (0.015)
Carbon monoxide, ppm (v)	40	40	40
Dioxins/furans, nanograms/dscm	125 (55) or 2.3	25 (11) or 0.6	25 (11) or 0.6
Hydrogen chloride, ppm or percent reduction	15% or 99%	15 or 99%	15 or 99%
Sulfur dioxide, ppm (v)	55	55	55
Nitrogen oxides, ppm (v)	250	250	250
Lead, mg per dscm (grains per thousand dscf) or percent reduction	1.2 (0.52) or 70%	0.07 (0.03) or 98%	0.04 (0.02) 90%
Cadmium, mg/dscm or (grains per thousand dscf) or percent reduction	0.16 (0.07) or 65%	0.04 (0.02) or 90%	0.04 (0.02) 90%
Mercury, mg/dscm (grains per thousand dscf) or percent reduction	0.55 (0.24) or 85%	0.55 (0.24) or 85%	0.55 (0.24) or 85%

Source: Code of Federal Regulations, Vol. 40, Part 259, *Standards for the Tracking and Management of Medical Waste*, U.S. Government Printing Office, Washington, DC, 2002, table 1 to subpart Ec.

[a] Based on 7% O_2, dry basis.

TABLE 20.4
Operating Parameters to be Monitored and Minimum Measurement and Recording Frequencies

	Minimum Frequency		Control System		
Operating parameters to be monitored	Data measurement	Data recording	Dry scrubber followed by fabric filter	Wet scrubber	Dry scrubber followed by fabric filter and wet scrubber
Maximum operating parameters					
Maximum charge rate	Continuous	1 × hour	x	x	x
Maximum fabric filter inlet temperature	Continuous	1 × minute	x		x
Maximum flue gas temperature	Continuous	1 × minute	x	x	
Minimum operating parameters					
Minimum secondary chamber temperature	Continuous	1 × minute	x	x	x
Minimum dioxin/furan sorbent flow rate.	Hourly	1 × hour	x	x	x
Minimum HCI sorbent flow rate	Hourly	1 × hour	x		x
Minimum mercury (Hg) sorbent flow rate	Hourly	1 × hour	x		x
Minimum pressure drop across the wet scrubber or minimum horsepower or amperage to wet scrubber	Continuous	1 × minute		x	x
Minimum scrubber liquid flow rate	Continuous	1 × minute		x	x
Minimum scrubber liquid pH	Continuous	1 × minute		x	x

Source: Code of Federal Regulations, *Vol. 40, Part 259, Standards for the Tracking and Management of Medical Waste*, U.S. Government Printing Office, Washington, DC, 2002, section 60 (subpart Ec).

20.5.4 Monitoring Requirements

The incineration facility must install, calibrate (to manufacturers' specifications), maintain, and operate devices for monitoring all applicable operating parameters (Table 20.4). The facility must obtain monitoring data at all times during incinerator operation.

20.5.5 Documentation

The incineration facility must maintain documentation at the facility that addresses the following:

- Summary of the applicable standards relevant to incinerator operation and emissions
- Description of basic combustion theory applicable to a medical waste incinerator
- Procedures for receiving, handling, and charging waste
- Incinerator startup, shutdown, and malfunction procedures
- Procedures for maintaining proper combustion air supply levels
- Procedures for operating the incinerator and associated air pollution control systems within the standards established
- Procedures for monitoring medical waste incinerator emissions
- Reporting and record keeping procedures
- Procedures for handling ash

The above information must be readily accessible to all operators. This information, along with records of training, must be available for inspection by EPA or the state regulatory agency.

20.5.6 Reporting and Record Keeping

The facility must maintain a range of routine operations information. For example, prior to initial startup of the incinerator, the following information should be available:

- The type(s) of waste to be combusted
- The design for maximum waste burning capacity
- The anticipated maximum charge rate

As regards routine operations:

- Concentrations of any pollutant listed in 40 CFR 60.52c or measurements of opacity
- Results of fugitive emissions tests
- Incinerator charge dates, times, weights, and hourly charge rates
- Fabric filter inlet temperatures
- Amount and type of dioxin/furan sorbent, Hg sorbent, and HCl sorbent used
- Secondary chamber temperatures recorded
- Horsepower or amperage to the wet scrubber
- Temperature at the outlet from the wet scrubber
- pH at the inlet to the wet scrubber
- Records indicating use of the bypass stack

Additional required data include:

- Days and durations of malfunctions, a description of the malfunction, and the corrective action taken
- Days for which emission rates or operating parameters exceeded applicable limits, a description of the excess readings, reasons for excess readings, and a description of corrective actions taken
- Results of performance tests that determine compliance with emission limits and to establish operating parameters
- All documentation produced as a result of siting requirements

The above records must be on hand at the facility for at least 5 years (40 CFR 60.58c).

An annual report must be submitted by medical waste incineration facilities for the following data:

- Data for site-specific operating parameters
- The results of any performance tests
- Any use of the bypass stack, the duration, reason for malfunction, and corrective action taken

20.6 TYPES OF MEDICAL WASTE INCINERATORS

As discussed in Chapter 9, the purpose of incineration is to destroy the organic component of waste through high-temperature combustion. A secondary function is waste detoxification. The residual ash from incineration may be hazardous per 40 CFR part 261 (Identification and Listing of Hazardous Waste). It must therefore be tested via the four characteristic tests (ignitability, corrosivity, reactivity, toxicity; Chapter 11) in order to assess possible hazardous nature.

Three general types of incinerators are in common use to destroy medical wastes: the rotary kiln, the multiple hearth, and the controlled-air incinerator. Some innovative incinerators have been used with varying degrees of success. The major components of an incineration system are shown in Figure 20.5.

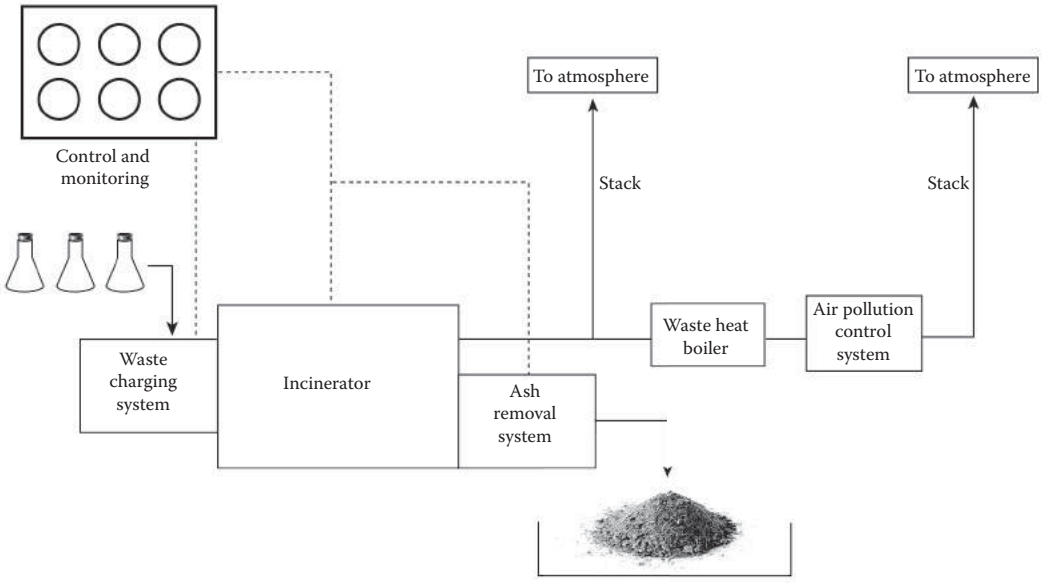


FIGURE 20.5 Major components of an incineration system for medical wastes. (From U.S. EPA, *Operation and Maintenance of Hospital Medical Waste Incinerators,* EPA/625/6-89/024, Center for Environmental Research Information, U.S. EPA, Cincinnati, OH, 1990b.)

20.6.1 Rotary Kiln

The rotary kiln incinerator was described in Chapter 15. The design includes a cylindrical, refractory-lined combustion chamber that is rotated at a slight incline. Waste is loaded at the upper end and is combusted as it is agitated along the length of the cylinder. The ash is discharged at the lower end. To comply with air emissions standards, rotary kilns must be equipped with secondary combustion chambers and air pollution control equipment such as a baghouse.

Rotary kiln incinerators have long been popular for the destruction of RCRA hazardous waste. The rotational action provides for good turbulence of the waste and allows for continuous-feed operations; so ash is regularly removed during routine operations. Only a limited number of rotary kiln incinerators are in use for medical waste incineration, however, due to their high capital, operating and maintenance costs. Repair and maintenance costs are especially high due to damage to the refractory lining from abrasive materials. A second disadvantage is that some wastes require processing, for example, shredding prior to incineration. As the waste is shredded, the potential exists for the release of potentially infectious material from the shredder or conveyance mechanisms (U.S. EPA 1991).

20.6.2 Multiple-Chamber Incinerator

Hospitals and similar health-related institutions have used the multiple-chamber incinerator for destroying infectious wastes for decades. There are two basic configurations, that is, the in-line design and the retort design (Figure 20.6). Combustion gases flow straight through in-line incinerators, turning only vertically. In the retort design, gases turn horizontally and vertically. Retort multiple-chamber incinerators are more compact and more efficient than are in-line systems at small capacities. In order to control combustion and to limit emissions, multiple chamber systems incorporate settling chambers and are designed to operate at very high levels of excess air. The generation of gaseous and particulate emissions can be substantial with these systems.

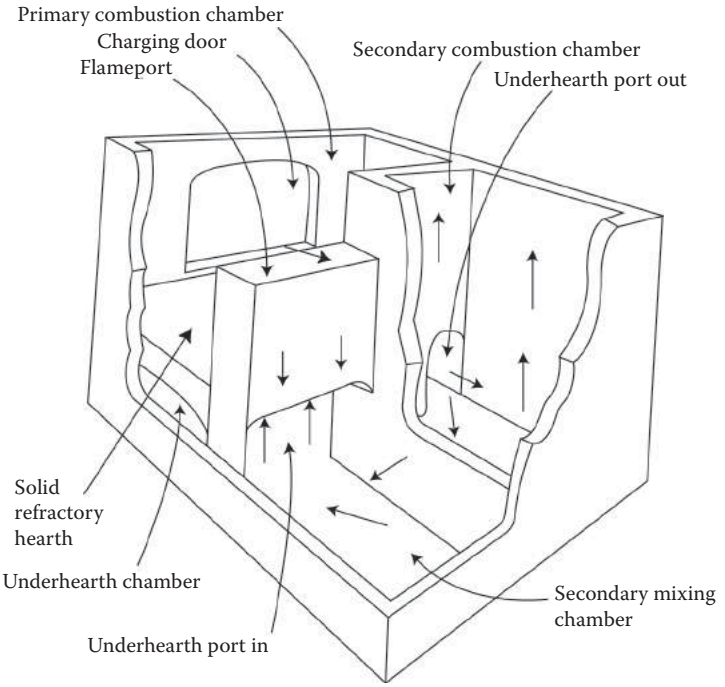


FIGURE 20.6 In-line and retort design of medical waste incinerators. (From U.S. EPA, *Seminar—Medical and Institutional Waste Incineration: Regulations, Management, Technology, Emissions, and Operations*, Center for Environmental Research Information (CERI 89-247), U.S. EPA, Cincinnati, OH, 1989a.)

Few multiple-chamber incinerators are currently being built; however, many older systems are still in use. Some were designed with grates within the primary combustion chamber. These grates allow for noncombusted waste to fall into the ash receptacle, with the potential for exposing operators to unburned infectious waste.

20.6.3 Controlled-Air Incinerators

Controlled-air incinerators use two or more separate combustion chambers to combust waste (Figure 20.7). The first chamber operates under starved air conditions to volatilize moisture, vaporize the volatile fraction, and combust the fixed carbon in the waste. Combustion gases are then passed to the secondary chamber where excess air is provided to complete the combustion of volatiles and other hydrocarbons emitted from the primary chamber. Turbulence is provided to promote mixing of the air and carbonaceous gases. The gas–air mixture is combusted at relatively high temperatures.

Controlled air incinerators possess several advantages over multiple-chamber incineration technology. The starved air environment of the primary chamber allows for slow, nonturbulent combustion that minimizes entrainment of particulates in combustion gases, and thus reduces particulate emissions to the atmosphere. The lower temperatures achieved in this chamber avoid the melting and fusion temperatures of most metals, glass, and other noncombustibles, thus minimizing slagging and formation of clinker. The high temperatures and excess air environment of the secondary chamber help to ensure more complete combustion of volatile gases, thus reducing hydrocarbon emissions. Controlled air incinerators are comparatively low in cost and accomplish efficient combustion, thus making them popular in the hospital industry.

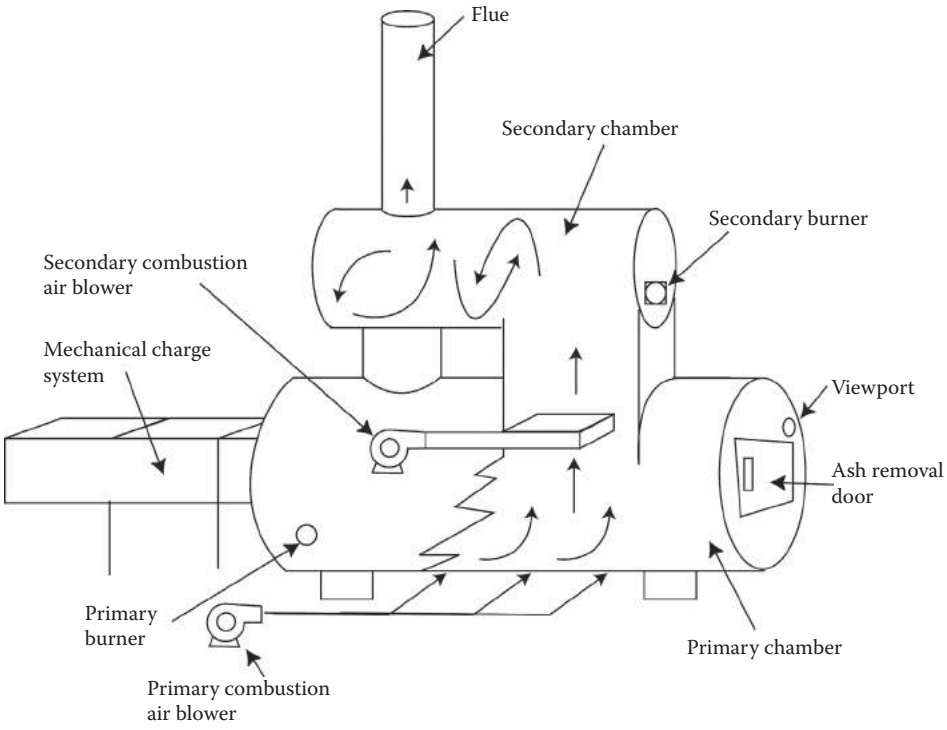


FIGURE 20.7 Controlled-air incinerator. (From U.S. EPA, *Hospital Incineration Operator Training Course Manual,* EPA 450/3-89-004, NTIS PB 89-189880, U.S. EPA, Research Triangle Park, NC, 1989b.)

20.7 MODES OF INCINERATOR OPERATION

Medical waste incinerators can be operated in one of three modes: batch, intermittent duty, and continuous duty. As the name implies, batch incineration involves burning a single parcel of waste, often only once per day. Waste is often loaded manually, combusted and cooled, after which ash is manually removed. Intermittent duty incinerators are loaded continuously and frequently with small waste batches and operate for less than 24 h per day. A typical operating cycle for an intermittent duty system includes a 15 to 30 min period of cleanout of ash from the previous day, 15 to 60 min preheat, 12 to 14 h waste combustion, 2 to 4 h burn down, and 5 to 8 h cool down. Continuous duty incinerators operate 24 h per day and use automatic charging units such as a ram feed system (Figure 20.8) to input waste into the firebox in small, frequent batches. A mechanism automatically removes the ash from the incinerator (U.S. EPA 1991).

EXAMPLE 20.1

A rotary kiln incinerator burns medical waste that contains 9.2% ash. The incinerator receives approximately 325 kg (about 715 lb) waste per hour over a 24 h period. Determine the amount of bottom ash to be disposed annually, if 20% of the ash is emitted as fly ash during combustion.

Solution

Total output (kg/h) as bottom ash from the incinerator is

$$(0.092)\ (325\ \text{kg/h}) = 30\ \text{kg/h}$$

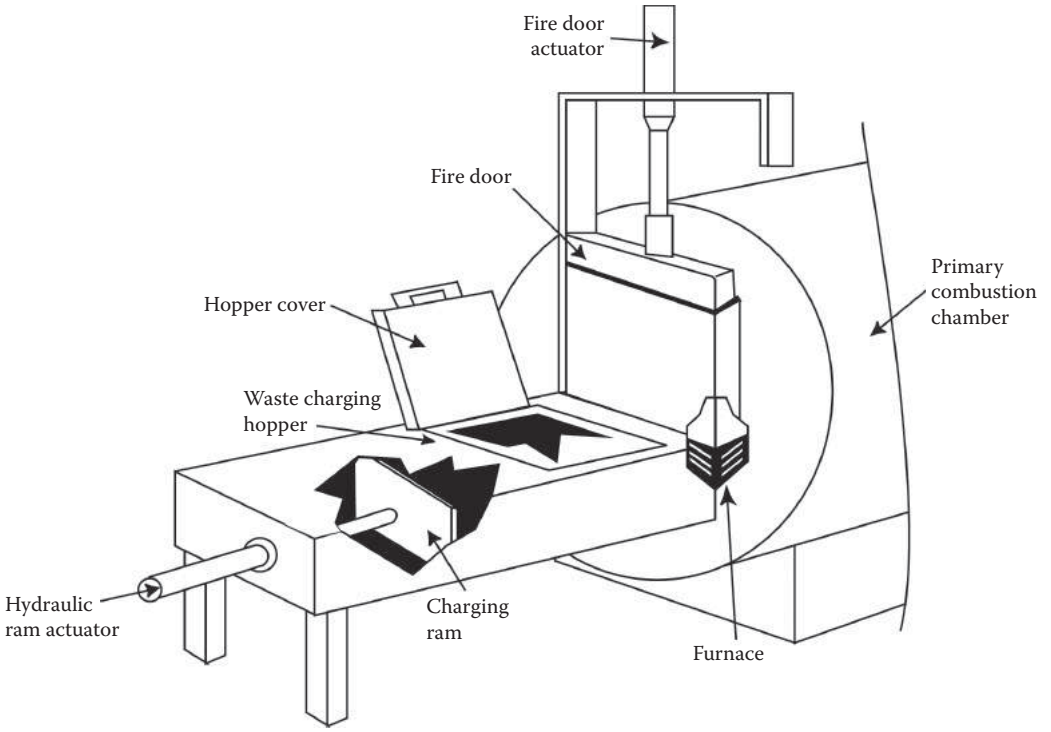


FIGURE 20.8 Hopper and mechanical feed system for a medical waste incinerator. (From U.S. EPA, *Operation and Maintenance of Hospital Medical Waste Incinerators,* EPA/625/6-89/024, Center for Environmental Research Information, U.S. EPA, Cincinnati, OH, 1990b.)

The rate of bottom ash produced per day is calculated as

$$(30)\ (24)\ (0.80) = 576 \text{ kg/day}$$

The rate of ash output per year is

$$(365)\ (576) = 210{,}240 \text{ kg/year}$$

EXAMPLE 20.2

An incinerator burns mixed hospital waste contaminated with mercury and having an ash content of 5.8%. The input waste feed rate is 1000 kg/h and the gas flow rate is 675 dscmm (approximately 23,825 dscfm). Upon analysis of the flue gas, it was found that the average Hg content in the particulates was 4.29 µg/g and the Hg concentration of the vapor was 0.20 mg/dscm. For this incinerator, emissions meet the particulate standard of 0.1832 g/dscm (0.08 g/dscf), and there is 99.8% efficiency of particulate collection by an electrostatic precipitator. Calculate the amount of Hg bound to the fly ash that is captured in the precipitator. Also, calculate the amount of Hg leaving the stack as vapor and with the fly ash. Note that 1 kg of collected residue ~15,430 g.

Solution

1. The amount of ash exiting the flue is calculated as

$$0.1832 \text{ g/dscm} \times 1 \text{ kg}/15{,}430 \text{ g} \times 675 \text{ dscmm/min} \times 60 \text{ min/h} \times 24 \text{ h/day} = 11.5 \text{ kg}$$

The amount of ash collected in the ESP:

$$(11.5 \text{ kg/d})/(1 - 0.998) = 5770 \text{ kg/day}$$

2. Hg exiting the stack with the fly ash:

$$(11.5 \text{ kg ash/day})(2.42 \times 10^{-6} \text{ g Hg/.001 kg ash}) = 0.03 \text{ g Hg/day}$$

Hg leaving the stack as vapor:

$$0.2 \times 10^{-3} \text{ g Hg/dscm} \times 675 \text{ dscm/min} \times 60 \text{ min/h} \times 24 \text{ h/day} = 194.40 \text{ g/day}$$

The total mercury exiting the stack = 194.40 + 0.03

$$= 194.43 \text{ g/day}$$

(Adapted from Reynolds, J.P., et al., *Handbook of Chemical and Environmental Engineering Calculations*, Wiley-Interscience, New York, 2002.)

20.8 ADVANTAGES AND DISADVANTAGES OF INCINERATION

The greatest advantage to using incineration for the disposal of medical and infectious waste is that the organic component of the waste can be reduced by up to 95% of its original volume. Therefore, significantly less waste must be handled, stored, or transferred to the disposal site (Hoeltge 1995). Incineration will also detoxify the biological component of the waste. These factors are important for both keeping operational costs down and reducing future liability.

Medical waste incineration has its own unique problems, however. First, following *The Law of the Conservation of Mass*, waste is physically transformed into a variety of solid residues, gaseous compounds, and particulate matter. As indicated in Chapter 9, there is the potential for adverse impacts to public health from these residues. A pressing concern involves the release of metals such as mercury. In decades past, hospitals had contributed almost 10% of all mercury from incineration in the United States (U.S. EPA 1997). However, advances in Hg scrubbing technology, combined with effective waste segregation prior to incineration, have contributed to significant reductions in Hg emissions to the atmosphere. Another harmful result of incineration involves generation of polychlorinated dibenzodioxins (PCDDs). PCDDs such as tetrachlorodibenzodioxin (TCDD) have been linked to cancer, birth defects, and a host of other health problems (ATSDR 2011). PCDDs can additionally enter the food chain and bioaccumulate.

All types of wastes may be treated by incineration; however, a special permit is required to incinerate low-level radioactive medical wastes. Ash from incineration of radioactive medical waste will remain radioactive. No other treatment technology may be used for radioactive or cytotoxic wastes.

20.9 MICROBIAL INACTIVATION

Microbial inactivation refers to those physical or chemical processes that render microorganisms incapable of multiplication. Such processes may either kill the organisms or injure them to the extent that repair and subsequent growth of cells is not possible. The effectiveness of medical waste treatment technologies tested during an EPA investigation is presented in Table 20.5.

Level I microbial inactivation destroys most disease-causing microorganisms. There is a kill of at least 10^5 vegetative bacteria and fungi, fungal spores, and viruses (in other words, an inactivation of at least 5 Log_{10} or greater); however, Level I may be unable to inactivate

TABLE 20.5
Evaluation of Level of Microbial Inactivation achieved by Medical Waste Treatment Technologies

Waste Treatment Technology	Microbial Inactivation			
	Level I	Level II	Level III	Level IV
			Steam autoclave	
Lab test results[a]	Yes	Yes	Yes	No
Field test results[b]	Yes	Yes	Yes	Yes
			Microwave	
Field test results[c]	NT	NT	Yes	No
			Radio frequency	
Field test results[d]	NT	NT	Yes	No
			Chemical	
Lab test results[e]	Yes	Yes	Yes[g]	Yes[g]
Field test results[f]	Yes	Yes	No[h]	No[h]

Source: Reproduced with kind permission from RTI, *Guidance for Evaluating Medical Waste Treatment Technologies,* Final Report, 94U-5400-005/01-F, Research Triangle Park, NC, 1993.

Note: NT = not tested.

[a] Benchtop and gravity displacement autoclaves, 121°C, 15 psi.

[b] Prevacuum system, 138°C, 30 psi; double-door gravity system, 163°C, 80 psi.

[c] Microwave treatment system (6 units at 2450 MHz each).

[d] Short wave RF system, 11–13 MHz.

[e] Chemical only, sodium hypochlorite 1000 ppm and 3000 ppm FAC prolonged exposure (≥3 h).

[f] Chemical/mechanical systems, sodium hypochlorite 1000, 2000, 3000 ppm FAC.

[g] Dependent on prolonged exposure (>3 h).

[h] Not achieved under normal operating conditions (<3 h exposure).

mycobacteria and bacterial spores. Level I inactivation may be accomplished by several physical or chemical processes.

Level II microbial inactivation is defined as significant inactivation of all microorganisms, with the exception of bacterial spores. Inhibition of at least 10^5 mycobacteria must occur in addition to Level I inactivation. Level II treatment implies some measure of tuberculocidal activity on the wastes (RTI 1993).

Level III inactivation indicates the kill of microbial life forms, as evidenced by inactivation of at least 10^4 of selected indicator spores that possess death curves similar to human pathogenic spores. Thus, *Bacillus subtilis* spores may be used to indicate Level III inactivation for moist heat treatment since they exhibit thermal death data similar to species of the pathogenic spore-forming *Clostridium*.

Level IV indicates the kill of microbial life forms, as evidenced by inactivation of 10^6 bacterial indicator spores recognized as most resistant to treatment. For example, the inactivation of at least 10^6 spores of *Bacillus stearothermophilus*, recognized as most resistant to moist heat, is an indication of Level IV inactivation by steam autoclaving (RTI 1993).

Nonincineration alternative treatment technologies are being increasingly relied upon, as public and regulatory pressures direct the medical industry away from incineration for treating medical and infectious waste.

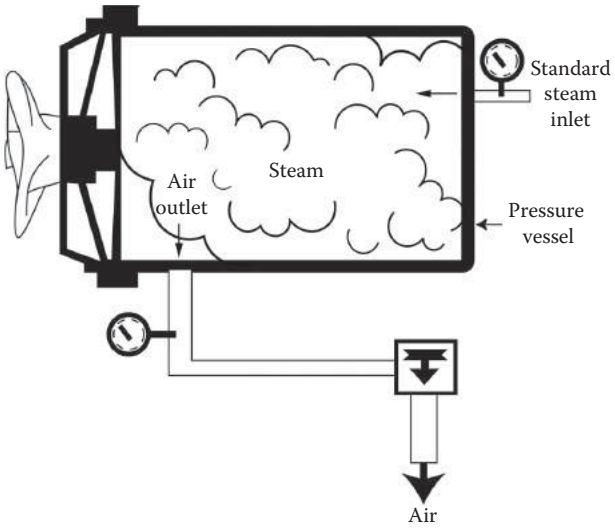


FIGURE 20.9 Autoclave system. (From Block, S. (Ed.), *Disinfection, Sterilization and Preservation*, 4th ed., Lea and Fibiger, Philadelphia, PA, 1977. Reproduced with kind permission of S. Bolck.)

20.9.1 Autoclaving (Steam Sterilization)

Autoclave treatment utilizes moisture, heat, and pressure to inactivate microorganisms. Steam sterilization was originally developed for equipment or material sterilization (for example, glassware and microbial media) prior to use. Steam autoclaving is now an effective on-site or off-site treatment technology for medical and infectious wastes. Most medical wastes can be treated, with the exception of radioactive wastes, body parts, or animal carcasses. Steam sterilizers treat medical waste by both small generators, such as healthcare clinics and physicians' offices, and by commercial medical waste treatment firms that handle waste for a large region.

Sterilization of medical waste involves placing contaminated waste into a sealed chamber and exposing it to pressurized steam of sufficient temperature for a specified length of time to render it noninfectious. For steam to penetrate the load, the air must be completely removed from the treatment chamber. Sterilization occurs primarily from the penetration of steam into the matrix. Heat conduction provides a secondary source of heat transfer.

Three basic types of autoclaves are in use: gravity systems, prevacuum systems, and retort systems. In the gravity system, steam replaces the air within the chamber, generally by forcing air out through a valve located at the base of the unit as the steam is introduced (Figure 20.9). Prevacuum systems use pumps to evacuate air from the chamber before steam is introduced. Retort systems are designed to operate at high steam pressures.

When the steam enters the chamber, the temperature increases to the desired setting. This is known as the *heat-up time* (steam penetration time). The *holding time* begins after the load has reached the minimum temperature required for achieving sterilization. The *exposure time* represents the entire period necessary to achieve sterilization and includes the sum of heat-up time and holding time, plus a margin of error.

20.9.2 Operational Issues

Autoclaves require pressurized vessels to ensure that the waste is being exposed to the correct temperatures for the proper amount of time. Temperature and time are essential for successful steam sterilization. Air must be removed completely from the chamber (thus also from the wastes) so that

steam can penetrate all areas and kill the organisms of concern. Factors affecting the operation of steam autoclave treatment of medical waste include:

- Temperature and pressure achieved by the autoclave
- Steam penetration of the waste
- Size of waste load
- Composition of waste
- Packaging of waste
- Orientation of wastes within autoclave

Steam autoclaves operate most effectively when the temperature measured at the center of the waste load approaches 121°C (250°F) and steam adequately penetrates the load. At a given temperature, the duration of treatment is the variable that determines heat conduction and steam penetration to the center of a load (RTI 1993). Optimum operational temperatures are approximately 132°C (270°F) and should not go below 250°F for maximum effectiveness.

As was shown in Table 20.2, the following wastes can be sterilized by autoclaving: cultures and stocks, pathological wastes, human blood and blood products, sharps (used and unused), animal waste, and isolation wastes. Body parts and contaminated animal carcasses are not suitable for steam sterilization because the density of these wastes may prevent adequate steam penetration. Radioactive, hazardous, and cytotoxic wastes are also not appropriate for treatment by steam autoclaving.

Waste liquid from the steam condensate is typically permitted for discharge directly to the sanitary sewer. Wastes may be shredded after sterilization, which will greatly reduce total waste volume.

20.9.3 Testing the Efficiency of Sterilization by Autoclaving

The thermally resistant species *B. subtilis* (*globigii*) ATCC 9372 (10^4) and *B. stearothermophilus* ATCC 12980 are commonly used for the verification of Level III and Level IV microbial inactivation, respectively. These organisms are available in commercial suspensions or as prepared spore strips. The test procedure is as follows: dried test spores are placed in a thermally resistant and steam-permeable container near the center of the waste load. The autoclave is operated under normal conditions. At the conclusion of the cycle, the test organisms are removed from the load. To recover the test organisms, test strips are inoculated into soybean–casein digest broth medium and incubated for at least 48 h (30°C for *B. subtilis* or 55°C for *B. stearothermophilus*). At the end of the incubation, the media is examined for turbidity as an indicator of bacterial growth. Any detected growth should be subcultured on to appropriate media to confirm the identity of the organism. To establish Level III inactivation, a minimum of 10^4 *B. subtilis* spores must be killed; to establish Level IV, a minimum total of 10^6 *B. stearothermophilus* must be killed.

Effective sterilization requires the correct application of several variables. Trained autoclave operators are essential for correct and safe operation. Training must include proper autoclave operation, as well as information about potential associated hazards. Process effectiveness should be monitored to ensure that treatment has been accomplished using time temperature charts, chemical indicators, and biological indicators (e.g., spore strips of *B. subtilis* or *B. stearothermophilus*) to ensure inactivation of the most resistant microorganisms (U.S. HHS 2011).

The ideal container for sterilization of medical wastes is corrosion-resistant, leakproof, capable of allowing complete steam penetration to its contents, and reasonably priced. In recent years, plastic bags have become the preferred container for many medical wastes. While assessing laboratory autoclave operation, however, loads contained in plastic bags have frequently been found to perform poorly. This effect was later found to be caused by inadequate steam penetration into the bags. When plastic bags are used to store medical wastes, steps should be taken to determine the necessary sterilizing time–temperature relationships and steam penetration.

20.9.4 Health Considerations with Autoclaving

Health impacts attributed to autoclaving medical wastes have not been documented. Operators may be exposed to hazardous constituents in the venting emissions if they come into contact with the steam, such as may occur when the autoclave door is opened at the end of the cycle. Therefore, it is important to exclude any waste containing potentially toxic constituents such as hazardous chemicals (e.g., RCRA waste) or radiological wastes.

20.9.5 Advantages and Disadvantages of Autoclaving

When properly operated, autoclaves are highly effective for the sterilization of infectious medical waste. They are most suitable for decontaminating laboratory wastes such as stocks and cultures of infectious agents, contaminated glassware, and biological tissue, and are capable of decontaminating other classes of infectious waste as well. For practical reasons, autoclaves are not appropriate for treating body parts.

An advantage of steam sterilization is that the technology has a long history of use by hospitals, laboratories, clinics, and other medical institutions for sterilization of both medical supplies and medical and infectious waste. Steam sterilization does not raise public concerns or require complex regulations, as does incineration of medical waste. Another advantage is their greater output capacity and minimal space requirements compared with those required for on-site incinerators (Turnberg 1989, 1996). In limited cases, autoclaved waste will occupy less space because air has been forced out (Liberman and Gordon 1989). Steam autoclave systems have low capital and operating costs and are comparatively easy to operate.

A major disadvantage of autoclaving is that the waste itself is not destroyed but is simply rendered nonpathogenic. Waste volume is not reduced after sterilization. Concerns also exist regarding emanation of odors during autoclave use. Drainage liquids must be stored, managed, and disposed properly. Some bags may block air, thus limiting steam penetration and complete sterilization. The presence of residual air within an autoclave may prevent complete sterilization by (Perkins 1983; U.S. EPA 1986):

- Reducing steam temperature, regardless of pressure
- Causing variations in temperature throughout the chamber
- Prolonging the time needed to attain maximum temperature
- Inhibiting stream penetration into porous materials

Factors causing incomplete displacement of air include the use of heat-resistant plastic bags (which trap air), deep containers (which may prevent displacement of air from the bottom), and improper loading (which may prevent free circulation of steam within chamber) (U.S. EPA 1986).

A significant concern with autoclave sterilization is that waste handlers are not able to determine, by observing an article, whether it has been sterilized; a bag of autoclaved waste at a landfill may resemble one that had not been sterilized. In some situations, landfills have refused to accept autoclaved waste due to concerns as to whether the waste was treated adequately. Some states have enacted regulations requiring not only that medical and infectious waste be decontaminated but also that it be rendered unrecognizable as medical waste. As a result, many steam sterilizers are now provided with waste shredding systems (Turnberg 1996).

20.9.6 Chemical Disinfection

A chemical disinfectant is an agent that destroys disease-causing agents such as pathogenic microorganisms. Disinfectant chemicals are registered under FIFRA (The Federal Insecticide, Fungicide, and Rodenticide Act) according to their application against specific types of pathogens.

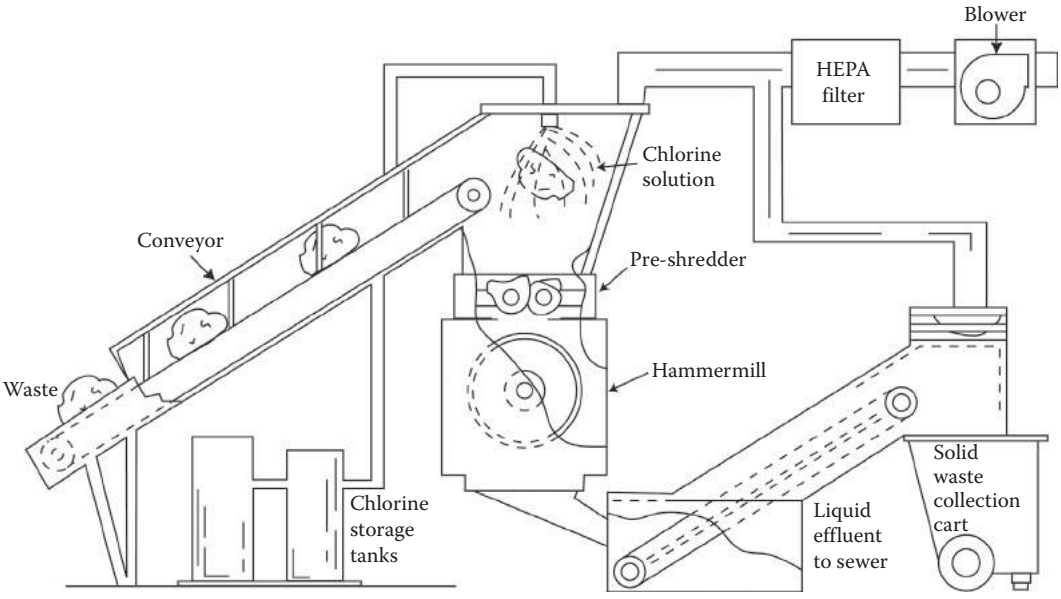


FIGURE 20.10 Combined shredding and disinfection system. (From U.S. EPA, *Medical and Institutional Waste Incineration: Regulations, Management, Technology, Emissions, and Operations*, EPA/625/4-91/030, Center for Environmental Research Information, Office of Research and Development, Cincinnati, OH, 1992.)

Chemical agents have been used for disinfecting infectious waste for many years. Treatment usually incorporates some type of mechanical destruction process (i.e., shredding) that reduces waste to a small particle size, thereby increasing particle surface area that increases contact with the chemical agent and ultimately sterilizes the waste.

Systems are available for small operations, such as laboratories, and for large operations, such as hospitals. In one disinfection system (Figure 20.10), waste is loaded onto a conveyor belt where it is transferred to a low-speed shredder to break bags and cardboard boxes. Beyond the shredder is a high-speed hammermill where the waste is pulverized to a fine particle size. During the shredding and pulverization steps, the waste is sprayed with a sodium hypochlorite (NaOCl) solution. Solids are separated from slurry by using a perforated conveyor belt. Liquids are diverted to a sanitary sewer, and the solids are collected for off-site disposal. Air is withdrawn from the system and passed through a series of filters and a chlorine-resistant HEPA filter, after which it is discharged to the air. The system can handle up to 675 kg (1500 lb) of medical waste per hour.

20.9.7 Types of Disinfection Agents

Classes of common antimicrobial chemicals and their advantages and disadvantages are listed in Table 20.6. Several chemical agents are being marketed for use in medical waste treatment systems. Some have been used in other applications, for example, treatment of drinking water. Example formulations include chlorine dioxide, sodium hypochlorite, a dry calcium oxide mixture, and peracetic acid.

20.9.8 Testing the Efficiency of Chemical Disinfection

Not all microorganisms are affected to the same degree by the same chemical. In addition, genetic mutation and natural selection will result in a pattern of resistance to numerous chemicals. The general scale of resistance to chemical treatment, from least to most resistant, is

- Vegetative bacteria
- Vegetative fungi and fungal spores

TABLE 20.6
Advantages and Disadvantages of Antimicrobial Agents

Class	Advantages	Disadvantages
Alcohols	Bactericidal	Nonsporicidal
	Tuberculocidal	Organic matter interference
	Virucidal	Incompatible with some rubber and plastics
	Fungicidal	
	Nonstaining	Highly flammable
	Nonirritating	
	Rapid action	
Quaternary ammonium compounds	Bactericidal	Nontuberculocidal
	Virucidal (lipophilic)	Nonsporicidal
	Fungicidal	Organic matter interference
	Pleasant odor	Nonvirucidal (hydrophilic)
Phenolic compounds	Bactericidal	Questionable virucide (hydrophilic)
	Fungicidal	Nonsporicidal
	Tuberculocidal	Skin irritant
	Virucidal (lipophilic)	Unpleasant odor
		Corrosive
Iodophor compounds	Bactericidal	Prolonged exposure for tuberculocidal and sporicidal activity
	Virucidal	
	Fungicidal	Corrosive
	Detergent action	Inactivation by organic matter
	Storage stability	
Glutaraldehyde	Bactericidal	Irritant
	Virucidal	Limited shelf life
	Fungicidal	
	Tuberculocidal	
	Sporicidal	
	Lack of organic matter interference	
	Noncorrosive	
Hypochlorite solution	Bactericidal	Prolonged exposure to sporicidal activity
	Virucidal	Corrosive
	Fungicidal	Bleaching agent
	Tuberculocidal	
Hydrogen peroxide	Bactericidal	Corrosive
	Virucidal	
	Fungicidal	
	Tuberculocidal	
	Sporicidal	

Source: Adapted from RTI, *Guidance for Evaluating Medical Waste Treatment Technologies,* Final Report, 94U-5400-005/01-F, Research Triangle Park, NC, 1993.

- Viruses
- Mycobacteria
- Bacterial spores

Several levels of antimicrobial activity are defined to indicate the types of organisms the chemical is expected to kill (Table 20.7). Antimicrobial chemicals typically include products with claims

TABLE 20.7
Selected Antimicrobial Efficacy Claims for Microbial Inactivation

Specific Claim	Definition
Sporicide and sterilant	An agent intended to inactivate all living microorganisms, especially bacterial spores.
Tuberculocide	An agent intended to inactivate mycobacteria, especially *Mycobacterium tuberculosis*. Tuberculocidal efficacy assumes inactivation of all viruses, fungi, and vegetative bacteria.
Virucide	An agent intended to destroy viruses. Virucidal efficacy may vary with regard to lipophilic and hydrophilic viruses.
Fungicide	An agent that inactivates fungi including fungal spores.
Bactericide	An agent that inactivates vegetative bacteria but not bacterial spores.
Germicide	An agent that inactivates one or more pathogenic microorganisms. (May include sporicide, tuberculocide, virucide, fungicide, or bactericide).

Source: Adapted from U.S. EPA, *Efficacy Data Requirements,* Office of Pesticides and Toxic Substances, U.S. EPA, Washington, DC, 1984; RTI, *Guidance for Evaluating Medical Waste Treatment Technologies,* Final Report, 94U-5400-005/01-F, Research Triangle Park, NC, 1993.

such as bactericidal, fungicidal, virucidal, sporicidal, and so on. The chemically resistant species *B. stearothermophilus* (ATCC 12980 or ATCC 10149) is commonly used to demonstrate a 10^4 reduction of viable spores. These organisms may be available in commercial suspensions or as prepared spore strips.

A sufficient number of *B. stearothermophilus* spores must be added to the treatment system to demonstrate satisfactory reduction. Disinfection systems are tested by comparing samples from the procedure with and without the test chemical. The recovered samples are neutralized, filtered, inoculated onto soybean–casein digest agar, and incubated at 55°C for at least 48 h. After incubation, the organisms must be quantified to confirm the appropriate level of spore reduction. The chemically treated spores should demonstrate a 10^4 reduction in comparison with spores treated with tap water.

20.9.9 Operational Issues

The effectiveness of disinfection treatment is determined by

- Characteristics of the disinfectant
- Concentration of the active ingredient
- Type of microorganisms in the waste
- Degree of contamination
- Characteristics of the waste
- Contact time of the disinfectant with the waste sample

Other relevant factors (e.g., pH; presence of electrolytes; complex formation; and adsorption, such as binding to small molecules or ions, macromolecules, or soil) additionally influence the effectiveness of a specific disinfectant.

Microbial inactivation by chemical agents is based upon active ingredient concentration, among other factors. It is essential to ensure that the formulation will not be diluted during the treatment process to the point where it is no longer effective. Some antimicrobial chemicals, such as quaternary ammonium compounds and halogens, may be readily inactivated when in contact with organic matter (e.g., whole blood) or hard water (Ca and Mg). Depletion of the disinfectant may also occur via volatilization losses, consumption of the chemical agent by chemical decomposition, or

metabolism by microorganisms (Kostenbauder 1983; Turnberg 1996). Such potential interference must be considered when selecting a formulation and its concentration for treatment of medical waste (RTI 1993).

20.9.10 FIFRA Registration

Under FIFRA, any chemical agent used in a treatment process may require registration with the EPA Pesticide Registration Office. If a manufacturer advertises that a chemical formulation can achieve a level of microbial inactivation (e.g., sterilant) for a specified use, that formulation must be registered with the EPA Office of Pesticide Registration (Turnberg 1996).

20.9.11 Advantages and Disadvantages of Chemical Disinfection

The combined shredding–chemical disinfection system is relatively simple. Furthermore, this treatment train substantially reduces waste volumes. After shredding, waste components are essentially unrecognizable. Disadvantages of chemical disinfection include relatively high capital and operating costs. Problems may arise with contaminants in the slurry, concentrations of disinfectant in the work space (a potential irritant to nose, eyes, and lungs), noise levels, and bioaerosol emissions (U.S. EPA 1991). Discharge permits may be required for the slurry. Microbes may become resistant to certain disinfectants.

20.9.12 Microwave Irradiation

During microwave treatment, waste is fed automatically to a grinding device where it is shredded and sprayed with steam to increase the moisture content to about 10%. The moist ground waste is heated by exposure to microwave irradiation over 2 h. Microwaves are electromagnetic waves having a frequency between those of infrared and radio waves. A frequency energy of 2450 MHz is absorbed by the waste to create friction in water molecules. Heat generated by this friction denatures proteins within the microbial cell, thereby inactivating it. Temperatures in the unit exceed 90°C. Factors affecting microwave treatment of medical waste include the frequency and wavelength of irradiation, duration of exposure, moisture content of the waste, process temperature, and waste mixing during treatment.

Microwave irradiation can treat most medical waste with the exception of cytotoxic, hazardous, or radioactive wastes. Contaminated animal carcasses, body parts, and human organs are excluded from treatment by microwave irradiation for aesthetic reasons.

Thermally resistant species such as *B. subtilis* (*globigii*) ATCC 9372 (10^4) may be used for verification of microbial inactivation. Dried spores are placed in a steam-permeable container and added to the waste stream after the waste is ground and sprayed with steam. The microwave unit is operated under routine conditions. At the conclusion of the cycle, the test strips containing the organisms are inoculated into soybean–casein digest broth medium and incubated for at least 48 h. *B. subtilis* should be cultured at 30°C. At the end of the incubation period, the media is examined for turbidity as a sign of bacterial growth. Any growth is cultured onto appropriate media to confirm the identity of the organism (RTI 1993).

QUESTIONS

1. List the primary institutions generating medical waste in the United States. In which specific institution is the majority produced?
2. What is the status of the Medical Waste Tracking Act?
3. How is incineration of medical waste regulated?

4. List and discuss the alternatives to incineration for treating and disposing of medical waste.
5. Which federal agencies other than EPA regulate potentially infectious medical waste?
6. What regulations exist regarding land disposal of medical waste?
7. What is the difference between *infectious waste* and *medical waste*?
8. Teeth are considered infectious waste. Under federal regulations, is it permissible to bring an extracted tooth home from the dentist?
9. The Robust Health Care Company generates very little infectious waste (less than 20 kg, or about 50 lb/month). How are they required to manage these wastes?
10. What exemptions exist to the definition of *regulated medical waste*?
11. What are the container requirements for RMW? How are sharps to be containerized?
12. What are the requirements regarding tracking of medical waste shipments? How are non-returned forms to be addressed?
13. What specific microorganisms are employed to test the efficiency of sterilization by autoclaving? Describe the procedure.

REFERENCES

ATSDR (Agency for Toxic Substances and Disease Registry). 2011. *Toxic Substances Portal – Chlorinated Dibenzo-p-Dioxins (CDDs)*. Available from: http://www.atsdr.cdc.gov/toxfaqs/tf.asp?id = 363&tid = 63

Block, S. (Ed.). 1977. *Disinfection, Sterilization, and Preservation*, 4th ed. Philadelphia, PA: Lea and Fibiger.

CFR (Code of Federal Regulations). 2002. *Vol. 40 Part 259, Standards for the Tracking and Management of Medical Waste*. Washington, DC: U.S. Government Printing Office.

Emery, R., Marcus, J., and Sprau, D. 1992. Characterization of low-level radioactive waste generated by a large university/hospital complex. *Health Phys* 62, 183–185.

Hoeltge, G. 1995. Managing the infectious waste of a surgery unit and laboratory. *Semin Dermatol* 14, 247–251.

Kostenbauder, H.B. 1983. Physical factors influencing the activity of antimicrobial agents. In *Disinfection, Sterilization, and Preservation*, 3rd ed. Block S. (Ed.). Philadelphia, PA: Lea and Febiger.

Lee, B.-K., Ellenbecker, M.J., and Moure-Ersaso, R. 2004. Alternatives for treatment and disposal cost reduction of regulated medical wastes. *Waste Manag* 24, 143–151.

Liberman, D. and Gordon J. (Eds.). 1989. *Biohazard Management Handbook.* New York: Marcel Dekker.

Lipman, L. 1992. New rules for medical waste. *Saf Health* 145, 40–43.

Perkins, J.J. 1983. *Principles and Methods of Sterilization in Health Services*, 2nd ed. Springfield, IL: Charles C. Thomas.

Reynolds, J.P., Jeris, J.S., and Theodore, L. 2002. *Handbook of Chemical and Environmental Engineering Calculations*. New York: Wiley-Interscience.

RTI (Research Triangle Institute). 1993. *Guidance for Evaluating Medical Waste Treatment Technologies*. Final Report, 94U-5400-005/01-F. Research Triangle Park, NC: RTI.

Turnberg, W.L. 1989. *Human Infection Risks Associated with Infectious Disease Agents in the Waste Stream: A Literature Review*. Washington State Infectious Waste Project—Report to the Legislature. Olympia, WA: Washington Department of Ecology.

Turnberg, W.L. 1996. *Biohazardous Waste. Risk Assessment, Policy, and Management*. New York: Wiley.

U.S. CDC (Centers for Disease Control). 1985. *Guideline for Handwashing and Hospital Environmental Control*. NTIS PB85-923404. Washington, DC: NTIS.

U.S. EPA (U.S. Environmental Protection Agency). 1984. *Efficacy Data Requirements*. Washington, DC: Office of Pesticides and Toxic Substances, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1986. *EPA Guide for Infectious Waste Management*. EPA/530-SW-86-014. Washington, DC: Office of Solid Waste, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1988. *Medical Waste Tracking Act of 1988*. Public Law 100–582. EPA/530-SW-89-008. Washington, DC: U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1989a. *Seminar—Medical and Institutional Waste Incineration: Regulations, Management, Technology, Emissions, and Operations*. Cincinnati, OH: Center for Environmental Research Information (CERI 89-247), U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1989b. *Hospital Incineration Operator Training Course Manual*. EPA 450/3-89-004. NTIS PB 89-189880. Research Triangle Park, NC: U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1989c. *Operation and Maintenance of Hospital Medical Waste Incinerators*. EPA 450/3-89-002. Research Triangle Park, NC: Control Technology Center, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1990a. *Medical Waste Management in the United States—First Interim Report to Congress*. Washington, DC: Office of Solid Waste, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1990b. *Operation and Maintenance of Hospital Medical Waste Incinerators*. EPA/625/6-89/024. Cincinnati, OH: Center for Environmental Research Information, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1991. *Medical and Institutional Waste Incineration: Regulations, Management, Emissions and Operations*. EPA/625/4-91/030. Washington, DC: Office of Research and Development, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 1992. *Medical and Institutional Waste Incineration: Regulations, Management, Technology, Emissions, and Operations*. EPA/625/4-91/030. Cincinnati, OH: Center for Environmental Research Information, Office of Research and Development.

U.S. EPA (U.S. Environmental Protection Agency). 1997. *Mercury Study Report to Congress: Volume I: Executive Summary*. EPA-452/R-97-003. Washington, DC: Office of Air Quality Planning & Standards and Office of Research and Development, U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency), Landrum, V.J., Barton, R.G., Neulicht, R., Turner, M., Wallace, D., and Smith, S. 1991. *Medical Waste Management and Disposal*. Park Ridge, NJ: Noyes Data Corporation.

U.S. HHS (U.S. Department of Health and Human Services). 2011. *Medical Devices, Guidance for Industry and FDA Staff – Biological Indicator (BI)*. Available from: http://www.fda.gov/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/ucm071261.htm

WEDC (Water, Engineering and Development Centre). 2002. *Emergency Sanitation: Assessment and Programme Design*. Loughborough: WEDC.

SUGGESTED READINGS

Aegis Bio-Systems. 2003. *The JYD-1500, Mobile Medical Waste Treatment System Using Steam Sterilization*. Available from: http://www.aegisco.com/techspec.htm

Bay Area Dioxins Project. 2003a. *Vendor List: Medical Waste Treatment, Environmental Best Practices for Health Care Facilities*. Available from: http://dioxin.abag.ca.gov/pilot_projs/MW_VendorList.pdf

Bay Area Dioxins Project. 2003b. *Why Are Hospitals Rethinking Regulated Medical Waste Management?* Environmental Best Practices for Health Care Facilities. Available from: http://dioxin.abag.ca.gov/pilot_projs/MW_Background.pdf

California Department of Waste Services. 2003. *Medical Waste Management Program.* Available from: http://www.dhs.cahwnet.gov/ps/ddwem/environmental/Med_Waste/medwasteindex.htm

Clean-Pro Industries. 2001. *Bio Set Cement Based Solidification Process for Hazardous Medical Waste Material*. Available from: http://www.users.qwest.net/~cleanpro/index18.html

Health Care Without Harm. 2001. *Medical Waste, Nonincineration Medical Waste Treatment Technologies. Executive Summary*. Available from: http://www.noharm.org/library/docs/Non-Incineration_Medical_Waste_Treatment_Te_2.pdf

Jang, Y.-C., Lee, C., Yoon, O.-S., and Kim, H. 2006. Medical waste management in Korea. *J Environ Manag* 80, 1–9.

New Jersey Department of Environmental Protection. 2001. *Alternative Medical Waste Disposal Technologies Authorized in New Jersey*. Available from: http://www.state.nj.us/dep/dshw/rrtp/aamwdt.htm

Patwary, M.A. 2012. *Medical Waste: An Emerging Environmental Threat in Developing Countries*. Lambert Academic Publishing. Saarbrücken, Germany.

Singh, S. and Prakash, V. 2007. Toxic environmental releases from medical waste incineration: a review. *Environ Monit Assess* 132, 67–81.

Studnicki, J. 1992. The management of hospital medical waste. *Hosp Top* 70, 11–21.

U.S. EPA (U.S. Environmental Protection Agency). 2003. Medical Waste. Available from: www.epa.gov/epaoswer/other/medical/index.htm

21 Construction and Demolition Debris

We have to discard the past and, as one builds
floor by floor, window by window,
and the building rises, so do we go throwing down
first, broken tiles, then pompous doors,
until out of the past dust rises as if to crash against the floor,
smoke rises as if to catch fire
and each new day it gleams like an empty plate

Pablo Neruda (1904–1973)
Past

21.1 INTRODUCTION

Construction and demolition (C&D) debris is generated when new structures are built and existing structures are renovated or demolished (Figure 21.1). Structures include residential and nonresidential buildings, and public works projects such as streets, highways, bridges, and piers.

Components of C&D debris include concrete, asphalt, wood, metals, gypsum wallboard, and roofing. State definitions of C&D debris may be expanded to include trees, stumps, soil, and rock from clearing construction sites.

21.2 CHARACTERISTICS OF C&D DEBRIS

Sources of C&D debris include homebuilders, homeowners, commercial developers, building contractors, highway and street contractors, bridge constructors, bituminous pavement contractors, home remodelers, demolition contractors, roofing contractors, drywallers, and excavating companies (Franklin Associates 1998). The major activities that generate C&D debris from buildings include the construction, demolition, and renovation of residential and nonresidential buildings (Figure 21.2). Residential buildings include single-family houses, duplexes, and high-rise multifamily housing. Nonresidential buildings include commercial, institutional, and industrial buildings. Approximately 170 million tons of building-related C&D debris were generated in the United States in 2003 (Table 21.1). Thirty-nine percent was generated from residential sources and 61% from nonresidential sources. Building demolitions account for 49% of the total C&D waste stream, renovations account for 42%, and construction activities generated the remaining 9% (U.S. EPA 2004).

Construction activities generally produce cleaner materials than do demolition. Demolition generates wastes with several materials bound together or contaminated with hazardous materials such as asbestos or lead-based paint. Renovation projects generate both C&D type wastes. The sources of C&D debris are listed in Table 21.2.

The composition of C&D debris is highly variable and is a function of the specific activities taking place at the site. For example, concrete is the largest component of building demolition debris, and wood is the largest waste component generated at construction and renovation sites. Typical components of C&D debris are listed in Table 21.3.



FIGURE 21.1 C&D debris results from construction, demolition, and renovation of residential and nonresidential structures.

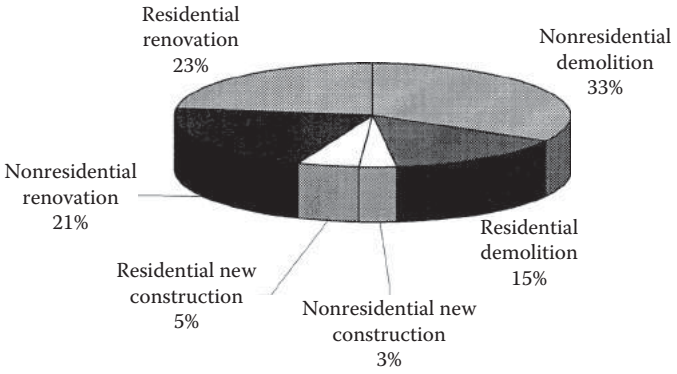


FIGURE 21.2 Generation of C&D debris from buildings. (Reproduced with kind permission from Franklin Associates, *Characterization of Building-Related Construction and Demolition Debris in the United States,* EPA530-R-98-010, Prairie Village, KS, 1998.)

TABLE 21.1
Summary of Estimated Building-Related C&D Debris Generation in 2003

	Residential		Nonresidential		Total	
Source	**Million Tons**	**Percent**	**Million Tons**	**Percent**	**Million Tons**	**Percent**
Construction	10	15	5	5	15	9
Renovation	38	57	33	32	71	42
Demolition	19	28	65	63	84	49
Total	67	100	103	100	170	100
Percent		39		61		100

Source: U.S. EPA, *Estimating 2003 Building-Related Construction and Demolition Materials Amounts*, 2004, Available from: http://www.epa.gov/osw/conserve/imr/cdm/pubs/cd-meas.pdf

TABLE 21.2
Representative Sources of C&D Wastes

Site clearance materials	Brush, tree, and stumpage materials
Excavated materials	Earth, fill, and other excavated rock and granular materials
Roadwork materials	Concrete slabs and chunks from concrete road construction
	Asphalt chunks and millings from asphalt pavement
	Bridge, overpass construction, and renovation materials
New construction materials	Residential, commercial, and industrial project sources
Renovation, remodeling, or repair materials	Residential, commercial, and industrial project sources
Demolition materials including wrecking, implosion, dismantling, and deconstruction	Residential, commercial, and industrial project sources
Disaster debris	Any/all of the above.

Source: Reproduced with kind permission from Franklin Associates, *Characterization of Building-Related Construction and Demolition Debris in the United States*, EPA530-R-98-010, U.S. EPA, Prairie Village, KS, 1998.

TABLE 21.3
Typical Components of C&D Debris

Material	**Examples**
Wood	Forming and framing lumber, stumps, plywood, laminates, scraps
Drywall	Sheetrock, gypsum, plaster
Metals	Pipes, rebar, flashing, steel, aluminum, copper, brass, stainless steel
Plastics	Vinyl siding, doors, windows, floor tile, pipes
Roofing	Asphalt and wood shingles, slate, tile, roofing felt
Rubble	Asphalt, concrete, cinder blocks, rock, soil
Brick	Bricks and decorative blocks
Glass	Windows, mirrors, lights
Miscellaneous	Carpeting, fixtures, insulation, ceramic tile

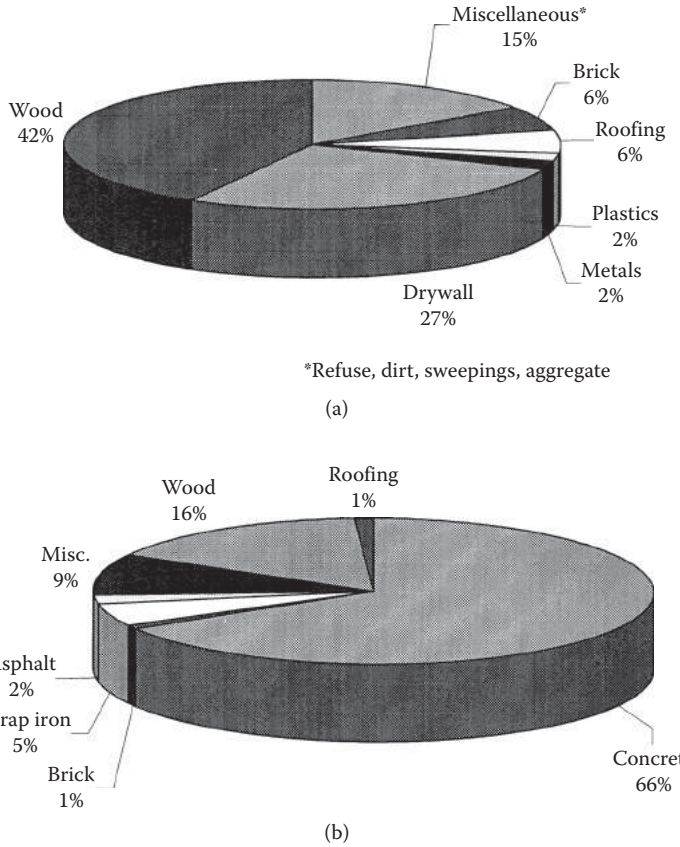


FIGURE 21.3 Comparison of wastes generated by (a) construction. (Reproduced with kind permission from Franklin Associates, *Characterization of Building-Related Construction and Demolition Debris in the United States,* EPA530-R-98-010, Prairie Village, KS, 1998) and (b) demolition (reproduced with kind permission of R.W. Rhine, Inc., Tacoma, WA).

Construction debris from building sites commonly consists of scraps of construction materials such as wood, sheetrock, masonry, and roofing materials. There is comparatively less concrete in construction debris than in demolition debris. Scrap from residential construction sites represents between 6% and 8% of the total weight of the building materials delivered to the site excluding the foundation, concrete floors, driveways, and patios (Franklin Associates 1998). A comparison of the composition of construction debris versus demolition debris is provided in Figure 21.3.

When buildings are demolished, large quantities of waste may be generated in a short period. Demolition techniques include imploding a structure with explosives, using a crane and wrecking ball technique, or deconstructing. A majority of demolition projects use a combination of the last two techniques depending on the materials present in the original project, physical size of the structure, surrounding buildings that cannot be impacted, and project time. The entire weight of a building, including concrete foundations, plumbing, walls, electrical workings, and so forth, may be generated as C&D debris when a building is demolished.

The quantities of C&D debris generated around the country vary markedly from one region or community to another. This variation is partly a result of differences in state regulations, current rate of growth, and development activity in the community. The amount of C&D debris generated in a region also depends on the overall economic status of the region, the occurrence of natural disasters, and special projects underway. In rapidly growing areas, the C&D waste stream consists primarily of construction debris with only small volumes of demolition debris.

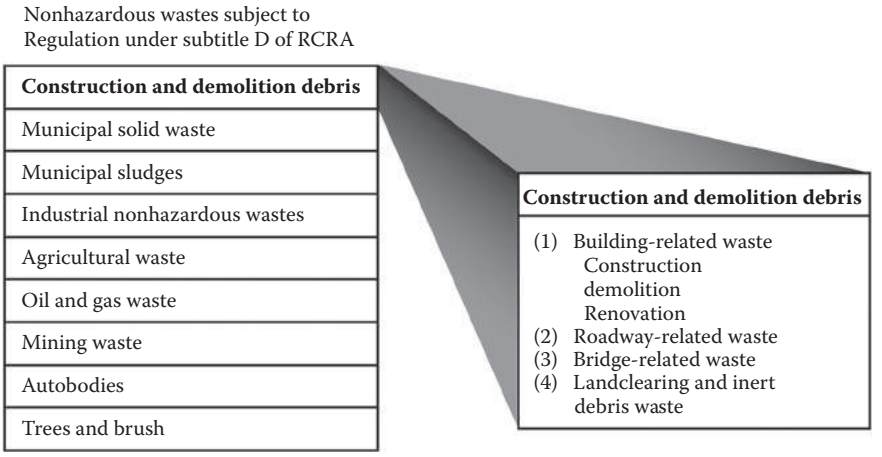


FIGURE 21.4 C&D debris as a component of subtitle D wastes. (Reproduced with kind permission from Franklin Associates, *Characterization of Building-Related Construction and Demolition Debris in the United States,* EPA530-R-98-010, Prairie Village, KS, 1998.)

In contrast, in older urban areas, demolition debris makes up the majority of the C&D waste stream.

21.3 MANAGEMENT OF C&D DEBRIS

C&D debris is characterized as a nonhazardous waste subject to regulation under RCRA subtitle D (Figure 21.4). As discussed in Chapter 1, other subtitle D wastes include municipal solid waste, solids from water and wastewater treatment plants, nonhazardous wastes from industrial processes, agricultural wastes, oil and gas wastes, mining wastes, discarded autos, and trees and brush.

C&D debris is most commonly managed via landfilling. Disposal sites include dedicated C&D landfills, MSW landfills, and unpermitted sites. About 52% of building-related C&D materials were disposed in 2003 (U.S. EPA 2004). Much of this material goes to specifically designated C&D landfills. A survey conducted for Environmental Protection Agency (EPA) identified about 1900 active C&D landfills in the United States (Franklin Associates 1998).

There is a trend toward increasing recovery of C&D debris in the United States. Of the total C&D waste generated, approximately 48% was recovered. This recovery rate is a 23% increase from 1996 data (U.S. EPA 2004). Approximately 3500 facilities process C&D materials in the United States (Architecture Week 2001).

The C&D materials most frequently recovered for recycling are concrete, asphalt, metals, and wood. Metals have the highest recycling rates among the materials recovered. The Steel Recycling Institute estimates the recycling rate for C&D steel at about 85%. This includes scrap steel from buildings, rebar from roads, and structural steel from bridges. About 500 wood processing facilities in the United States obtain wood from C&D debris. The leading states for wood processing plants are North Carolina, Oregon, and California.

21.4 MANAGEMENT OF SELECTED C&D WASTE COMPONENTS

21.4.1 Aggregate

Portland cement concrete and asphalt concrete are the two predominant materials used in road construction. Both consist primarily of aggregate and cement. Aggregate is composed of inert mineral materials including crushed stone, sand, gravel, slag, or rock dust. Cement and asphalt serve as binders.

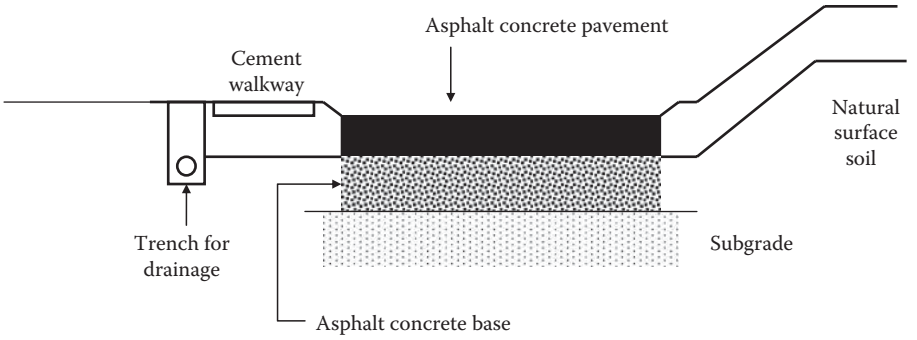


FIGURE 21.5 Cross-section of a road showing the various base layers.

Aggregate is used as a replacement for road-base gravel or it is incorporated directly into asphalt or concrete.

A typical roadway is constructed in several layers: pavement, base, and sometimes subbase (subgrade). The pavement is the surface layer and is composed of Portland cement concrete or asphalt concrete. The base layer supports the pavement and is composed of aggregate. The subbase layer supports the base and is also made of aggregate (Figure 21.5). The subbase layer has less strength but is useful and cost-effective for bringing the road up to grade. The subbase layer includes a larger proportion of sand, silt, and clay than the aggregate base layer (CIWMB 2002c).

Recycled aggregate originates primarily from Portland cement concrete and asphalt concrete from road maintenance and demolition. Aggregate is recycled via crushing and sorting operations. Portland cement concrete and asphalt concrete are delivered to the processor in large chunks. Heavy crushing equipment breaks the chunks into aggregate of manageable size. A crushing plant may include a hopper to receive the material, a jaw to break it into smaller pieces, an impact crusher to reduce further its size, a vibrating screen to sort to the required specifications, and a conveyor belt with a rotating magnet to remove metal contamination such as rebar (CIWMB 2002c).

Aggregate is recycled for many purposes, including:

- in paved roads as aggregate base, aggregate subbase, and shoulders
- in gravel roads as surfacing
- as a base for building foundations
- as fill for utility trenches

The primary market for aggregate, however, is as a road base and subbase.

21.4.2 Drywall (Sheetrock, Gypsum)

Drywall, also referred to as gypsum board, wallboard, plasterboard, and rockwall, is the primary product used in the United States for interior wall construction. It is composed of a sheet of gypsum covered on both sides with a paper facing and a paperboard backing. Gypsum is a naturally occurring mineral composed of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$). Drywall sheets are manufactured in sizes from 4 ft × 8 ft to 4 ft × 16 ft, and range in thickness from ¼ in. to 1 in.

Most drywall waste is generated from new construction (64%), followed by demolition (14%), manufacturing (12%), and renovation (10%). Approximately 15 million tons of new drywall are manufactured per year in the United States. About 12% of new construction drywall is discarded during installation.

Drywall is recycled by first separating the paper backing from the gypsum material. The paper can be recycled into new paper backing, and the gypsum is remixed and used in the manufacture of new

drywall. The paper content of drywall waste limits the amount of recycled gypsum allowed in new product because paper content affects the fire rating. Other potential markets for drywall waste include:

- Cement plants. The gypsum is added to clinker to control setting time.
- Stucco additive.
- A bulking material for sludge drying and composting.
- Water treatment. Recycled gypsum can settle suspended clay particles in turbid water.
- Manure treatment. Recycled gypsum can be mixed with animal wastes to react with ammonia and reduce odor.
- Combine with wood shavings for animal bedding. Gypsum may substitute for sawdust or sand to absorb moisture.
- Grease absorption. Recycled gypsum can be sprinkled on shop floors to absorb spilled oil and grease.
- Athletic field marker. Gypsum is used to mark lines on athletic fields.
- Agriculture.

New construction drywall can be recycled as a soil amendment. Specific applications include (CIWMB 2002e):

- General agriculture
- Mushroom culture
- Forestry and mine land reclamation
- Nurseries
- City parks and recreation areas
- Residential lawns (sod)
- Golf courses
- Compost additives

Gypsum provides a number of practical benefits to soils; for example, it neutralizes some soil acidity and adds plant nutrients such as calcium and sulfur. Gypsum also improves water penetration and workability of an impermeable sodic (i.e., high Na^+) soil. Recycled gypsum could be used to leach out sodium salts from soil along roadways where salt is applied during winter. Gypsum can also reduce the plasticity of soils with high clay content. Regardless of reuse option, however, the following contaminants should be removed:

- Nails
- Tape
- Joint compound. This compound is made primarily of limestone or gypsum; however, if the structure was built before the mid-1970s, asbestos may occur.
- Paint usually covers demolition drywall. Structures built before 1978 may contain lead-based paint.

Drywall waste from new construction sites is freer of contaminants than is demolition drywall, and it is the most commonly recycled. Grinding equipment ranges from a large facility to a small mobile chipper. A hammermill is often used. The machinery grinds the drywall, producing about 93% gypsum powder and 7% (by weight) shredded paper. The gypsum can be sold as a powder, with or without paper, or molded into pellets. Drywall recycling produces dust, which often is collected via a baghouse or similar filter system. The amount of drywall waste can be reduced in construction by building standard-sized walls and flat ceilings, and by ordering custom-sized sheets for nonstandard walls. Wastes also are reduced by finding substitutes that are reusable, such as modular partitions for commercial buildings (CIWMB 2002e).

21.4.3 Wood Waste Recycling

Wood waste generated at construction sites is often of better quality and purity and has a better potential for reuse than wood from demolition sites, as the former material is more easily separated from other wastes. Demolition wood is often low in demand because of contamination and due to the difficulty in separating wood from other building materials.

In wood processing facilities, wood is chipped to a fine size. The processed wood is used as mulch, compost bulking agent, animal bedding, and fuel. Wood waste from construction or demolition is appealing as a fuel because of its low moisture content.

Treated wood in C&D debris merits special mention. Wood treatment involves the addition of chemicals, either as a surface application or internally within pore spaces, to enhance resistance to decay by fungi, insects, and marine borers. Wood treatment chemicals include creosote, pentachlorophenol, and chromated copper arsenate (CCA), among others. CCA currently constitutes about 80% of the wood preservation chemicals currently in use. Copper serves as a fungicide, arsenic serves as an insecticide, and chromium is used to "fix" the copper and arsenic into the wood (Morrell and Huffman 2004). Typical CCA-treated wood applications include telephone poles, fence posts, decks, and other components of home construction.

At C&D debris landfills, CCA-treated wood is disposed along with untreated wood, concrete, and drywall. As long as the wood is disposed after being used for its intended purpose, CCA-treated wood is exempt from designation as a hazardous waste under RCRA. At C&D debris recycling facilities, some CCA-treated wood may be separated and recovered for reuse. Management of treated wood from C&D sites is cumbersome because CCA-treated wood cannot be easily separated from the remainder of the wood waste stream. It is difficult to visually distinguish CCA-treated wood from untreated wood. When painted or weathered, identification of CCA-treated wood becomes even more difficult.

Treated wood recovered from C&D debris recycling has been used as fuel for industrial boilers. Since arsenic can volatilize, combustion units that burn C&D debris containing CCA-treated wood must be equipped with appropriate air pollution controls.

21.4.4 Metals Recycling

Metals have the highest recycling rates among materials recovered from C&D sites. Favorable markets have been in existence for ferrous metals as well as for copper and brass. The recycling rate for C&D steel is about 85%. This number not only includes scrap steel from buildings but also from streets, bridges, and highways.

21.4.5 Asphalt Shingles

Asphalt roofing shingles are composed of an asphalt-saturated felt mat with small rock grains added. The felt backing (mat) is made of organic felt, paper, or fiberglass. Organic shingles contain 30%–36% asphalt. A mineral filler and stabilizer (limestone, silica, and dolomite) is added, as are mineral granules (ceramic-coated natural rock, sand-sized).

The two major applications of asphalt roofing are residential (often slanted) and commercial (often flat). Asphalt shingles are used primarily on slanted residential roofs. Built-up roofing, which consists of roofing felt between layers of tar and gravel, is commonly used on flat commercial roofs. These two materials comprise the majority of the waste arising from roof replacement or repair. About two-thirds of all residential roofing activities use asphalt shingles. Other roofing materials include wood, tile, and concrete (NAHB, 1996).

Approximately 11 million tons of waste asphalt roofing shingles is generated in the United States per year (U.S. EPA 2005). Reroofing accounts for 10 million tons, with 1 million tons from manufacturing scrap. Old roofs are often covered with a set of new shingles, so some tear-offs contain two layers.

To recycle shingles for use in new products, the shingles must be ground to a specified size and the contaminants removed. Primary grinding may produce fragments measuring 2 or 3 in. across. Secondary grinding may be needed to produce smaller pieces; for example, aggregate base may require ¾ in. or smaller, and asphalt pavement may require ½ or ¼ in. or smaller. Depending on desired use, the shingles may have to be sieved after grinding (CIWMB 2002d). For virtually all uses, contaminants must be removed. Possible contaminants include metals, which can be removed by a rotating magnet, and wood.

Common uses for recycled asphalt shingles include asphalt for paving and new roofing materials. Asphalt shingle scrap can be used in a variety of products, including:

- Asphalt pavement
- Aggregate base and subbase
- Cold patch for potholes, sidewalks, utility cuts, driveways, ramps, bridges, and parking lots
- Pothole patch
- Road and ground cover
- New roofing
- Fuel oil

Meeting the specifications for paving and roofing materials limits the above applications. Pre-consumer manufacturing scrap is used in hot mix asphalt; however, postconsumer scrap (8–10 million tons per year), which is less uniform in composition, is not as widely used in hot mix asphalt (Button et al. 1997; Franklin Associates 1998).

21.4.6 Asbestos Shingles

Asbestos is a naturally occurring mineral of both the serpentine and amphibole groups. Its historical popularity has been due to its ability to withstand excess heat and its resistance to conducting electricity and chemical decomposition. Furthermore, asbestos can be woven into useful fabrics, pastes, and muds for use in construction.

The occurrence of asbestos-containing shingles in roof replacement jobs is rather low. The total asbestos content of asphalt shingles manufactured in 1963 was 0.02%; in 1977, the percentage decreased to 0.00016% (CIWMB 2002d). Asbestos is no longer used in the manufacture of asphalt roofing shingles; however, due to the practice of covering an old roof with new shingles, asbestos still may be found in the shingle waste stream.

The agencies regulating asbestos include EPA, OSHA, and city and county health departments. EPA regulates friable asbestos over 1%. OSHA regulates friable and nonfriable asbestos over 0.1%. Processors need to contact these agencies to determine relevant permitting and monitoring requirements (Figure 21.6).

21.5 REDUCTION OF C&D DEBRIS

As with all other waste management methods and technologies, waste minimization must be given high priority in order to limit adverse environmental impacts, hold down disposal costs, and minimize future liability. Regarding C&D wastes, reduction strategies should begin with the earliest choices made in the building process, including architectural design and material selection (U.S. EPA 2002). Design concepts should include waste prevention, product durability, and recyclability of materials.

Waste prevention techniques minimize the amount of materials used during construction and renovation. For example, a technique from the homebuilding field known as “optimum value engineering” or “efficient framing” reduces the amount of wood used in the framing process without sacrificing structural integrity (U.S. EPA 2002). Durable products are often more expensive



FIGURE 21.6 Buildings undergoing demolition must be assessed for possible asbestos content.

and contain more material than their traditional counterparts; however, they offer long-term benefits through lower maintenance and replacement costs. In addition, products that are more durable can enhance safety and prevent other building features from deteriorating.

The durability of a building is not only determined solely by construction materials but also by the quality of construction. For example, constructing a roof and window frames to prevent water infiltration helps to ensure that interior walls and ceilings last longer.

21.6 DECONSTRUCTION

The amount of waste created by building demolition can be minimized through waste reduction techniques, including a process known as *deconstruction*. This process maximizes the salvage of building materials for reuse or recycling by selectively disassembling buildings. Deconstruction concentrates on recovering items such as flooring, siding, windows, doors, bricks, plumbing fixtures, ceiling tiles, and structural components. Some projects have demonstrated that enormous quantities of demolition debris can be reused in new structures under construction at the demolition site. When the Seattle Kingdome was demolished in 2000, a total of 97% of the structural waste was recycled into the new stadium complex, resulting in savings of more than $3 million. In addition, truck traffic to and from the site was reduced by about 4500 trips. Before constructing the 4 Times Square Office Tower in Manhattan, the contractor first removed six existing buildings. By salvaging all usable materials and recycling as much of the remaining C&D debris as possible, the contractor saved more than $800,000 by selling the salvaged material and reducing disposal fees.

Out of two buildings deconstructed at a demolition project at the closed Presidio Army Compound in San Francisco, workers salvaged about 85% of the first building and approximately 40% of the second building. Material sorting was performed on-site. Salvaged items included timber, dimensional lumber, flooring, windows, ceiling vent covers, iron work, plumbing fixtures, and siding. Material sales took place at the deconstruction site, avoiding the significant costs of transportation, whereas the remaining materials were taken to a warehouse and sold within eight months. The Presidio Army Compound was turned over to the National Park Service following cleanup (Regula-Thompson 1997).

Several buildings at a former naval supply center in the port of Oakland were deconstructed. A warehouse had over 400,000 board feet of lumber, including old-growth Douglas fir and redwood. An open house was held at the port, and invitations were sent to local architects and contractors advertising the materials available (Regula-Thompson 1997).

Deconstruction is labor-intensive and often relies on the use of hand tools and manpower to take apart buildings and structures. When deconstructing buildings, workers must take

precautions to protect themselves from exposure to substances such as lead-based paint and asbestos (U.S. EPA 2002).

Benefits of deconstruction include (CEC 1997):

- Lower building removal costs. Deconstruction can cost less than demolition because costs are offset by reselling materials salvaged during the process.
- Avoidance of disposal costs. The majority of materials from deconstructed structures can be salvaged, thereby decreasing debris going to landfills and avoiding shipping costs and tipping fees.
- Increased employment opportunities. Deconstruction is an opportunity to create interim jobs. Deconstruction projects have been linked to job training programs where less skilled workers gain experience in carpentry, construction, and materials recovery.
- Regulatory compliance. Many states now require a substantial reduction in the amount of solid wastes disposed in landfills by a specified date.
- Local business development. Salvage industries have strong growth potential.
- Cheaper and better quality building materials. Reused materials are less expensive and sometimes of higher quality than new materials. For instance, some wood structures on military bases contain old growth wood, which is excellent quality and rare lumber.
- Reduced environmental impacts. Deconstruction has fewer environmental impacts on adjacent property because it creates less dust and noise than demolition.
- Diverts valuable materials from landfills and provides consumers and builders with an alternative to buying building products made from virgin resources.

21.7 HAZARDOUS MATERIALS

A number of hazardous materials may be removed from structures during demolition, including floor lamps, mercury thermostats, and polychlorinated biphenyls (PCB) containing lighting ballasts (Table 21.4). Mercury found in residential properties usually occurs in household appliances and lights. Items such as fluorescent and high-intensity discharge lamps, thermostats, water heaters, furnaces, and ranges often store mercury-containing parts (Purdue Research Foundation 1996). Boiler rooms often contain mercury devices. Mercury switches are frequently associated with heating and cooling equipment. Some homes have mercury gas flow regulators attached to the gas meter; some larger buildings have mercury manometers to regulate gas flow. Some of these wastes are managed as Universal Waste (see Chapter 18), whereas others such as lead components may require more stringent management and disposal.

TABLE 21.4
Common Building Components Containing Hazardous Materials

Component	Hazardous Material
Fluorescent light bulbs	Mercury
High-intensity discharge (HID) lamps	Mercury
Thermostats	Mercury
Lighting ballasts for fluorescent light bulbs and HID lamps	PCBs, bis(2-ethylhexyl) ester, di(2-ethylhexyl) phthalate (DEHP)
Silent wall switches	Mercury
Batteries	Lead, cadmium
Roof vent flashings	Lead
Lead pipes and lead-painted surfaces	Lead
Discarded paint, oil, pesticides, cleaning agents	Assorted
CCA (chromated copper arsenate)-treated wood	Chromium, arsenic

QUESTIONS

1. What federal regulations exist for management of C&D debris?
2. What C&D materials are most frequently recovered from C&D sites? Of these, which has the highest rate of recycling?
3. Are land clearing debris such as stumps, rocks, and soil included in state definitions of C&D debris? Check the U.S. EPA website, http://www.epa.gov/region09/waste/solid/c&d.html, for California's and Hawaii's definitions of C&D debris.
4. Will it cost a typical contractor more to recycle or to reuse C&D debris? Discuss.
5. How do U.S. states regulate C&D debris? Are state programs relatively consistent? Check the U.S. EPA website, http://www.epa.gov/region09/waste/solid/c&d.html for state regulations from Arizona, California, Hawaii, and Nevada.
6. In your community, find out how C&D debris is managed. Is it typically landfilled or recycled? Who is in charge of managing and transporting C&D debris: private haulers or the municipality?
7. How does gypsum, $CaSO_4$, affect soil physical and chemical properties? Is it a noxious compound or does it benefit soil?
8. How is CCA-treated wood managed under RCRA? Is it to be handled as a hazardous waste?
9. Are there any hazards associated with burning CCA-treated wood?
10. How are old asphalt shingles recycled? What are common uses for recycled shingles?
11. What federal agencies regulate asbestos-containing shingles? What are the minimum asbestos contents to be eligible for regulation?
12. Describe *deconstruction*. If an academic building on your campus were to be deconstructed, what would the primary recovered materials be? Consider plumbing, wiring, and interior woodwork, external facades, and so on, in addition to components such as stone, steel girders, and metallic doors.
13. Is deconstruction worth the effort? List the potential benefits of deconstruction.

REFERENCES

Architecture Week. 2001. *Recycling Construction debris*. Available from: http://www.architectureweek.com/2001/0926/environment_1-2.html

Button, J.W., and Williams, D. 1997. From roofing to roads: the use of recycled shingles in hotmix asphalt. *C&D Debris Recycling* 4(4): 26.

Center for Economic Conversion. 1997. When is Deconstruction Cost Effective? Technical Brief 1. Deconstruction. Green Base Conversion Strategies. Techniques for Creating Environmentally Sustainable Development on Closing Military Bases.Mountain View, CA.

CIWMB (California Integrated Waste Management Board). 2002a. *Construction and Demolition Recycling Fact Sheet, Lumber Waste*. Available from: http://www.ciwmb.ca.gov/ConDemo/Pubs.htm

CIWMB (California Integrated Waste Management Board). 2002b. *Construction and Demolition Recycling Fact Sheet, Asphalt Pavement Recycling*. Available from: http://www.ciwmb.ca.gov/ConDemo/Pubs.htm

CIWMB (California Integrated Waste Management Board). 2002c. *Construction and Demolition Recycling Fact Sheet, Recycled Aggregate*. Available from: http://www.ciwmb.ca.gov/ConDemo/Pubs.htm

CIWMB (California Integrated Waste Management Board). 2002d. *Construction and Demolition Recycling Fact Sheet, Asphalt Roofing Shingles Recycling*. Available from: http://www.ciwmb.ca.gov/ConDemo/Pubs.htm

CIWMB (California Integrated Waste Management Board). 2002e. *Construction and Demolition Recycling Fact Sheet, Drywall Recycling*. Available from: http://www.ciwmb.ca.gov/ConDemo/Pubs.htm

Franklin Associates. 1998. *Characterization of Building-Related Construction and Demolition Debris in the United States*. EPA530-R-98-010. Prairie Village, KS: U.S. EPA.

Morrell, J.J. and Huffman, J. 2004. Copper, chromium, and arsenic levels in soils surrounding posts treated with chromated copper arsenate (CCA). *Wood Fiber Sci* 36(1), 119–128.

NAHB (National Association of Home Builders) Research Center. 1996. *Waste Management Update 2: Asphalt Roofing Shingles*. Washington, DC: NAHB Research Center.

Purdue Research Foundation. 1996. *Mercury in Buildings*. West Lafayette, IN. Available from: http://danpatch.ecn.purdue.edu/~mercury/src/frame

Regula-Thompson, B. 1997. *Creative Reuse: Military Base Buildings: Carefully Pounding Swords Into Plowshares*, Mar/Apr 1997, CalMAX Creative Reuse. Available from: http://www.ciwmb.ca.gov/CalMAX/Creative/default.htm

U.S. EPA (U.S. Environmental Protection Agency). 2002. *Waste Wise Update: Building for the Future*. EPA 530-N-02-003, Solid Waste and Emergency Response (5306W). Washington, DC: U.S. EPA.

U.S. EPA (U.S. Environmental Protection Agency). 2004. *Estimating 2003 Building-Related Construction and Demolition Materials Amounts*. Available from: http://www.epa.gov/wastes/conserve/imr/cdm/pubs/cd-meas.pdf

U.S. EPA (U.S. Environmental Protection Agency). 2005. *Tear-off Asphalt Shingles Recycling, OSWER Innovations Pilot*. Available from: http://www.epa.gov/oswer/iwg/pilots/docs/2005_0520_asphalt_formatted_final.pdf

SUGGESTED READINGS

CIWMB (California Integrated Waste Management Board). 2000a. *Designing with Vision … A Technical Manual for Material Choices in Sustainable Construction, 431-99-009*. Sacramento, CA: CIWMB.

CIWMB (California Integrated Waste Management Board). 2000b. *Green Building Basics*, 400-99-014. Sacramento, CA: CIWMB.

CIWMB (California Integrated Waste Management Board). 2002a. *Military Base Closure Handbook: A Guide to Construction and Demolition Materials Recovery*, 433-96-074. Sacramento, CA: CIWMB.

CIWMB (California Integrated Waste Management Board). 2002b. *Wood Waste: How to Keep Wood Waste Out of Landfills*, 500-94-017. Sacramento, CA: CIWMB.

Langewiesche, W. 2002. *American Ground: Unbuilding the World Trade Center.* New York: North Point Press, 205.

22 Electronics Waste

Farewell, German radio with your green eye and your bulky box
Together almost composing a body and soul.
…. your eye would grow nervous, the green pupil widen and shrink
…your old age was announced by a cracked voice,
then rattles, then coughing, and finally blindness (your eye faded), and total silence.
Sleep peacefully, German radio

Adam Zagajewski (1945–)
Electric Elegy

22.1 INTRODUCTION

Electronics waste (e-waste) is an inevitable and unavoidable by-product of the current technological revolution. e-Waste is a collective term, embracing consumer and business appliances, products, components, and accessories nearing the end of their useful life due to obsolescence, malfunction, or exhaustion (e.g., batteries). Common examples of e-waste include personal and mainframe computers, printers, televisions, VCRs, stereos, copiers, and fax machines. There is no standardized definition for e-waste; however, electronics *equipment* may be defined as those devices whose primary functions are provided by electronic circuitry and components, that is, semiconductor devices (integrated circuits, transistors, and diodes), passive components (resistors, capacitors, and inductors), electro-optical components (cathode ray tubes [CRTs], LEDs, CCDs, lasers, etc.), sensors (transducers and MEM devices), and electronics packaging (printed circuit boards, connectors) (IAER 2002). According to the Consumer Electronics Association (CEA 2008), Americans own approximately 24 electronic products per household. Some major categories of electronics equipment are listed in Table 22.1.

e-Waste comprises about 5% of municipal solid waste (MSW) and is one of the fastest growing fractions of the waste stream (Electronics Takeback Coalition 2011). Today's computer industry innovates rapidly, bringing new technologies and "upgrades" to market every 18 months, on average. The average lifespan of a personal computer is currently 2 years (CAW 2012).

In 2010, the United States disposed 384 million units of e-waste, totaling 2.4 million tons. A recent Environmental Protection Agency (EPA) study estimated that the amount of e-waste in U.S. landfills will grow fourfold in the next few years (CAW 2012). New products rapidly heading to the market create additional waste problems; for example, the disposable cellular telephone became available for marketing in the late 1990s. In addition, disposable DVDs made a brief appearance on the market in the early 2000s.

The issue of how to manage e-waste is a pressing one. Many obsolete and malfunctioning electronic products can be reused, rebuilt, or recycled. However, electronics that malfunction often are not repaired due to the relatively low price of replacing them.

Only 600,000 tons or 17.7% of electronics waste was recycled in 2008, according to EPA (up from 13.6 in 2008). The remainder was either disposed or stockpiled. These data compared with 34% of all MSW recycled. Most were disposed or remain in storage. It is estimated that nearly 75% of unwanted electronics are in storage, partly because of the uncertainty as to how to manage such items.

TABLE 22.1
Categories of Electronics Equipment

User	Application
Consumer	Video: televisions, VCRs, camcorders, digital cameras, control boxes
	Audio: stereo systems and components, CD players, radios
	Communications: cell phones, pagers, PDAs
	Personal: computers, printers, calculators
	Game systems
Automotive	Control systems
	Audio systems
	Instrumentation
	Computers and peripheral equipment: CPUs, monitors, printers, scanners, storage devices, servers, networking systems
	Financial systems: retail/check-out, banking/teller, ATMs
	Security systems: monitoring and detection equipment
	Entertainment: radio, television and movie production equipment, transmission systems, sound and video projection equipment, amusements
	Office equipment: copiers, fax machines, imaging systems, printing systems
Industrial	Telecommunications equipment: telephones, switching systems, PBXs, transmitters, receivers, microwave systems
	Test and measurement equipment: oscilloscopes, power supplies, signal processors
	Medical equipment: EKGs, MRIs, CAT scan, X-ray, monitors
	Manufacturing equipment: control systems, data entry devices, workstations, instruments, process tools
Aerospace	On-board control systems
	Communications systems
	Navigation systems
	Radar and traffic control systems
	In-flight entertainment systems
Military/defense	Weapons control systems
	Communications systems
	Navigational systems
	Security systems
	Encryption systems

Source: Reproduced with kind permission from IAER, *Electronics Equipment,* Albany, NY, 2002, Available from: http://www.iaer.org/electronicsequipment.htm.

More than 3.2 million tons of electronics discards is disposed in landfills in the United States annually (U.S. EPA 2011). It is believed that most households and small businesses disposing e-wastes opt to send them to landfills or incinerators rather than to recyclers. However, landfilling and incineration of e-wastes pose significant health and environmental hazards.

Obsolete electronic equipment is also a concern because electronics are manufactured using valuable resources such as precious metals, engineered plastics, and glass. The elemental breakdown of a personal desktop computer is listed in Table 22.2. When electronic equipment is disposed and new equipment is manufactured in its place, virgin resources are extracted, additional energy is required, valuable resources are wasted, and air and water pollution are generated.

22.2 MAJOR TYPES OF ELECTRONIC EQUIPMENT

Several major types of electronic equipment are encountered in the MSW streams in all U.S. states. These items and their significance are described below.

TABLE 22.2
Elemental Breakdown of a Personal Desktop Computer

Element/Compound	Content (% of Total Weight)	Weight of Material (lb)	Recycling Efficiency (Current Recyclability) (%)	Use and Location
Plastics	22.9907	13.8	20	Includes organics and oxides (other than silica)
Lead	6.2988	3.8	5	Metal joining, radiation shield/ CRT, PWB
Aluminium	14.1723	8.5	80	Structural conductivity/housing, CRT, PWB, connectors
Germanium	0.0016	<0.1	0	Semiconductor/PWB
Gallium	0.0013	<0.1	0	Semiconductor/PWB
Iron	20.4712	12.3	80	Structural, magnetivity/(steel) housing, CRT, PWB
Tin	1.0078	0.6	70	Metal joining/PWB, CRT
Copper	6.9287	4.2	90	Conductivity/CRT, PWB, connectors
Barium	0.0315	<0.1	0	Vacuum tube/CRT
Nickel	0.8503	0.51	80	Structural, magnetivity/(steel) housing, CRT, PWB
Zinc	2.2046	1.32	60	Battery, phosphor emitter/ PWB, CRT
Tantalum	0.0157	<0.1	0	Capacitors/PWB, power supply
Indium	0.0016	<0.1	60	Transistor, rectifiers/PWB
Vanadium	0.0002	<0.1	0	Red phosphor emitter/CRT
Terbium	<0	<0	0	Green phosphor activator, dopant/CRT, PWB
Beryllium	0.0157	<0.1	0	Thermal conductivity/PWB, connectors
Gold	0.0016	<0.1	99	Connectivity, conductivity/ PWB, connectors
Europium	0.0002	<0.1	0	Phosphor activator/PWB
Titanium	0.0157	<0.1	0	Pigment, alloying agent/ (aluminum) housing
Ruthenium	0.0016	<0.1	80	Resistive circuit/PWB
Cobalt	0.0157	<0.1	85	Structural, magnetivity/(steel) housing, CRT, PWB
Palladium	0.0003	<0.1	95	Connectivity, conductivity/ PWB, connectors
Manganese	0.0315	<0.1	0	Structural, magnetivity/(steel) housing, CRT, PWB
Silver	0.0189	<0.1	98	Conductivity/PWB, connectors
Antimony	0.0094	<0.1	0	Diodes/housing, PWB, CRT
Bismuth	0.0063	<0.1	0	Wetting agent in thick film/ PWB
Chromium	0.0063	<0.1	0	Decorative, hardener/(steel) housing
Cadmium	0.0094	<0.1	0	Battery, blue–green phosphor emitter/housing, PWB, CRT

Continued

TABLE 22.2 (*Continued*)
Elemental Breakdown of a Personal Desktop Computer

Element/Compound	Content (% of Total Weight)	Weight of Material (lb)	Recycling Efficiency (Current Recyclability) (%)	Use and Location
Selenium	0.0016	0.00096	70	Rectifiers/PWB
Niobium	0.0002	<0.1	0	Welding alloy/housing
Yttrium	0.0002	<0.1	0	Red phosphor emitter/CRT
Rhodium	<0	<0	50	Thick film conductor/PWB
Platinum	<0	<0	95	Thick film conductor/PWB
Mercury	0.0022	<0.1	0	Batteries, switches/housing, PWB
Arsenic	0.0013	<0.1	0	Doping agents in transistors/ PWB
Silica	24.8803	15	0	Glass, solid state devices/CRT, PWB

Source: Reproduced with kind permission of Microelectronics and Computer Technology Corporation, *Composition of a Desktop Personal Computer, Electronics Industry Environmental Roadmap*. MCC, Austin, TX, 1996.

22.2.1 Personal Computers

Over 81% of U.S. households possess a computer. These include desktop, laptop, handheld models, and others (U.S. Census 2010). Homes and businesses also use a range of peripheral devices (e.g., modems, scanners, printers). The composition of each item varies significantly. Similarly, the recycling processes and economics of each item differ markedly. When a desktop PC is resold, recycled, or scrapped, most recyclers and "demanufacturers" will break it down into: (1) monitors; (2) central processing units (CPUs) (including components such as circuit boards, hard drives, and chips); and (3) peripherals.

22.2.2 Laptop Computers

Laptop computers function similarly to desktop models; however, components are miniaturized and adapted for mobile use. Some of the key components of laptops include: (1) CPU; (2) memory (RAM); (3) power supply—typically an internal rechargeable battery; (4) battery—lithium ion; more recent models use the new lithium polymer technology. These have replaced nickel metal hydride batteries; (5) display—most are based on CCFL or LED lighting; (6) internal storage; (7) input—pointing stick, touchpad, and integrated keyboard; (8) ports, including USB ports, an external monitor port, audio, and an Ethernet network port; and (9) cooling system.

22.2.3 Cathode Ray Tube Computer Monitors

The cathode-ray tube (CRT) is the "picture tube" that produces the image on the monitor screen of older desktop PCs. The primary concern associated with CRT monitors is the presence of lead (Pb).

22.2.4 Computer Central Processing Units

The CPU is the component that actually performs the computing. CPU components that possess value for recycling and demanufacturing include circuit boards, hard drives, memory chips, microprocessor chips, and video cards. These components contain a range of precious metals.

22.2.5 Computer Peripherals

Peripherals are devices that are needed to operate a computer such as the keypad or mouse; that perform additional functions such as printers, scanners, and modems; or that connect different parts of the computer such as cables.

22.2.6 Desktop Telecommunications Equipment (Telephones, Fax Machines)

This category includes desk telephones, fax machines, and communication radios. These products are found in most homes and businesses. PCs, televisions, and desktop telecommunications equipment possess components or materials having a negative or zero net value when recycled. The *net value* is defined as the value of recovered components or materials minus the cost to recover the materials such as cables.

22.2.7 Mainframe Computers and High-End Telecommunications Equipment

Mainframe computers are composed of a large and powerful CPU connected to a number of workstations, each consisting of a monitor and keypad that access the mainframe via automated servers. High-end telecommunications equipment consists of switching equipment for a building or company-wide telephone equipment, and equipment used in commercial audio, video, or telephone applications.

Both mainframe computers and high-end telecommunications equipment possess high-value components or materials that can be recycled with a positive net value. As a result, such equipment is typically purchased by recyclers and demanufacturers, generating substantial revenue (Florida DEP 2002).

22.2.8 Televisions with CRTs

The average American home has 2.9 televisions (Gopal 2009). This number compares with about 81% of households having computers. Yearly television sales have equaled or exceeded 20 million units for the past decade.

Over the previous decades, CRT-equipped televisions had been manufactured in a variety of sizes and styles, including black-and-white and color picture quality. Television "size" is usually measured as a diagonal line across the screen. Common groupings among recyclers and demanufacturers are 19 in. or less and larger than 19 in. Generally, larger TVs, especially console models, are more labor intensive (and therefore more expensive) to demanufacture and recycle (Florida DEP 2002).

Following federal rules for high-definition televisions that became effective in 2004, the numbers of televisions purchased (and CRT-types subsequently discarded) have significantly increased.

22.2.9 Flat Screen Televisions

Approximately 37 million flat screen television sets are sold annually in the United States (Paczkowski 2012). Common configurations of flat screens include liquid crystal displays (LCDs), plasma panels, and electroluminescent panels.

LCDs and plasma displays do not use CRT technology. An LCD monitor includes the front and back frame, circuit boards, the liquid crystal subassembly with driver circuit, and the backlight unit. Electrode patterns are made of a layer of indium tin oxide. The backlight unit includes a frame, fluorescent tubes, a prism, a diffuser, a reflector, and a protective layer. The liquid crystal subassembly drive circuit has a gold coating. Figure 22.1 provides a schematic of a plasma screen.

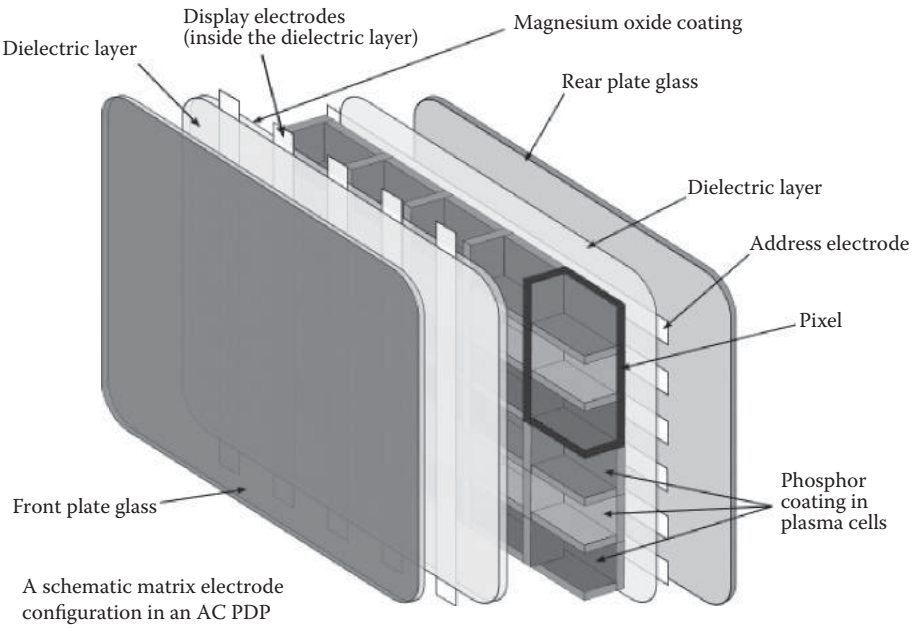


FIGURE 22.1 Schematic of a plasma screen.

22.2.10 Mobile Telephones

Handheld telecommunications equipment such as cellular phones possess components or materials having a negative or zero net value when recycled.

A cell phone's shelf life is only about 18 months for the average consumer (Concord 2012). According to EPA, 141 million mobile phones were discarded in 2009 and only 12 million of those were collected for recycling.

Cell phones contain precious metals and plastics similar to those used in desktop PCs and flat screen television sets. Cell phone circuit boards contain copper, gold, lead, zinc, beryllium, tantalum, and other hazardous metals.

22.3 HAZARDS OF e-WASTE

Electronic equipment contains metals and other materials that are hazardous when improperly managed. For example, e-waste constitutes the source of about 70% of the heavy metals (including Hg and Cd) found in landfills (LRQA 2007).

The central component of earlier computer monitors and televisions is the CRT, which contains leaded glass. CRTs are second only to automotive batteries in terms of Pb contribution to the U.S. MSW stream. Other primary applications of Pb in computers are for soldering printed circuit boards and other electronic components. Consumer electronics constitute 40% of Pb found in landfills.

Cadmium (Cd) occurs in electronic components such as SMD chip resistors, infrared detectors, and semiconductors. Older CRTs also contain Cd. Cd also is used as a plastic stabilizer. The largest source of Cd in MSW is rechargeable nickel–cadmium (Ni–Cd) batteries.

Some manufacturers continue to use Cr(VI) as corrosion protection for untreated and galvanized steel plates and as a decorative coating and hardener for steel housing.

e-Waste is also a leading source of mercury (Hg) in MSW. Approximately 22% of the yearly global consumption of Hg is used in electrical and electronic equipment (Realff et al. 2004). Mercury is used in thermostats, position sensors, relays, and switches (e.g., on printed circuit boards and in measuring equipment) and discharge lamps. Furthermore, it is used in medical equipment,

data transmission, telecommunications, and cellular telephones. Mercury is also used in batteries, switches and housing, and printed wiring boards.

An analysis commissioned by the Microelectronics and Computer Technology Corporation (MCC) estimated that total electronics plastic scrap amounted to more than 525,000 metric tons (580,000 tons) per year. This same study estimated that the largest volume of plastics used in electronics manufacturing (26%) was polyvinyl chloride (PVC). Although many computer companies have reduced or phased out PVC, there is still a huge volume of PVC contained in the computer scrap that continues to grow. PVC is a difficult plastic to recycle and it contaminates other plastics in the recycling process.

The use of PVC in computers has been mainly for cabling and computer housings. Most computer moldings are now, however, being manufactured of acrylonitrile-butadiene styrene (ABS) plastic. PVC cabling is used for its fire-retardant properties, but there are concerns that if combusted, fumes may contribute to fatalities. The production and burning of PVC products generate chlorinated dibenzodioxins and furans. Hence, there are pressures to switch to alternatives for safety reasons. Such alternatives include low-density polyethylene and thermoplastic olefins.

Brominated flame retardants commonly occur in electronic products. In PCs, they are used mainly in four applications: printed circuit boards and components such as connectors, plastic covers, and cables. They are also used in plastic covers of television sets and in domestic kitchen appliances. Recent research indicates that polybrominated diphenylethers (PBDE) might act as endocrine disrupters (SEPA, n.d.). PBDEs also form polybrominated dibenzofurans (PBDFs) and polybrominated dibenzodioxins (PBDDs) during the extruding process (Hoque et al. 1998; SVTC 2001). The German chemical industry halted the production of these chemicals in 1986 (Brenner 1986; SVTC 2001). Table 22.3 lists common brominated and chlorinated flame retardants used in electronics.

22.3.1 Cathode Ray Tubes

Until recently, CRTs were widespread in computer monitors, televisions, and other video display devices. In picture production, x-rays are inevitably generated within the CRT; therefore, Pb is incorporated within CRT glass to protect the viewer from exposure to x-rays. The average

TABLE 22.3
Halogenated Compounds Used in Electronics

Brominated flame retardants (BFRs)	
Polybrominated biphenyls (PBBs)	Currently restricted by the European Union's Restriction on Hazardous Substances Directive
Polybrominated biphenyl ethers (PBDEs)	Restricted by the European Union's Restriction on Hazardous Substances Directive (RoHS).
Deca bromodiphenyl ether (Deca-BDE)	In 2008, the European Court ruled that Deca-BDE must be banned in all electronic products sold in the European Union.
Tetrabromobisphenol A (TBBPA)	
Hexabromocyclododecane (HBCD)	
Chlorine-based compounds	
Polyvinyl chloride (PVC)	Used as coatings for computer cables and wires.
Trichloroethylene	Industrial solvent, used by semiconductor industry for many years. Classified by the U.S. EPA as a human carcinogen.
Trichloroethane	Solvent used to clean chips in the semiconductor industry.

Source: Electronics TakeBack Coalition, *Flame retardants & PVC in electronics*, n.d., Available from: http://www.electronicstakeback.com/toxics-in-electronics/flame-retardants-pvc-and-electronics/

TABLE 22.4
Weight of Glass and Pb Contents for CRTs

Screen Size	Total Glass Weight (lb)	Total Pb in Lead Panel CRT (lb)	Total Pb in No-Lead Panel CRT (lb)
		Portable and Table Televisions	
8" and under	12.9	1.30	1.08
9" and 10"	15.0	1.47	1.21
13" and 14"	17.2	1.75	1.46
20"	28.2	2.70	2.21
25"	43.5	4.05	3.28
29"–31"	81.2	7.99	6.62
35"	117.4	11.28	9.27
		Console Televisions	
26" and under	48.8	4.54	3.68
27"–32"	68.5	6.61	5.44
35" and above	117.4	11.28	9.27
		Monitors	
14"	19.7	na	1.68
15"	19.7	na	1.68
17"	25.7	na	2.08
19"–21"	28.0	na	2.28

Source: Reproduced with kind permission of Monchamp, A., et. al., *Cathode Ray Tube Manufacturing and Recycling: Analysis of Industry Survey*, 2001, Available from: http://www.eiae.org/chemicals/files/EIA_CRT_5-01.pdf.

Note: na = not applicable.

television and PC monitor CRT for the period between 1995 and 2000 measured 18.6 in. and had a Pb content ranging from 1 to 1.2 kg (2.14 to 2.63 lb) (Monchamp et al., 2001). Table 22.4 summarizes the weight of glass and the Pb content of various-sized CRTs manufactured in the United States.

Figure 22.1 shows the locations of Pb within a typical color CRT used in a television or PC monitor. The Pb in the funnel and face plate glass is incorporated (i.e., it is *not* a simple coating) into the glass matrix as lead oxide (PbO). This Pb formulation is stable and immobile; in theory, therefore, it is not expected to leach during the TCLP (see Chapter 11) or in a landfill environment. The Pb in the frit that joins the face plate glass to the funnel glass is in the form of a PbO paste. This Pb readily leaches when subjected to the TCLP.

The CRT cone is an electromagnet that encircles the electron gun at the rear (narrow) end of the CRT (Figure 22.2). The cone, wrapped with a copper yoke, directs the electron beams produced by the electron gun to the faceplate of the CRT to produce the image. A circuit board processes the incoming signal to control the operation of the electron gun in order to provide the correct image on the screen.

22.3.2 Flat Screen TVs and Laptop Computers

LCDs manufactured before 2009 use cold cathode fluorescent lamps, or CCFLs, to backlight the display. The CCFL display contains mercury, which is the primary concern associated with flat screen monitors. Over the next few years, it is expected that hundreds of millions of CCFL-backlighted LCDs will retire each year (Purdue 2012).

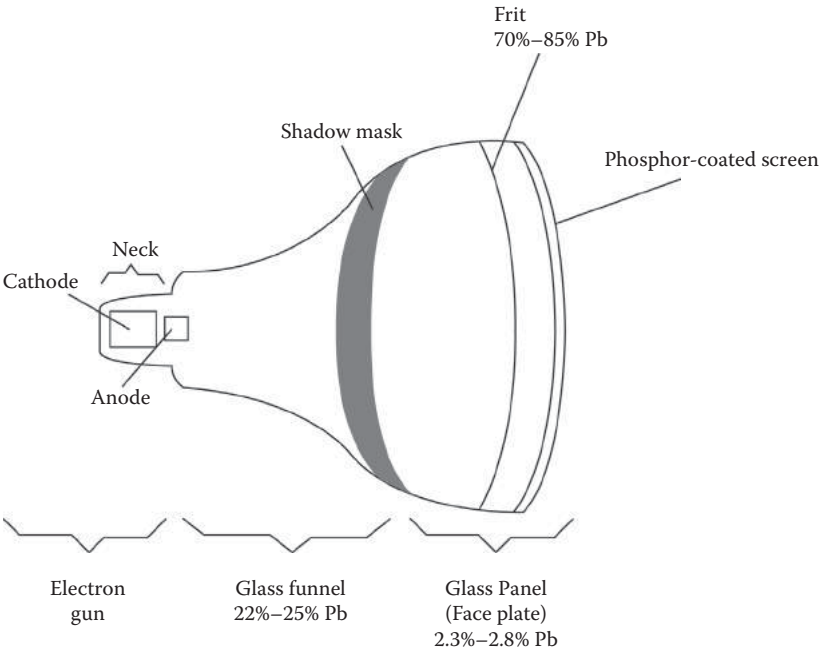


FIGURE 22.2 Cross-section of a CRT showing Pb contents. (Reproduced with kind permission of the Silicon Valley Toxics Coalition, *Californians against Waste and Materials for the Future*, San Jose, CA, Available from: http://www.svtc.org/cleancc/pubs/ppc-ttv1.pdf.)

22.4 RCRA AND e-WASTES

Recall from Chapter 11 that under the Resource Conservation and Recovery Act (RCRA), a solid waste is a discarded material that is

- Abandoned (materials that are disposed, incinerated, or stored in lieu of disposal)
- Recycled
- Inherently waste-like

22.4.1 Hazardous Waste

Hazardous wastes are either listed or are characteristic hazardous wastes (ignitable, corrosive, reactive, and toxic). The RCRA regulations require that the solid waste generator conduct the waste determination. Research has shown that CRTs usually fail the TCLP for toxicity (Townsend et al. 2004; Keith et al. 2008). The California Department of Toxic Substances Control confirmed that the CRTs in computer monitors, television sets, ATMs, and other devices contain TCLP-soluble Pb concentrations that classify them as hazardous waste when they are discarded (Harris 2001; SVTC 2001). Monochrome monitors do not usually exceed TCLP limits and could probably be segregated from color monitors for disposal. California law considers nonfunctioning CRTs from televisions and monitors to be hazardous waste.

The Universal Waste Management Standards (40 CFR part 273), created in 1995, streamline the hazardous waste regulations by removing barriers to collection programs, reducing complexities of management, and reducing costs of compliance. As discussed in Chapter 18, there are four types of federal Universal Wastes: batteries, certain pesticides, mercury-containing thermostats, and lamps (e.g., fluorescent bulbs). States can add their own universal wastes, and some have done so for CRTs.

22.4.2 EPA CRT Rule

In 2006, EPA created a rule dedicated for CRTs rather than designate them as a Universal Waste. The purpose of the rule is to encourage greater reuse, recycling, and better management of this rapidly growing waste stream. The agency formulated a rule designed specifically for CRTs for the following reasons:

- Computers are heavy devices, and the weight cut-offs for Universal Wastes are impractical. (Seven or eight monitors are sufficient to exceed the limits for CESQGs).
- CRTs may resemble commodities more than wastes if handled properly, that is, the glass can be sold to make new CRT glass, Pb can be sent to a lead smelter, and so on.

Under EPA rules, most electronics waste is either nonhazardous waste or a nonwaste. Several hazardous waste exclusions and exemptions apply to encourage reuse and recycling of electronics discards. One of the RCRA incentives for reuse and recycling is the assertion that equipment having potential for reuse is not a waste. Furthermore, a waste can be converted into a nonwaste via the appropriate processing; for example, raw materials and similar commodities can be extracted from the waste.

Some key components of the 2006 rule include:

- Households may send used monitors to any collector for recycling or disposal.
- CESQGs, that is, nonresidential generators of <100 kg per month (about seven or eight computers) are not subject to most subtitle C standards.
- When a user sends CRTs to a reseller for potential reuse or repair, the items are considered products, not wastes.
- Intact, off-specification CRTs sent for recycling are products, not wastes.

In 2012, EPA proposed a rule to revise export provisions of the Cathode Ray Tube Final Rule published in 2006. These proposed changes will allow EPA to obtain additional information on the export of used CRTs to ensure that they are managed in compliance with the regulations.

22.4.3 Circuit Boards

Circuit boards are expected to fail the TCLP for Pb and, therefore, should not be disposed in a sanitary landfill. Circuit boards tend to be recycled or handled as scrap metal, in which case they are not covered under RCRA. Current regulatory requirements for circuit boards are summarized as follows (U.S. EPA 2012a):

- Whole unused circuit boards are considered unused commercial chemical products, which are unregulated.
- Whole used circuit boards not only meet the definition of spent materials but also meet the definition of scrap metal. Therefore, those that are recycled are exempt from the hazardous waste regulations.
- Shredded circuit boards are excluded from the definition of solid waste if they are in containerized storage prior to recovery. Shredded circuit boards cannot contain mercury switches, mercury relays, Ni–Cd batteries, or lithium batteries.

22.5 ELECTRONICS RECYCLING

At present, there is no federal mandate to recycle e-waste. There have been numerous attempts to develop a federal law; however, to date, there is no consensus on a federal approach.

Electronics recycling is a new but growing industry and embraces computers, telecommunications, and consumer electronics equipment (e.g., televisions and audio equipment). About 35 million units of electronic equipment were collected and recycled in 2009 (U.S. EPA 2012b). Computer peripherals, desktop PCs, and CRT computer monitors are the most common equipments recycled; however, the actual percentage of electronics recycled is low. Approximately 25% of electronics were collected for recycling in 2009, with computers, televisions, and mobile phones recycled at 38%, 17%, and 11%, respectively (U.S. EPA 2011). By comparison, over 67% of white goods were recycled in the United States in 2003 (APWA 2009).

Electronic products are manufactured with valuable raw materials that can be reused or recycled. Millions of pounds of materials are recovered annually from electronics including steel, aluminum, copper, precious metals, glass, and plastic. The major sources of electronics products for recycling have been manufacturers and large users. Currently, 75% of the equipment being recycled originates from electronics manufacturers and large organizations (more than 500 employees). Only a very small amount of electronics is being recovered from households (U.S. EPA 2013).

Recovered electronics equipment is recycled by a small group of companies due to the large capital investment and substantial infrastructure required. In the United States, the five largest recycling firms handle more waste electronics equipment than all the other companies combined. In addition, electronics recyclers are geographically concentrated; half of all electronics recycling firms are in the mid-Atlantic and Midwest regions of the United States (APWA 2009).

The electronics recycling industry can be considered a chain of handlers and processors (NSC 1999). The major steps in the chain are

- Collection/separation
- Direct resale of computers or components
- Parts and materials recovery
- Smelting/refining of metals
- Other parties—resellers and not-for-profit organizations

22.5.1 Residential Collection Programs

In order to establish a consistent and high-volume stream of electronics discards, adequate and consistent collection is essential. The costs of residential collection and the inherently lower value of obsolete consumer electronics create economic and logistical obstacles for the public and private sectors. In recent years, a number of programs have been tested to develop approaches to residential collection to overcome these obstacles. EPA has developed such programs, and several states have followed with programs of their own.

In the EPA pilot program, a variety of different collection models were evaluated including curbside collection, drop-off events, establishment of a permanent collection depot (Figure 22.3), and point of purchase (retail) collection. The weighted average of all electronics items collected by the various programs was as follows (U.S. EPA 2002):

- Televisions (36%)
- Audio and stereo equipment (16%)
- Monitors (11%)
- Computers (8%)
- VCRs (6%)

Most of the collected equipment was outdated and in poor condition; therefore, it had low scrap value and was expensive to handle. Items that contained CRTs predominated, which drove up program costs. There were some notable differences in efficiencies and costs between the program models used; for example, curbside collection yielded more pounds of material collected per



FIGURE 22.3 Residential collection and drop-off programs have become popular in many U.S. communities. (Figure 22.3a from Iowa Department of Natural Resources; Figure 22.3b from California Department of Resources Recycling and Recovery (CalRecycle); Figure 22.3c from U.S. Environmental Protection Agency.)

resident, but high transportation costs resulted. Also, the cost per item collected was lower for 1-day collection events due to lower transportation and operating costs. Net costs for the collection program ranged from $0.17 to $0.50 per pound. Predominant costs were for transportation, demanufacturing, and disposal. Adequate planning and promotion were considered essential to overall effectiveness of the electronics waste collection program (U.S. EPA 2002).

Data regarding optimizing collection programs are still lacking in a number of areas, including:

- Up front costs
- Operational costs
- Transportation costs (to the demanufacturer and recycler)
- Economies of scale effects, which should lower program costs in the long run

Other general conclusions were as follows (U.S. EPA 2002):

- Transportation, demanufacturing, and disposal are the main cost considerations for collection programs. New programs, however, incur a number of one-time costs.
- Recovered computers have the most material value, but CRTs, which are costly to manage, are frequently collected. The number of CRTs managed has a major impact on net costs.
- Geographic location affects transportation costs to demanufacturers and recyclers. For example, CRT recyclers are more prevalent on the east coast; however, smelters are more viable options for the Midwest and West regions.
- Compared with residentially collected electronics, commercially used electronics have a higher recovered value, is more uniform, and is easier to disassemble.
- The ability to sell at least a few products for positive income makes a big difference in the overall cost of a collection program.

A number of original equipment manufacturers (OEMs), including Compaq, Dell, Gateway, HP, IBM, and Micron, offer electronics leasing and take-back services. Environmental considerations are an incentive; however, demand from large corporate customers is driving the development of these services. OEMs such as HP are taking computers back from their higher volume customers but do not widely advertise these services. Many corporate customers have become aware of the implications of improper disposal, for example, through regulatory liability and loss of proprietary information.

22.5.2 Reuse and Resale

Reuse and resale are potential outlets for recovered computers. Schools, nonprofit organizations, and low-income households, as well as foreign markets, often welcome the opportunity to acquire older computers. Certain laws, such as the 21st Century Classrooms Act for Private Technology Investment (a provision to the Taxpayer Relief Act of 1997), provide tax incentives for corporations to donate late model computers. However, donated equipment varies greatly in terms of quality and reusability. Also, new computers continue to be faster and cheaper, thereby reducing incentives for computer reuse. According to the Florida DEP, only one usable PC can be constructed from every three computers donated. The availability and cost of computer software for older computers has also been a barrier to computer reuse. Because of copyright requirements, valuable computer software (e.g., word processing) is often erased from PCs prior to donation.

22.5.3 Deconstruction

As seen in Chapter 21, *demanufacturing* a product is the opposite of manufacturing it. Demanufacturers take apart the electronic device to recover usable components such as memory, disk drives, and microprocessor chips, and to recover scrap materials with value such as copper cables and circuit boards. Using this approach, more value is recovered from obsolete electronic products than would be recovered if the whole product were scrapped. Unfortunately, computers have been designed in a manner that makes disassembly difficult.

When a shipment arrives at the processing facility, pallets and containers are unloaded at a central point. Upon arrival, contents are verified and examined for integrity and breakage.



FIGURE 22.4 To resell, deconstruct, or scrap? Testing PC components.



FIGURE 22.5 PC monitors approved for donation.

The equipment is unwrapped, sorted by type, and each type is weighed and counted. The components may then be segregated on the basis of overall condition, age, and other factors. An intact computer may first undergo simple testing of components (Figure 22.4). In many operations, usable components such as hard drives and CRTs are immediately removed for rebuilding or resale (Figures 22.5 and 22.6). Computer and television CRTs are opened and completely disassembled into glass, plastics, copper-bearing materials, and other components (Figure 22.7). Many will separate the hard drives, power supply, printed circuit boards, keypads, mouse, and the steel PC housing (Figure 22.8).

22.5.4 Processing and Recycling e-Waste Components

e-Waste recycling produces three types of commodities: glass, metals, and plastics. Some of the practical aspects of e-waste deconstruction and recycling are shown in Table 22.5.



FIGURE 22.6 Old CRTs awaiting shipment to a recycler.



FIGURE 22.7 Disassembly of a PC.



FIGURE 22.8 PC hard drives separated for eventual recycling.

TABLE 22.5
Practical Aspects of Electronics Deconstruction and Recycling

Metals	Negligible amounts of metals, such as copper, nickel and steel, can be recovered from CRTs. Later models yielded less precious metals than older ones. The copper wire yoke and the shadow masks are also presumed to be hazardous waste.
Plastics	High-value engineering plastic resins, such as high-impact polystyrene (HIPS), acrylonitrile-butadiene styrene (ABS), and polycarbonates (PC) are sold in some domestic markets. Some companies have developed processes to recycle these plastics. However, most plastics are exported to international markets.
Glass	CRT glass recyclers separate cullet into the following streams: • Broken color dirty mix without metals—dirty broken panels • Broken color dirty mix with metals—dirty whole panels • Dirty sorted funnels—whole CRTs • Monochrome CRTs "Mix" refers to panel and funnel glass combined; "dirty" refers to glass with coatings. Broken color dirty mix with metals is broken CRTs with the banding and masks. Broken color dirty mix without metals is color CRTs that have metal banding, gun, and mask removed. Dirty sorted funnels and panels must be free of all metals except pins molded into the glass. Panel received with frit is considered broken dirty color mix without metals.

Source: Reproduced with kind permission of the Materials for the Future Foundation, *CRT Glass to CRT Glass Recycling. The Monitor of Electronics Recycling Issues*, 2001, Available from: http://www.materials4future.org/PUBS/g2g%20final.pdf.

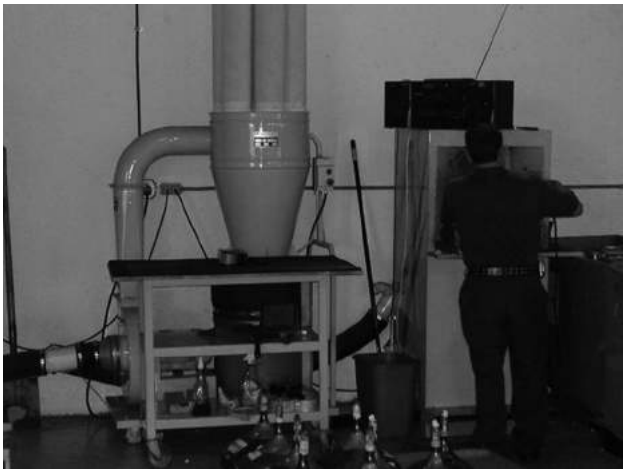


FIGURE 22.9 Unit operation for CRT recycling. A compactor crushes the CRT; the unit is linked with a HEPA baghouse to capture all dust and vapors.

22.5.4.1 CRT Glass

Until recently, CRT glass was recycled into new CRT displays (Figure 22.9); however, due to the rise of flat screen technologies, the demand for CRT glass has collapsed worldwide. Many state regulations require CRT glass to be recycled rather than disposed. Unfortunately, however, there are too few domestic end-markets for this material (WMW 2011).

Few alternative solutions exist for CRT glass. One U.K.-based company collects glass from televisions and CRTs to make tiles that offer an attractive and commercially viable alternative to products made from granite, marble, and ceramics (Recyclinglives n.d.).

22.5.5 Metals

Once electronic devices and components have been collected and segregated, recoverable metals are extracted through one of three processes (MOEA 1995):

1. Mechanical reclamation involves shredding and grinding electronic articles to a fine powder. Metals are then separated from the powder. The powder is managed by means of recycling or energy reclamation.
2. Chemical reclamation (hydrometallurgy) uses a bath to dissolve components and their packaging. Metals are then extracted chemically.
3. Thermal reclamation (pyrometallurgy).

The technology selected depends on several factors. The choice is typically driven by which technology will provide the best return on investment. The total value extracted from electronics scrap can range from hundreds to thousands of dollars per ton, depending on the kind of scrap collected and the technology used to reclaim metals.

Precious metals, such as gold, platinum, silver and palladium, and copper, and steel-bearing materials are often sent to a smelter for recycling. Smelting is defined as a high-temperature metallurgical process in which mineral concentrates and fluxes (such as silica and limestone) are processed in one or more steps to separate molten metal from impurities. In terms of electronics wastes, Pb (from CRT tubes), copper (CRT yokes), and gold (circuit board fingers) are all recoverable by smelting. Some demanufacturing facilities are equipped with the appropriate furnaces for gold and silver recovery.

Lead is recovered in one of two types of smelters. Primary smelters process sulfide concentrates, sulfates, oxides, and metallic scrap. Primary smelting requires a sulfur (S) removal process such as a sinter or acid plant process to capture S and convert it into H_2SO_4. Secondary smelters process only Pb oxides and metallic scrap. Secondary production of Pb begins with recovery of scrap from obsolete or damaged CRTs and new scrap composed of product wastes and smelter refinery residues (MFF 2002).

During smelting, an oven heats the Pb to 1260°C (2300°F). Silica is used as a fluxing agent to separate molten Pb from impurities, which form a slag. CRT glass can be used in the blast furnace as a fluxing agent. Scrap materials and fluxing agents are placed in a blast furnace where coke is burned at high temperatures. Carbon within the coke reacts with the heated air to form gases that chemically reduce the feeds to molten Pb and slag. The fluxing agents, limestone, and iron form a slag that floats to the top of the molten bath. Lead bullion plus the slag flow out of the bottom of the furnace in a continuous molten stream where the slag is separated from the Pb bullion. The molten Pb collects in pots where it is allowed to cool. A residue (dross) forms on the surface of molten Pb as it cools. This dross is removed from the surface and the Pb bullion is further processed in a drossing furnace. The molten slag is tapped from the furnace and granulated. Once the impurities have been removed, the refined Pb is ready to cast (MFF 2002).

The copper yoke on the CRT possesses positive scrap value and is also recovered in the smelting process. A CRT yoke contains 0.9–2.3 kg (2–5 lb) of copper. During smelting, the feedstock is dried and fed into one of several furnace types. There, sulfide minerals are partially oxidized and melted to yield a layer of *matte*, which is a mixed copper–iron sulfide, and the slag, which is an upper layer of waste. The matte is further processed by a method known as converting. The slag is tapped from the furnace and is stored or discarded. Another product of the smelting process is SO_2, which is collected, purified, and converted to H_2SO_4 for sale. Iron and S are removed during the converter process and the remaining molten copper is refined to produce high-purity copper (MFF 2002).

22.5.6 Circuit Boards

The PC circuit board contains copper, very small amounts of gold, and other precious and semiprecious metals that give the circuit board much of its scrap value. Printed circuit boards

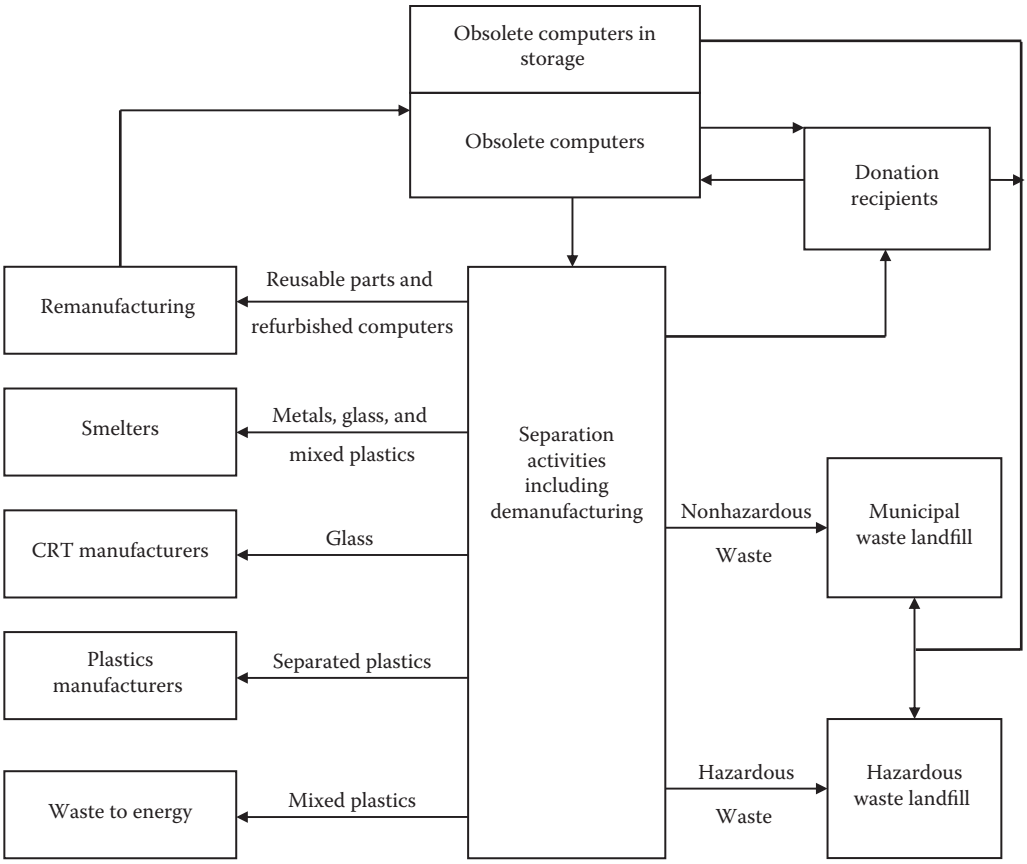


FIGURE 22.10 Flow chart showing options for electronics recycling. (From U.S. Geological Survey, *Obsolete Computers, "Gold Mine," or High-Tech Trash?* 2001, Resource Recovery from Recycling, Fact Sheet 060-01, by D. Bleiwas and T. Kelly. Available from: http://pubs.usgs.gov/fs/fs060-01.)

can be processed to recover the value of its raw materials. Several companies offer recycling services as an alternative to off-site disposal of obsolete printed circuit boards. These services typically remove raw materials of value such as gold, silver, copper, and lead from the board (NFESC 2002).

Scrap gold may be alloyed with other metals, including copper and zinc. Furthermore, gold may be bound with various formulations of plastic and so must be recovered and purified for eventual resale. Depending upon their composition, gold ores are treated by several methods. Processes commonly include gravity separation, amalgamation, cyanidation, and flotation. Some gold ores (or scrap) may be smelted and others roasted to process them for further treatment. In other refining processes, gold is treated with acids or chlorine gas that react with impurities but not with the gold itself. Finally, the refined gold is melted and cast into bars or bricks.

A flow chart showing e-waste recycling options appears in Figure 22.10.

22.6 INTERNATIONAL ISSUES IN ELECTRONICS MANAGEMENT

A substantial overseas market exists for used personal computers and television sets. The volumes of electronics being shipped overseas are not accurately known; similarly, the fates of these waste electronics are unknown. However, the prices being paid for used electronics indicate that reuse, demanufacturing, and recycling are occurring.

A significant portion of U.S. e-wastes is being exported to less-developed countries for processing and disposal. Ninety percent of U.S. e-waste is exported to China and Nigeria (Sthiannopkao and Wong 2012). However, these countries possess neither the technology nor the infrastructure to properly and safely recycle such wastes. As a result, some wastes are being treated and disposed under unsafe conditions.

The majority of the used electronics are sold to foreign recycling processors before recycling or disassembly; therefore, the exported e-waste is classified as a commodity rather than as hazardous waste to be regulated under RCRA. In other words, electronics shipped by recyclers overseas often do not fall under the RCRA's requirement that the recycler provide prior notification of shipment to EPA and obtain consent from the receiving nation of the waste. Ultimately, EPA cannot determine whether the exports of e-waste are actually being recycled or not (Lai 2011).

22.7 BARRIERS TO RECYCLING e-WASTE

The infrastructure in the United States for electronics collection, reuse, and recycling is currently insufficient to manage the huge volumes of existing, not to mention projected, waste volumes. Electronic products have traditionally been designed for disposal and are difficult to disassemble, thus making them expensive to recycle. e-Wastes are bulky, posing transportation and storage problems. Finally (and at the core of any recycling discussion), markets for reclaimed materials are poorly developed.

Problems associated with developing innovative and sustainable technologies for e-waste recycling include: policy and legislative barriers, such as the lack of specific legal frameworks and a low national priority for e-waste; technology and skills barriers, such as the lack of environmental health and safety standards; lack of a collection infrastructure; and business and financing barriers, such as the high costs of logistics (ClickGreen 2010).

Requiring consumers and small businesses to pay the cost of recycling and disposal on the back-end has been ineffective. Reliance on back-end disposal fees reduces incentives for proper recycling, promotes "sham" recycling, and results in improper disposal that ultimately requires clean-up at a cost to taxpayers (SVTC 2001).

22.8 PRODUCT STEWARDSHIP AND ELECTRONICS

Given the complexity of most electronic products, the inherent difficulty in their recycling, and the sheer volumes produced, it is evident that improvements in their manufacture, using a more efficient and environmentally appropriate context, would be welcome. The recent concept of *product stewardship* is clearly relevant at this point. Product stewardship can be defined as (NWPSC 2001)

> whoever designs, makes, sells or uses a product takes responsibility for minimizing its environmental impact. This responsibility spans the product's life cycle—from selection of raw materials to design and production processes to its use and disposal.

Product stewardship can apply to any type of waste and addresses the environmental impact of a product at all stages of its life cycle, from design and manufacture, to packaging and distribution, to end-of-life management. Product stewardship transfers the responsibility for end-of-life management from the public sector (i.e., government and taxpayers) alone to a shared responsibility that includes the private sector (manufacturers and purchasers). The ultimate goal of this arrangement is to encourage environmentally beneficial design and recycling and to reduce the flow of wastes to landfills and incinerators (NWPSC 2001). For example, it is considered appropriate to internalize the cost of waste management into the price of electronic devices at the time of purchase. Such up-front fees can be placed in reserve and eventually allocated to cover the eventual costs for deconstruction, processing, and recycling.

Several European and Asian nations have established product stewardship models that involve numerous types of products, including electronics. European nations have been in the vanguard in addressing the e-waste problem by proposing an ambitious system of *extended producer responsibility*. In 2001, the European Union Parliament adopted a directive that requires producers of electronics to take responsibility, financial and otherwise, for the recovery and recycling of e-waste. A second directive requires manufacturers to phase out the use of hazardous materials in electronics products.

In the United States, the *National Strategy for Electronics Stewardship* was published in 2011. The strategy provides four overarching goals:

1. Build incentives for design of greener electronics, and enhance science, research, and technology development in the United States.
2. Ensure that the federal government leads by example to consider environmental impacts across entire product lifecycles, and to cover additional types of electronics.
3. Increase safe and effective management and handling of used electronics in the United States.
4. Reduce harm from U.S. exports of e-waste and improve safe handling of used electronics in developing countries.

The strategy offers a comprehensive set of recommendations for more responsible management of electronic waste—one that is innovative and flexible—that allows Americans to manage electronics more sustainably, and simultaneously promotes new and innovative technologies.

22.9 CONCLUSIONS

Modern, consumer-driven technological society relies on an ever-growing and constantly changing supply of electronic products. These products are concurrently one of the fastest growing segments of the waste stream. It has been estimated that a half-billion computers have entered the U.S. waste stream over the past decade or more. This number does not include televisions or other unwanted electronic products. The total volume of e-waste is projected to increase markedly unless reuse and recycling options become more available and convenient for the user.

Two pressing issues must be addressed in managing e-waste. The first is how to handle the existing waste stream. Few of such items ever were designed with any consideration for reuse or recycling. The second concern is how to manage future electronic equipment. Regulatory and public pressure will encourage innovative and recycling-oriented design strategies. By applying the principles of product stewardship, electronic equipment can be manufactured with fewer toxic constituents and designed with upgradability, durability, and recyclability in mind.

QUESTIONS

1. What are the trends in generation of e-waste in the United States over the past two decades? How are the majority of e-wastes managed (landfill, stockpile, reuse, etc.)? Does the current recycling rate for these products correspond with generation rate?
2. What is the contribution of consumer electronic products to the lead (Pb) input to sanitary landfills? What is the contribution to Cd input and Mercury input?
3. How does a mainframe computer differ from a typical desktop PC in terms of recyclability? How does a laptop differ from a desktop in this respect?
4. The Pb in CRT funnel and face plate glass occurs as PbO and is considered stable and immobile. Under what conditions, therefore, is the lead in computer CRTs considered hazardous?
5. Where do mercury, chromium, and Cd occur in a personal computer? List specific components.

6. What are the health effects that may be associated with PVC and brominated flame retardants in computers?
7. How does desktop computer plastic differ in terms of recyclability with plastic from a nonfood container (e.g., HDPE or PVC)? You may wish to refer to Chapter 6 (Recycling).
8. What is the benefit in promulgating a separate rule for CRT recycling rather than simply relying on the Universal Waste Rule?
9. How are computer circuit boards managed under RCRA?
10. How would you expect generation of e-waste to change over the next decade? What components may disappear from the waste stream? What new products may begin to appear in large quantities?
11. In your opinion, are current federal and state regulations that address e-waste management and recycling adequate to ensure environmental quality over the long term? Should there be mandatory federal and state recycling of personal computers, laptops, and cellular telephones?
12. List all the major electronic appliances and devices in your home. How long have you owned each? What is the expected lifetime of each? Which do you feel can be safely disposed in the trash when their usable lifetime is complete? Which should be recycled or shipped for special disposal?
13. In your community, how are e-wastes handled? Is there a community drop-off center or an annual special waste disposal event? Is public education adequate so that local citizens are informed about e-waste? If there is a local collection program, check with the local waste authority as to where these wastes are shipped for recycling.
14. Contact your university inventory agent and inquire as to how old or obsolete desktop PCs and laptops are managed. How many are replaced each year? Are the obsolete computers made available for public purchase, or are they donated or recycled? If recycled, discuss where they are sent and how they are managed.
15. What are the major cost considerations for a community considering establishment of an e-waste recycling program? Which steps are likely to be most costly?
16. List possible hazards to workers involved in demanufacture of PCs, television sets, and similar equipment.
17. List some of the practical difficulties in recycling electronic waste.
18. A fire has occurred in an office that houses several dozen desktop and laptop PCs, telephones, a photocopy machine, a DVD player, and a flat screen television monitor. List possible hazards to persons entering the office during and immediately following the fire. You may want to check Materials Safety Data Sheets (available on the Internet) of certain components to determine possible combustion products.
19. Locate sources on the Internet that describe the manufacture of personal computers. What wastes may be generated during the manufacture of PC circuit boards and plastic monitor housing?

REFERENCES

APWA (American Public Works Association). 2009. *Electronics Recycling*. Available from: http://www2.apwa.net//Documents/Advocacy/_SW_%20Electronics%20Recycling_FINAL%281%29.pdf

Brenner, K. 1986. Formation of polybrominated dibenzofurans (PBDFs) and dioxins (PBDDs) during extrusion production of a polybutyleneterephtalate (PBTP) glassfibre resin blended with decabromodiphenylether (PBDPE)/Sb203, Product and workplace analysis, Brenner, Kniew, BASSF.

CAW (Californians Against Waste). 2012. *Poison PCs and Toxic TVs: The Greatest Threat to the Environment You've Never Heard of*. Available from: http://cawrecycles.org/issues/ca_e-waste/poison_pc_report

CEA (Consumer Electronics Association). 2008. *Market Research Report: Trends in CE Reuse, Recycle and Removal*. Arlington, VA: CEA.

ClickGreen. 2010. *Increase in E-waste is Growing "Out of Control."* Available from: http://www.clickgreen.org.uk/research/trends/121247-increase-in-e-waste-is-growing-%E2%80%9Cout-of-control%E2%80%9D.html

Concord. 2012. *E-waste, Solid Waste Services*. Available from: http://www.concordnc.gov/Departments/Solid-Waste-Services/Residential/E-Waste

Electronics TakeBack Coalition. n.d. *Flame retardants & PVC in electronics*, n.d. Available from: http://www.electronicstakeback.com/toxics-in-electronics/flame-retardants-pvc-and-electronics/

Electronics TakeBack Coalition. 2011. *Facts and Figures on E-Waste and Recycling*. Available from: http://www.electronicstakeback.com/wp-content/uploads/Facts_and_Figures_on_EWaste_and_Recycling.pdf

Florida DEP (Florida Department of Environmental Protection). 2002. *Major Types of Electronic Equipment*. Available from: http://www8.myflorida.com/waste/categories/electronics/pages/major_types.htm

Gopal, P. 2009. Average American Home Now has Three TVs. *Bloomberg Businessweek*. Available from: http://www.businessweek.com/the_thread/hotproperty/archives/2009/07/the_average_ame.html

Harris, P. 2001. Chief, State Regulatory Programs Division, Hazardous Waste Management Program, Department of Toxic Substances Control, in a March 20, 2001 letter to Sheila Davis of Materials for the Future Foundation.

Hoque, A., Sigurdson, A.J., Burau, K.D., Humphrey, H.E.B., Hess, K.R., and Sweeney, A.M. 1998. Cancer among a Michigan cohort exposed to polybrominated biphenyls in 1973. *Epidemiology* 9, 373–378.

IAER (International Association of Electronics Recyclers). 2002. *Electronics Equipment.* Available from: http://www.iaer.org/electronicsequipment.htm

Keith, A., Keesling, K., Fitzwater, K., Pichtel, J., and Houy, D. 2008. Assessment of Pb, Cd, Cr and Ag leaching from electronics waste using four extraction methods. *J Environ Sci Health A* 43(14), 1–8.

Lai, K. 2011. E-waste regulation under RCRA. *J Energ Environ Law*. Available from: http://gwujeel.wordpress.com/2011/11/26/e-waste-regulation-under-the-rcra/

LRQA (Lloyd's Register Quality Assurance). 2007. *Waste Electrical and Electronic Equipment (WEEE): The Hidden Price for the Technological Revolution, E-Waste Management*. Available from: http://www.lrqa.in/Images/Waste%20Electrical%20and%20Electronic%20Equipment_tcm99-200737.pdf

Materials for the Future Foundation. 2001. *CRT Glass to CRT Glass Recycling. The Monitor of Electronics Recycling Issues*. Available from: http://www.materials4future.org/PUBS/g2g%20final.pdf

MCC (Microelectronics and Computer Technology Corporation). 1996. *Composition of a Desktop Personal Computer, Electronics Industry Environmental Roadmap*. Austin, TX: MCC.

MFF (Materials for the Future Foundation). 2002. *How Lead Smelting Works, The Monitor of Electronics Recycling Issues*. Available from: http://www.materials4future.org/PUBS/smelting%20final.pdf

MOEA (Minnesota Office of Environmental Assistance). 1995. *Management of Waste Electronic Appliances*. Saint Paul, MN: MOEA.

Monchamp, A., Evans, H., Nardone, J., Wood, S., Proch, E., and Wagner, T. 2001. *Cathode Ray Tube Manufacturing and Recycling: Analysis of Industry Survey*. Available from: http://www.eiae.org/chemicals/files/EIA_CRT_5-01.pdf

NFESC (Naval Facilities Engineering Service Center). 2002. *Printed Circuit Board Recycling.* Available from: http://www.p2library.nfesc.navy.mil/P2_Opportunity_Handbook/2_II_8.html

NSC (National Safety Council). 1999. *Electronic Product Recovery and Recycling (EPR2) Baseline Report*. Washington, DC: NSC—Environmental Health Center.

NWPSC (Northwest Product Stewardship Council). 2001. *Defining Product Stewardship*. Available from: http://www.productstewardship.net/definingStewardship.html

Paczkowski, J. 2012. *Flat-Panel TV Sales Flatten in U.S*. Available from: http://allthingsd.com/20120327/flat-panel-tv-sales-flatten-in-u-s/

Purdue. 2012. New Tools to Aid in Recycling Flat-Screen Monitors, TVs. *Purdue News*. Available from: http://www.purdue.edu/newsroom/releases/2012/Q4/new-tools-to-aid-in-recycling-flat-screen-monitors,-tvs.html

Realff, M.J., Raymond, M., and Ammons, J.C. 2004. E-waste: an opportunity. *Mater Today* 7(1), 40–45.

Recyclinglives. n.d. *Recycling CRT*. Available from: http://www.recyclinglives.com/what-we-do/recycling/recycling-crt/

SEPA (Swedish Environmental Protection Agency). n.d. *Persistent Organic Pollutants*. Available from: http://smn.environ.se/miljonat/english/sokning/sokning.htm

Sthiannopkao, S. and Wong, M.H. 2012. Handling e-waste in developed and developing countries: initiatives, practices, and consequences. *Sci Total Environ*. Available from: http://www.ncbi.nlm.nih.gov/pubmed/22858354

SVTC (Silicon Valley Toxics Coalition). 2001. *Californians against Waste and Materials for the Future*. San Jose, CA. Available from: http://www.svtc.org/cleancc/pubs/ppc-ttv1.pdf

Townsend, T.G., Vann, K., Mutha, S., Pearson, B., Jang, Y.-C., Musson, S., and Jordan, A. 2004. *RCRA Toxicity Characterization of Computer CPUs and Other Discarded Electronic Devices*. Gainesville, FL: University of Florida.

U.S. Census. 2010. *Computer and Internet Use*. Available from: http://www.census.gov/hhes/computer/publications/2010.html
U.S. EPA (U.S. Environmental Protection Agency). 2002. *Electronics Waste*. Available from: http://www.epa.gov/reg3wcmd/eCyclingwaste.htm
U.S. EPA (U.S. Environmental Protection Agency). 2011. *Regulations/Standards, 2011, Electronics Waste Management in the United States through 2009*. EPA 530-S-11-001. Available from: http://www.epa.gov/osw/conserve/materials/ecycling/docs/summarybaselinereport2011.pdf
U.S. EPA (U.S. Environmental Protection Agency). 2012a. *Regulations/Standards*. Available from: http://www.epa.gov/osw/conserve/materials/ecycling/rules.htm
U.S. EPA (U.S. Environmental Protection Agency). 2012b. *Regulations/Standards, Statistics on the Management of Used and End-of-Life Electronics*. Available from: http://www.epa.gov/osw/conserve/materials/ecycling/manage.htm
U.S. EPA (U.S. Environmental Protection Agency). 2013. *eCycling*. Available from: http://www.epa.gov/epaoswer/hazwaste/recycle/ecycling/trends.htm
U.S. Geological Survey. 2001. *Obsolete Computers, "Gold Mine," or High-Tech Trash? Resource Recovery from Recycling*. Fact Sheet 060-01. By D. Bleiwas and T. Kelly. Available from: http://pubs.usgs.gov/fs/fs060-01/
WMW (Waste Management World). 2011. *Market for Recycled CRT Glass Drying Up as Volumes Rise*. Available from: http://www.waste-management-world.com/articles/2011/09/market-for-recycled-crt-glass-drying-up-as-volumes-rise.html

SUGGESTED READINGS AND WEBSITES

Available from: http://www.dtsc.ca.gov/LawsRegulationsPolicies/CRTs/CRT_final_regs.html
CIWMB (California Integrated Waste Management Board). 2003. *Electronic Equipment: Reducing Waste at the CIWMB*. Available from: http://www.ciwmb.ca.gov/Electronics/CaseStudies/CIWMB.htm
Computer Takeback Campaign. n.d. *Legislation and Policy*. Available from: http://www.computertakeback.com/legislation_and_policy/e_waste_legislation_in_the_us/index.cfm
Dean, K. 2003. *Recyclers Pledge to Cut E-waste*. Available from: http://www.wired.com/news/technology/0,1282,57802,00.html
Interagency Task Force on Electronics Stewardship. 2011. *National Strategy for Electronics Stewardship*. Available from: http://www.epa.gov/wastes/conserve/materials/ecycling/taskforce/docs/strategy.pdf
Mayfield, K. 2003. *E-Waste: Dark Side of Digital Age*. Available from: http://www.wired.com/news/technology/0,1282,57151,00.html
News Limited. 2003. *HK Urged to Stop Exporting E-waste*. Available from: http://www.news.com.au/common/story_page/0,4057,7010453%255E15306,00.html
UN Environment Programme. 2009. *Recycling – From E-Waste to Resources, Sustainable Innovation and Technology Transfer Industrial Sector Studies*. Available from: http://www.unep.org/pdf/pressreleases/E-waste_publication_screen_finalversion-sml.pdf
U.S. EPA (U.S. Environmental Protection Agency). 2003. *Electronics Challenge*. Available from: http://www.epa.gov/wastewise/wrr/celect.htm

Part V

Appendix

List of Acronyms and Abbreviations

API	American Petroleum Institute
ASTM	The American Society for Testing and Materials
BDL	below detection limit
b-dRDF	binder (lime) enhanced densified refuse derived fuel
BOD	biochemical oxygen demand
BTEX	benzene, toluene, ethylbenzene, and xylene
C & D	construction and demolition
CEM	continuous emission monitoring
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CESQG	conditionally exempt small quantity generator
CFR	Code of Federal Regulations
CO	carbon monoxide
CO_2	carbon dioxide
COD	chemical oxygen demand
CWA	Clean Water Act
dBa	decibels on the A scale sound level meter
DIY	Do-it-yourself
DoD	Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
d-RDF	densified refuse-derived fuel
DRE	destruction and removal efficiency
EPA	Environmental Protection Agency
ESP	electrostatic precipitator
°F	degrees Fahrenheit
FMC	flexible membrane cap
FML	flexible membrane liner
GAC	granular activated carbon
g/dscm	grams per dry standard cubic meter
GPAD	gallons per acre per day
HAZMAT	hazardous material
HCl	hydrochloric acid (or hydrogen chloride)
HDPE	high-density polyethylene
HHV	higher heat value
HMTUSA	Hazardous Material Transportation Uniform Safety Act of 1990
HSWA	Hazardous and Solid Waste Amendments
HTIS	Hazardous Technical Information Service
ID	inside diameter
ISO	International Organization for Standardization
LCS	leachate collection system
LDPE	low-density polyethylene
LDS	leachate detection system
LEL	lower explosive limit

LHV	lower heating value
LQG	large quantity generator
MCL	maximum contaminant level
MRF	materials recovery facility
MSW	municipal solid waste
MW	megawatt
NA	North American
NEPA	National Environmental Policy Act
ng	nanogram ($1\ g \times 10^{-9}$)
NIMBY	Not in My Backyard
NIMEY	Not In My Election Year
NO_x	nitrogen oxides
nos	not otherwise specified
NPL	National Priorities List
ORM	Other Regulated Material
OSHA	Occupational Safety and Health Administration
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PCDD	polychlorinated dibenzodioxin
PCDF	polychlorinated dibenzofuran
PCP	pentachlorophenol
PETE	polyethylene terephthalate
PM	particulate matter
POTW	publicly owned treatment works
PP	polypropylene
ppb	parts per billion
ppm	parts per million
PS	polystyrene
psi	pounds per square inch
PVC	polyvinyl chloride
RCRA	Resource Conservation Recovery Act
RDF	refuse-derived fuel
SG	specific gravity
SI	System International, the metric system of units
SOx	sulfur oxides
SQG	small quantity generator
SVE	soil vapor extraction
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids
TOC	total organic carbon
TPH	total petroleum hydrocarbons
TSCA	Toxic Substances Control Act
TSDF	treatment, storage and disposal facility
UEL	upper explosive limit
UN	United Nations
U.S. EPA	United States Environmental Protection Agency
UST	underground storage tank
VOA	volatile organic acid
VOC	volatile organic compound

Glossary of Terms

Actinomycetes: a group of heterotrophic, mostly filamentous aerobic microorganisms. Actinomycetes contribute to the stabilization of solid waste via composting.

Activated carbon: roasted carbonaceous material used to remove potentially toxic or undesirable substances from gaseous or aqueous waste.

Activated sludge: biological solids, rich in microbial biomass, produced in an activated sludge basin during secondary wastewater treatment.

Acute toxicity: detrimental effects of a chemical that occur within a relatively short time frame (hours to months).

Acutely hazardous waste: waste that is deemed so hazardous that small amounts are regulated by the U.S. EPA strictly as larger amounts of other hazardous waste. Acutely hazardous wastes are listed in 40 CFR 261.31 and designated with the symbol (H), and in addition those wastes listed in 40 CFR 261.33(e) with EPA Waste Numbers beginning with the letter "P".

Adsorption: the attraction and adhesion of ions or molecules from an aqueous solution onto a solid particle or surface.

Aerobic: system or process in which oxygen, O_2, is required or is present. The biological state of living and growing in the presence of oxygen.

Aerosol: minute droplets of liquid that can remain suspended in the air for prolonged periods.

Afterburner: device used to burn or oxidize the combustible constituents remaining in the exhaust gases produced by prior combustion processes.

Air, combustion (excess): air supplied in excess of the theoretical quantity of air needed for complete combustion.

Air, combustion (primary): air supplied to a combustion system for the initial oxidation of the fuel or waste, often through the fuel bed.

Air combustion (secondary): air introduced above or beyond the fuel bed by natural, induced, or forced draft. Often called overfire air when supplied above the fuel bed.

Air, combustion (stoichiometric): theoretical quantity of air required for complete combustion, calculated from the initial chemical composition of the waste.

Air knife: device for separating light materials from heavier materials in MSW by passing the materials through a plane of moving air.

Air pollution: any chemical or physical change in air that adversely affects biota, materials, or both.

Aliphatic hydrocarbons: class of hydrocarbons that contain no aromatic rings. The class includes alkanes, alkenes, alkynes, and cyclic hydrocarbons.

Alkalinity: a quantitative measure of the capacity of liquids or suspensions to neutralize strong acids. Alkalinity results from the presence of bicarbonates, carbonates, hydroxides, silicates and phosphates, and some other substances.

Alkylaromatic: Aromatic compounds containing alkyl substituents. The more important compounds are benzene-based with one or more methyl, ethyl, or propyl substituents.

Alkynes: The family of hydrocarbons composed of molecules that contain one or more carbon–carbon triple bonds.

Alkene: The family of hydrocarbons composed of molecules that contain one or more carbon–carbon double bonds. Members of this family also are known as olefins.

Anaerobic: a system or process in which oxygen, O_2, is not required or is absent.

Anoxic conditions: environments lacking molecular oxygen.

Aquifer: underground water-bearing geologic formation capable of yielding a significant amount of groundwater to wells or springs.

Aquifer, confined: an aquifer possessing a confining layer between the zone of saturation and the surface.

Aquifer, unconfined: an aquifer that has no confining layers between the zone of saturation and the surface.

Aromatic hydrocarbons: the family of hydrocarbons composed of molecules whose structures are based on benzene; that is, six-membered rings, with alternating double and single carbon–carbon bonds.

Ash: the noncombustible solid by-products or residue from incineration processes.

Autogenous: burn without the need for supplemental fuels.

Bacteria: single-celled microscopic organisms, simple in structure. Some types are capable of causing human, animal, or plant diseases. Others are important in MSW or sewage stabilization.

Bacteria, aerobic: bacteria that require the presence of dissolved or molecular oxygen for their metabolic processes.

Bacteria, anaerobic: bacteria that do not require oxygen for metabolism; in many cases, their growth often is hindered by the presence of oxygen.

Bacteria, facultative: bacteria that can exist and reproduce under either aerobic or anaerobic conditions.

Baghouse (fabric filter): emission control device containing an array of cylindrical bags used to trap solid particulates.

Baler: a machine used to reduce the volume of materials by compression.

Bentonite: an aluminosilicate clay formed by the weathering of feldspars. Bentonites swell when wet and from a dense cement-like material. Bentonite is commonly used as a landfill liner and to fill around well casings.

Benzene: C_6H_6. An aromatic hydrocarbon characterized by a six-carbon ring, with alternating double and single bonds.

Berm: a constructed ridge of soil.

Bioaccumulation: the retention of a substance by an organism, with consequent increase in concentration as the substance progresses through a food chain.

Bioaerosol: finely dispersed airborne particulates that contain organisms, some of which may be pathogenic, for example, bacteria or mold.

Biochemical oxygen demand (BOD): a determination of the amount of organic matter in a sample based on measuring the microbial oxygen consumption necessary to decompose the material.

Biodegradability: the degree to which a substance may be decomposed by the enzymatic activities of microorganisms.

Biodegradable plastic: a plastic that can be decomposed by microorganisms.

Biodegradable waste: organic material that is capable of being decomposed by microorganisms.

Biodegradation: decomposition of a substance into more elementary compounds by the action of microorganisms.

Bioremediation: the use of biological processes to degrade organic contaminants in water or soil.

Bottom ash: the relatively coarse, uncombusted residue of incineration that accumulates on the grate of a furnace.

Btu (British thermal unit): the quantity of heat required to raise the temperature of one lb of water from 63°F to 64°F. 1 Btu = 252 Cal = 0.252 kcal.

Bulky waste: large items of MSW, such as household appliances and furniture.

Burners: Devices that burn used oil for energy recovery in boilers, industrial furnaces, or in hazardous waste incinerators.

Burner, secondary (afterburner): burner installed in the secondary combustion chamber of an incinerator to maintain a minimum temperature and complete the combustion process.

Clean Air Act of 1990: air quality laws that set air quality standards and maximum contaminant levels, and mandates state implementation programs to achieve compliance.

Calorie: the quantity of heat required to raise the temperature of 1 g of water from 14.5°C to 15.5°C.

Carbon dioxide (CO_2): an odorless, colorless by-product of combustion and microbial decomposition.

Carbon monoxide (CO): a colorless, odorless, and highly toxic gas associated with incomplete combustion of organic materials.

Carbon–nitrogen ratio (C/N ratio): the ratio of carbon to nitrogen in a material. This value is a practical consideration for MSW composting.

Carcinogen: cancer-causing agent. A chemical or material that has the potential to induce the abnormal, excessive, and uncoordinated proliferation of certain cell types, or the abnormal division of cells.

Cation: a positively charged ion.

Cation exchange capacity: the ability of a soil or other material to sorb cations; the number of negatively charged sites on a unit weight of material.

Cell, landfill: a single disposal unit of a landfill in which waste is surrounded by compacted soil and covered after filling.

CERCLA: the Comprehensive Environmental Response, Compensation, and Liability Act of 1980. CERCLA sets liability standards for environmental impairment and authorizes identification and remediation of abandoned waste sites. The program implementing this act is commonly called Superfund.

Chlorofluorocarbons (CFCs): a group of man-made compounds used primarily as refrigerants and as propellants for aerosol cans. The use of CFCs as propellants was prohibited in 1979 because of their effect on atmospheric ozone depletion. An example of a CFC is Freon-12, CCl_2F_2.

CFR: Code of Federal Regulations. The U.S. government document in which all federal regulations are published. Each title or chapter is concerned with a different federal department or agency.

Characteristic hazardous waste: any solid waste that is demonstrated to be hazardous on the basis of the characteristics of ignitability, corrosivity, reactivity, and toxicity.

Charging chute: a passage through which waste materials enter an incinerator from above by the force of gravity.

Charging ram: a reciprocating device used to push MSW into an incinerator's combustion chamber.

Chemical precipitation: the use of chemicals to remove dissolved and suspended matter from solution.

Chlorinated dibenzodioxins: a group of polychlorinated compounds characterized by two benzene rings linked by two oxygen bridges in the presence of chlorine atoms.

Chlorinated dibenzofurans: a group of polychlorinated compounds characterized by two benzene rings linked by one oxygen bridge in the presence of chlorine atoms.

Chronic effect: an adverse effect on an organism, with symptoms that develop slowly over a long period of time.

Chronic toxicity: harmful effects of a chemical or material that take a relatively long time (e.g., years, decades) to appear.

Clay: soil particle measuring less than 0.002 mm in diameter.

Closed composting: a reactor system where feedstock is completely enclosed in a chamber in which moisture, aeration, temperature, and so on, are closely controlled. Sometimes referred to as in-vessel composting.

Combustible gas indicator: a portable instrument that detects whether the ambient atmosphere is at an explosive level. Also known as an explosimeter.

Combustion chamber (primary): a chamber in an incinerator where ignition and burning of the waste occurs.

Combustion chamber (secondary): a chamber in an incinerator where combustible solids, vapors, and gases from the primary chamber are burned. Also known as an afterburner.

Combustion, complete: the complete oxidation of a fuel, with either the theoretical amount of air or excess air.

Commercial waste: waste produced by commercial facilities, including retail stores and other service organizations.

Commingled recyclables: mixed recyclable materials separated from MSW at the point of generation. Further separation into individual components occurs at the collection vehicle or at a centralized materials recovery facility.

Composite liner: a liner system composed of an engineered soil layer overlain by a synthetic flexible membrane liner (FML) or geomembrane.

Composting: the controlled, usually aerobic, microbial degradation of organic waste yielding a relatively nontoxic product of potential value as a soil conditioner.

Conditionally exempt generator of hazardous waste (CESQG): facility that generates less than 100 kg of hazardous waste in a calendar month.

Confined aquifer: an aquifer bounded above and below by impermeable beds; an aquifer containing confined groundwater.

Construction and demolition waste: wastes resulting from construction, renovation, remodeling, repair, and demolition operations on houses, commercial buildings, roads, or other structures.

Corrosive hazardous waste: a waste with a pH less than 2.0 or greater than 12.5, or a material capable of corroding steel at the rate of 6.35 mm (0.250 inch) per year at a temperature of 130°F.

Cover material: material, generally soil, used to cover compacted MSW in a sanitary landfill.

Cradle-to-grave hazardous waste management: the system formulated under RCRA to track transfers of hazardous waste from generators through haulers to approved treatment, storage, or disposal facilities.

Crusher: a mechanical device used to compress waste material to a greater density.

Cullet: glass scrap, usually broken into small pieces.

Curbside collection: waste collection at individual households or commercial buildings by municipal or private haulers for subsequent transport to a disposal or other management facility.

Curing of compost: the process by which compost, after the main composting activity, is allowed to set and undergo final chemical and physical changes. Cured compost is stable, can be stored for long periods, and is relatively odorless.

CWA: Clean Water Act of 1987. One of the major regulatory acts to control the spread of water pollutants. CWA requires NPDES permits for a facility to discharge pollutants from a point source.

Cyclone separator: a mechanical device that uses rotating air flow to sort materials according to mass.

Demolition waste: waste materials resulting from the destruction of buildings, roads, and other structures. Major components are typically concrete, wood, bricks, plaster, glass, metal, and other miscellaneous materials.

Dioxins: see "Chlorinated dibenzodioxins."

Disinfection: any process that kills or inactivates most pathogenic microorganisms.

DRE: Destruction and Removal Efficiency. A parameter to evaluate the treatment potential of incineration and other thermal treatment facilities.

Drop-off centers: locations in a community where residents deliver their recyclables or solid waste.

Dross: the scum that forms on the surface of molten metal.

Eddy current separator: a separation device used at materials recovery facilities for segregating nonferrous metals from a waste stream. An alternating magnetic field induces currents in nonferrous metals, which in turn produce a repulsive force and changes the path of motion of the metals.

Electrostatic precipitator: a device for collecting particulates from a gas stream by inducing an electrical charge on the particles in a strong electric field, then removing the particles attracted to electrodes.

Encapsulation: placement of a toxic substance into an inert material such as concrete, glass, or paraffin to isolate it from the environment.

Energy recovery: the retrieval of energy from the combustion of organic materials in an incinerator or methane gas from landfills.

EPA: see United States Environmental Protection Agency.

EPA hazardous waste number: the number assigned by the U.S. EPA to each hazardous waste listed in subpart D of 40 CFR 261, and to each characteristic waste identified in subpart C of 40 CFR 261.

EPA identification number: the number assigned by EPA to each generator, transporter, and treatment, storage, or disposal facility.

EPA Region: the states and territories found in any one of the ten standard federal regions of the United States.

Evapotranspiration: return of water to the atmosphere by the action of both evaporation and release by vegetation.

Exothermic reaction: chemical reaction which releases energy.

Fabric filter: see Baghouse.

Facility: the structures, land, and so on, used for treating, storing, or disposing of waste. A facility may consist of several treatment, storage, or disposal units.

Fermentation: microbial process in which organic compounds serve as both primary electron donors and ultimate electron acceptors.

Ferrous metals: iron and steel. Ferrous metals are attracted to a magnet.

Field capacity: the maximum quantity of water held by saturated material (e.g., compacted solid waste, soil) against the force of gravity.

Final closure: activities mandated to terminate the use of and operations at a landfill.

Flashpoint: minimum temperature at which vapors above a volatile combustible substance ignite in air and support combustion when exposed to a flame.

Fly ash: very fine particulate matter that is carried off an incinerator grate and to the air pollution control equipment, the flue, or both.

Fungi: nonphotosynthetic unicellular and multicellular microorganisms that require organic compounds for growth. Fungi are important agents of decay; many are capable of degrading complex organic compounds such as lignin and cellulose.

Furans: see "Chlorinated dibenzofurans."

Fusion temperature: temperature at which a solid material (e.g., soil) will melt (fuse).

Gaylord: a large reusable corrugated container used for shipping materials. The volume is approximately 1 m^3.

Glasphalt: an asphalt product that incorporates cullet (crushed glass) in the mix. Glasphalt is used as a road-building material.

Grate: devices used to support and transport the burning input material in an incinerator.

Gravel: rock fragments measuring from 2 mm to 64 mm in diameter.

Halogenated organic compounds: organic compounds that contain halogens such as chlorine, bromine, or fluorine within their structure.

Hammermill: a size reduction device that operates by impacting input material with freely-swinging heavy metal hammers pinned to a horizontal or vertical shaft rotating at a high velocity.

HSWA: Hazardous and Solid Waste Amendments. Amendments to RCRA passed in 1984. HSWA incorporated requirements for regulating the operations of UST systems into RCRA. It also exempted petroleum products from the definition of a hazardous substance.

Landfilling: controlled disposal of municipal solid waste within an engineered facility in a series of compacted layers. The waste is covered, usually daily, with soil or similar materials.

Large quantity hazardous waste generator: a facility that generates more than 1000 kg (2,220 lbs) of hazardous waste per calendar month.

Leachate: the chemically and biologically contaminated liquid that has percolated through or drained from waste.

Leachate collection and removal system: a system of collection drains, pipes, and pumps installed at the base of a landfill and used to collect any accumulated leachate.

Lift: a layer of landfill cells in a designated area of a sanitary landfill occurring at approximately the same elevation.

Light nonaqueous phase liquid: contaminant that is not soluble in water and is less dense than water. LNAPLs float on groundwater.

Liner: a protective layer, manufactured of natural (e.g., soil) or synthetic (polymeric) materials, installed along the bottom or sides of a landfill. The purpose of a liner is to reduce migration of leachate into groundwater beneath the site or laterally away from the site.

Listed hazardous waste: a solid waste appearing in the 40 CFR part 261, subpart D, list of wastes known to possess hazardous and/or toxic properties.

LNAPL: see light nonaqueous phase liquid.

Magnetic separator: mechanical device that uses a magnet to sort ferrous materials from other solid wastes.

Manifest: see "Uniform Hazardous Waste Manifest."

Manure: fecal wastes originating from livestock, poultry, etc.

Mass burn: combustion of solid wastes without any prior processing of the waste (i.e., no resource recovery).

Mass burn incinerator: incinerator capable of burning MSW without prior sorting or processing.

Materials recovery: retrieval of potentially useful materials from MSW.

Materials recovery facility (MRF): building fitted with equipment and staffed to sort recyclable materials and convert them to a saleable form.

Maximum achievable control technology: Section 112 (b) of the Clean Air Act requires EPA to promulgate emission standards which require installation of MACT to control sources of 189 chemicals considered harmful to the environment.

Maximum contaminant level: as established by the Safe Drinking Water Act, the maximum amount of a contaminant in water detectable by standard analytical methods. The Act requires EPA to set MCLs in water delivered to users of public water systems.

MCL: see Maximum Contaminant Level.

Mechanical pulp: pulp produced by physically grinding wood into fibers. The primary use of mechanical pulp is for newsprint.

Methane (CH_4): an odorless, colorless, nonpoisonous explosive gas generated during anaerobic microbial decomposition of organic materials. Methane is a common gas generated in a sanitary landfill.

µg: microgram; 1/1,000,000, or 10^{-6} g.

µg/kg: micrograms per kg, or 10^{-6} g per kg.

µg/L: micrograms per liter, or 10^{-6} g per liter.

mg: milligram; one thousandth of a gram, or 1/1000g = 10^{-3} g.

mg/g: milligrams per kg, or 10^{-3} g per kg.

mg/kg: milligrams per kg, or 10^{-3} g per kg.

mg/L: milligrams per liter, or 10^{-3} g per liter.

Microorganisms: microscopic organisms, including bacteria, actinomycetes, yeasts, fungi, some algae, slime molds, protozoa, and some multicellular organisms.

Mixed MSW: refuse that is not sorted into categories of materials.

Moisture content: the amount of water in a material, typically expressed as a percentage of the total mass.

Monofill: a landfill utilized for disposal of one type of waste (e.g., fly ash).

MRF: see "Materials Recovery Facility."

MSDS: Material Data Safety Sheet. Sheet containing relevant health and safety information about a chemical or product. The information relates to toxicity, treatment, flammability, reactivity, and so on, and is required by OSHA §651 and EPCRA §311(a)(1).

MSW: see "Municipal solid waste."

Municipal solid waste (MSW): solid waste generated at residences, commercial establishments, and institutions. Also known as domestic solid waste. MSW excludes construction or demolition debris and automobile scrap.

Mutagen: agent that permanently damages genetic material.

National Priorities List (NPL) sites: abandoned and/or uncontrolled waste sites posing the most severe threats to human health and the environment. The sites have been designated as Superfund sites for cleanup.

Neutralization: treatment process that changes the pH of highly acidic or highly basic substances to near-neutral (pH = 7).

ng: nanogram; one billionth of a gram or 10^{-9} g.

ng/L: nanograms per liter; 10^{-9} g per liter, or 1/1,000,000,000 gram per liter; 1 ng/L = 1 ppb.

Nonspecific hazardous waste sources: listed hazardous waste that arise from a variety of manufacturing and industrial processes. Also known as "F-listed" hazardous waste.

NPDES: National Pollutant Discharge Elimination System. A permit system defined under the Clean Water Act to restrict or control discharges into surface waters.

NPL: see "National Priorities List."

Open burning: combustion of solid waste but without adequate control of combustion conditions.

Open dumping: disposal of solid waste with no consideration to limit pollution or nuisance conditions.

Organic: compounds that contain carbon in combination with one or more elements, typically derived from living organisms.

OSHA: Occupational Safety and Health Administration. Federal agency established by the Occupational Safety and Health Act of 1970.

Oxidation: chemical reaction that involves the removal of electron(s) from an atom, thus resulting in an increase in the atom's oxidation state. Oxidation typically involves combining a substance with oxygen.

Oxidation and reduction: treatment of a hazardous waste to change the oxidation state of a substance such that the waste will be converted to a less toxic form, and its mobility altered or both (e.g., promote precipitation of a waste from solution).

Ozone: O_3, a highly reactive form of oxygen which serves as an effective disinfectant.

PAH: polycyclic aromatic hydrocarbon. Also known as polyaromatic hydrocarbon. Petroleum hydrocarbons containing multiple, fused benzene rings. Several PAHs are hazardous to health and the environment.

Paraffin hydrocarbons: family of hydrocarbons that contain no carbon–carbon multiple bonds. Paraffin hydrocarbons are also known as saturated hydrocarbons or alkanes.

Particulates: aerosols, dusts, fumes, mists, smoke, or matter suspended in the atmosphere.

Pathogenic: substance that may cause disease.

Pathological waste: wastes that contain microorganisms or viruses capable of causing disease.

PCBs: polychlorinated biphenyls. Molecule consisting of two benzene (phenyl) rings connected by a carbon–carbon bridge and bound to several chlorine atoms. PCBs have been used in electrical transformers and in various manufacturing processes. These compounds are resistant to natural degradation processes and are considered a health threat.

PCP: pentachlorophenol. A chlorinated phenol used as a wood preservative. PCP is a hazardous substance.

Percolation: downward movement of water through unsaturated soil, rock, or waste in a landfill by the force of gravity. The ease with which a fluid can flow through a solid material.

Petroleum: a naturally occurring mixture of several hundred hydrocarbons. Crude petroleum is refined (distilled) to produce gasoline, diesel, jet fuel, and other products.

pH: a measure of hydrogen ion concentration and, hence, the acidity or alkalinity of a solution. pH is defined as $-\log[H^+]$.

Polyvinyl chloride (PVC): polymer manufactured from vinyl chloride ($CH_2 = CHCl$) monomers and commonly used in consumer items and construction materials (e.g., "plastic" pipe).

Porosity: ratio of void space in a porous material (e.g., soil, solid waste) to the total volume.

POTW: Publicly owned treatment works. Wastewater treatment facility as designated under the Clean Water Act.

Pozzolanic material: material capable of reacting with lime and water to form concrete.

ppb: parts per billion; µg/L or µg/kg. 0.001% = 10,000 ppb.

ppm: parts per million; mg/L or mg/kg.

Precipitation: process in which dissolved or suspended matter in water aggregates to form solids that separate from the liquid phase by gravity.

PVC: see "Polyvinyl chloride."

Putrescible: capable of being rapidly decomposed by microorganisms so as to cause nuisance from odors and gases. A putrescible waste has a tendency to become highly odorous as it decomposes.

Pyrolysis: thermal decomposition of a material in the absence of oxygen. The high temperatures and starved air conditions evaporate the moisture and decompose the material into various hydrocarbon gases and liquids and a carbon-like residue called char.

RCRA: see "Resource Conservation and Recovery Act."

Reactivity: tendency of a substance to react vigorously or explosively with air, water, or other substances and generate harmful vapors or fumes.

Recycling: separating and processing a component of the waste stream for eventual reuse. Recycling embraces separation of a material from the waste stream, processing, and purchase of the manufactured product.

Recycling diversion rate: amount of recyclables collected and processed into new products, divided by total amount of MSW generated.

Reduction: chemical reaction in which an atom gains electrons, thereby decreasing its oxidation state. Opposite of an oxidation reaction.

Refuse: solid waste

Refuse-derived fuel (RDF): fuel produced from the carbonaceous component of MSW.

Resource Conservation and Recovery Act: originally passed in 1976 and amended in 1986, RCRA is the principal act under which the U.S. EPA regulates hazardous wastes, landfills, and USTs. Objectives of the act include protection of human health and the environment; controlling hazardous waste from the point of generation, transportation, ultimate treatment, storage, disposal, or all of these; and promoting natural resource conservation by reducing the amount of wastes generated.

Resource recovery: retrieval of materials or energy from MSW for the purposes of recycling or reuse.

Returnable bottle: bottle that is returned to the bottler after the original beverage is consumed.

Reuse: using a component of MSW for its original purpose (e.g., refillable beverage bottles).

Rotating biological contactor: mechanical unit in which wastewater is treated aerobically via promoting the formation of microbial films on thin plastic disks that are alternately rotated through a waste stream and air.

Rubbish: nonbulky, domestic, and commercial solid waste, not to include putrescible garbage.

Run-off: rainwater, leachate, or other liquid that drains over land away from a facility.

Run-on: rainwater, leachate, or other liquid that drains over land onto a facility.

Safe Drinking Water Act: federal law amended in 1986 that guarantees safe drinking water to all Americans. Requires EPA to set MCLs for water delivered to users of public drinking water.

Sanitary landfill: an engineered, usually subsurface disposal site. The site is designed and operated so as to compact the waste to the smallest possible volume, to cover the waste with soil at the end of each day, and to minimize adverse effects to groundwater, control landfill gases, and to prevent litter, odor, and other nuisance conditions.

Sanitation: the control of environmental factors that affect human health and hygiene.

Screening: separation of pulverized waste material into selected sizes by using one or more sieve-like devices.

Scrubber: air pollution control device that removes certain gases by passing exhaust gases through a mist of water or an alkaline liquid spray.

SDWA: see "Safe Drinking Water Act."

Secure landfill: landfill designed specifically for disposal of hazardous waste. Mandated under HSWA, secure landfills are equipped with double liners and other containment features to minimize leachate and emissions from the landfill.

Shears: size-reduction device that cuts material by using large blades.

Shredder: mechanical device used to break up waste materials into smaller pieces.

Slag: a glassy substance formed from fusion of materials in an incinerator.

Slurry: fluid mixture of water and fine insoluble particles.

Small quantity hazardous waste generator: facility that generates 100–1000 kg of hazardous waste and no more than 1 kg of acutely hazardous waste in a calendar month.

Smoke: an aerosol consisting of particulates from incomplete combustion of carbonaceous materials.

Soil conditioner: substances which improve the aeration, water holding capacity, and other soil properties necessary for optimum plant growth.

Soil permeability: ease with which water can pass through a soil. See also hydraulic conductivity.

Solid waste: garbage, refuse, sludge, and so on, from a waste treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semisolid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from individual and community activities.

Solid Waste Disposal Act: the original United States waste disposal act, passed in 1965 to regulate solid and hazardous waste disposal and resource recycling. SWDA was amended in 1970, 1973, 1976, 1984, and 1986.

Solid waste management: planning and implementation by a city, municipality, and so on, to handle solid waste.

Solidification: methods used to immobilize toxic substances within hazardous waste by using lime, cement, or fly ash with water to set into concrete.

Source separation: separation of the components of MSW into different recyclable fractions, carried out at the household or commercial establishment level.

Source-separated recyclables: recyclable materials separated from each other and from mixed waste at the point of generation.

Specific hazardous waste sources: listed hazardous wastes that are generated from a specific source or industry. Also known as "K-List" hazardous wastes.

Spoil: soil or rock that has been removed from its original location.

Static pile composting: method of composting in which a pile of waste is aerated in place with the use of aeration pipes installed within the waste pile.

Stoichiometric quantities: the amounts of reactants or products that result in a balanced chemical reaction.

Subtitle C: the component of RCRA that addresses the management of hazardous wastes. A subtitle C waste is a hazardous waste and must be disposed in a permitted facility.

Subtitle D: the component of RCRA that addresses solid waste and solid waste disposal facilities (i.e., sanitary landfills).

Superfund: the program that implements the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

SW-846: test methods for evaluating solid waste and physical/chemical methods. SW-846 is a four-volume compendium of approved test methods, sampling, and monitoring guidance for use in solid waste analyses.

SWDA: see "Solid Waste Disposal Act."

Synthetic liner: landfill liner manufactured of polymeric materials, for example, polyvinyl chloride.

TCLP: see "Toxicity Characteristic Leaching Procedure."

Teratogen: a physical or chemical agent that causes nonhereditary birth defects; that is, the developing fetus is negatively impacted.

Tipping fee: fee charged for delivering MSW to a landfill, incinerator, or recycling facility. The tipping fee is expressed in cost per unit weight or volume.

Tipping floor: unloading floor for vehicles that are delivering refuse to a materials recovery facility, incinerator, or other processing facility.

TSCA: see Toxic Substances Control Act.

Toxicity: capacity of a substance to produce injury or illness through ingestion, inhalation, or absorption through any body surface.

Toxicity Characteristic Leaching Procedure (TCLP): an analytical extraction and test to determine the leaching potential of hazardous contaminants in landfilled solid waste. The test utilizes an acid solution to simulate leaching activity in a landfill. If the TCLP test results in concentrations of toxic constituents above EPA–specified limits, the tested waste is declared hazardous.

TPH: Total petroleum hydrocarbons. A large family of several hundred chemical compounds that originate from crude oil. EPA Method 418.1 or 8015 describes the procedures for quantifying the petroleum hydrocarbon content of a sample.

Transfer station: facility used for removing refuse from collection trucks for transfer into long-haul trucks.

Trommel: rotating inclined drum fitted with holes or screens and used to separate the components of MSW by size.

Toxic Substances Control Act: a federal law promulgated to control the use and manufacture of pesticides and manufactured chemicals.

TSDF: treatment, storage and disposal facility. A facility permitted under RCRA to accept, treat, and dispose or store hazardous wastes.

Underground storage tank (UST): tank that contains petroleum products or hazardous substances and has 10% of its volume underground.

Uniform Hazardous Waste Manifest: the shipping document required for the "cradle–grave" management of hazardous wastes, originated and signed by a generator of hazardous waste. This is EPA Form 8700-22 and, if necessary, EPA Form 8700-22A.

United States Environmental Protection Agency: the chief federal agency charged with setting regulations to protect the environment.

Universal waste: a group of wastes regulated under the Universal Waste Rule (40 CFR part 273). The wastes include batteries, pesticides, thermostats, and certain lamps. The primary purpose of the rule is to promote appropriate recycling and disposal of several potential hazardous wastes produced in large quantities by businesses regulated under RCRA. Until recently, such wastes were managed solely as RCRA hazardous wastes.

Used oil: any oil that has been refined from crude oil or any synthetic oil that has been used and as a result of such use is contaminated by physical or chemical impurities, as stated in 40 CFR part 279.

Used oil marketer: company that helps move shipments of used oil to burners.

Used oil re-refiners and processors: facilities that remove impurities from used oil. The oil product will be burned for energy recovery or reused.

Used oil transporter: company that collects used oil from a source for delivery to re-refiners or burners.

Used oil transfer facility: site where used oil is held for more than 1 day, but not longer than 35 days.

Vegetative cover: plant growth occurring on soil, spoils, landfill covers, and so on.

Virgin material: raw material for industrial processes that has not been previously used.

Virus: small, noncellular particle, typically composed of a strand of ribonucleic acid in a protein coat; many viruses cause disease in humans and other organisms.

Viscosity: the resistance of a material to shear or flow, and a measure of the material's adhesive–cohesive or frictional properties.

Volatile matter: material capable of being vaporized or evaporated quickly.

Waste: a material perceived to have no value or negative economic value.

Waste exchange: organization that promotes the exchange of waste materials between industries. One company's wastes may serve as the feedstock for another industry.

Water Pollution Control Act: federal legislation passed in 1965 and amended in 1972 that addresses industrial water pollution by requiring wastewater treatment plants (POTWs) and management plans.

Waterwall incinerator: incinerator combustion chamber constructed for capturing energy by heating water or steam within tubes installed within the combustion chamber walls.

Wetland: areas that are inundated for a part of each year. Under the Clean Water Act, projects that are expected to change wetlands must have a §404 permit.

White goods: large metal household appliances (e.g., stoves, dryers, refrigerators, etc.).

Windrow: long row of heaped material, often compost, left on the ground.

Windrow composting: a composting method in which waste is placed in long rows that are periodically "turned" to promote aeration.

WPCA: see "Water Pollution Control Act."

Solubility Product Constants at 25°C

Substance	Formula	K_{sp}
Aluminum hydroxide	$Al(OH)_3$	1.3×10^{-33}
Aluminum phosphate	$AlPO_4$	6.3×10^{-19}
Barium carbonate	$BaCO_3$	5.1×10^{-9}
Barium chromate	$BaCrO_4$	1.2×10^{-10}
Barium fluoride	BaF_2	1.0×10^{-6}
Barium hydroxide	$Ba(OH)_2$	5×10^{-3}
Barium sulfate	$BaSO_4$	1.1×10^{-10}
Barium sulfite	$BaSO_3$	8×10^{-7}
Barium thiosulfate	BaS_2O_3	1.6×10^{-6}
Bismuthyl chloride	BiOCl	1.8×10^{-31}
Bismuthyl hydroxide	BiOOH	4×10^{-10}
Cadmium carbonate	$CdCO_3$	5.2×10^{-12}
Cadmium hydroxide	$Cd(OH)_2$	2.5×10^{-14}
Cadmium oxalate	CdC_2O_4	1.5×10^{-8}
Cadmium sulfide[a]	CdS	8×10^{-28}
Calcium carbonate	$CaCO_3$	2.8×10^{-9}
Calcium chromate	$CaCrO_4$	7.1×10^{-4}
Calcium fluoride	CaF_2	5.3×10^{-9}
Calcium hydrogen phosphate	$CaHPO_4$	1×10^{-7}
Calcium hydroxide	$Ca(OH)_2$	5.5×10^{-6}
Calcium oxalate	CaC_2O_4	2.7×10^{-9}
Calcium phosphate	$Ca_3(PO_4)_2$	2.0×10^{-29}
Calcium sulfate	$CaSO_4$	9.1×10^{-6}
Calcium sulfite	$CaSO_3$	6.8×10^{-8}
Chromium(II) hydroxide	$Cr(OH)_2$	2×10^{-16}
Chromium(III) hydroxide	$Cr(OH)_3$	6.3×10^{-31}
Cobalt(II) carbonate	$CoCO_3$	1.4×10^{-13}
Cobalt(II) hydroxide	$Co(OH)_2$	1.6×10^{-15}
Cobalt(III) hydroxide	$Co(OH)_3$	1.6×10^{-44}
Cobalt(II) sulfide[a]	CoS	4×10^{-21}
Copper(I) chloride	CuCl	1.2×10^{-6}
Copper(I) cyanide	CuCN	3.2×10^{-20}
Copper(I) iodide	CuI	1.1×10^{-12}
Copper(II) arsenate	$Cu_3(AsO_4)_2$	7.6×10^{-36}
Copper(II) carbonate	$CuCO_3$	1.4×10^{-10}
Copper(II) chromate	$CuCrO_4$	3.6×10^{-6}
Copper(II) ferrocyanide	$Cu[Fe(CN)_6]$	1.3×10^{-16}
Copper(II) hydroxide	$Cu(OH)_2$	2.2×10^{-20}
Copper(II) sulfide[a]	CuS	6×10^{-37}
Iron(II) carbonate	$FeCO_3$	3.2×10^{-11}
Iron(II) hydroxide	$Fe(OH)_2$	8.0×10^{-16}
Iron(II) sulfide[a]	FeS	6×10^{-19}
Iron(III) arsenate	$FeAsO_4$	5.7×10^{-21}
Iron(III) ferrocyanide	$Fe_4[Fe(CN)_6]_3$	3.3×10^{-41}

Continued

Substance	Formula	K_{sp}
Iron(III) hydroxide	$Fe(OH)_3$	4×10^{-38}
Iron(III) phosphate	$FePO_4$	1.3×10^{-22}
Lead(II) arsenate	$Pb_3(AsO_4)_2$	4×10^{-36}
Lead(II) azide	$Pb(N_3)_2$	2.5×10^{-9}
Lead(II) bromide	$PbBr_2$	4.0×10^{-5}
Lead(II) carbonate	$PbCO_3$	7.4×10^{-14}
Lead(II) chloride	$PbCl_2$	1.6×10^{-5}
Lead(II) chromate	$PbCrO_4$	2.8×10^{-13}
Lead(II) fluoride	PbF_2	2.7×10^{-8}
Lead(II) hydroxide	$Pb(OH)_2$	1.2×10^{-15}
Lead(II) iodide	PbI_2	7.1×10^{-9}
Lead(II) sulfate	$PbSO_4$	1.6×10^{-8}
Lead(II) sulfide[a]	PbS	3×10^{-28}
Lithium carbonate	Li_2CO_3	2.5×10^{-2}
Lithium fluoride	LiF	3.8×10^{-3}
Lithium phosphate	Li_3PO_4	3.2×10^{-9}
Magnesium ammonium phosphate	$MgNH_4PO_4$	2.5×10^{-13}
Magnesium arsenate	$Mg_3(AsO_4)_2$	2×10^{-20}
Magnesium carbonate	$MgCO_3$	3.5×10^{-8}
Magnesium fluoride	MgF_2	3.7×10^{-8}
Magnesium hydroxide	$Mg(OH)_2$	1.8×10^{-11}
Magnesium oxalate	MgC_2O_4	8.5×10^{-5}
Magnesium phosphate	$Mg_3(PO_4)_2$	1×10^{-25}
Manganese(II) carbonate	$MnCO_3$	1.8×10^{-11}
Manganese(II) hydroxide	$Mn(OH)_2$	1.9×10^{-13}
Manganese(II) sulfide[a]	MnS	3×10^{-14}
Mercury(I) bromide	Hg_2Br_2	5.6×10^{-23}
Mercury(I) chloride	Hg_2Cl_2	1.3×10^{-18}
Mercury(I) iodide	Hg_2I_2	4.5×10^{-29}
Mercury(II) sulfide[a]	HgS	2×10^{-53}
Nickel(II) carbonate	$NiCO_3$	6.6×10^{-9}
Nickel(II) hydroxide	$Ni(OH)_2$	2.0×10^{-15}
Nickel(II) sulfide[a]	NiS	3×10^{-19}
Scandium fluoride	ScF_3	4.2×10^{-18}
Scandium hydroxide	$Sc(OH)_3$	8.0×10^{-31}
Silver acetate	$AgC_2H_3O_2$	2.0×10^{-3}
Silver arsenate	Ag_3AsO_4	1.0×10^{-22}
Silver azide	AgN_3	2.8×10^{-9}
Silver bromide	AgBr	5.0×10^{-13}
Silver chloride	AgCl	1.8×10^{-10}
Silver chromate	Ag_2CrO_4	1.1×10^{-12}
Silver cyanide	AgCN	1.2×10^{-16}
Silver iodate	$AgIO_3$	3.0×10^{-8}
Silver iodide	AgI	8.5×10^{-17}
Silver nitrite	$AgNO_2$	6.0×10^{-4}
Silver sulfate	Ag_2SO_4	1.4×10^{-5}
Silver sulfide[a]	Ag_2S	6×10^{-51}
Silver sulfite	Ag_2SO_3	1.5×10^{-14}
Silver thiocyanate	AgSCN	1.0×10^{-12}
Strontium carbonate	$SrCO_3$	1.1×10^{-10}

Continued

Substance	Formula	K_{sp}
Strontium chromate	$SrCrO_4$	2.2×10^{-5}
Strontium fluoride	SrF_2	2.5×10^{-9}
Strontium sulfate	$SrSO_4$	3.2×10^{-7}
Thallium(I) bromide	TlBr	3.4×10^{-6}
Thallium(I) chloride	TlCl	1.7×10^{-4}
Thallium (I) iodide	TlI	6.5×10^{-8}
Thallium(III) hydroxide	$Tl(OH)_3$	6.3×10^{-46}
Tin(II) hydroxide	$Sn(OH)_2$	1.4×10^{-28}
Tin(II) sulfide[a]	SnS	1×10^{-26}
Zinc carbonate	$ZnCO_3$	1.4×10^{-11}
Zinc hydroxide	$Zn(OH)_2$	1.2×10^{-17}
Zinc oxalate	ZnC_2O_4	2.7×10^{-8}
Zinc phosphate	$Zn_3(PO_4)_2$	9.0×10^{-33}
Zinc sulfide[a]	ZnS	2×10^{-25}

[a] Sulfide equilibrium of the type:

$$MS(s) + H_2O_{(l)} \rightarrow M_2{}^{+}{}_{(aq)} + HS^-_{(aq)} + OH^-_{(aq)}$$

Metric Conversion Chart

To convert U.S. System to Metric System

Length
Mil to millimeter: multiply by 0.0254
Inch to millimeter: multiply by 25.4
Inch to centimeter: multiply by 2.54
Foot to centimeter: multiply by 30.48
Foot to meter: multiply by 0.3048
Yard to meter: multiply by 0.9144

Area
$Inch^2$ to $millimeter^2$: multiply by 645.16
$Inch^2$ to $centimeter^2$: multiply by 6.4516
$Foot^2$ to $centimeter^2$: multiply by 929.03
$Foot^2$ to $meter^2$: multiply by 0.0929
$Yard^2$ to $meter^2$: multiply by 0.8361

Volume
$Inch^3$ to $centimeter^3$: multiply by 16.3871
Gallon to $decimeter^3$: multiply by 3.7854
Gallon to $meter^3$: multiply by 0.0038
$Foot^3$ to $meter^3$: multiply by 0.0283
$Yard^3$ to $meter^3$: multiply by 0.7646

Mass
Pound to gram: multiply by 453.5924
Pound to kilogram: multiply by 0.4536
Pound to metric ton: multiply by 0.00045
U.S. ton to metric ton: multiply by 0.9072

Density
lb/in^3 to kg/m^3: multiply by 27.680
lb/ft^3 to g/cm^3: multiply by 0.0160
lb/ft^3 to kg/m^3: multiply by 16.0185
lb/in^3 to g/cm^3: multiply by 27.68

Temperature
Degrees F to degrees C: (°F – 32)/(1.8)

Energy and Power
Btu to J: multiply by 1055.1
Btu to W * h: multiply by 0.2931
Btu/lb to kJ/kg: multiply by 2.326
Btu/(lb*F) to J/(kg*C): multiply by 4187

Output
lb/min to g/s: multiply by 7.560
lb/h to kg/h: multiply by 0.4536

Velocity
in./min to cm/s: multiply by 0.0423
ft/s to m/s: multiply by 0.3048

To convert Metric System to U.S. System

Length
Millimeter to mil: multiply by 39.37
Millimeter to inch: multiply by 0.0394
Centimeter to inch: multiply by 0.3937
Centimeter to foot: multiply by 0.0328
Meter to foot: multiply by 3.2808
Meter to yard: multiply by 1.0936

Area
$Millimeter^2$ to $inch^2$: multiply by 0.0016
$Centimeter^2$ to $inch^2$: multiply by 0.155
$Centimeter^2$ to $foot^2$: multiply by 0.0011
$Meter^2$ to $foot^2$: multiply by 10.7639
$Meter^2$ to $yard^2$: multiply by 1.1960

Volume
$Centimeter^3$ to $inch^3$: multiply by 0.061
$Decimeter^3$ to gallon: multiply by 0.2642
$Meter^3$ to gallon: multiply by 264.17
$Meter^3$ to $foot^3$: multiply by 35.3147
$Meter^3$ to $yard^3$: multiply by 1.3079

Mass
Gram to pound: multiply by 0.0022
Kilogram to pound: multiply by 2.2046
Metric ton to pound: multiply by 2204.6
Metric ton to U.S. ton: multiply by 1.1023

Density
kg/m^3 to lb/in^3: multiply by 0.000036
g/cm^3 to lb/ft^3: multiply by 62.43
kg/m^3 to lb/ft^3: multiply by 0.0624
g/cm^3 to lb/in^3: multiply by 0.03613

Temperature
Degrees C to degrees F: (1.8 * °C) + 32

Energy and Power
J to Btu: multiply by 0.00095
W * h to Btu: multiply by 3.412
kJ/kg to Btu/lb: multiply by 0.4299
J/(kg*C) to Btu/(lb*F): multiply by 0.000239

Output
G/s to lb/min: multiply by 0.1323
kg/h to lb/h: multiply by 2.2046

Velocity
cm/s to in./min: multiply by 23.6220
m/s to ft/s: multiply by 3.2808

ENVIRONMENTAL ENGINEERING

Second Edition

WASTE MANAGEMENT PRACTICES

Municipal, Hazardous, and Industrial

Waste Management Practices: Municipal, Hazardous, and Industrial, Second Edition addresses the three main categories of wastes (hazardous, municipal, and "special" wastes) covered under federal regulation outlined in the Resource Conservation and Recovery Act (RCRA), an established framework for managing the generation, transportation, treatment, storage, and disposal of several forms of waste.

Focusing on integrating the technical and regulatory complexities of waste management, this book covers the historical and regulatory development of waste management and the management of municipal solid wastes. It also addresses hazardous wastes and their management, from the perspectives of identification, transportation, and requirements for generators as well as treatment, storage, and disposal facilities.

Features:

- Covers the three main categories of wastes under regulation in the United States
- Incorporates an extensive set of problems, presented at the end of several chapters as appendices
- Includes numerous review/homework questions at the end of each chapter
- Highlights special categories of waste that may not fit precisely into either RCRA Subtitle D (Solid Wastes) or Subtitle C (Hazardous Wastes)

In addition to the end-of-chapter problems provided in all chapters of this book, the text also contains practical exercises using data from field situations.

Waste Management Practices: Municipal, Hazardous, and Industrial, Second Edition is an ideal textbook or reference guide for students and professionals involved in the management of all three categories of wastes.

K19078

ISBN: 978-1-4665-8518-8
90000
9 781466 585188

CRC Press
Taylor & Francis Group
an informa business
www.crcpress.com

6000 Broken Sound Parkway, NW
Suite 300, Boca Raton, FL 33487
711 Third Avenue
New York, NY 10017
2 Park Square, Milton Park
Abingdon, Oxon OX14 4RN, UK

www.crcpress.com