

大 学 环 境 教 育 丛 书

影 印 版

George Tchobanoglous
Hilary Theisen
Samuel Vigil

Integrated Solid Waste Management

Engineering Principles and Management Issues

固体废物的全过程管理

—— 工程原理及管理问题



清华大学出版社

McGraw-Hill



Integrated Solid Waste Management
Engineering Principles and Management Issues

固体废物的全过程管理

——工程原理及管理问题

George Tchobanoglous

Hilary Theisen

Samuel Vigil

清华大学出版社

McGraw-Hill

(京)新登字 158 号

INTEGRATED SOLID WASTE MANAGEMENT/George Tchobanoglous,
Hilary Theisen, Samuel Vigil

Copyright © 1993 by The McGraw-Hill Companies, Inc.

IESBN 0-07-063237-5

Original English Language Edition Published by The McGraw-Hill Companies,
Inc.

All Rights Reserved.

For Sale in Mainland China only.

本书影印版由 McGraw-Hill 出版公司授权清华大学出版社在中国境内(不包括香港特别行政区、澳门特别行政区和台湾地区)独家出版、发行。
未经出版者书面许可,不得以任何方式复制或抄袭本书的任何部分。

本书封面贴有清华大学出版社激光防伪标签,无标签者不得销售。

北京市版权局著作权合同登记号: 01-1999-1264

书 名: 固体废物的全过程管理——工程原理及管理问题

作 者: George Tchobanoglous, Hilary Theisen, Samuel Vigil

出版者: 清华大学出版社(北京清华大学学研楼, 邮编 100084)

[http:// www. tup. tsinghua. edu. cn](http://www.tup.tsinghua.edu.cn)

印刷者: 清华大学印刷厂

发行者: 新华书店总店北京发行所

开 本: 787×960 1/16 印张: 62.25

版 次: 2000 年 3 月第 1 版 2000 年 3 月第 1 次印刷

书 号: ISBN 7-302-01012-9/X·23

印 数: 0001~3000

定 价: 69.50 元

出版前言

在跨入 21 世纪之际,面临不断恶化的生存环境,人类清醒地认识到要走可持续发展之路。而发展环境教育是解决环境问题和实施可持续发展战略的根本。高等学校的环境教育,是提高新世纪建设者的环境意识,并向社会输送环境保护专门人才的重要途径。为了反映国外环境类教材的最新内容和编写风格,同时也为了提高学生阅读专业文献和获取信息的能力,我们精选了一些国外优秀的环境类教材,组成大学环境教育丛书(影印版),本书即为其中的一册。所选教材均在国外被广泛采用,多数已再版,书中不仅介绍了有关概念、原理及技术方法,给出了丰富的数据,还反映了作者不同的学术观点。

我们希望这套丛书能对高等院校师生和广大科技人员有所帮助,同时对我国环境教育的发展作出贡献。

清华大学出版社
McGraw-Hill 出版公司
2000 年 1 月

ABOUT THE AUTHORS

George Tchobanoglous is a professor of civil and environmental engineering at the University of California at Davis. He received a B.S. in civil engineering from the University of the Pacific, an M.S. in sanitary engineering from the University of California at Berkeley, and a Ph.D. in environmental engineering from Stanford University. His principal research interests are in the areas of solid waste management, wastewater treatment, wastewater filtration, aquatic systems for wastewater treatment, and individual on-site treatment systems. He has authored or coauthored over 200 technical publications and 10 textbooks. He is the principal author of the predecessor of this textbook. Unless otherwise noted, all of the photographs in this textbook were taken, developed, and printed by him. Professor Tchobanoglous serves nationally and internationally as a consultant to both governmental agencies and private concerns. An active member of numerous professional societies, he is past president of the Association of Environmental Engineering Professors. He has served as a member of the California Waste Management Board. He is a registered civil engineer in California and a Diplomat of the American Academy of Environmental Engineers.

Hilary Theisen is Vice President and Director of the solid waste and resource recovery program at Brown and Caldwell Consultants. He received a B.S. in civil engineering from the University of Minnesota and an MBA from the University of Santa Clara. His broad solid waste management experience started as a consultant in 1966. In the mid 1970s he directed solid waste operations in Sacramento County, California, which provided collection, transfer, recycling, and disposal services in a community of 380,000 people. At Brown and Caldwell Consultants, he oversees the production of studies, designs, and reports for public agencies and private industry. He has provided consulting services throughout the United States, Argentina, Taiwan, Puerto Rico, and Venezuela. He has authored numerous papers and articles on solid waste management and is the coauthor of the predecessor of this textbook, *Solid Waste: Engineering Principles and Management Issues*. He is a registered professional engineer in California, Hawaii, Oregon, and Washington.

Samuel Vigil is a professor of civil and environmental engineering at California Polytechnic State University, San Luis Obispo. He received a B.S. in civil engineering from the University of California at Berkeley, an M.S. in environmental engineering from Texas A&M University, and a Ph.D. in environmental engineering from the University of California at Davis. His principal research interests are in the areas of gasification of solid wastes, recycling technologies, computer modeling of integrated waste management systems, and computer-aided engineering. He has authored or coauthored 26 publications and holds a U.S. Patent in energy conversion. Professor Vigil is active as a consultant to state and local governments and has also consulted internationally in Europe, Latin America, and Southeast Asia. He is active in the Solid Waste Processing Division of the American Society of Mechanical Engineers, the Air and Waste Management Association, and the American Public Works Association. A Navy veteran, Professor Vigil is a Commander in the Naval Reserve Civil Engineer Corps. He is a registered civil engineer in California and a Diplomate of the American Academy of Environmental Engineers.

PREFACE

Solid wastes are all the wastes arising from human and animal activities that are normally solid and are discarded as useless or unwanted. Because of their intrinsic properties, discarded waste materials are often reusable and may be considered a resource in another setting. *Integrated Solid Waste Management* is the term applied to all of the activities associated with the management of society's waste. The basic goal of Integrated Solid Waste Management is to manage society's waste in a manner that meets public health and environmental concerns and the public's desire to reuse and recycle waste materials.

The need for a text that puts the engineering and scientific details of Integrated Solid Waste Management into the framework of resource management has grown significantly in recent years. This textbook is a response to that need. Both the student and the practitioner will find in this book the engineering principles, the data, the engineering and scientific formulas, and examples of the day-to-day issues associated with the management of municipal solid waste. The book integrates and expands the principles of solid waste management that were introduced in a predecessor text entitled, *Solid Wastes: Engineering Principles and Management Issues*.

ORGANIZATION

This book is organized into six parts. To understand the many facets of solid waste management, it is important to know how the field has evolved from the technology of horse-drawn carts to legislation-driven technology. The historical

development of this field and its current perspectives are presented in Part I. To answer the question of whether solid waste is an untapped resource or a disposal problem, information must be available on the sources, composition, and properties of solid waste. These subjects are considered in Part II.

Because solid waste management has the dual functions of resource recovery and waste disposal, there is no one best place to apply the appropriate technology. In each situation, engineering principles must be applied to evaluate equipment and facility options, to make operational choices, and to develop management systems. The basic engineering principles that are an integral part of solid waste management are presented in Part III.

Advanced engineering principles related to the separation, processing, and transformation of solid waste are presented in Part IV. Separate chapters are included on materials separation and processing technologies, thermal conversion technologies, and biological and chemical conversion technologies. Because the reuse and/or sale of recovered materials is of considerable importance, a separate chapter is devoted to this subject.

The need for continuing care of the land remains after landfills are closed. Closure, restoration, and rehabilitation of landfills are presented in Part V. Both active and abandoned landfill sites are considered as there are thousands of sites that existed before current regulatory standards for closure were developed.

Important management issues that must be evaluated in the development and operation of Integrated Solid Waste Management systems are discussed in Part VI. For many communities, the critical issues arise from state mandates for waste diversion from landfills. Two chapters are devoted to this important topic. The methodology for completing solid waste management plans and documents, mandated by federal and state laws, is considered in the final chapter.

IMPORTANT FEATURES OF THIS BOOK

To illustrate the principles and facilities involved in the field of Integrated Solid Waste Management, over 530 illustrations, graphs, and diagrams are included. To help the reader understand the material presented in this textbook, detailed solved examples and case studies are presented in Chapters 3 through 20. Whenever possible, spreadsheet solutions are presented. To help the readers of this textbook hone their analytical skills, a series of discussion topics and problems are included at the end of each chapter. Selected references are also included at the end of each chapter.

To further increase the utility of this textbook, a series of appendixes have been included. A glossary of terms is presented in Appendix A. Physical characteristics of water and landfill gases are presented in Appendixes B and C, respectively. The statistical analysis of solid waste management data is delineated in Appendix D. Cost data for solid waste equipment and facilities are presented in Appendix E. The remaining appendixes deal with information related to the analysis and design of landfills.

USE OF THIS BOOK

Enough material is presented in this textbook to support up to three quarters or two semester-length courses at either the undergraduate or graduate level. Drafts of this book have been used at both levels at the University of California, Davis, and at the California Polytechnic State University. The first eleven chapters comprise a basic introduction to the field of Integrated Solid Waste Management. In the publisher's outside review process, it was suggested that the material presented in Chapters 12 through 15, which deals with materials recovery and waste transformation, be combined with the material presented in Chapter 9. To have combined these chapters would have altered the basic objective of this textbook. The material presented in Chapters 12 through 20 has been included to allow the book to be used for an advanced course in materials recovery and transformation and for a course dealing with policy issues in integrated solid waste management. A suggested outline for an introductory course in integrated solid waste management is presented below.

Topic	Reading
Introduction and evolution of solid waste management	Chapters 1 and 2
Sources, composition, and properties	Chapters 3, 4, and 5
Solid waste generation rates	Chapter 6
Waste handling, separation, storage, and processing at the source	Chapter 7
Collection of solid waste and source-separated materials	Chapter 8
Separation processing, and transformation of waste materials	Chapter 9
Waste/transfer and transport	Chapter 10
Disposal of solid wastes and residual matter	Chapter 11
Closure of landfills (added for semester course)	Chapter 16
Remedial actions for abandoned waste disposal sites (added for semester course)	Chapter 17
Recycling of waste materials (added for semester course)	Chapter 15

A suggested outline for a graduate course dealing with materials recovery, processing, and waste transformation is presented below.

Topic	Reading
Introduction and evolution of solid waste management	Chapters 1 and 2
Sources, composition, and properties	Chapters 3, 4, and 5
Solid waste generation rates	Chapter 6
Introduction to materials processing	Sections 9-1-9-6
Materials processing and recovery	Chapter 12
Introduction to thermal conversion technologies	Section 9-7
Thermal conversion technologies	Chapter 13
Introduction to biological and chemical conversion technologies	Section 9-8
Biological and chemical conversion technologies	Chapter 14
Recycling of waste materials	Chapter 15
Strategies for selecting the proper mix of technologies	Chapter 18

The following outline is appropriate for a course dealing with integrated solid waste management policy issues.

Topic	Reading
Evolution of waste management and legislation	Chapters 1 and 2
Sources, composition, and properties of solid waste	Chapters 3 and 4
Solid waste generation and collection rates	Chapter 6
Management issues: meeting mandated diversion goals/planning	Chapters 18, 19, and 20
Issues in waste handling, separation, storage, and processing at the source	Readings from Chapter 7
Issues in collection/transfer and transport	Readings from Chapters 8 and 10
Issues in materials recovery	Readings from Chapters 9, 12, and 15
Issues in the disposal of solid wastes and residuals	Readings from Chapter 11
Issues in the closure, restoration, and rehabilitation of landfills	Readings from Chapters 16 and 17
Strategies for selecting the proper mix of technologies	Selected readings

In an undertaking of the magnitude of this textbook, it is impossible to avoid errors. Any corrections, criticisms, or suggestions for improvements will be appreciated by the authors. Additional information and data are also welcomed.

ACKNOWLEDGMENTS

This textbook could not have been written without the help of a number of people. The help and support of the following individuals are acknowledged gratefully: the solid waste management classes of the senior author that worked with and corrected earlier draft versions of this textbook; Professor Michael Stallard, who reviewed several drafts of Chapter 11 and offered valuable suggestions for organizing the material; Ms. Doreen Brown Salizar for her help with the example problems in Chapter 11; Dr. Masoud Kayhanian, who reviewed and revised Chapter 14; Mr. Bill Freeman, who researched and prepared the first draft of Chapter 15; Mrs. Eva Vigil, who researched and prepared the section on landfill revegetation in Chapter 16; Professors Audrey Levine, Don Modesitt, Alan Molof, Roberto Narbaitz, Jerry Ongerth, Fred Pohland, Debra Reinhart, Kanti Shah, and Albert Yeung, who taught with draft versions of this textbook and offered many valuable suggestions; and Rosemary Tchobanoglous, who proofread much of the text. The following outside reviewers made helpful suggestions on both the content and organization of the text: Charles Cole, Pennsylvania State University–Harrisburg; Robert E. Deyle, Florida State University; and Kanti L. Shah, Ohio Northern University.

In addition, the help of the following organizations is acknowledged gratefully: Paul Geisler and Paul Hart of Davis Waste Removal for allowing us to photograph all aspects of their collection and recycling operation; Joe Garbarino of Marin Recycling for allowing us to photograph all aspects of his multifaceted operation; NORCAL Waste Systems, for allowing us to photograph their

transfer station operation at San Francisco, CA; The County Sanitation Districts of Los Angeles County, CA; the County of Orange, CA; Escambia County, FL; Oakland Scavengers and Waste Management, Inc.; Yolo County, CA, who allowed us to take photographs at landfills operated under their jurisdiction; and the equipment manufacturers who supplied photographs of equipment and facilities.

We should also mention Dr. Marguerite Torrey and Mr. Jerome Colburn, our copy editors, whose concern for logic and correctness deserves special thanks. Finally, we are pleased to acknowledge the key role played by Kristina Williamson, senior production editor at Publication Services. Her attention to detail and her tireless efforts in coordinating and formatting this book went well beyond the call of duty.

*George Tchobanoglous
Hilary Theisen
Samuel Vigil*

CONTENTS

Preface	xi
---------	----

Part I Perspectives

1	Evolution of Solid Waste Management	3
1-1	Solid Waste—A Consequence of Life	3
1-2	Waste Generation in a Technological Society	5
1-3	The Development of Solid Waste Management	7
1-4	Integrated Solid Waste Management	15
1-5	Operation of Solid Waste Management Systems	18
1-6	Discussion Topics and Problems	21
1-7	References	22
2	Legislative Trends and Impacts	23
2-1	Major Legislation	23
2-2	Impact of Federal Legislation	27
2-3	Governmental Agencies	32
2-4	Enforcing the Hierarchy of Integrated Solid Waste Management	34
2-5	Future Trends	35
2-6	Discussion Topics and Problems	36
2-7	References	36

Part II Sources, Composition, and Properties of Solid Waste

3	Sources, Types, and Composition of Municipal Solid Wastes	39
3-1	Sources of Solid Wastes	40
3-2	Types of Solid Wastes	40
3-3	Composition of Solid Wastes	45
3-4	Determination of the Composition of MSW in the Field	58

3-5	Types of Materials Recovered from MSW	59
3-6	Future Changes in Waste Composition	64
3-7	Discussion Topics and Problems	67
3-8	References	67
4	Physical, Chemical, and Biological Properties of Municipal Solid Waste	69
4-1	Physical Properties of MSW	69
4-2	Chemical Properties of MSW	76
4-3	Biological Properties of MSW	87
4-4	Physical, Chemical, and Biological Transformations of Solid Waste	90
4-5	Discussion Topics and Problems	97
4-6	References	98
5	Sources, Types, and Properties of Hazardous Wastes Found in Municipal Solid Waste	99
5-1	Properties and Classification of Hazardous Wastes	99
5-2	Sources, Types, and Quantity of Hazardous Wastes Found in MSW	103
5-3	Significance of Hazardous Wastes in MSW	110
5-4	Physical, Chemical, and Biological Transformations of Hazardous Waste Constituents Found in MSW	113
5-5	Management of Hazardous Wastes in MSW	119
5-6	Discussion Topics and Problems	121
5-7	References	122

Part III Engineering Principles

6	Solid Waste Generation and Collection Rates	125
6-1	Importance of Waste Quantities	125
6-2	Measures and Methods Used to Assess Solid Waste Quantities	126
6-3	Solid Waste Generation and Collection Rates	137
6-4	Factors That Affect Waste Generation Rates	142
6-5	Quantities of Materials Recovered from MSW	146
6-6	Quantities of Household Hazardous Wastes	147
6-7	Waste Characterization and Diversion Studies	149
6-8	Discussion Topics and Problems	152
6-9	References	157
7	Waste Handling and Separation, Storage, and Processing at the Source	159
7-1	Handling and Separation of Solid Waste at the Source	159
7-2	Waste Handling and Separation at Residential Dwellings	160
7-3	Waste Handling and Separation at Commercial and Industrial Facilities	170
7-4	Storage of Solid Wastes at the Source	170

7-5	Processing of Solid Wastes at Residential Dwellings	181
7-6	Processing of Solid Wastes at Commercial and Industrial Facilities	190
7-7	Discussion Topics and Problems	190
7-8	References	191
8	Collection of Solid Waste	193
8-1	Waste Collection	193
8-2	Types of Collection Systems, Equipment, and Personnel Requirements	204
8-3	Analysis of Collection Systems	210
8-4	Collection Routes	228
8-5	Alternative Techniques for Analysis of Collection Systems	237
8-6	Discussion Topics and Problems	238
8-7	References	245
9	Separation and Processing and Transformation of Solid Waste	247
9-1	Reuse and Recycling Opportunities for Waste Materials	248
9-2	Materials Recovered at Drop-off and Buy-back Centers	251
9-3	Options for the Separation of Waste Materials	253
9-4	Introduction to the Unit Operations Used for the Separation and Processing of Waste Materials	255
9-5	Facilities for Handling, Moving, and Storing Waste Materials	265
9-6	Development and Implementation of MRFs	270
9-7	Waste Transformation through Combustion	291
9-8	Waste Transformation through Aerobic Composting	302
9-9	Impact of Source Reduction and Waste Recycling on Waste Transformation Processes	317
9-10	Selection of Proper Mix of Technologies	320
9-11	Discussion Topics and Problems	320
9-12	References	323
10	Transfer and Transport	325
10-1	The Need for Transfer Operations	325
10-2	Types of Transfer Stations	328
10-3	Transport Means and Methods	343
10-4	Transfer Station Design Requirements	352
10-5	Location of Transfer Stations	354
10-6	Discussion Topics and Problems	357
10-7	References	360
11	Disposal of Solid Wastes and Residual Matter	361
11-1	The Landfill Method of Solid Waste Disposal	362
11-2	Landfill Classification, Types, and Methods	371
11-3	Landfill Siting Considerations	377
11-4	Composition and Characteristics, Generation, Movement, and Control of Landfill Gases	381

11-5	Composition, Formation, Movement, and Control of Leachate in Landfills	417
11-6	Surface Water Management	447
11-7	Structural and Settlement Characteristics of Landfills	457
11-8	Environmental Quality Monitoring at Landfills	460
11-9	Layout and Preliminary Design of Landfills	468
11-10	Landfill Operation	485
11-11	Landfill Closure and Postclosure Care	490
11-12	Landfill Process Computations	491
11-13	Discussion Topics and Problems	531
11-14	References	538

Part IV Separation, Transformation, and Recycling of Waste Materials

12	Materials Separation and Processing Technologies	543
12-1	Unit Operations for the Separation and Processing of Waste Materials	543
12-2	Size Reduction	544
12-3	Size Separation	552
12-4	Density Separation	559
12-5	Magnetic and Electric Field Separation	565
12-6	Densification (Compaction)	570
12-7	Selection of Facilities for Handling, Moving, and Storage of Waste Materials	578
12-8	Movable Equipment Used for Materials Handling	582
12-9	Design of Materials Recovery Facilities (MRFs)	583
12-10	Discussion Topics and Problems	606
12-11	References	608
13	Thermal Conversion Technologies	611
13-1	Fundamentals of Thermal Processing	611
13-2	Combustion Systems	618
13-3	Pyrolysis Systems	627
13-4	Gasification Systems	630
13-5	Environmental Control Systems	636
13-6	Energy Recovery Systems	657
13-7	Discussion Topics and Problems	666
13-8	References	668
14	Biological and Chemical Conversion Technologies	671
14-1	Biological Principles	671
14-2	Aerobic Composting	684
14-3	Low-Solids Anaerobic Digestion	697
14-4	High-Solids Anaerobic Digestion	701
14-5	Development of Anaerobic Digestion Processes and Technologies for Treatment of the Organic Fraction of MSW	705

14-6	Other Biological Transformation Processes	710
14-7	Chemical Transformation Processes	710
14-8	Energy Production from Biological Conversion Products	713
14-9	Discussion Topics and Problems	713
14-10	References	715

15	Recycling of Materials Found in Municipal Solid Waste	717
15-1	Key Issues in Materials Recycling	718
15-2	Aluminum Cans	720
15-3	Paper and Cardboard	723
15-4	Plastics	728
15-5	Glass	735
15-6	Ferrous Metal (Iron and Steel)	738
15-7	Nonferrous Metals	742
15-8	Yard Wastes Collected Separately	743
15-9	Organic Fraction of MSW	747
15-10	Construction and Demolition Wastes	749
15-11	Wood	752
15-12	Waste Oil	754
15-13	Used Tires	758
15-14	Lead-Acid Batteries	760
15-15	Household Batteries	762
15-16	Future Recycling Opportunities	763
15-17	Discussion Topics and Problems	764
15-18	References	765

Part V Closure, Restoration, and Rehabilitation of Landfills

16	Closure of Landfills	769
16-1	Development of a Closure Plan	769
16-2	Revegetation of Closed Landfill Sites	778
16-3	Long-term Postclosure Care	790
16-4	Legal Framework	796
16-5	Discussion Topics and Problems	797
16-6	References	798
17	Remedial Actions at Inactive Waste Disposal Sites	799
17-1	Impact of Inactive Landfills	800
17-2	Quantifying the Problem and Completing the Site Designation	803
17-3	Hazardous Waste Landfill Remediation	810
17-4	Other Designated Waste Landfill Remediation	811
17-5	Discussion Topics and Problems	816
17-6	References	817

Part VI Solid Waste Management and Planning Issues

18	Meeting Federal- and State-Mandated Diversion Goals	821
18-1	Strategies for Meeting Diversion Goals	822
18-2	Source Reduction	824
18-3	Recycling—Source Separation of Wastes	828
18-4	Recycling—Materials Recovery	834
18-5	Waste Transformation through Composting	844
18-6	Discussion Topics and Problems	845
18-7	References	846
19	Implementation of Solid Waste Management Options	847
19-1	Changing Priorities in Integrated Solid Waste Management	847
19-2	Collection System Mechanization	848
19-3	Energy Recovery	855
19-4	Landfill Disposal	864
19-5	Discussion Topics and Problems	871
19-6	References	872
20	Planning, Siting, and Permitting of Waste Management Facilities	873
20-1	Planning in Solid Waste Management	873
20-2	Developing a Facilities Plan	880
20-3	Securing a Site and Obtaining Permits	885
20-4	Discussion Topics and Problems	904
20-5	References	904
	Appendixes	
A	Glossary	905
B	Metric Conversion Factors	913
C	Physical Properties of Water	915
D	Presentation and Analysis of Solid Waste Management Data	917
E	Typical Cost Data and Cost-Estimating Procedures for Equipment Used in Solid Waste Management Systems	931
F	Solubility of Landfill Gases Dissolved in Water	937
G	Carbonate Equilibrium	941
H	Physical Properties of Selected Volatile and Semivolatile Organic Compounds	943
I	Landfill Gas Flow Head Loss Computations	945
	Indexes	
	Name Index	951
	Subject Index	957