

EPA 625/1 - 79-011

PROCESS DESIGN MANUAL
FOR
SLUDGE TREATMENT AND DISPOSAL

U.S. ENVIRONMENTAL PROTECTION AGENCY
Municipal Environmental Research Laboratory
Office of Research and Development

Center for Environmental Research Information
Technology Transfer

September 1979

NOTICE

The mention of trade names or commercial products in this publication is for illustrative purposes only and does not constitute endorsement or recommendation for use by the USEPA.

FOREWORD

The formation of the United States Environmental Protection Agency marked a new era of environmental awareness in America. This Agency's goals are national in scope and encompass broad responsibility in the areas of air and water pollution, solid wastes, pesticides, and radiation. A vital part of EPA's national pollution control effort is the constant development and dissemination of new technology.

It is now clear that only the most effective design and operation of pollution control facilities using the latest available techniques will be adequate to ensure continued protection of the nation's waters. It is essential that this new technology be incorporated into the contemporary design of pollution control facilities to achieve maximum benefit of our expenditures.

The purpose of this manual is to provide the engineering community and related industry with a new source of information to be used in the planning, design, and operation of present and future wastewater pollution control facilities. It is recognized that there are a number of design manuals and manuals of standard practice, such as those published by the Water Pollution Control Federation, available in the field, and that each of these adequately describes and interprets current engineering practices as related to traditional plant design. It is the intent of this manual to supplement this existing body of knowledge by describing new treatment methods and by discussing the application of new techniques for more effectively removing a broad spectrum of contaminants from wastewater".

Much of the information presented is based on the evaluation and operation of pilot, demonstration, and full-scale plants. The design criteria thus generated represent typical values. These values should be used as a guide and should be tempered with sound engineering judgment based on a complete analysis of the specific application.

This manual is one of several available from Technology Transfer to describe technological advances and new information. Future editions will be issued as warranted by advancing state-of-the-art to include new data as they become available and to revise design criteria as additional full-scale operational information is generated.

ABSTRACT

The purpose of this manual is to present a contemporary review of sludge processing technology, with particular emphasis on design methodology. This is a revision of a manual originally published in October 1974.

The revised edition incorporates chapters on design approach, disinfection, composting, transport, storage, sidestream treatment, and instrumentation. Other sections have been considerably expanded.

Design examples are used throughout the manual to illustrate design principles.

TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	iii
ABSTRACT	iv
LIST OF TABLES	xx
LIST OF FIGURES	xxxvi
ACKNOWLEDGEMENTS	xlix
CHAPTER 1. PURPOSE AND SCOPE	I- I
1.1 Purpose	I- 1
1.2 Scope	1- 2
1.3 Process Classification ..	1- 2
1.4 References	1- 2
CHAPTER 2. GENERAL CONSIDERATIONS	2- 1
2.1 Introduction and Scope ..	2- 1
2.2 Legal and Regulatory Considerations	2- 1
2.2.1 Effect of Effluent Discharge Limitations on Wastewater solids Management	2- 1
2.2.2 Restrictions on Wastewater Solids Treatment	2- 2
2.2.2.1 Air Emissions Limits ..	2- 2
2.2.2.2 Nuisances	2- 3
2.2.2.3 State and Local Requirements ..	2- 3
2.2.3 Laws and Regulations Governing Wastewater Solids Utilization and Disposal	2- 3
2.2.3.1 Federal Water Pollution Control Act ..	2- 4
2.2.3.2 Resource Conservation and Recovery Act	2- 3
2.2.3.3 Toxic Substances Control Act	2- 5
2.2.3.4 Marine Protection, Research and Sanctuaries Act	2- 5
2.2.3.5 Environmental Policy Acts	2- 5
2.2.3.6 State and Local Reuse and Disposal Requirements	2- 5
2.2.4 The Comprehensive Nature of Section 405 of the Clean Water Act ..	2- 5
2.3 Other Non-Technical Factors Affecting Wastewater Solids Management	2- 6
2.3.1 Availability of Construction Funds	2- 6
2.3.2 Special Funding Requirements	2- 7

TABLE OF CONTENTS (continued)

	Page
2.3.3 Time Span of Decisions	2- 7
2.3.4 Uncertainties	2- 8
2.3.5 The Design Team	2- 9
2.3.6 Public Involvement	2- 9
2.3.7 Social and Political Factors Affecting Waste Export	2- 10
2.4 References	2- 11
CHAPTER 3. DESIGN APPROACH	3- 1
3.1 Introduction	3- 1
3.2 Systems Approach	3- 1
3.3 The Logic of Process Selection	3- 2
3.3.1 Identification of Relevant Criteria	3- 2
3.3.2 Identification of System Options	3- 4
3.3.3 System Selection Procedure	3- 6
3.3.3.1 Base and Secondary Alternatives	3- 6
3.3.3.2 Choosing a Base Alternative: First Cut	3- 7
3.3.3.3 Choosing a Base Alternative: Second Cut	3- 10
3.3.3.4 Third Cut	3- 11
3.3.3.5 Subsequent Cuts	3- 12
3.3.4 Parallel Elements	3- 12
3.3.5 Process Selection at Eugene, Oregon	3- 13
3.4 The Quantitative Flow Diagram	3- 18
3.4.1 Example: QFD for a Chemically Assisted Primary Treatment Plant	3- 18
3.4.2 Example: QFD for Secondary Plant With Filtration	3- 24
3.5 Sizing of Equipment	3- 24
3.6 Contingency Planning	3- 29
3.6.1 Example of Contingency Planning for Breakdowns	3- 29
3.7 Other General Design Considerations	3- 34
3.7.1 Site Variations	3- 34
3.7.2 Energy Conservation	3- 35
3.7.3 Cost-Effective Analyses	3- 36
3.7.4 Checklists	3- 38
3.8 References	3- 39
CHAPTER 4. WASTEWATER SOLIDS PRODUCTION AND CHARACTERIZATION	4- 1
4.1 Introduction	4- 1
4.2 Primary Sludge	4- 1
4.2.1 Primary Sludge Production	4- 1
4.2.1.1 Basic Procedures for Estimating Primary Sludge Production	4- 1
4.2.1.2 Industrial Waste Effect	4- 2
4.2.1.3 Ground Garbage Effect	4- 3
4.2.1.4 Other Sludges and Sidestreams	4- 3

TABLE OF CONTENTS (continued)

	<u>Page</u>
4.2.1.5 Chemical Precipitation and Coagulation	4 3
4.2.1.6 Peak Loads	4 3
4.2.2 Concentration Properties	4 6
4.2.3 Composition and Characteristics	4 7
4.3 Biological Sludges	4 9
4.3.1 General Characteristics	4 9
4.3.2 Activated Sludge	4- 9
4.3.2.1 Processes Included	4 9
4.3.2.2 Computing Activated Sludge Production - Dry Weight Basis	4 9
4.3.2.3 Example: Determination of Biological Sludge Production	4- 19
4.3.2.4 Interaction of Yield Calculations and the Quantitative Flow Diagram (QFOj)	4- 24
4.3.2.5 Concentration of Waste-Activated Sludge	4- 25
4.3.2.6 Other Properties of Activated Sludge	4- 27
4.3.3 Trickling Filters	4- 29
4.3.3.1 Computing Trickling Filter Sludge Production - Dry Weight Basis	4- 29
4.3.3.2 Concentration of Trickling Filter Sludge	4- 33
4.3.3.3 Properties - Trickling Filter Sludge	4- 34
4.3.4 Sludge from Rotating Biological Reactors	4- 34
4.3.5 Coupled Attached-Suspended Growth Sludges	4 35
4.3.6 Denitrification Sludge	4- 36
4.4 Chemical Sludges	4- 36
4.4.1 Introduction	4- 36
4.4.2 Computing Chemical Sludge Production - Dry Weight Basis	4- 37
4.4.3 Properties of Chemical Sludges	4- 38
4.4.4 Handling Chemical Sludges	4- 38
4.4.4.1 Stabilization	4- 39
4.4.4.2 Chemical and By-Product Recovery	4- 39
4.5 Elemental Analysis of Various Sludges	4- 39
4.5.1 Controlling Trace Elements	4- 39
4.5.2 Site-Specific Analysis	4 41
4.5.3 Cadmium	4- 42
4.5.4 Increased Concentration During Processing	4- 43
4.6 Trace Organic compounds in Sludge	4- 44
4.7 Miscellaneous Wastewater Solids	4- 45
4.7.1 Screenings	4- 46
4.7.1.1 Quantity of Coarse Screenings	4- 46
4.7.1.2 Quantity of Fine Screenings	4- 48
4.7.1.3 Properties of Screenings	4- 48
4.7.1.4 Handling Screenings	4- 48
4.7.1.5 Screenings From Miscellaneous Locations	4- 49
4.7.2 Grit	4- 50

TABLE OF CONTENTS (continued)

	<u>Page</u>
4.7.2.1 Quantity of Grit	51
4.7.2.2 Properties of Grit	52
4.7.2.3 Handling Grit	53
4.7.3 Scum	45
4.7.3.1 Quantities of Scum	55
4.7.3.2 Properties of Scum	56
4.7.3.3 Handling Scum	57
4.7.4 Septage	59
4.7.4.1 Quantities of Septage	59
4.7.4.2 Properties of Septage	59
4.7.4.3 Treating Septage in Wastewater Treatment Plants	60
4.7.5 Backwash	61
4.7.6 Solids From Treatment of Combined Sewer Overflows	62
4.8 References	61
CHAPTER 5. THICKENING	5- 1
5.1 Introduction	5- 1
5.1.1 Definition	5- 1
5.1.2 purpose	5- 1
5.1.3 Process Evaluation	5- 1
5.1.4 Types and Occurrence of Thickening Processes	5- 2
5.2 Sedimentation Basins	5- 2
5.2.1 Primary Sedimentation	5- 2
5.2.2 Secondary Sedimentation	5- 3
5.3 Gravity Thickeners	5- 3
5.3.1 Introduction	5- 3
5.3.2 Theory	5- 3
5.3.3 System Design Considerations	5- 5
5.3.3.1 Minimum Surface Area Requirements	5- 6
5.3.3.2 Hydraulic Loading	5- 8
5.3.3.3 Drive Torque Requirements	5- 8
5.3.3.4 Total Tank Depth	5- 9
5.3.3.5 Floor Slope	5- 10
5.3.3.6 Other Considerations	5- 11
5.3.4 Design Example	5- 12
5.3.5 Cost	S- IS
5.3.5.1 Capital Cost	S- IS
5.3.5.2 Operating and Maintenance Cost	S- IS
5.4 Flotation Thickening	5- 16
5.4.1 Dissolved Air Flotation (DAF)	5- 18
5.4.1.1 Theory	5- 19
5.4.1.2 System Design Considerations	5- 19
5.4.2 Design Example	5- II
5.4.3 Cost	5- 35
5.4.3.1 Capital Cost	5- 35
5.4.3.2 Operating and Maintenance Costs	5- 16
5.5 Centrifugal Thickening	5- 16

TABLE OF CONTENTS (continued)

	Page
5.5.1 Introduction	5- 36
5.5.2 Theory	5- 0B
5.5.3 System Design Considerations	5- 39
5.5.3.1 Disc Nozzles	5- 39
5.5.3.2 Imperforate Basket	5- 45
5.5.3.3 Solid Bowl Decanter	5- 49
5.5.4 Case History	5- 53
5.5.5 Cost	5- 55
5.5.5.1 Capital Cost	5- 55
5.5.5.2 Operating and Maintenance Cost	5- 56
5.6 Miscellaneous Thickening Methods	5- 59
5.6.1 Elutriation Basin	5- 59
5.6.2 Secondary Anaerobic Digesters	5- 60
5.6.3 Facultative Sludge Lagoons	5- 60
5.6.4 Ultrafiltration	5 -60
5.7 References	5 -60
CHAPTER 6. STABILIZATION	6- 1
6.1 Introduction	6- 1
6.2 Anaerobic Digestion	6- 2
6.2.1 Process Description	6- 2
6.2.1.1 History and Current Status	6- 2
6.2.1.2 Applicability	6-)
6.2.1.3 Advantages and Disadvantages	6- 4
6.2.1.4 Microbiology	6- 5
6.2.2 Process Variations	6- 7
6.2.2.1 Low-Rate Digestion	6- 7
6.2.2.2 High-Rate Digestion	6- 7
6.2.2.3 Anaerobic Contact Process	6- 15
6.2.2.4 Phase Separation	6- 16
6.2.3 Sizing of Anaerobic Digesters	6- 18
6.2.3.1 Loading Criteria	6- 1e
6.2.3.2 Solids Retention Time	6- 18
6.2.3.3 Recommended Sizing Procedure	6- 20
6.2.4 Process Performance	6- 2J
6.2.4.1 Solids Reduction	6- 26
6.2.4.2 Gas Production	6- 29
6.2.4.3 Supernatant Quality	6- 31
6.2.5 Operational Considerations	6- 34
6.2.5.1 pH	6- 34
6.2.5.2 Toxicity	6- 36
6.2.6 System Component Design	6- 42
6.2.6.1 Tank Design	6- 42
6.2.6.2 Heating	6- 46
6.2.6.3 Mixing	6- 52
6.2.6.4 Covers	6- 62
6.2.6.5 Piping	6- 66
6.2.6.6 Cleaning	6- 67
6.2.7 Energy Usage	6- 72
6.2.8 Costs	6- 74

TABLE OF CONTENTS (continued)

	<u>Page</u>
6.2.9 Design Example	6- 74
6.2.9.1 Design Loadings ..	6- 74
6.2.9.2 System Description .	6- 75
6.2.9.3 Component Sizing	6- 77
6.3 Aerobic Digestion	6- 82
6.3.1 Process Description ..	6- 82
6.3.1.1 History	6- 82
6.3.1.2 Current Status	6- 82
6.3.1.3 Applicability	6- 82
6.3.1.4 Advantages and Disadvantages ..	6- 82
6.3.1.5 Microbiology ..	6- 83
6.3.2 Process variations ..	6- 84
6.3.2.1 Conventional Semi-Batch Operation .	6- 84
6.3.2.2 Conventional Continuous Operation	6- 84
6.3.2.3 Auto-Heated Mode of Operation	6- 85
6.3.3 Design Considerations ..	6- 86
6.3.3.1 Temperature ..	6- 86
6.3.3.2 Solids Reduction ..	6- 86
6.3.3.3 Oxygen Requirements ..	6- 88
6.3.3.4 Mixing	6- 89
6.3.3.5 pH Reduction	6- 90
6.3.3.6 Dewatering ..	6- 91
6.3.4 Process Performance ..	6- 92
6.3.4.1 Total Volatile Solids Reduction ..	6- 92
6.3.4.2 Supernatant Quality ..	6- 93
6.3.5 Design Example	6- 93
6.3.6 Cost	6- 99
6.3.6.1 Capital Cost	6- 99
6.3.6.2 Operation and MaIntenance Cost	6- 99
6.4 Lime Stabilization	6-100
6.4.1 Process Description ..	6-101
6.4.1.1 History	6-101
6.4.1.2 Current Status ..	6-102
6.4.1.3 Applicability.....	6-102
6.4.1.4 Theory of the Process ..	6-103
6.4.2 Design Criteria ..	6-103
6.4.2.1 pH and Contact Time	6-104
6.4.2.2 Lime Dosage	6-104
6.4.3 Process Performance ..	6-107
6.4.3.1 Odor Control	6- 108
6.4.3.2 Pathogen Reduction	6-109
6.4.3.3 Dewatering and Settling ..	6-110
6.4.3.4 Chemical Characteristics	6-110
6.4.4 Process Design	6-112
6.4.4.1 Design of Lime Handling Facilities ..	6- 112
6.4.4.2 Mixing Tank Design	6-118
6.4.5 Costs and Energy Usage ..	6-121
6.4.5.1 Capital and Operating Costs ..	6-121
6.4.5.2 Energy Usage	6-122

TABLE OF CONTENTS (continued)

	<u>Page</u>
6.4.6 Design Example	6-124
6.4.6.1 Design Loading	6-124
6.4.6.2 System Description	6-124
6.4.6.3 Component Sizing	6-126
6.5 Chlorine Stabilization	6-127
6.5.1 Process Description	6-128
6.5.2 Uses, Advantages, and Disadvantages	6-131
6.5.3 Chlorine Requirements	6-132
6.5.4 Characteristics of Chlorine-Stabilized Materials	6-133
6.5.4.1 Stabilized Sludge	6-133
6.5.4.2 Supernatant/Filtrate/Subnatant Quality	6-134
6.5.5 Costs	6-134
6.5.5.1 Operating Costs	6-135
6.5.5.2 Capital Costs	6-136
6.6 References	6-138
 CHAPTER 7. DISINFECTION	 I
7.1 Introduction	1
7.2 Pathogenic Organisms	1
7.2.1 Pathogen Sources	2
7.2.2 Pathogen Characteristics	2
7.2.2.1 Viruses	2
7.2.2.2 Bacteria	3
7.2.2.3 Parasites	6
7.2.2.4 Fungi	6
7.2.3 Pathogen Occurrence in the United States	6
7.3 Pathogen Survival During Sludge Stabilization Processes	7
7.3.1 Pathogen Reduction During Digestion	7
7.3.1.1 Viruses	7
7.3.1.2 Bacteria	7
7.3.1.3 Parasites	9
7.3.2 Long Term Storage	10
7.3.3 Chemical Disinfection	10
7.3.3.1 Lime	10
7.3.3.2 Chlorine	10
7.3.3.3 Other Chemicals	11
7.4 Pathogen Survival in the Soil	11
7.4.1 Viruses	11
7.4.2 Bacteria	11
7.4.3 Parasites	12
Potential Human Exposure to Pathogens	12
Heat Disinfection Processes	13
7.6.1 Sludge Pasteurization	11
7.6.1.1 Process Description	15
7.6.1.2 Current Status	16
7.6.1.3 Design Criteria	16

TABLE OF CONTENTS (continued)

	<u>Page</u>
7.6.1.4 Instrumentation and Operational Considerations	7- 17
7.6.1.5 Energy Impacts	7- 17
7.6.1.6 Cost Information	7- 17
7.6.1.7 Design Example	7- 20
7.6.2 Other Heat Processes	7- 24
7.6.2.1 Heat-Conditioning	7- 25
7.6.2.2 Heat-Drying	7- 25
7.6.2.3 High Temperature Processes	7- 25
7.6.2.4 Composting	7- 25
7.7 Pathogen Reduction With High-Energy Radiation	7- 26
7.7.1 Reduction of Pathogens in Sludge With Electron Irradiation	7- 26
7.7.1.1 Process Description	7- 21
7.7.1.2 Status	7- 28
7.7.1.3 Design Considerations	7- 28
7.7.1.4 Instrumentation and Operational Considerations	7- 30
7.7.1.5 Energy Impacts	7- 30
7.7.1.6 Performance Data	7- 30
7.7.1.7 Production Production and Properties	7- 31
7.7.1.8 Cost Information	7- 31
7.7.2 Disinfection with Gammmer Irradiation	7- 32
7.7.2.1 Process Description	7- 33
7.7.2.2 Current Status - Liquid Sludge	7- 33
7.7.2.3 Current Status - Dried or Composted Sludge	7- 34
7.7.2.4 Design Criteria	7- 35
7.7.2.5 Instrumentation and Operational Considerations	7- 35
7.7.2.6 Energy Impacts	7- 36
7.7.2.7 Performance Data	7- 37
7.7.2.8 Cost Information	7- 38
7.8 References	7- 4
CHAPTER 8. CONDITIONING	8- 1
8.1 introduction	8- 1
8.2 Selecting a Conditioning Process	8- 1
8.3 Factors Affecting Wastewater Solids Conditioning	8- 1
8.3.1 General Wastewater Solids Properties	8- 1
8.3.1.1 Particle Size and Distribution	8- 3
8.3.1.2 Surface Charge and Degree of Hydration	8- 4
8.3.1.3 Particle Interaction	8- 4
8.3.2 Physical Factors	8- 4
8.3.2.1 Effect of Processing Prior to Conditioning	8- 5
8.3.2.2 Conditioner Application	8- 5
8.4 Inorganic Chemical Conditioning	8- 6
8.4.1 Introduction	8- 6

TABLE OF CONTENTS (continued)

	<u>Page</u>
8.4.2 Dosage Requirements	8- 6
8.4.3 Availability	8- 7
8.4.4 Storage, Preparation, and Application Equipment	8- 8
8.4.5 Design Example	8- 8
8.4.6 Cost	8- 9
8.4.6.1 Capital Cost	8- 9
8.4.6.2 operation and Maintenance Cost	8- 10
8.5 Chemical Conditioning With Polyelectrolytes	8- 11
8.5.1 Introduction	e- 11
8.5.2 Background on Polyelectrolytes	8- 14
8.5.2.1 Composition and Physical Form	8- 14
8.5.2.2 Structure in Solution	8- 17
8.5.2.3 How Polyelectrolyte Conditioning Works	8- 17
8.5.3 Conditioning for Thickening	8- 18
8.5.3.1 Gravity Thickening	8- 18
8.5.3.2 Dissolved Air Flotation Thickening	8- 18
8.5.3.3 Centrifugal Thickening	8- 20
8.5.4 Conditioning for Dewatering	8- 20
8.5.4.1 Drying Beds	8- 20
8.5.4.2 Vacuum Filters	8- 20
8.5.4.3 Recessed Plate Pressure Filters	8- 21
8.5.4.4 Belt Filter Presses	8- 23
8.5.4.5 Centrifuges	8- 24
8.5.5 Storage, Preparation, and Application Equipment	8- 25
8.5.6 Case History	e- 25
8.5.7 Cost	e- 27
8.5.7.1 Capital Cost	8- 27
8.5.7.2 Operation and Maintenance Cost	8- 29
8.6 Non-Chemical Additions	8- 29
8.7 Thermal Conditioning	8- 31
8.7.1 Advantages and Disadvantages	8- 33
8.7.2 Process Sidestreams	8- 34
8.7.2.1 Gaseous Sidestreams	8- 34
8.7.2.2 Liquid Sidestreams	8- 35
8.7.3 Operations and Cost	8- 36
8.7.3.1 General Considerations	8- 36
8.7.3.2 USEPA Survey Results	8- 38
8.8 Elutriation	8- 39
8.9 Freeze-Thaw	8- 40
8.9.1 Indirect Mechanical Freezing	8- 40
8.9.2 Direct Mechanical Freezing	e- 41
8.9.3 Natural Freezing	e- 41
8.10 Mechanical Screening and Grinding	8- 41
8.11 Miscellaneous Processes	8- 42
8.11.1 Bacteria	e- 42
8.11.2 Electricity	8- 42
8.11.3 Solvent Extraction	8- 43

TABLE OF CONTENTS (continued)

	<u>Page</u>
8.11.4 Ultrasonic	8- n
8.12 References	8- n
CHAPTER 9. DEWATERING	9- 1
9.1 Introduction	9- 1
9.1.1 Process Evaluation	9- 1
9.1.2 Methods of Dewatering	9- 3
9.2 Natural Sludge Dewatering Systems	9- 3
9.2.1 Drying Beds	9- 3
9.2.1.1 Basic Components and Operation	9- 4
9.2.1.2 Types of Drying Beds	9- 5
9.2.1.3 Process Design Criteria	9- 7
9.2.1.4 Costs	9- 12
9.2.2 Drying Lagoons	9- 11
9.2.2.1 Basic Concept	9- 15
9.2.2.2 Design Criteria	9- 15
9.2.2.3 Costs	9- 16
9.3 Centrifugal Dewatering Systems	9- 17
9.3.1 Introduction	9- 17
9.3.2 Imperforate Basket	9- 18
9.3.2.1 Principles of Operation	9- 18
9.3.2.2 Application	9- 19
9.3.2.3 Performance	9- 19
9.3.2.4 Case History	9- 19
9.3.3 Solid Bowl Decanters	9- 23
9.3.3.1 Application	9- n
9.3.3.2 Performance	9- 24
9.3.3.3 Other Considerations	9- 24
9.4 Filtration Dewatering Systems	9- 25
9.4.1 Introduction	9- 25
9.4.2 Basic Theory	9- 26
9.4.3 Filter Aids	9- 26
9.4.4 Vacuum Filters	9- 27
9.4.4.1 Principles of Operation	9- 28
9.4.4.2 Application	9- 32
9.4.4.3 Performance	9- 32
9.4.4.4 Other Considerations	9- 33
9.4.4.5 Case History	9- 39
9.4.4.6 Costs	9- 41
9.4.5 Belt Filter Press	9- n
9.4.5.1 Principles of Operation	9- 45
9.4.5.2 Application	9- 47
9.4.5.3 Performance	9- 47
9.4.5.4 Other Considerations	9- 47
9.4.5.5 Design Example	9- 49
9.4.5.6 Costs	9- 51
9.4.6 Recessed Plate Pressure Filters	9- 52
9.4.6.1 Principles of Operation	9- 52
9.4.6.2 Application	9- 55
9.4.6.3 Performance	9- 56

TABLE OF CONTENTS (continued)

	Page
9.4.6.4 Other Considerations	9- 56
9.4.6.5 Case History	9- 59
9.4.6.6 Cost	9- 60
9.4.7 Screw and Roll Press	9- 63
9.4.7.1 Screw Press	9- 63
9.4.7.2 Twin-Roll Press ..	9- 66
9.4.8 Dual Cell Gravity (DCG) Filter	9- 67
9.4.9 Tube Filters	9- 68
9.4.9.1 Pressure Type	9- 68
9.4.9.2 Gravity Type	9- 68
9.5 Other Dewatering Systems	9- 69
9.5.1 Cyclones	9- 69
9.5.2 Screens	9- 70
9.5.3 Electro-Osmosis	9- 70
9.6 References	9- 70
CHAPTER 10. HEAT DRYING	10- 1
10. Introduction	10- 1
10.2 Heat-Drying Principles	10- 1
10.2.1 Drying Periods	10- 1
10.2.2 Humidity and Mass Transfer	10- 2
10.2.3 Temperature and Heat Transfer	10- 0
10.3 Energy Impacts	10- 5
10.3.1 Design Example	10- 6
10.3.2 Energy Cost of Heat-Dried Sludges Used for Fertilizers	10- 11
10.4 Environmental Impacts	10- 12
10.4.1 Air Pollution	10- 12
10.4.2 Safety	10- 11
10.4.3 Sidestream Production	10- 11
10.5 General Design Criteria	10- 13
10.5.1 Drying Capacity	10- 13
10.5.2 Storage Requirements	10- 11
10.5.3 Heat Source	10- 11
10.5.4 Air Flow	10- 11
10.5.5 Equipment Maintenance	10- 15
10.5.6 Special Considerations	10- 15
10.6 Conventional Heat Dryers	10- 15
10.6.1 Flash-Drying	10- 16
10.6.1.1 Process Description ..	10- 16
10.6.1.2 Case Study: Houston, Texas	10- 18
10.6.2 Rotary Dryers	10- 19
10.6.2.1 Direct Rotary Dryers ..	10- 19
10.6.2.2 Indirect Drying ..	10- 22
10.6.2.3 Direct-Indirect Rotary Dryers	10- 24
10.6.3 Incinerators	10- 25
10.6.4 Toroidal Dryer	10- 25
10.6.4.1 Process Description	10- 25
10.6.4.2 Current Status	10- 21
10.6.5 Spray-Drying	10- 21

TABLE OF CONTENTS (continued)

	<u>Page</u>
10.6.5.1 Process Description	10- 27
10.6.5.2 Current Status	10- 27
10.7 Other Heat-Drying Systems .	10- 28
10.7.1 Solvent Extraction- -BEST Process	10- 28
10.7.1.1 Process Description .	10- 28
10.7.1.2 Current Status .	10- 29
10.7.1.3 operating Experience	10- 30
10.7.2 Multiple-Effect Evaporation- -Carver Greenfield Process	10- 30
10.7.2.1 Process Description .	10- J!
10.7.2.2 Current Status	10- 31
10.6 References .	10- J2
 CHAPTER 11. HIGH TEMPERATURE PROCESSES	 11- 1
11.1 Introduction	11- 1
11.2 Principles of High Temperature Operations	11- 1
11.2.1 Combustion Factors	11- 3
11.2.1.1 Sludge Fuel Values .	11- 3
11.2.1.2 Oxygen Requirements for Complete Combustion	11- 6
11.2.1.3 Factors Affecting the Heat Balance ...	11- 7
11.2.2 Incineration Design Example	11- 10
11.2.2.1 Problem Statement .	11- 10
11.2.2.2 Approximate Calculation Method	11- 13
11.2.2.3 Theoretical Calculation Method	11- 20
11.2.2.4 Comparison of Approximate and Theoretical Calculation Methods	11- "
11.2.3 Pyrolysis and Starved-Air Combustion Calculations	11- 25
11.2.4 Heat and Material Balances .	11- 28
11.3 Incineration	11- 29
11.3.1 Multiple-Hearth Furnace	11- 31
11.3.2 Fluid Bed Furnace	11- "
11.3.3 Electric Furnace ..	11- "
11.3.4 Single Hearth Cyclonic Furnace	11- 55
11.3.5 Design Example: New Sludge Incineration Process	11- 59
11.3.5.1 Approach	11- 61
11.3.5.2 Preliminary Design	11- 62
11.4 Starved-Air Combustion	11- 65
11.4.1 Development and Application .	11- 68
11.4.2 Advantages and Disadvantages of SAC	11- 71
11.4.3 Conversion of Existing Multiple-Hearth Incineration Units to SAC .	11- 75
11.4.4 Design Example: Retrofit of an Existing Multiple-Hearth Sludge Incinerator to a Starved-Air Combustion Reactor	11- 76
11.4.4.1 Approach	11- 77
11.4.4.2 Preliminary Design .	11- 78

TABLE OF CONTENTS (continued)

	<u>Page</u>
11.4 Starved-Air Combustion	11- 65
11.4.1 Development and Application "	11- 68
11.4.2 Advantages and Disadvantages of SAC	11- 71
11.4.3 Conversion of Existing Multiple-Hearth Incineration Units to SAC	11- 75
11.4.4 Design Example: Retrofit of an Existing Multiple-Hearth Sludge Incinerator to a Starved-Air Combustion Reactor	11- 76
11.4.4.1 Approach	11- 77
11.4.4.2 Preliminary Design	11- 78
11.5 Co-Combustion of Sludge and Other Material	11- 81
11.5.1 Co-Combustion with Coal and Other Residuals "	11- 81
11.5.2 Co-Combustion with Mixed Municipal Refuse (MMR)	11- 83
11.5.2.1 Refuse Combustion Technology	11- 84
11.5.2.2 Sludge Combustion Technology	11- 87
11.5.3 Institutional Constraints	11- 02
11.5.4 Conclusions about Co-Combustion	11- 94
11.6 Related Combustion Processes Used in Wastewater Treatment	11- 94
11.6.1 Screenings, Grit, and Scum Reduction	11- 94
11.6.2 Lime Recalcination	11- 96
11.6.3 Activated Carbon Regeneration	11- 98
11.6.3.1 Granular Carbon Systems (GAC)	11- 99
11.6.3.2 Powdered Activated Carbon (PAC)	11-100
11.6.3.3 Jet Propulsion Laboratory Activated- Carbon Treatment System (JPL-ICTS)	11-100
11.7 Other High Temperature Processes	11- 102
11.7.1 High Pressure/High Temperature Wet Air oxidation	11-102
11.7.2 REACT-O-THERMtm "	11-109
11.7.3 Modular Starved-Air Incinerators	11-110
11.1.4 Pyro-Soltm Process	11-110
11.1.5 Bailie Process	11- 113
11.1.6 Wright-Malta Process	11- 113
11.1.7 Molten Salt Pyrolysis "	11- 115
11.8 Air Pollution Considerations	11-115
11.8.1 National Ambient Air Quality Standards {NAAQS)-State Implementation Plans (SIP)	11- 116
11.8.2 National Emission Standards for Hazardous Air Pollutants (NESHAPS)	11-117
11.8.3 Standards of Performance (or New Stationary Sources (NSPS)	11-118
11.8.4 New Source Review Standards (NSR)	11-119
11.8.5 Prevention of Significant Deterioration (PSD)	11- 119
11.8.6 The Permit Process	11- 120
11.8.7 Air Emissions Test Procedures	11-120
11.8.8 Design Example	11- 120

94

TABLE OF CONTENTS (continued)

	<u>Page</u>
11.8.8.1 Identify Applicable State and Local Regulations	11-121
11.8.8.2 Establish Air Pollution Abatement Procedures	11-123
11.9 Residue Disposal	11-132
11.10 References	11-136
CHAPTER 12. COMPOSTING	12- 1
12.1 Introduction	12- 1
12.2 The Composting Process	12- 2
12.2.1 Moisture	12- 1
12.2.2 Temperature	12- 4
12.2.3 pH	12- 5
12.2.4 Nutrient Concentratioo	12- 5
12.2.5 Oxygen Supply	12- 5
12.2.6 Design Criteria and Procedures	12- 5
12.3 Unconfined Composting Systems	12- 11
12.3.1 Windrow Process	12- 12
12.3.1.1 Energy Requicements	12- II
12.3.1.2 Public Health and Environmental Impacts	12- 16
12.3.1.3 Design Example	12- 18
12.3.2 Aerated Static Pile Process	12- 22
12.3.2.1 Individual Aerated Piles	12- 23
12.3.2.2 Extended Aerated Piles	12- 24
12.3.2.3 Current Status	12- II
12.3.2.4 Oxyqen Supply	12- 26
12.3.2.5 Bulking Agent	12- 26
12.3.2.6 Energy Requirements	12- 27
12.3.2.7 Public Health and Environmental Impacts	12- 27
12.3.2.8 Design Example	12- 29
12.3.3 Case Stlldies (Unconfined Systems)	12- 36
12.3.3.1 Joint Water Pollution Control plant, Carson, California	12- 36
12.3.3.2 Beltsville, Maryland	12- 38
12.3.3.3 Bangor, Maine	12- II
12.3.3.4 Durham, New Hampshire	12- II
12.3.3.5 Cost Analysis	12- II
12.4 Confined Composting System	12- 51
12.4.1 Description of Process	12- 51
12.4.2 Metro-Waste Aerobic Thermophilic bio-Reactor	12- 51
12.4.3 Dano Bio-Stabilizer Plant	12- 51
12.4.4 BAV aio- ReactOr	U - S)
12.5 European Composting Experience	12- 51
12.6 References	12- 57
CHAPTER 13. MISCELLANEOUS PROCESSES	11- 1
13.1 Introduction	11- 1

TABLE OF CONTENTS (cont inued)

	<u>Page</u>
13.2 Chemical Fixation Process	13- 1
13.3 Encapsulation Process	13- 3
13.3.1 Polyethylene Process	13- 3
13.3.2 Asphalt Process	13- ●
13.4 Earth wsm Conversion Process	13- ●
13.4.1 Process Arrangement	13- 4
13.4.2 Advantages of the Earth wsm Conversion Process	13- 6
13.4.3 Possible Operating Difficulties	13- ♯
13.4.4 Limitations	13- ♯
13.5 References	13- ♯
CHAPTER 14. TRANSPORTATION	14- 1
14.1 Pumping and Pipelines	14- 1
14.1.1 Simplified Head-Loss Calculations	14- 1
14.1.2 Application of Rheology to Sludge Pumping Problems	14- 3
14.1.2.1 Solution of Pressure Drop Equation	14- ●
14.1.2.2 Design Example	14- 8
14.1.2.3 Thixotropy and Other Time-Dependent Effects	14- 12
14.1.2.4 Obtaining the Coefficients	14- 14
14.1.2.5 Additional Information	14- 17
14.1.3 Types of Sludge Pumps	14- 17
14.1.3.1 Centrifugal Pumps	14- 17
14.1.3.2 Torque Flow Pumps	14- 18
14.1.3.3 Plunger Pumps	14- 19
14.1.3.4 Piston Pumps	14- 21
14.1.3.5 Progressive Cavity Pumps	14- 22
14.1.3.6 Diaphragm Pump	14- ♯
14.1.3.7 Rotary Pumps	14- 26
14.1.3.8 Ejector Pumps	14- 21
14.1.3.9 Gas Lift Pumps	14- 21
14.1.3.10 Water Eductors	14- 28
14.1.4 Application of Sludge Pumps	14- 29
14.1.5 Pipe, Fittings, and Valves	14- 29
14.1.6 Long Distance Pumping	14- 31
14.1.6.1 Experience	14- 31
14.1.6.2 Design Guidance	14- 32
14.1.7 In-Line Grinding	14- 36
14.2 Dewatered Wastewater Solids Conveyance	14- 37
14.2.1 Manual Transport of Screenings and Grit	14- 37
14.2.2 Belt Conveyors	14- 37
14.2.3 Screw Conveyors	14- 40
14.2.4 Positive Displacement Type Conveyors	14- 4
14.2.5 Pneumatic Conveyors	14- 4
14.2.6 Chutes and Inclined Planes	14- 44
14.2.7 Odors	14- ♯
14.3 Long Distance Wastewater Solids Hauling	14- ♯
14.3.1 Truck Transportation	14- ♯

TABLE OF CONTENTS (continued)

	<u>Page</u>
14.3.1.1	Types of Trucks 14- 47
14.3.1.2	Owned Equipment vs. Contract Hauling 14- 48
14.3.1.3	Haul Scheduling 14- 49
14.3.1.4	Trucking Costs 14- 49
14.3.2	Rail Transport 14- 49
14.3.2.1	Advantages and Disadvantages of Rail Transport 14- 49
14.3.2.2	Routes 14- 50
14.3.2.3	Haul Contracts 14- 50
14.3.2.4	Railcar Supply 14- 51
14.3.2.5	Ancillary Facilities 14- 53
14.3.2.6	Manpower and Energy Requirements 14- 53
14.3.3	Barge Transportation 14- 54
14.3.3.1	Routes and Transit Times 14- 54
14.3.3.2	Haul or System Contracting 14- 55
14.3.3.3	Barge Selection and Acquisition 14- 56
14.3.3.4	Ancillary Facilities 14- 57
14.3.3.5	Spill Prevention and Cleanup 14- 57
14.4	References 14- 57
CHAPTER 15.	STORAGE 15- 1
15.1	Introduction 15- 1
15.1.1	Need for Storage 15- 1
15.1.2	Risks and Benefits of Solids Storage within Wastewater Treatment System 15- 1
15.1.3	Storage Within Wastewater Sludge Treatment Processes 15- 2
15.1.4	Effects of Storage on Wastewater Solids 15- 2
15.1.5	Types of Storage 15- 4
15.2	Wastewater Treatment Storage 15- 5
15.2.1	Storage Within Wastewater Treatment Processes 15- 5
15.2.1.1	Grit Removal 15- 6
15.2.1.2	Primary Sedimentation 15- 7
15.2.1.3	Aeration Reactors and Secondary Sedimentation 15- 9
15.2.1.4	Imhoff and Community Septic Tanks 15- 10
15.2.1.5	Wastewater Stabilization Ponds 15- 11
15.2.2	Storage Within Wastewater Sludge Treatment Processes 15- 11
15.2.2.1	Gravity Thickeners 15- 12
15.2.2.2	Anaerobic Digesters 15- 12
15.2.2.3	Aerobic Digesters 15- 18
15.2.2.4	Composting 15- 18
15.2.2.5	Drying Beds 15- 18
15.3	Dedicated Storage Facilities 15- 18
15.3.1	facilities Provided Primarily for Storage of Liquid Sludge 15- 19
15.3.1.1	Holding Tanks 15- 19

TABLE OF CONTENTS (continued)

	<u>Page</u>
15.3.1.2 Facultative Sludge Lagoons ..	15- 23
15.3.1.3 Anaerobic Liquid Sludge Lagoons	15- 41
15.3.1.4 Aerated Storage Basins	15- 43
15.3.2 Facilities Provided Primarily for Storage of Dewatered Sludge	15- 46
15.3.2.1 Drying Sludge Lagoons .	15- 47
15.3.2.2 Confined Hoppers or Bins .	15- 51
15.3.2.3 Unconfined Stockpiles ..	15- 56
15.4 References	15- 58
 CHAPTER 16. SIDESTREAMS FROM SOLIDS TREATMENT PROCESSES	
16.1 Sidestream Production .	16- 1
16.2 Sidestream Quality and Potential Problems	16- 2
16.3 General Approaches to Sidestream Problems	16- 1
16.3.1 Elimination of Sidestream	16- 4
16.3.2 Modification of Upstream Solids Processing Steps	16- 4
16.3.3 Change in Timing, Return Rate, Or Return Point	16- 5
16.3.4 Modification of Wastewater Treatment Facilities .	16- 5
16.3.5 Separate Treatment of Sidestreams	16- 7
16.3.5.1 Anaerobic Digester Supernatant	16- 8
16.3.5.2 Thermal Conditioning Liquor	16- 10
16.4 References .	16- 17
 Chapter 17. INSTRUMENTATION	
17.1 Introduction .	17- 1
17.1.1 Purposes of Instrumentation .	17- 1
17.1.2 Instrumentation Justification and Design Considerations	17- 1
17.2 Measurements	17- 41
17.2.1 Level Measurements	17- 41
17.2.1.1 Bubblers	17- 41
17.2.1.2 Diaphragms .	17- 41
17.2.1.3 Capacitance Transmitters	17- 44
17.2.1.4 Ultrasonic Transmitters	17- 44
17.2.1.5 Tape-Supported Floats	17- 45
17.2.2 Flow Measurements	17- 45
17.2.2.1 Venturi Tubes ..	17- 46
17.2.2.2 Nozzles .	17- 46
17.2.2.3 Magnetic Meters	17- 46
17.2.2.4 Ultrasonic Meters .	17- 47
17.2.2.5 Doppler Meters .	17- 47
17.2.2.6 Rotameters	17- 48
17.2.2.7 Propeller Meters .	17- 48
17.2.2.8 Pitot Tubes .	17- 48
17.2.2.9 Weirs and Plumes ..	17- 49
17.2.2.10 Orifice Plates ..	17- 49

TABLE OF CONTENTS (continued)

	<u>Page</u>
17.2.2.11 Turbine Meters	17- 49
17.2.2.12 Vortex Meters	17- 50
17.2.2.13 Positive Displacement	17- 50
17.2.2.14 Pump and Transport Displacement Systems	17- 50
17.2.3 Pressure Measurement	17- 50
17.2.3.1 Bourdons or Bellows	17- 51
17.2.3.2 Diaphragms	17- 52
17.2.4 Temperature Measurements	17- 52
17.2.4.1 Resistance Temperature Detectors (RTDs)	17- 53
17.2.4.2 Thermocouples	17- 53
17.2.5 Weight Measurements	17- 54
17.2.5.1 Static	17- 54
17.2.5.2 Mass Flow	17- 54
17.2.6 Density and Suspended Solids Measurements	17- 55
17.2.6.1 Density	17- 55
17.2.6.2 Suspended Solids Measurements	17- 56
17.2.7 Time Measurements	17- 51
17.2.8 Speed Measurements	17- 51
17.2.9 Moisture Content Measurements	17- 51
17.2.10 Dissolved Oxygen Measurements	17- 58
17.2.11 pH Measurements	17- 58
17.2.12 Chemical Oxygen Demand Measurements	17- 59
17.2.13 Ammonia Measurements	17- 59
17.2.14 Gas Measurement and Analysis	17- 59
17.2.14.1 Composition Analyzer	17- 59
17.2.14.2 Calorimeter	17- 60
17.2.15 Stack Gas Measurements and Analysis	17- 60
17.2.16 Odor Measurements	17- 61
17.2.17 Aerobic Condition Measurements	17- 61
17.2.18 Blanket Level Measurements	17- 61
17.2.19 Hydrocarbons and Flammable Gas Detectors	17- 63
17.2.20 Radiation Monitoring	17- 63
17.2.21 Machinery Protection	17- 64
17.2.21.1 Empty Pipe Detectors	17- 64
17.2.21.2 Vibration - Acceleration and Displacement Systems	17- 64
17.2.21.3 Flow Loss Monitors	17- 65
17.2.21.4 Overload Devices	17- 65
17.2.21.5 Flame Safeguard Equipment	17- 65
17.3 Sampling Systems	17- 66
17.4 Operator Interface	17- 61
17.4.1 Location	17- 61
17.4.2 Indicator Boards	17- 68
17.5 References	17- 68
CHAPTER 18. UTILIZATION	18- 1
18.1 Introduction	18- 1
18.2 Sludge as a Soil Ambient	18- 2

TABLE OF CONTENTS (continued)

	<u>Page</u>
18.2.1 Perspective	18- 2
18.2.2 Principles and Design Criteria for Applying Wastewater Sludge to Land	18- 3
18.2.2.1 Preliminary Planning	18- 5
18.2.2.2 Site selection	18- 5
18.2.2.3 Process Design	18- 5
18.2.2.4 Facilities Design	18- 6
18.2.2.5 Facility Management, Operations, and Monitoring	18- 7
18.3 Sludge as an Energy Source	18- B
18.3.1 Perspective	18- 8
18.3.2 Recovery of Energy From Sludge	18- 9
18.3.2.1 Treatment of Digester Gas	18- 9
18.3.2.2 Gas-Burning Equipment	18- 11
18.3.3.3 Generators	18- 15
18.3.3 Examples of Energy Recovery	18- 15
18.3.3.1 Energy Recovery From Digester Gas	18- 15
18.3.3.2 Recovery of Energy From Incinerator Flue Gas	18- 25
18.3.4 Other Factors Affecting Heat Recovery	18- 34
18.4 Other uses of Wastewater Solids and Solid By-Products	18- 35
18.5 References	18- 36
CHAPTER 19. DISPOSAL TO LAND	19- 1
19.1 Introduction	19- 1
19.1.1 Regulatory Agency Guidance	19- 1
19.2 Sludge Landfill	19- 1
19.2.1 Definition	19- 1
19.2.2 Sludge Landfill Methods	19- 2
19.2.2.1 Sludge-Only Trench Fill	19- 2
19.2.2.2 Sludge-Only Area Fill	19- 3
19.2.2.3 CO-Disposal with Refuse	19- 5
19.2.2.4 Suitability of Sludge for Landfilling	19- 6
19.2.3 Preliminary Planning	19- 6
19.2.3.1 Sludge Characterization	19- 6
19.2.3.2 Selection of a Landfilling Method	19- 8
19.2.3.3 Site Selection	19- B
19.2.4 Facility Design	19- 12
19.2.4.1 Regulations and Standards	19- 12
19.2.4.2 Site Characteristics	19- 13
19.2.4.3 Landfill Type and Design	19- 14
19.2.4.4 Ancillary Facilities	19- 15
19.2.4.5 Landfill Equipment	19- 18
19.2.4.6 Flexibility and Reliability	19- 18
19.2.4.7 Expected Performance	19- 19
19.2.4.8 Environmental Impacts	19- 20
19.2.5 Operations and Maintenance	19- 20
19.2.5.1 Operations Plan	19- 20

LIST OF TABLES

<u>Number</u>		<u>Page</u>
CHAPTER 3		
3- 1	Example of Initial Screening Matrix for Base Sludge Disposal Options	3- 8
3- 2	Example of Process Compatibility Matrix	3- 9
3- 3	Example of Treatment/Diposal Compatibility Matrlx	3- 9
3- 4	Example of Numerical Rating System for Alternatives Analysis	3- 10
3- 5	Estimated Costs of Alternatives for Eugene-Springfield	3- 13
3- 6	Mass Balance Equations for Flowsheet of Figure 3-7	3- 21
3- 7	Mass Balance Equations for Flowsheet of Figure 3-9	3- 26
3- 8	Solid Properties Checklist	3- 37
3- 9	Process Design Checklist	3- 37
3-10	Public Health and Environmental Impact Checklist	3- 38
CHAPTER 4		
4- 1	Predicted Quantities of Suspended Solids and Chemical Solids Removed in a Hypothetical Primary Sedimentation Tank	4- 8
4- 2	Primary Sludge Characteristics	4- 8
4- 3	Alternate Names and Symbols for Equation (4-1)	4- 11
4- 4	Values of Yield and Decay Coefficients for Computing Waste-Activated Sludge	4- 12
4- 5	Design Data for Sludge Production Example	4- 21
4- 6	Activated Sludge Characteristics	4- 28
4- 7	Trickling Filter Solids Production	4- 30
4- 8	Daily Variations in Trickling Filter Effluent, StOckton, California	4- 33
4- 9	Description of Sloughing Events	4- 33
4-10	Concentration of Trickling Filter Sludge Withdrawn from Final Clarifiers	4- 34
4-11	Trickling Filter Sludge Composition	4- 35
4-12	Sludge from Combined Attached-Suspended Growth Processes	4- 36
4-13	Metals in Ferric Chloride Solutions	4- 40

List OF TABLES (continued)

<u>Number</u>		<u>Page</u>
4-14	Progress in Source Control of Toxic Pollutants	4- 41
4-15	Cadmium in Sludge	4- 42
4-16	Increased Metals Concentration During Processing	4- 43
4-17	Aroclor (PCB) 1254 Measurements in Sludge	4- 44
4-18	Chlorinated Hydrocarbon Pesticides in Sludge	4- 45
4-19	Screening Experience	4- 47
4-20	Analyses of Screenings	4- 49
4-21	Methods of Handling Screenings	4- 50
4-22	Grit Quantities	4- 52
4-23	Sieve Analysis of Grit	4- 53
4-24	Scum Production and Properties	4- 57
4-25	Methods of Handling Scum	4- 58
4-26	Characteristics of Domestic Septage	4- 60
4-27	Metals Concentrations in Solids from Treatment of Combined Sewer Overflows	4- 62

CHAPTER 5

5- 1	Advantages and Disadvantages of Gravity Thickeners	5- 3
5- 2	Typical Gravity Thickener Surface Area Design Criteria	5- 7
5- 3	Reported Operating Results at Various Overflow Rates for Gravity Thickeners	5- 8
5- 4	Typical Uniform Load (w _j Values)	5- 9
5- 5	Definition of Torques Applicable to Circular Gravity Thickeners	5- 10
5- 6	Types of Municipal Wastewater Sludges Being Thickened by DAF Thickeners	5- 18
5- 7	Advantages and Disadvantages of DAF Thickening	5- 19
5- 8	Typical DAF Thickener Solids Loading Rates Necessary to Produce a Minimum 4 Percent Solids Concentration	5- 23
5- 9	Field Operation Results From Rectangular DAF Thickeners	5- 24
5-10	Reported DAF Thickener Hydraulic Loading Rates	5- 27
5-11	Advantages and Disadvantages of Disc Nozzle Centrifuges	5- 40
5-12	Typical Performance of Disc Nozzle Centrifuge	5- 43
5-13	Advantages and Disadvantages of Imperforate Basket Centrifuge	5- 45
5-14	Typical Thickening Results Using Imperforate Basket Centrifuge	5- 47
5-15	Advantages and Disadvantages of Solid Bowl Decanter Centrifuges	5- 50

LIST OF TABLES (continued)

<u>Number</u>		<u>Page</u>
5-16	Typical Characteristics of the New Type Thickening Decanter Centrifuge WAS	5- 52
5-17	Estimated Capital and O&M Cost for Various Centrifuges for Thickening of Waste-Activated Sludge at Village Creek - Fort Worth, Texas	5- 55
CHAPTER 6		
6- 1	Type and Reference of Full-Scale Studies on High Rate Anaerobic Digestion of Municipal Wastewater Sludge	6- 3
6- 2	Results of Recirculating Digested Sludge to the Thickener at Bowery aay Plant, New York	6- 11
6- 3	Operating and Performance Characteristics for the Bench-Scale, Two-Phase Anaerobic Digestion of Waste-Activated Sludge	6- 17
6- 4	Typical Design Criteria for Sizing Mesophilic Anaerobic Sludge Digesters	6- 19
6- 5	Solids Retention Time Design Criteria for High Rate Digestion	6- 24
6- 6	Average Physical and Chemical Characteristics of Sludge From Two-Stage Digester System	6- 25
6- 7	Materials Entering and Leaving Two-Stage Digester System	6- 26
6- 8	Gas Production for Several Compounds in Sewage Sludge	6- 29
6- 9	Characteristics of Sludge Gas	6- 31
6-10	Supernatant, Characteristics of High-Rate, Two-Stage, Mesophilic, Anaerobic Digestion at Various Plants	6- 33
6-11	Effect of Ammonia Nitrogen on Anaerobic Digestion	6- 37
6-12	Influent Concentrations and Expected Removals of Some Heavy Metals in Wastewater Treatment Systems	6- 38
6-13	Total Concentration of Individual Metals Required to Severely Inhibit Anaerobic Digestion	6- 39
6-14	Total and Soluble Heavy Metal Content of Digesters	6- 40
6-15	Stimulating and Inhibitory Concentrations of Light Metal Cations	6- 40
6-16	Synergistic and Antagonistic Cation Combinations	6- 41
6-17	Heat Transfer Coefficients (or Hot Water Coils in Anaerobic Digesters	6- 47
6-18	Heat Transfer Coefficients for Various Anaerobic Digestion Tank Materials	6- 52

LIST OF TABLES (continued)

<u>Number</u>		<u>Page</u>
6-19	Relationship Between the Velocity Gradient and Unit Gas Flow	6- 63
6-20	Design Loading Assumptions	6- 79
6-21	Selected Aerobic Digestion Studies on Various Municipal Wastewater Sludges	6- 83
6-22	Characteristics of Mesophilic Aerobic Digester Supernatant	6- 93
6-23	Summary of Current Aerobic Digester Design Criteria	6- 94
6-24	Aerobic Digestion Labor Requirements	6-100
6-25	Lime Requirement to Attain pH 12 for 30 Minutes at Lebanon, Ohio	6-105
6-26	Lime Doses Required to Keep pH Above 11.0 at Least 14 Days	6-105
6-27	Bacteria in Raw, Anaerobically Digested, and Lime Stabilized Sludges at Lebanon, Ohio	6-109
6-28	Chemical Composition of Sludges at Lebanon, Ohio, Before and After Lime Stabilization	6-111
6-29	Chemical Composition of Sludge and Supernatant Before and After Lime Stabilization	6-113
6-30	Characteristics of Quicklime and Hydrated Lime	6-114
6-31	Mechanical Mixer Specifications for Sludge Slurries	6-122
6-32	Estimated Average Annual Costs for Lime Stabilization Facilities ..	6-123
6-33	Estimated Chlorine Requirements for Sludge and Sidestream Processing	6-133
6-34	Actual Operating Costs for Chlorine Stabilization System ..	6-135
6-35	Chlorine Stabilization Capital Costs, 1979	6-137

CHAPTER 7

7- 1	Pathogenic Human Viruses Potentially in Wastewater Sludge	7- 3
7- 2	Pathogenic Human Bacteria Potentially in Wastewater Sludge	7- 4
7- 3	Pathogenic Human and Animal Parasites Potentially in Wastewater Sludge	7- 5
7- 4	Pathogenic Fungi Potentially in wastewater Sludge	7- 6
7- 5	Pathogen Occurrence in Liquid Wastewater Sludges	7- 8
7- 6	Pathogen Survival in Soils	7- 12
7- 7	Time and Temperature Tolerance for Pathogens in Sludge	7- 14

LIST OF TABLES (continued)

<u>Number</u>		<u>Page</u>
CHAPTER 8		
8- 1	Effects of Either Polyelectrolyte Conditioning or Thermal Conditioning Versus No Conditioning on a Mixture of Primary and Waste-Activated Sludge Prior to Gravity Thickening	8- 2
8- 2	Typical Conditioning Dosages of Ferric Chloride (FeCl ₃) and Lime (CaO) for Municipal Wastewater Sludges	8 7
8- 3	Suppliers of Polyelectrolytes	8 14
8- 4	Representative Dry Powder Cationic Polyelectrolytes	8- 16
8- 5	Representative Liquid Cationic Polyelectrolytes	8- 16
8- 6	Typical Polyelectrolyte Additions for Various Sludges	9- 11
8- 7	Typical Levels of Dry Polyelectrolyte Addition for: Belt Filter Presses	9- 23
8- a	Typical Levels of Dry Polyelectrolyte Addition for: Solid Bowl Decanter Centrifuges Conditioning Various Sludges	9- 28
8- b	Performance of Solids Handling System at Bissell Point, St. Louis STP 1972-1976	9- 26
8-10	Performance of Solids Handling System at Bissell Point, St. Louis STP 1977-1978	e- 28
8-11	Advantages and Disadvantages of Ash Addition to Sludge for Conditioning	8- 33
8-12	General Characteristics of Separated Liquor From Thermal Conditioned Sludge	8- 36
8-13	Filtrate and/or Centrate Characteristics From Dewatering Thermal Conditioned Sludge	8- 38
8-14	USEPA July 1979 Survey of Existing Municipal Wastewater Thermal Conditioning	8- 39
8-15	Comparison of Sewage Sludge Handling and Conditioning Processes	8- 41
CHAPTER 9		
9- 1	pilot-Scale Sludge Dewatering Studies	9- 2
9- 2	Advantages and Disadvantages of Using Sludge Drying Beds	9- 3
9- 3	Advantages of a Wedge-Wire Drying Bed	9- 7
9- 4	Characterization of Sand Bed Drainage	9- 9
9- SA	Summary of Recognized Published Sand Bed Sizing Criteria for Anaerobically Digested, Non-Conditioned Sludge	9- 10
9- 5B	Summary of Recognized Published State Bed Sizing Criteria for Sand Beds by USEPA Regions Square feet/Capita	9- 11
9- 6	Wedge-Wire System Performance Data	9- 12

LIST OF TABLES (continued)

<u>Number</u>		<u>Page</u>
9- 7	Sludge Drying Beds, Labor Requirements	9- 13
9- 8	Advantages and Disadvantages of Using Sludge Drying Lagoons	9- 11
9- 9	Sludge Drying Lagoons, Labor Requirements	9- 17
9-10	Advantages and Disadvantages of Basket Centrifuges	9- 18
9-11	Typical Performance Data for an Imperforate Basket Centrifuge	9- 20
9-12	Specific Operating Results for Imperforate Basket	9- 20
9-13	Operating Results for Basket Centrifuge Dewatering of Aerobically Digested Sludge at Burlington, Wisconsin	9- 22
9-14	Advantages and Disadvantages of Solid Bowl Decanter Centrifuges	9- 21
9-15	Typical Performance Data for a Solid Bowl Decanter Centrifuge	9- 24
9-16	Precoat Process Performance on Fine Particulate Sludges	9- 27
9- 11	Advantages and Disadvantages of Using Rotary Drum vacuum Filters	9- 28
9-18	Typical Dewatering Performance Data for Rotary Vacuum Filters - Cloth Media	9- 34
9-19	Typical Dewatering Performance Data for Rotary Vacuum Filters - Coil Media	9- 35
9-20	Specific Operating Results of Rotary Vacuum Filters - Cloth Media	9- 35
9- 21	Specific Operating Results of Rotary Vacuum filters - Coil Media	9- 36
9- 22	Operational Cost for Lakewood, Ohio Vacuum Filter Operations	9- 41
9-23	Advantages and Disadvantages of Belt Filter Presses	9- 45
9-24	Typical Dewatering Performance of Belt Filter Presses	9- 48
9-25	Labor Requirements for Belt Filter Presses	9- 51
9- 26	Advantages and Disadvantages of Recessed Plate Pressure Filters	9- 52
9-27	Expected Dewatering Performance for a Typical Fixed Volume Recessed Plate Pressure Filter	9- 56
9-28	Specific Operating Results of Fixed Volume Recessed Plate Pressure Filters	9- 57
9-29	Typical Dewatering Performance of a Variable Volume Recessed Plate Pressure Filter	9- 57
9- 30	Pressure Filtration and Incineration Operational Cost	9- 61
9- 31	Performance Results From a Screw Press	9- 65

LIST OF TABLES (cont inued)

<u>Number</u>		<u>Page</u>
9- 32	Summary of Performance Results For a Dual Cell Gravity Filter - Mentor, Ohio	9- 68
CHAPTER 10		
10- 1	Estimated 1911 Costs for Dewatering, Drying and Bagging at Largo, Florida ,.....	10- 22
CHAPTER 11		
11- 1	Chemical Reactions Occurring During Combustion ,.....	11- 4
11- 2	Representative Heating Values of Some Sludges ,.....	11- 5
11- 3	Theoretical Air and Oxygen Requirements for Complete Combustion ..	11- 7
11- 4	Approximate Combustion Calculat ion - Supplemental Fuel Requirements ,.....	11- 18
11- 5	Combustion Calculations- Molal Uasis ,.....	11- 21
11- 6	Combustion Calculations- Molal Basis ..	11- 23
11- 7	Comparison Between an Approximate and a Theoretical calculation of Furnace Combustion ,.....	11- 25
11- 8	Hypothetical Wastewater Treatment Plant Design Data	11- 31
11- 9	Heat and Material Balance for Sludge Incineration In a Multiple-Hearth Furnace ,.....	11- 39
11-10	Typical Hearth Loading Rates for a Multiple-Hearth Furnace	11- 48
11-11	Heat and Material Balance for Sludge Incineration in a Fluid Bed furnace ,.....	11- 51
11-12	Heat and Material Balance for Sludge Incineration in an Electric Infrared Furnace	11- 51
11-13	Heat and Material Balance for Sludge Incineration in a Cyclonic Furnace	11- 60
11-14	Design Example: Wastewater Treatment Plant Operating Data	11- 61
11-15	Design Example Sludge Furnace Design Criteria ,.....	11- 62
11-16	Design Example: Heat and Material Balance for a Fluid Bed Furnace ,.....	11- 63
11-11	Heat and Material Balance for Starved-Air Combustion of Sludge in a Multiple-Hearth Furnace	11- 10
11-18	Heat and Material Balance Comparison of Starved-Air Combustion and Incineration	11- 72
11-19	Design Example: Wastewater Treatment Plant Operating Data	11- 77

LIST OF TABLES (continued)

<u>Number</u>		<u>Page</u>
11-20	Design Example: Heat and Material Balances for Multiple-Hearth Furnaces	11- 79
11-21	Conventional Approaches to Co-Combustion of Wastewater Sludge and Mixed Municipal Refuse	11- 83
11-22	Heat and Material Balance for Co-Combustion by Starved-Air Combustion in a Multiple-Hearth Furnace	11- 91
11-23	Carbon Regeneration Methods	11- 99
11-24	Basic Types of Pyrolysis, Thermal Gasification, and Liquefaction Reactors - New, Demonstrated, or Under Development	11-103
11-25	Health Effects of Air Pollutants	11-118
11-26	san Francisco Bay Area - Maximum Allowable Pollutant Concentrations	11-124
11-27	Uncontrolled Emission Rates from Multiple-Hearth Furnaces	11-125
11-28	Design Example: Exhaust Gas Data from a Multiple-Hearth Furnace	11-130
11-29	Design Example: Auxiliary Fuel Correction for a Multiple-Hearth Furnace	11-130
11-30	Design Example: Multiple-Hearth Furnace Pollutant Concentrations After Scrubbing	11-131
11-31	Description of Solid and Liquid Waste Classifications	11-133
11-32	Classification of Waste Disposal Sites	11-134
	CHAPTER 12	
12- 1	Suggested Monitoring Program for a Municipal Wastewater Sludge Composting Facility	12- 6
12- 2	Densities of Various Compost Bulking Agents	12- 12
12- 3	Beltville Equipment	12- 41
12- 4	Beltville Actual and Projected Operating Costs	12- 43
12- 6	Estimated Annual Labor and Equipment Requirements, Bangor, Maine	12- 46
12- 6	Bangor Equipment	12- 54
12- 7	Bangor Materials Requirements for 2,170 Wet Ton Annual Sludge Input	12- 46
12- 8	Facility Processing 10 Dry Tons of Sludge per Day	12- 50
12- 9	European Wastewater Sludge Composting Processes	12- 57
	CHAPTER 13	
13- 1	Partial List of Fixation Processes	13- 2
13- 2	Parameters for Earthworm Conversion	13- 6

LIST Of TABLES (cont inued)

<u>Number</u>		<u>Page</u>
13- 3	Possible Operating Difficulties in earthworm Conversion	13- 8
CHAPTER 14		
14- 1	Summarized Calculations for Non-Newtonian Flow Example Problem	14- 11
14- 1	Pressure Required to Exceed Yield Stress - Example Problem	14- 12
14- 3	Applications for Sludge Pumps	14- 30
14- 4	Typical Long Pipelines Carrying Unstabilized Sludged	14 32
14- 5	Typical Long Pipelines Carrying Digested Sludge	14- 32
14 6	Long Pipelines for Unstabilized Sludge: Additional Locations	14- 34
14- 7	Long Pipelines for Digested Sludge: Additional Locations	14- 34
14- 8	Typical Minimum Tank Car Requirements	14- 52
14- 9	Typical Transit Times for Railroad Transportation	14- 53
14-10	Manpower Requirements for Railroad Transport	14- 54
14-11	Tug Costs for Various Barge Capacities	14- 55
14-12	Typical Barge Sizes and Costs	14- 56
CHAPTER 15		
15- 1	Wastewater Solids Storage Applicability	15- 5
15- 1	Calculations for Digester Effluent Mass Flow Rate from Equation 15-1 ..	15- 16
15- 3	Advantages and Limitations of Using Facultative Sludge Lagoons for Long-Term Storage	15- 24
15- 4	Sacramento Central Wastewater Treatment Plant Volatile Reductions, Digested Sludge Quantities and FSL Area Loadings	15- 33
15- 5	Sacramento Central Wastewater Treatment Plant PSL Design Data	15- 35
15- 6	Sacramento Central Wastewater Treatment Plant PSL Sludge Inventory, Dry Tons	15- 35
15- 7	Sacramento Central Wastewater Treatment Plant Recycled FSL Supernatant Quality	15- 36
15- 8	Sacramento Central Wastewater Treatment Plant Comparison of Digested FSL and Removed Sludge Analytical Data	15- 37
15- 9	Sacramento Central Wastewater Treatment Plant Odor Risk for 40 Acres of FSLs, Annual Events (Days)	15- 39
1 5	Sacramento Regional Wastewater Treatment Plant Ultimate Odor Risk for 124 Acres of FSL, Annual Events (Days) ..	15- 41

LIST Of TABLES (continued)

<u>Number</u>		<u>Page</u>
15- 11	1978 Removed Sludge-Prairie Plan Land Reclamation Project, The Metropolitan Sanitary District of Greater Chicago	15- 44
15-12	1973/1974 Supernatant-Praire Plan Reclamation Project, The Metropolitan Sanitary District of Greater Chicago	15- 45

CHAPTER 16

16- 1	Effect of Polymer on Elutriation	16- 5
16- 2	Effect of Supernatant Return ..	16- 6
16- 3	Estimated Increase in Wastewater Stream Biological Treatment capacity Require'] t,) Handle Sidestreams From Various Solids Treatment Processes	16- 7
16- 4	Possible Digester Supernatant Treatment Processes	16- 10
16- 5	Chlorine Treatment of Digester Supernatant	16- 11
16- 6	Aerobic Oigestion of Heat Treatment Liquor	16- 13
16- 7	Activated Sludge Treatment of Thermal Conditioning Liquor	16- 14
16- 8	Aerobic Biological Filtration of Thermal Condition Liquor ..	16- 15
16- 9	Chlorine Oxidation Treatment of Thermal Conditioning Liquor	16- 16

CHAPTER 17

17- 1	Thickening	17- 3
17- 2	Stabilization ..	17- 5
17- 3	Disinfection	17- 8
17- 4	Conditioning	17- 10
17- 5	Dewatering	17- 13
17- 6	Heat Drying	17- 17
17- 7	High Temperature Proce"s	17- 22
17- 8	Composting	17- 27
17- 9	Miscellaneous Conversion Processes	17- 30
17-10	Transportation	17- 31
17-11	Storage	17- 32
17-12	Sidestreams	17- 36

CHAPTER 18

18- 1	Comparison of Current and Potential Sludge Utilization to Commercial Fertilizer Consumption in the United States	18- 3
18- 2	Examples of Communities Practicing Land Utilization	18- 4

LIST OF TABLES (continued)

<u>Number</u>		<u>Page</u>
CHAPTER 19		
19- 1	Suitability of Sludges for Landfilling	19- 7
19- 2	Sludge and Site Conditions	19- 9
19- 3	Landfill Design Criteria	19- 15
19- 4	Leachate Quality From Sludge-Only Landfill	19- 16
19- 5	Landfill Equipment Performance Characteristics	19- 19
19- 6	Typical Equipment Type and Number as a Function of Landfill Method and Site Loading	19- 21
19- 7	Potential Environmental Problems and Control Practices	19- 23
19- 8	Surface Application Methods and Equipment for Liquid Sludges	19- 30
19- 9	Subsurface Application Methods and equipment for Liquid Sludges	19- 31
19-10	Furrow Slope Evaluation	19- 33
19-11	Methods and Equipment for Application of Dewatered Sludges	19- 35
19-12	Colorado Springs Population and Wastewater Flow Projections	19- 40
19-13	Colorado Springs Projected Cost of Sludge Management System	19- 43
19-14	Colorado Springs Climatic Conditions Affecting Sludge Disposal	19- 44
19-15	Colorado Springs Dedicated Land Disposal Subsurface Injection System Design Data	19- 49
19-16	Sacramento Regional Wastewater Treatment Plant Projected 1985 Wastewater Flow and Loadings	19- 51
19-17	Sacramento Regional Wastewater Treatment Plant Projected Digested Sludge Production	19- 51
19-18	Sacramento Test DLD Runoff Water Analysis	19- 55
19-19	Sacramento Regional Wastewater Treatment Plant Projected 1985 DLD Staffing Requirements	19- 58
19-20	Sacramento Regional Wastewater Treatment Plant Projected Costs of Sludge Management System Following Anaerobic Digestion	19- 59

LtST OF FtGURES

<u>Number</u>		<u>Page</u>
CHAPTER 1		
1- 1	Classification of Treatment Disposal Options	1- J
CHAPTER 3		
J- 1	Criteria for System Selection	J- J
J- 2	Components for System Synthesis	J- 4
J- J	Flowsheet Developed From Components for System Synthesis	J- 5
J- 4	Parallel Elements	J- 12
J- 5	Candidate Base Alternatives for Eugene- Springfield	J- 14
J- 6	Flowsheet for the Eugene-Springfield Sludge Management System	J- 17
J- 7	Blank OFD for Chemically-Assisted Primary Plant	J- 19
J- 8	OFO for Chemically-Assisted Primary Plant	J- 22
J- 9	OFD for Secondary Plant with Filtration	J- 25
3-10	Contingency Planning Example	J- 30
CHAPTER 4		
4- 1	Typical Relationship Between Peak Solids Loading and Duration of Peak for Some Large American Cities	4- 5
4- 2	Peak Sludge Loads, St. Louis Study	4- 6
4- J	Net Growth Rate Curves	4- 18
4- 4	Schematic for Sludge Quantity Example	4- 20
4- 5	Sludge Wasting Methods	4- 26
4- 6	VSS Production Data for Three Trickling Media Designs	4- 32
CHAPTER 5		
5- 1	Typical Concentration Profile of Municipal Wastewater Sludge in a Continuously Operating Gravity Thickener	5- •
5- 2	Typical Gravity Thickener Installation	5- 5
5- J	Cross Sectional View of a Typical Circular Gravity Thickener	5- 6
5- 4	Annual O&M Man-Hour Requirements - Gravity Thickeners	5- 16
5- 5	Annual Power Consumption - Continuous Operating Gravity Thickeners	5- 17

LIST OF FIGURES (continued)

<u>Number</u>		<u>Page</u>
5- 6	Estimated June 1975 Maintenance Material Cost For Circular Gravity ThiCkeners	5- 18
5- 7	Typical Rectangular, Steel Tank, Recycle Pressurization Dissolved Air Flotation Thickener	5- 21
5- 8	Float Concentration and Subnatant Suspended Solids Versus Solids Loading of a Waste-Activated Sludge - Without Polymers .	5- 25
5- 9	Float Concentration and Subnatant Suspended Solids Versus Solids Loading of a Waste-Activated Sludge - with Polymers	5- 26
5-10	Effect of Hydraulic Loading on Performance in Thickening Waste-Activated Sludge	5- 28
5-11	Float Concentration and Subnatant Suspended Solids Versus Air-Solids Ratio With Polymer For a Waste-Activated Sludge	5- 29
5-12	float Concentration and Subnatant Suspended Solids Versus Air-Solids Ratio Without Polymer For a Waste-Activated Sludge .	5- 30
5-13	Annual O&M Man-Hour Requirements - OAF Thickeners	5- 37
5-14	Annual Power Consumption - Continuous Operating OAF Thickeners	5- 3B
5-15	Estimated June 1975 Maintenance Material Cost For OAF ThiCkeners	5- 39
5-16	Typical Disc Nozzle Centrifuge in the Field	5- 40
5-17	Schematic of a Disc Nozzle Centrifuge	5-
5-18	Typical Disc Nozzle Pretreatment System	5-
5-19	Effect of Activated Sludge Settleability on Capture and Thickening	5-
5-20	General Schematic of Imperforate Basket Centrifuge	5- 46
5-21	Relative Influence of One Pocess variable as a Function of Feed Solids Content for Imperforate Basket Centrifuge Holding All Other Process Variables Constant	5- 48
5-22	Schematic of Typical Solid Bowl Decanter Centrifuge	5- 50
5-23	Solid Bowl Decanter Centrifuge Installation	5- 51
5-24	Estimated June 1975 Solid Bowl Decanter Installation capital Cost	5- 56
5-25	Annual O&M Requirements - Solid Bowl Decanter Centrifuge	5- 58
5-26	Estimated June 1975 Maintenance Material Cost for Solid Bowl Decanter Centrifuge	5- 59

CHAPTER 6

6- 1	Summary of the Anaerobic Digestion Process ,	6- 5
6- 2	Low-Rate Anaerobic Digestion System	6- 8

LIST OF FIGURES (continued)

<u>Number</u>		<u>Page</u>
6- 3	Single- Stage, High- Rate Anaerobic Digestion System	6- 9
6- 4	Flow Diagram for the Torpey Process	6- 10
6- 5	Two-Stage, High-Rate Anaerobic Digester System	6- 12
6- 6	Carbon and Nitrogen Balance for a Two-Stage, High-Rate Digestion System	6- 14
6- 7	Effect of Recycling Digester Supernatant on the Suspended Solids Flow Through an Activated Sludge plant	6- 11
6- 8	Anaerobic Contact Process	6- 15
6- 9	Two-Phase Anaerobic Digestion Process	6- 16
6-10	Effect of SRT on the Relative Breakdown of Degradable Waste Components and Methane Production	6- 21
6-11	Effect of Temperature and SRT on the Pattern of Methane Production and Volatile Solids Breakdown	6- 22
6-12	Effect of Solids Retention Time and Temperature on Volatile Solids Reduction in a Laboratory-Scale Anaerobic Digester	6- 27
6-13	Volatile Solids Reduction vs Temperature x SRT for Three Types of Feed Sludges	6- 28
6-14	Effect of Temperature on Gas Production	6- 30
6-15	Relationship Between pH and Bicarbonate Concentration Near 95°F (35°C)	6- 11
6-16	Cylindrical Anaerobic Digestion Tanks	6- 43
6-17	Rectangular Anaerobic Digestion Tank	6- 11
6-18	Egg-Shaped Anaerobic Digestion Tank at Terminal Island Treatment Plant, Los Angeles	6- 43
6-19	Schematic of the Heat Reservoir System for a Jacketed Pipe or Spiral Heat Exchanger	6- 11
6-20	Spiral Heat Exchanger Operating Off Secondary Heat Loop at Sunnyvale, California	6- 11
6-21	Effect of Solids Concentration on the Raw Sludge Heating Requirement	6- 11
6-22	Circulation Patterns Produced by Draft Tube and Free Gas Lift Mixers	6- 11
6-23	Draft Tube and Free Gas Lift Pumping Rate	6- 11
6-24	Comparison of Lance and Draft Tube Mixing in Clean Water	6- 11
6-25	Effect of Temperature on the Viscosity of water	6- 60
6-26	Effect of Solids Concentration and Volatile Content on the Viscosity of Digesting Sludge	6- 61
6-27	Types of Digester Covers	6- 11
6-28	Overall View of Four Digesters with Downes floating Covers at Sunnyvale, California	6- 11
6-29	Typical Digester Supernatant Collection System	6- 68

LIST OF FIGURES (continued)

<u>Number</u>		<u>Page</u>
6-30	Digester Drain System	6- 71
6-31	Digester Washwater Cleaning by Cyclonic Separators, Grit Oewaterers, and Static Screens at Los Angeles County Carson Plant	6- 12
6-32	Energy Flow Through an Anaerobic Sludge Digestion System	6- 73
6-33	Construction Costs for Anaerobic Digestion Systems	6- 75
6-34	Operating, Maintenance, and Energy Costs for Anaerobic Sludge Digestion Systems	6- 76
6-35	Conceptual Design of an Anaerobic Sludge Digestion System	6- 80
6-36	Process Flow Diagram for a Conventional Continuously Operated Aerobic Digester	6- 85
6-37	Reaction Rate K_d Versus Anaerobic Digester Liquid Temperatures	6- 87
6-38	Effect of Solids Concentration on Reaction Rate K_d	6- 88
6-39	Influence of Sludge Age and Liquid Temperatures on the Oxygen Uptake Rates in Aerobic Digesters	6- 89
6-40	Design Chart for Low Speed Mechanical Aerators in Non-Circular Aeration Basins to Calculate Energy Requirements for Meeting Oxygen Requirements	6- 90
6-41	Effect of Sludge Age on pH During Aerobic Digestion	6- 91
6-42	Volatile Solids Reduction as a Function of Digester Liquid Temperature and Digester Sludge Age	6- 92
6-43	Summary of Results for Aerobic Digestion Design Example	6- 98
6-44	Lime Doses Required to Raise pH of a Mixture of Primary Sludge and Trickling Filter Humes at Different Solids Concentrations	6-106
6-45	Change in pH During Storage of Primary Sludge Using Different Lime Dosages ..	6-107
6-46	Effect of pH on Hydrogen Sulfide-Sulfide Equilibrium .	6-108
6-47	Conceptual Design for a Lime Stabilization Facility .	6-125
6-48	Schematic Diagram of a Chlodne Oxidation System	6-129
CHAPTER 7		
7- 1	Potential Pathogen Pathways to Man	7- 13
7- 2	Flow Scheme for Sludge Pasteurization With Single-Stage Heat Recuperation	7- 15

LIST Of FIGURES (continued)

<u>Number</u>		<u>Page</u>
7- 3	Energy Requirements for Sludge Pasteurization Systems	18
7- 4	Construction Costs for Sludge Pasteurization Systems Without Heat Recovery .	19
7- 5	Construction Costs for Sludge Pasteurization Systems With Heat Recovery .	20
7- 6	Labor Requirements for Sludge Pasteurization Systems	21
7- 7	Maintenance Material Costs for Sludge With Heat Recovery	24
7- 9	Equipment Layout for Electron Beam facility	28
7-10	Electron Beam Scanner and Sludge Spreader	29
7-11	Schematic Representation of Cobalt-60 Irradiation facility at Geiselbullach, West Germany ..	31
7-12	Gamma Radiation Treatment of Liquid Sludge Power Requirements	36
7-13	Radiation Treatment of Dewatered Sludge - Power Requirements	37
7-14	Gamma Radiation Treatment of Liquid Sludge - Capital Costs	39
7-15	Gamma Radiation Treatment of Liquid Sludge Labor Requirements	40
7-16	Gamma Radiation Treatment of Liquid Sludge Maintenance Material Supplies and Costs	41
7-17	Gamma Radiation Treatment Facility for Handling 25 Tons per Day or More of Dewatered Sludge	41
7-18	Gamma Radiation Treatment of Dewatered Sludge Capital Cost	42
7-19	Gamma Radiation Treatment of Dewatered Sludge-Label Requirements	43
7-20	Gamma Radiation Treatment of Dewatered Maintenance Materials and Supplies Cost	44

CHAPTER 8

8- 1	Basic Parameters for Evaluation of a Sludge Conditioning System	8- 2
8- 2	Particle Size Distribution of Common Materials	8- 3
8- 3	Typical Concentration Profile of Municipal Wastewater Sludge in a Continuously Operating Gravity Thickener .	8- 5
8- 4	Capital Cost of Ferric Chloride Storage and Feeding Facilities	8- 10
8- 5	Capital Cost of Lime Storage and Feeding Facilities .	13- 11
8- 6	Ferric Chloride Storage and Feeding Operating and Maintenance Work-Hour Requirements	8- 11
8- 7	Electrical Energy Requirements for a Ferric Chloride Chemical Feed System	8- 12

LIST OF FIGURES (continued)

<u>Number</u>		<u>Page</u>
8-9	Lime Storage and Feeding Operation and Maintenance Work-Hour Requirements	8- 12
8-10	Electrical Energy Requirements for a Lime Feed System	8- 13
8-10	Polyacrylamide Molecule - Backbone of the Synthetic Organic Polyelectrolytes	8- 15
8-11	Typical Configuration of a Cationic Polyelectrolyte in Solution	8- 17
8-12	Schematic Representation of the Bridging Model for the Destabilization of Colloids by Polymers	8- 19
8-13	Effect of Biological Solids on Polymer Requirements in Belt Press Dewatering	8- 24
8-14	Relative Influence of Polymer Addition on Imperforate Basket Centrifuge Process Variables	8- 24
8-10	Polymer Storage and Feeding Operation and Maintenance Work-Hour Requirements	8- 29
8-16	Electrical Energy Requirements for a Polymer Feed System	8- 30
8-17	General Thermal Sludge Conditioning Flow Scheme for a Non-Oxidative System	8- 32
8-18	General Thermal Sludge Conditioning Flow Scheme for an Oxidative System	8- 33

CHAPTER 9

9- 1	Schematic of Sludge Dewatering in a Drying Bed System	9- 4
9- 2	Typical Sand Drying Bed Construction	9- 6
9- 3	Typical Paved Drying Bed Construction	9- 6
9- 4	Cross Section of a Wedge-Wire Drying Bed	9- 7
9- 5	Estimated June 1975 Maintenance Material Cost for Open Sand Drying Beds	9- 13
9- 6	1977 Flow Diagram of Burlington, Wisconsin Wastewater Treatment Plant	9- 11
9- 7	Flow Diagram of a Filtration System	9- 25
9- 8	Cutaway View of a Drum or Scraper-Type Rotary Vacuum Filter	9- 29
9- 9	Operating Zones of a Rotary Vacuum Filter	9- 29
9-10	Cross Sectional View of a Coil Spring - Belt Type - Rotary Vacuum Filter	9- 3D
9-11	Typical Coil Spring - Belt Type - Rotary Vacuum Filter Installation	9- 31
9-12	Cross Sectional View of a Fiber Cloth - Belt Type - Rotary Vacuum Filter	9- 32
9-13	Typical Fiber Cloth - Belt Type - Rotary Vacuum Filter	9- 33
9-14	Rotary Vacuum Filter System	9- 36

LIST OF FIGURES (continued)

<u>Number</u>		<u>Page</u>
10- 1	Estimate of Energy Required to Dry Wastewater Sludge as a Function of Dryer Feed Solids Content	10- 6
10- 2	Schematic for Sludge Drying Example	10- 7
10- 3	Flash Dryer System (Courtesy of C.E. Raymond) ..	10- 11
10- 4	Schematic for a Rotary Dryer	10- 20
10- 5	Jacketed Hollow-Flight Dryer {Courtesy Bethlehem Corporation)	10- 23
10- 6	Toroidal Drying System	10- 26
10- 7	Schematic of BEST Process	10- 29

CHAPTER 11

11- 1	Basic Elements of High Temperature Processes . . .	11- 1)
11- 2	Effect of Excess Air and Excess Temperature on Supplemental fuel Requirements	11- B
11- 3	Effect of Dry Solids Heating Value and Sludge Moisture on Capability for Autogenous Combustion	11- 11
11- 4	Effect of Sludge Moisture Content and Combustible Solids Content on Supplemental Fuel Consumption	11- 12
11- 5	Hypothetical Wastewater Treatment Plant Flowsheet	11- 30
11- 6	Cross Section of a Multiple-Hearth Furnace	11- 33
11- 7	Shaft Cooling Air Arrangement in a Multiple-Hearth Furnace .	11- 34
11- 8	Process Zones in a Multiple-Hearth Furnace	11- 35
11- 9	Flowsheet for Sludge Incineration in a Multiple-Hearth Furnace	11- 33
11-10	Multiple-Hearth Furnace Start-Up Fuel Requirements	11- 41
11-11	Multiple-Hearth Furnace Construction Cost	11- 42
11-12	Multiple-Hearth Furnace Operating and Maintenance Labor Requirements	11- 44
11-13	Multiple-Hearth Furnace Fuel Requirements	11- 45
11-14	Multiple-Hearth Furnace Electrical Power Requirements	11- 46
11-15	Multiple-Hearth Furnace Maintenance Material Costs	11- 11
11-16	Heat Balance for the Recycle Concept in a Multiple-Hearth Furnace	11- 49
11-17	Cross Section of a Fluid Bed Furnace	11- 50
11-18	Flowsheet for Sludge Incineration in a Fluid Bed Furnace	11- 52
11-19	Fluid Bed furnace Fuel Requirements	11- 5)
11-20	Fluid Bed Furnace Electrical Power Requirements	11- 54

LIST OF FIGURES (continued)

<u>Number</u>		<u>Page</u>
11- 21	Cross Section of an Electric Infrared Furnace ••	11- 55
11- 22	Flowsheet for Sludge Incineration in an Electric Infrared Furnace ••••••••••••••••••••	11- 56
11- 23	Cross Section of a Cyclonic Furnace ••••••••••	11- 58
11- 24	Flow-sheet for Sludge Incineration in a Cyclonic Furnace ••••••••••••••••••••••••••	11- 59
11-25	Design Example: Heat and Material Balance in a Fluid Bed Furnace .	11- 64
11-26	Comparison of Excess Air Requirements: Incineration vs. Starved-Air Combustion ••••••••••	11- 66
11-21	Flowsheet for Starved-Air Combustion in a Multiple-Hearth Furnace ••••••••••••••••••••••	11- 69
11-28	Design Example: Starved-Air Combustion in a Multiple-Hearth Furnace .	11- 82
11- 29	Typical Grate-Fired Waterwalled Combustion Unit ••••••••••••••••••••••••••••••••••••••	11- 11
11-30	Vertical Shaft Reactors ••••••••••••••••••••••	11- 87
11- 31	Autogenous Combustion Requirements for Co-Disposal ••••••••••••••••••••••••••••••••	11- 11
11- 32	Flowsheet for CO-Combustion Full Scale Test at the Central Contra Costa Sanitary District, California ••••••••••••••••••••••••••••••••	11- 90
11- 33	Flowsheet for Co-Combustion at the Western Lake Superior Sanitary District, Duluth, Minnesota ••••••••••••••••••••••••••••••••	11- 93
11- 34	Cross Section of the Watergate Furnace for Scum Incineration ••••••••••••••••••••••••••	11- 97
11- 35	JPL Activated Carbon Treatment System ••••••••••	11-101
11- 36	Volatile Solids and COD Content of Heat Treated Sludge ••••••••••••••••••••••••••••••	11-105
11- 31	Flowsheet for High Pressure/High Temperature Wet Air Oxidation ••••••••••••••••••••••••••	11-106
11- 38	Wet Air Oxidation - Electrical Energy Requirements ••••••••••••••••••••••••••••••	11-108
11- 39	React-O-Therm™ on Sludge/Liquid Waste Destruction ••••••••••••••••••••••••••••••	11- 109
11-40	Modular Controlled-Air Incinerator Configurations ••••••••••••••••••••••••••••••	11-111
11-41	Pyro-Sol Limited Pyrolysis System ••••••••••••••	11-112
11-42	Bailie Process Flowsheet ••••••••••••••••••••	11- 113
11- 43	Wright-Malta Process Flowsheet ••••••••••••••	11- 114
11-44	Air Emissions ••••••••••••••••••••••••••••••	11-115
11- 45	San Francisco Bay Area Quality Management District: Auxiliary Fuel and Oxygen Correction ••••••••••••••••••••••••••••••	11- 126

CHAPTER 12

12- 1	Effect of Solids Content on the Ratio of Wood Chips to Sludge by Volume .	12- 4
-------	--	-------

LIST OF FIGURES (continued)

<u>Number</u>		<u>Page</u>
14- 2	Comparison of Behaviors of Wastewater Sludge and Water Flowing in Circular Pipelines	14- 6
14- 3	Friction Factor for Sludge, Analyzed as a Bingham Plastic	14- 7
14- 4	Friction Factors for Example Problem	14- 12
14- 5	Pressure Drops for Example Problem	14- 13
14- 6	Viscometer Test of Sewage Sludge	14- 16
14- 7	Centrifugal Pump	14- 18
14- 8	Torque Flow Pump	14- 19
14-12	Progressive Cavity Pump	14- 23
14-13	Diaphragm Pump	14- 25
14-14	Rotary Pump	14- 27
14-15	Ejector Pump	14- 28
14- 16	Belt Conveyor	14- 38
14-17	Inclined Belt Conveyor Features	14- <1
14-18	Flexible Flat Belt Conveyor	14- 42
14-19	Screw Conveyor	14- 42
14-20	Tabular Conveyor	14- 43
14-21	Bucket Elevator	14- 44
14-22	Pneumatic Ejector	14- 44
14-23	Pneumatic Conveyor	14- 44

CHAPTER 15

15- 1	Solids Balance and Flow Diagram-Design Example Single-Phase Concentration and Displacement Storage	15- 13
15- 2	Effect of Various Operating Strategies on Dewatering Unit Feed Rates	15- 14
15- 3	Proposed Design for Blending Digester--Sacramento Regional Wastewater Treatment Plant	15- 21
15- 4	26,000 Gallon Sludge Equalization Tank (Typical of Two) Also Solids Stabilization Facility	15- 22
15- 5	Schematic Representation of a Facultative Sludge Lagoon (FSL)	15- 25
15- 6	Typical Brush-Type Surface Mixer, Sacramento, California	15- 27
15- 7	Typical FSL Layout	15- 29
15- 8	Typical FSL Cross Section	15- 29
15- 9	Layout for 124 Acres of FSLs--Sacramento Regional Wastewater Treatment Plant	15- 30
15-10	Sacramento Central Wastewater Treatment Plant Surface Layer Monitoring Data for FSLs 5 to 8	15- 34
15- 11	Sacramento Central Wastewater Treatment Plant 1977 Fecal Coliform Populations for Various Locations in the Solids Treatment-Disposal Process	15- 38
15-12	Typical Wind Machines and Barriers Sacramento, California	15- 40

LIST OF FIGURES (continued)

Number		<u>Page</u>
12- 2	Locations for Temperature and Oxygen Monitoring at One End of a Windrow or Individual Aerated Pile	12- 7
12- 3	Sludge Composting Mass Balance Diagram	12- 9
12- 4	Temperature Profile of a Typical Compost Windrow	12-14
12- 5	Turning a Windrow at Los Angeles Compost Site ."	12- 15
12- 6	Destruction of Pathogenic Organisms as a Function of Time and Temperature Ouring Composting of Digested Sludge by the Windrow Method	12- 17
12- 7	Process Flow Diagram - Windrow Composting Sludge - 10 MGD Activated Sludge Plant	12- 21
12- 8	Configuration of Individual Aerated Piles	12- 22
12- 9	Aeration Pipe Set-Up for Individual Aerated pile	12- 23
12-10	Configuration of Extended Aerated Pile	12-25
12-11	Destruction of Pathogenic Organisms as a Function of Time and Temperature During Composting of Undigested Sludge by the Aerated Pile Method	12- 28
12-12	Odor Filter Piles at Beltsville .	12- 29
12-13	Process Flow Diagram for the Extended PUE Compost Sludge Facility - 10 MGD Activated Sludge Plant	12- 32
12-14	Design Example Extended Aerated Pile Construction	12- 34
12-15	Compost Piles Being Taken Down	12- 35
12-16	Finished Screened Compost	12-37
12-17	Composting/Drying System - County Sanitary Districts - Los Angeles .	12- 39
12-18	Composting Site Layout - Bangor, Maine	12-44
12-19	Cross Section of Aeration Pipe Trench Durham Compost Pad Design	12-48
12-20	Typical Process Flow Schematic Confined Composting System	12-52
12-21	Partial Diagram Metro - Waste System - Resource Conversion Systems, Inc	12- 53
12-22	Typical Layout of a Dano Bio-Stabilizer Plant	12- 54
12-23	BAV Bioreactor	12- 56

CHAPTER 13

13- 1	Diagram of an Earthworm Conversion Process	13- 5
-------	--	-------

CHAPTER 14

14- 1	Approximate Friction Head-Loss for Laminar Flow of Sludge	14- 3
-------	---	-------

LIST OF FIGURES (continued)

<u>Number</u>		<u>Page</u>
14- 2	Comparison of Behaviors of Wastewater Sludge and Water Flowing in Circular Pipelines .	14- 6
14- 3	Friction Factor for Sludge, Analyzed as a Bingham Plastic	14- 7
14- 4	Friction Factors (or Example Problem ...)	14- 12
14- 5	Pressure Drops for Example Problem	14- 13
14- 6	Viscometer Test of Sewage Sludge	H- 16
14- 7	Centrifugal Pump	H- 18
14- 8	Torque Flow Pump	H- 19
14-12	Progressive Cavity Pump	H- 23
14-13	Diaphragm Pump	H- '5
14-14	Rotary Pump	H- 27
14-15	Ejector Pump	14- 28
14-16	Belt Conveyor	H- 38
14-17	Inclined Belt Conveyor Features	14- 41
14-18	Flexible Flat Belt Conveyor	H- "
14-19	Screw Conveyor	H- "
14-20	Tabular Conveyor	H- 43
14-21	Bucket Elevator	14- 44
14-22	Pneumatic Ejector	H- 45
14-23	Pneumatic Conveyor	14- 45

CHAPTER 15

15- 1	Solids Balance and Flow Diagram-Design Example Single-Phase Concentration and Displacement Storage	15- 13
15- 2	Effect of Various Operating Strategies on Dewatering Unit Feed Rates .	15- 17
15- 3	Proposed Design for Blending Digester--Sacramento Regional Wastewater Treatment Plant	15- 21
15- 4	26,000 Gallon Sludge Equalization Tank (Typical of Two I Aliso Solids Stabilization Facility ...)	15- 22
15- 5	Schematic Representation of a Facultative Sludge Lagoon (FSL)	15- 25
15- 6	Typical Brush-Type Surface Mixer, Sacramento, California	15- 27
15- 7	Typical FSL Layout	15- 29
15- B	Typical FSL Cross Section	15- 29
15- 9	Layout for 124 Acres of FSLs--Sacramento Regional Wastewater Treatment Plant	15- 30
15-10	Sacramento Central Wastewater Treatment Plant Surface Layer Monitoring Data for FSLs 5 to '8	15 -34
15-11	Sacramento Central Wastewater Treatment Plant 1977 Fecal Coliform Populations for Various Locations in the Solids Treatment-Disposal Process.....	15- 38
15-12	Typical Wind Machines and Barriers Sacramento, California	15- 40

LIST OF FIGURES (continued)

<u>Number</u>		<u>Page</u>
15-13	Anaerobic Liquid Sludge Lagoons, Prairie Plan Land Reclamation Project, the Metropolitan Sanitary District of Greater Chicago	15- 42
15-14	Plan View of Drying Sludge Lagoon Near West-Southwest Sewage Treatment Works, Chicago	15- 49
15-15	Cross Section of Draw-Off Box Area Drying Sludge Lagoon Near West-Southwest Sewage Treatment Works, Chicago	15- 50
15-16	Cross Section of Drying Sludge Lagoon With Slackline Cable Near West-Southwest Treatment Works, Chicago	15- 50
15-17	Isometric of Sludge Storage and Truck Loading Station, Joint Water Pollution Control Plant, Los Angeles County, California	15- 55
15-18	Storage Bin Discharge Control System, Joint Water Pollution Control Plant, Los Angeles County, California	15- 57
CHAPTER 16		
16- 1	Example of Sidestream Production	16- 2
16- 2	Possible Treatment Scheme for Anaerobic Digester Supernatant	16- 9
16- 3	Aerobic Digestion of Heat Treatment, Batch Tests	16-12
16- 4	Flow Diagram, Anaerobic Filtration of Heat Treatment Liquor	16-14
16- 5	Schematic Diagram of Plant for Processing Heat Treatment Liquor	16-16
16- 6	Chlorine Treatment of Heat Treatment Liquor	16-17
CHAPTER 17		
17- 1	Typical Bubbler Schematic With Air Purge Capabilities	17- 42
17- 2	Typical Bubbler Schematic With Diaphragm Element	17- 43
17- 3	Cylindrical Chemical Seal for Sludge Pressure Measurement	17- 52
17- 4	Direct Reading Olfactometer (DRO)	17- 62
17- 5	Aeration Control Graphic Panel and Console Lights Set Manually on Graphic Panel	17- 69
17- 6	Incinerator-Digester Control Graphic Panel Lights Controlled by Remote Valve Limit Switches	17- 70
CHAPTER 18		
18- 1	The Release, Conversion, Forms and Uses of Energy From Sludge	18- 10

LIST OF FIGURES (continued)

<u>Number</u>		<u>Page</u>
18- 2	Schematic of Combined Boiler/Condenser System for Hot Water Production	18- 12
18- 3	Process Schematic for Example of Energy Recovery From Digester Gas	18- 16
18- 4	Energy Flowsheet for Example of Energy Recovery From Digester Gas	18- 18
18- 5	Mean Molal Heat Capacities of Gases at Constant Pressure (Mean Values From 77 ° to TOP) ..	18- 23
18- 6	Flowsheet for Example of Energy Recovery From Incinerator Flue Gas	18- 27
18- 7	Steam Conditions for Example of Recovery of Energy From Incinerator of Flue Gas	18- 28
18- 8	Energy Flowsheet for Example of Energy Recovery From Incinerator Flue Gas	18- 32

CHAPTER 19

19- 1	Wide Trenching Operation. North Shore Sanitary District	19- 4
19- 2	Dewatered Sludge Landspreading, Metropolitan Denver Sewage Disposal District No. I, Denver, Colorado	19- 36
19- 3	Flow Diagram Sludge Management System, Colorado Springs, Colorado	19- 41
19- 4	Overall Sludge Disposal Site Layout, Colorado Springs, Colorado	19- 42
19- 5	Sludge Application Rate-DLO System Colorado Springs, Colorado	19- 45
19- 6	Estimated Net OLD Area Requirements Sludge Applied at 5 Percent Solids Concentration, Colorado Springs, Colorado	19- 46
19- 7	Estimated Net OLD Area Requirements at Various Sludge Concentrations, Colorado Springs, Colorado	19- P
19- 8	Sludge Application Rates by Subsurface Injection, Colorado Springs, Colorado	19- 48
19- 9	Prototype Dredging Operation, Sacramento Regional County Sanitation District	19- 50
19-10	Prototype Subsurface Injection Operations Sacramento Regional County sanitation District	19- 52
19-11	Flow Diagram - Projected 1992 Normal Solids Treatment and Disposal Operation, Sacramento Regional Wastewater Treatment Plant	19- 53

ACKNOWLEDGEMENTS

This design manual was prepared as part of the Technology Transfer Series of the Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. Development, coordination and preparation were carried out by Brown and Caldwell, Consulting Engineers, Walnut Creek, California, with the assistance of Environmental Technology Consultants, Inc., of Springfield, Virginia. Technical review and coordination were provided by the Office of Water Program Operations, USEPA, Washington, D.C. Additional technical review and contributions were provided by Regions V and IX of the USEPA, by the Metropolitan sanitary District of Greater Chicago, and by the Technical Practice Committee of the Water Pollution Control Federation. USEPA project officers on this manual were Dr. Joseph B. Farrell, Municipal Environmental Research Center, and Dr. James E. Smith, Jr., Center for Environmental Research Information, Cincinnati, Ohio.